the influence of room contents on horizontal illuminance conditions in electrically lit commercial interiors

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abstract

The majority of traditional lighting design methods assume that the space between the working plane and the plane of the luminaires is empty. The presence of furniture and equipment affects light distribution and may influence the final illuminance pattern. Obstructions found in typical commercial interiors may include VDU's, filing cabinets, dividing partitions and the office occupants themselves. Whilst the empty space approximation provides a capable method of calculation of average working plane illuminance in an empty room, the lack of realism has become a notable concern.

The review of published work pertaining to lighting design methods for non-empty interiors shows that a large body of knowledge exists regarding the role of obstructions in the lighting design process. Some techniques have been proposed to the lighting community but there is a need for development, better presentation and dissemination of the results before the empty room assumption can be rendered obsolete.

The investigation detailed in this document is concentrated into two main areas that result in the development of a design method capable of compensating for the likely effects of obstructions in spaces where the precise nature of the room contents is not known.

The first part of the design method is a modification of the conventional Lumen Method. This modified method can be used by the designer to predict and compensate for a reduction in average working plane illuminance due to room contents. An extensive computer simulation was used to generate obstruction loss data for a vast array of different scenarios from which a set of general characteristics was devised. The modification takes the form of a supplemental factor in the Lumen Method equation. The additional factor is dependent on a combination of luminaire type and the amount of furniture present within the space. Techniques are also proposed for predicting furniture density. The results of the design method are verified by comparison with a number of photometric surveys and with other prediction methods. Additionally, the use and validation of the technique by two major lighting companies is described.

The second part of the investigation covers the development of a 'rule-of-thumb' technique that can be used by the designer to determine luminaire spacings. The luminaire spacing is related to the uniformity of illuminance achieved in the installation, but this is also affected by the presence of obstructions. The new technique gives guidance pertaining to the use of appropriate luminaire spacing-to-mounting-height ratio's in obstructed interiors.

contents

Chapter one – Introduction

Chapter 2 – Advances in lighting design for non-empty interiors

Chapter 3 – The components of an obstructed interior

Chapter 4 – Measured light losses in commercial interiors

Chapter 5 – Computer synthesis of obstructed spaces

Chapter 6 – An average illuminance lighting design method for obstructed interiors

Chapter 7 – The influence of SHR on illuminance conditions in obstructed interiors

Chapter 8 – Conclusions and recommendations

Appendix One

Appendix Two

Appendix Three

Chapter 1

Introduction

1.1 Background

General lighting schemes are usually designed to produce an average horizontal illuminance on the working plane, such that a task located anywhere within the installation will receive an adequate level of illuminance. The majority of designs of this type are planned assuming that the space between the working plane and the luminaire plane is empty. This "empty space" assumption will be incorrect for the majority of commercial interiors, as most will contain some form of interior furnishing.

In a typical office suite, equipment such as partitions, VDT's, filing cabinets and the users of the office themselves, will project above the working plane and cause disruption to the planned light distribution, both in terms of local variation of illuminance and an overall reduction in average working plane illuminance. (See figure 1.1). The risk of obstruction light loss is further increased by recent developments in lighting practice, prompted by the problems of VDT users, the pressure to increase energy efficiency and the modern trend towards designing large open plan offices, which can then be subdivided with partitioned

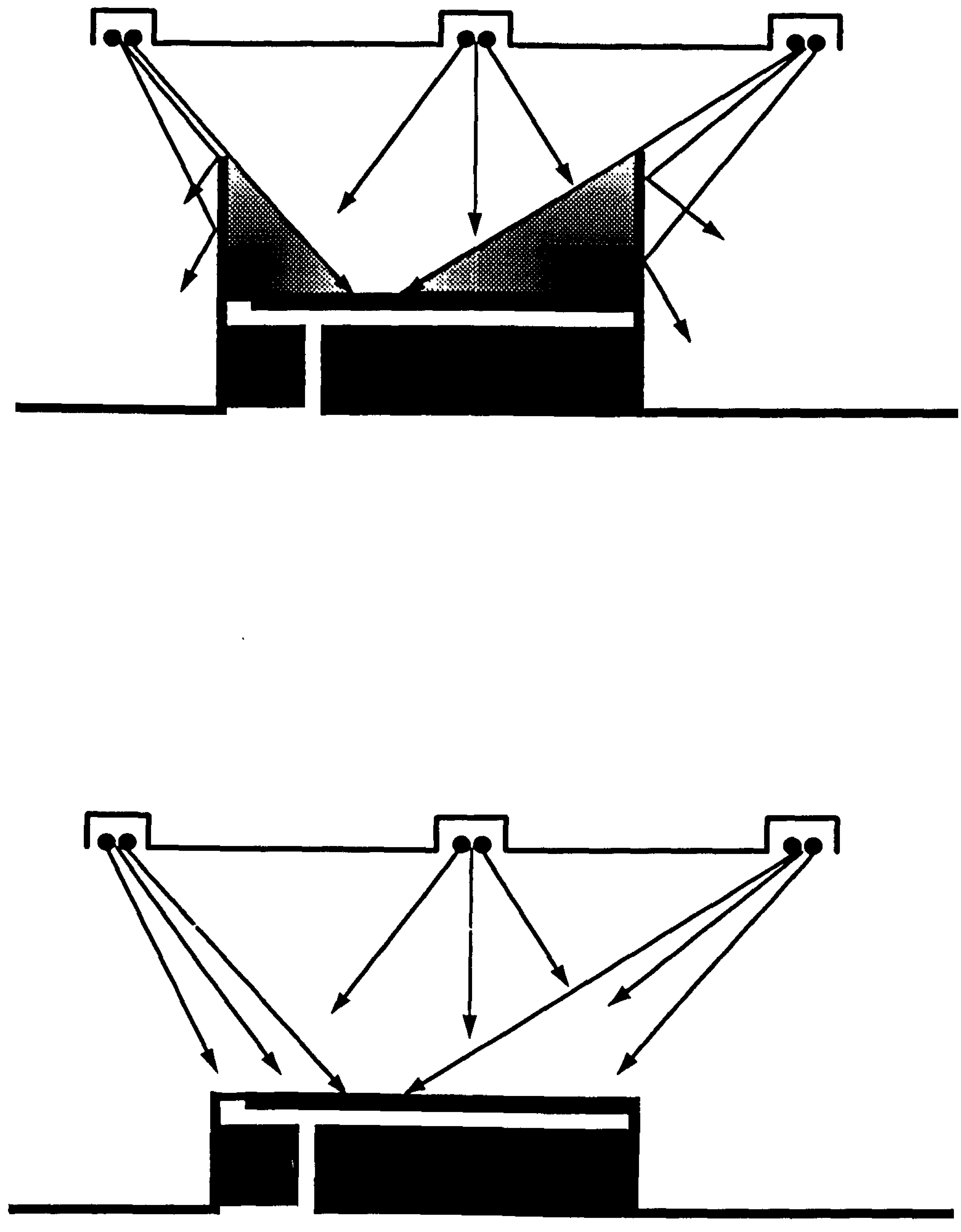

Figure 1.1: Illustration of the effect of obstructions on the illuminance received on the working plane.

workstations.

Contemporary lighting design methods, although accounting for the optical properties of luminaires, room geometry and reflectance characteristics, they do not consider the presence of obstructions and are therefore limited in practice to the design of empty spaces. There is much concern within the lighting community regarding realistic assumptions in lighting design calculation techniques. Additionally, the recent changes to European lighting design standards towards specifying maintained illuminance† at the task as opposed to the standard service illuminance‡ will allow installations to be checked for compliance to performance specifications more readily. Both of the aforementioned developments emphasize the requirements for a new design method that will improve the shortcomings in current techniques and take account of the influence of obstructions.

At present, several of the relevant lighting codes of practice and standards acknowledge that obstructions will influence the distribution of light onto the working plane. The CIBSE Code for Interior Lighting[1], for instance, notes that difficulty in achieving required uniformity standards may occur in areas containing substantial obstruction and that an increased number of luminaires may be necessary if there is a high degree of obstruction over the working plane. The design guidance of other lighting bodies, such as the IESNA Handbook[2] and the DIN 5035 Part 1[3] also offer similar non-numerical advice. Some guidance is available regarding the role of obstructions in the design of lighting installations for special cases, such as libraries[4] or spaces containing uniformly positioned cubicle workstations[2]. None, however, offer numerical design guidance that may be used by designers planning

† the minimum illuminance at which maintenance must be carried out.

‡ the illuminance at some point approximately half way between the new installation and the time when maintenance must be carried out.

lighting schemes for spaces where the furniture layout or content is unknown – the case for the majority of lighting designs.

1.2 Previous research

At the University of Liverpool, research has approached lighting design methods for obstructed interiors in two stages[5,6]. The research has also been divided into two distinct areas. Firstly, there was the modification to the current technique used to calculate the spacing-to-mounting-height ratio (SHR) of a luminaire. The SHR is intended for use by the designer when determining the limits of luminaire spacings that can be used in practice to achieve the required uniformity standards. As with the current lighting design methods the technique for calculating SHR assumed an empty space. A modification to this method, proposed and developed by previous researchers, took the form of a modified spacing-to-mounting-height ratio, which could be selected by the designer as being appropriate to the amount of obstruction and the luminaire type being used. This work was at the stage where it was almost ready to be applied as a design tool in practice.

The second area of research investigated the relationship between the installation parameters (luminaire type, room size and properties and obstruction size and properties) and the magnitude of obstruction light loss caused over the working plane. The main thrust of this work has been the development of a computer program for use in calculating the percentage reduction in average working plane illuminance caused by obstructions. This work demonstrated that it was feasible to predict light losses in obstructed spaces based on a knowledge of the contents of the room.

1.3 Extending the previous research

Throughout the course of the research into obstructed spaces, a series of concepts, relationships and tools have been developed and refined. A comprehensive body of knowledge was assembled regarding the role of obstructions in the lighting design process and using this knowledge some limited design techniques were proposed. There is a need, however, for development, better presentation and dissemination of the results before the empty room assumption can be rendered obsolete. The limitations of the previous research were eliminated. The standard obstruction configurations were redefined to extend their applicability. The computer software developed by the previous researchers was converted to operate on a more suitable platform and several refinements were made to the program algorithms. Penultimately, these tools and concepts were used to develop an average illuminance lighting design method that could be applied to a practical range of installation parameters and compensate for the effects of a variety of obstruction configurations. The final extension of the previous research takes the form of readily implemented, "rule-of-thumb" advice regarding the spacing of luminaires in obstructed spaces to achieve required uniformity standards, an area void of guidance in any of the relevant Codes or Standards.

The development of the aforementioned design method and the luminaire spacing guidance is described in this thesis, which is divided into seven chapters. Chapters Two and Three describe the background to the research and outline the preparatory stages before the development of the new design method was undertaken. Chapter Four describes a series of photometric surveys that were undertaken to expand on the limited knowledge available in that area and to provide validation data against which trends and magnitudes of results could be verified. Chapters Five, Six and Seven are the core of the research, describing the evolution of the average illuminance lighting design method for obstructed spaces and the luminaire spacing guidance.

Chapter Two reviews the many advances that have been made in lighting design methods for obstructed spaces since the last published review, almost ten years ago. It summarises the approaches taken by the various major Codes and Standards and reviews the "quantitative" approach to the modelling of obstructed spaces. This includes the theoretical basis and practical uses of the various computer based methods, the available measured data and the empirically developed design methods. In addition to this the "qualitative" aspects of visual conditions in obstructed spaces are also identified.

Chapter Three investigates the various components of an obstructed interior and the software developed by the University of Liverpool for the research and design of obstructed interiors. Firstly, the development of a set of standard obstructions is reviewed and some modifications to the obstructions are proposed, based upon current practice found in furniture surveys of modern commercial interiors. Several practical applications of the standard obstructions are proposed. The development of the computer software is also reviewed and the refinements made to the software before it was used in the generation of design data are described.

Chapter Four is concerned with the field measurement of the amount of light absorbed by room contents in commercial interiors. Some twenty-four surveys are reported, in which the horizontal working plane illuminance was measured for states of interior furnishing ranging from empty to uniform distributions of standard obstruction, and in some cases, under the actual working conditions. The size, disposition and photometric characteristics of all room furnishings were also recorded. The interiors contained lighting equipment that is representative of good modern practice.

Chapters Five and Six outline the development of the average illuminance design method. Chapter Five describes the basis on which an extensive set of design data was generated, using the computer software described in Chapter Three. The results were validated against measured data, found in the photometric surveys described in Chapter Four and against results found by previous researchers. Chapter Six details the means through which the data set was converted into a form suitable for use by practicing designers. The use of the new method is illustrated by examples and validated by comparison with other published techniques. Details of how the design method was validated by independent sources within the lighting industry are also reported.

Chapter Seven is an investigation into the influence of SHR on illuminance conditions in obstructed interiors. The various methods of determining luminaire spacings are described, as is the obstructed-spacing-to-mounting-height ratio put forward by previous researchers. The relationship between SHR and task uniformity, diversity of illuminance and obstruction loss is investigated using commercially available lighting design software. The results of this synthesis are used to derive some general "rules-of-thumb" for use by designers.

Finally, Chapter Eight discusses the work in general and some conclusions are drawn. General recommendations, arising from this research, for the future development of this work and other areas of investigation, are put forward.

1.4 References

1. *CIBSE Code for interior lighting*, "4.4.2.1 General lighting", *Chartered Institution of Building Services Engineers*, London, pp. 136, (1994).

2. *IESNA Handbook: Reference and application*, "12. Basic lighting calculations", *Illuminating Engineering Society of North America*, pp.483–487.

3. *Deutsches Intitut für Normung*, "Artificial lighting of interiors, DIN 5035 Part 1 & 2", *DIN*, Berlin, (1979).

4. *Chartered Institution of Building Services Engineers*, "Lighting Guide LG5: Libraries", *CIBSE*, London, (1994).

5. *McEwan I*, "The effect of obstructions on the design of artificial lighting installations", *Ph.D. Thesis*, University of Liverpool, (1986).

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Chapter 2

Advances in lighting design methods for non-empty interiors

2.1 Introduction

Traditional lighting design techniques assume an empty room, despite the fact that interiors will contain obstructions such as equipment, furniture or machinery, which may adversely influence illuminance conditions. A paper published some ten years ago in *Lighting Research and Technology*, reviewed the subject of the treatment of obstruction in interior lighting design[1]. The work on the subject at that time consisted of a limited number of photometric surveys of installations, some hand calculation methods based on empirical data and simulation of installations based mainly on finite element computing techniques. In general the simulation methods were analysis tools for specialist applications and research and as such were neither suitable for, or available to, practicing designers. The hand calculation techniques were similarly limited in their range of application and were mainly used for particular design problems such as offices equipped with cellular partitions.

In the last ten years there has been considerable work in this subject area. Recent developments in lighting equipment, prompted by the need for energy conservation, or to address the problems of lighting areas equipped with VDTs, have tended to increase the potential problems caused by obstructions. A considerable amount of research has been undertaken in many parts of the world and a range of design tools have been developed that acknowledge, and attempt to overcome, the problems of lighting interiors containing significant amounts of interior obstruction. Most of the new design methods are based on computer software. The wider availability of computer technology to designers in the various sectors of the lighting and building services industry has meant that the subject is of concern to a wider audience than a decade ago. In addition, a number of Codes and Standards now seem to recognise that the problem exists and offer a variety of guidance.

This chapter reviews the many advances that have been made over the last decade. It examines the "quantitative" approaches of modelling of obstructed spaces, the now widely available computer based design methods, measured photometric data and empirical design methods. "Qualitative" aspects of visual conditions in obstructed spaces are also identified. In addition, the design guidance promulgated on the subject in the major Codes and Standards is summarised. A number of limitations of existing work and areas of necessary future development are identified.

2.2 Codes and Standards

Except in the case of specialist applications, the problems caused by obstruction did not feature greatly in lighting Codes and Standards until comparatively recent years. The guidance on the design of library lighting, for example, makes recommendations regarding the placement of luminaires relative to shelving systems and recommends the use of local lighting to make good deficiencies in illuminance provided by the general lighting system[2]. A number of developments have forced the producers of Codes to address the problem of obstructions. Much use is now made of mirrored and louvred luminaires, designed for use at wide spacings, whose characteristics mean that light will be directed at relatively flat angles of incidence to areas of the working plane remote from luminaires. This will cause shadows from any room contents. Additionally, changes in European lighting design standards involve specifying "maintained illuminance" at the task – the minimum average illuminance at which maintenance must be carried out – which exposes the deficiencies of the current lighting design methods. Methods that are largely based on the "empty room" assumption. Maintained illuminance also enables the resulting installations to be readily checked for compliance with a specification. This section outlines the guidance on the subject set out by the various major lighting authorities.

2.2.1 Chartered Institution of Building Services Engineers

The CIBSE Code for Interior Lighting[3] notes that local reductions in illuminance will be caused if large objects of furniture or equipment project substantially above the working plane. It contains a general warning about the inadvisability of spacing luminaires at, or near, their recommended maximums under such circumstances. In its section on design, the use of the lumen method for empty rooms is described. It is pointed out that "absorption of light by room contents such as furniture and equipment may reduce the achieved illuminance on the working plane" but apart from two references, does not elaborate in quantitative terms.

The CIBSE Lighting Guide 7, "Lighting for Offices"[4], contains a paragraph on the subject. It makes the point that most of the lighting related problems in offices are encountered after occupation due to the day to day clerical activities, but rather optimistically, suggests that relocation and tidying will solve many of the problems. It then goes on to point out the dangers of the use of extreme spacing of luminaires in areas equipped with dividing screens or partitions and the likelihood of light absorption by contents but, again, does not mention likely magnitudes.

The CIBSE Lighting Guide 1, "The Industrial Environment"[5], recognises that obstruction caused by machinery, overhead conveyors, pipe work, and the like, is a common feature of many industries. It recommends three approaches to reduce the problem. The first is to site the luminaires below any overhead obstruction and the second is to use at least two luminaires to light any part of a space. Finally, a reduction in luminaire spacing is recommended, typically one third of the maximum spacing to height ratio, but depending on size, reflectance and number of obstructions.

2.2.2 *Illuminating Engineering Society of North America*

The NAIES Handbook[6] contains general guidance relating to design and recommendations specific to applications. The document states that the actual illuminance in partitioned spaces will be less than that predicted by using the empty room approach and recommends that partitions be included in an appropriate calculation method, one of which is described in Section 2.4.2. The section discussing office lighting contains detailed guidance on both quantitative, qualitative and psychological lighting issues. The problems of calculation of illuminance in open plan offices are discussed and it is pointed out that predictions based on the empty room assumption can be misleading. Light losses of between 10% and 50% are quoted for "an average density of partitions 150cm high", depending on reflectance. Point-by-point computer calculation methods or mock-ups are recommended for illuminance prediction in partitioned workstation areas so that the designer may maintain the appropriate luminance ratios between task, surround and background. The problems of the requirement for flexibility in lighting design office planning are pointed out. Lighting systems tailored to specific furniture configurations may become afflicted by problems of shadowing or glare if, at some later date, the furniture layout is radically changed. Finally, the psychological effect of the elements of an office space are briefly mentioned (see Section 2.5).

2.2.3 Other lighting bodies

The DIN 5035 Part 1 specifies "nominal illuminance" values over task areas equipped and ready for use and states that these values should take into account the influence of objects in a fully furnished room[7]. The standard points out that most design methods are based on the empty room and that (unspecified) corrections are necessary to the standard lumen method to account for this. The CIE Guide on Interior Lighting[8] and the Australian Interior lighting Standard[9] make no specific mention of the problem apart from a general warning about shadows on task areas from some types of source.

2.3 Quantitative methods

This section describes quantitative approaches to solution of the problems of obstruction in interior lighting. Important recent advances in modelling techniques are outlined and the use of computer software for the production of both design data and design solutions is discussed.

2.3.1 Modelling of obstructed spaces

Complex numerical techniques that are capable of modelling light dissipation and distribution within obstructed interiors are well established. Most recently work, in this area has taken the form of the optimisation and refinement of the most popular techniques. The following sections describe the most widely used modelling techniques and the relevant refinements.

2.3.1.1 Finite element methods

Finite element methods are now used in many branches of engineering as the basis of computer programs for the solution of analysis and design problems that involve radiant exchange of energy. The method used in modelling lighting installations consists of a set of discreet, non-overlapping areas or "elements" which represent surfaces or light sources. The elements are either whole surfaces – floor, ceilings, walls, room contents or working plane – or discrete divisions of these surfaces. The photometric behaviour of each element is analysed in turn, and the contribution of all elements is summed. The resulting set of simultaneous equations is solved by matrix methods. When obstructions are placed in a space, the number of elements is increased and the radiant exchange between room surfaces is modified due to the reduced ability of elements to "see" each other. In practical terms, the realism of the results is related to the size and distribution of the element mesh – generally larger numbers of small elements give more accurate results but at the cost of increased computer time. A number of applications of the finite element method were described by McEwan and Carter[1]. Research work over the last decade has concentrated on extension of the method into new applications and attempted to improve the computational efficiency and decrease run time. Efforts to extend the approach to the analysis of interiors having non-diffuse surfaces have, however, proven extremely difficult[10].

Numan and Moore developed a method to assess the flux exchange in obstructed spaces based on the finite element method[11]. Partially obstructed surfaces were considered to be composed of zones without obstructions, separated by dummy planes projecting from the edge of the obstruction, which have full view of all surfaces of the zone they separate. These dummy planes were considered as transparent windows through which radiation travels from one surface to another.

The method uses the form factor concept between fully viewed surfaces in order to approximate the form factor between partially obstructed surfaces. The radiation travelling between surfaces of neighbouring zones is first received at a dummy plane and then distributed to the surfaces of neighbouring zones. If the dummy plane is assumed to be a secondary diffuse source, the fractions of the radiant energy received on each of the surfaces, through the dummy plane, can be determined by the form factor between the dummy plane and the surfaces under consideration.

Zhang and Ngai describe a finite element technique for application to lighting calculations in a multi-partitioned space[12]. The research used a concept developed by Mistrick - the use of two superimposed finite element systems in order to reduce calculation time[13]. *Zhang and Ngai's* procedure is divided into three stages. Firstly, a global finite element mesh is established consisting of an array of elements on each room surface, the size and arrangement of which depends on the priority assigned to each of the surfaces. Secondly, a finer element mesh is created which is superimposed on surfaces where detailed lighting distribution data is required. Figure 2.1 illustrates this concept. Finally, a series of flux exchange equations are derived with the superimposed fine element mesh acting as both receiving and transmitting surfaces. The initial exitances and the form factors of the superimposed fine mesh are updated as the calculation proceeds, without changing the characteristics of the global finite element mesh in the entire system. The authors compared the results of the new procedure with the standard finite element method for both direct and indirect lighting systems and comparable results with reduced run time was claimed.

Ikemoto and Isomura[14] developed a number of simplifications to the finite element method, with the aim of reducing run time whilst

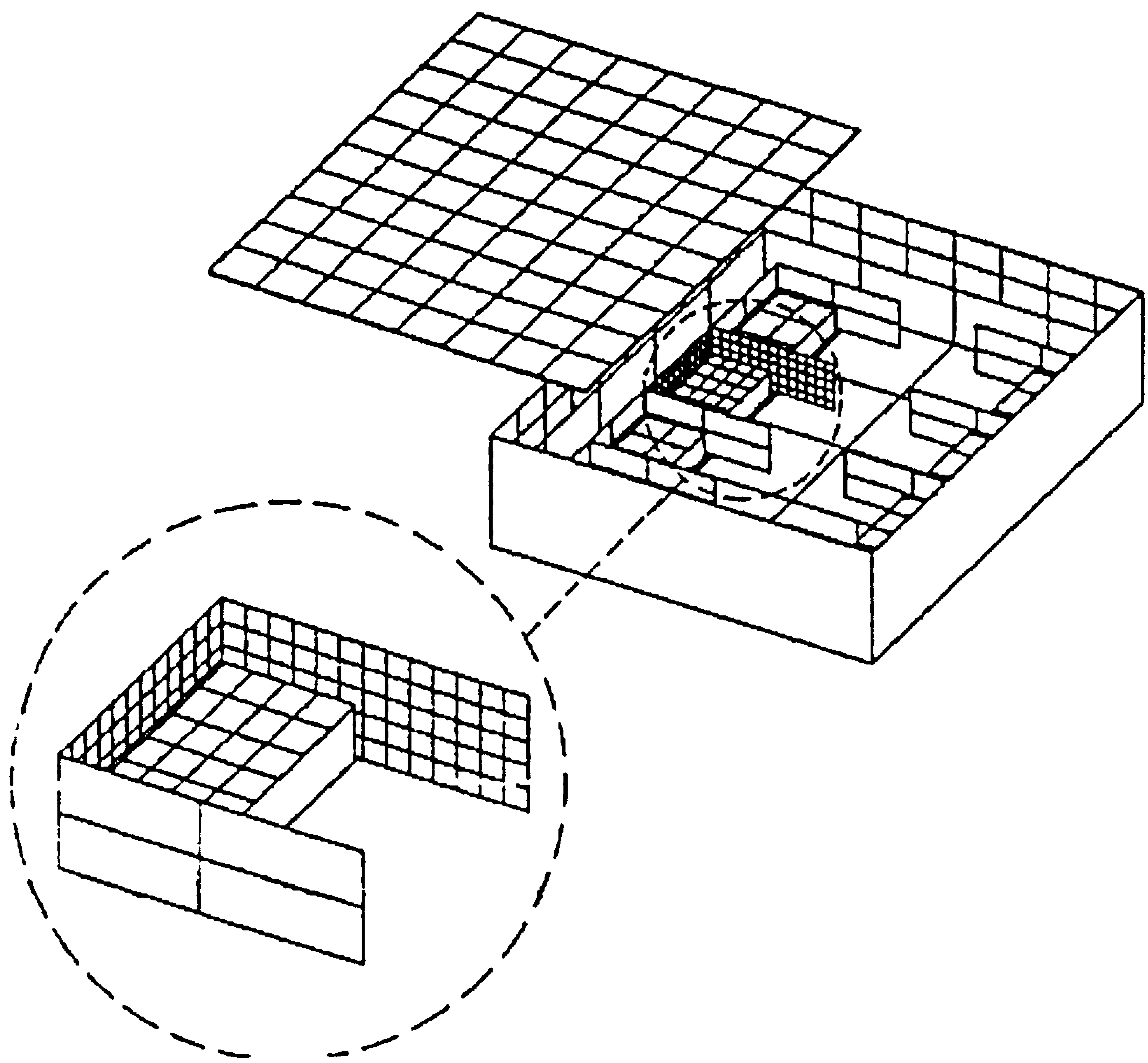


Figure 2.1: Zhang and Ngai's discrete element system showing the second fine mesh superimposed on the global mesh at a prioritised location

retaining computational accuracy. The most important modifications were to limit the number of elements on any surface to twenty-five, which in turn limited the number of form factor calculations. Additionally, the inter-reflection calculation was terminated after the second bounce. A reduction in accuracy of about 1% and of run time of 90% compared with other finite element applications was claimed.

2.3.1.2 Monte Carlo methods

In the last decade, lighting researchers have investigated the potential of the Monte Carlo technique for lighting calculations in an effort to overcome some of the drawbacks of finite element methods. The basis of the Monte Carlo method is the tracing of the actual path of a particle of light from its source to its eventual absorption at a surface. At each change of direction of a particle, caused by reflection or transmission, the new direction is calculated according to statistical probabilities defined by the photometric properties of the incident surface. Light sources may be simulated in two ways. The first is the use of scaled random numbers which represent the emitted particles in proportion to the luminous intensity distribution of the luminaire or alternatively, the assignment to each particle of a weighting proportional to the luminous intensity in the direction of travel with particles emitted evenly over equi-angular steps. Specular surfaces and obstructions are treated in the same manner as diffuse surfaces and room surfaces. The illuminance of an area of a room or obstruction surface is proportional to the total number of times a surface intercepts a particle path, taking into account the particle weighting value. In general, the accuracy of the simulation is proportional to the square root of the number particles traced and hence the resulting amount of computation is large. A rectangular coordinate system for all room and obstruction surfaces is used, defined with respect to an arbitrary origin.

Tregenza[15] and *Stanger*[16] developed techniques for the application of the Monte Carlo method in lighting. Both established that the technique could potentially be used to model complex interiors but that the major drawback was that accurate results required considerable computation time. More recently *Kajiyama and Kodaira*[17] investigated the illuminance distribution over the working plane of the room equipped with low partitions. A good correlation between computed and measured results was claimed. However the computation time was enormously long, despite the use of several techniques to increase the speed. The actual calculation time was in the order of 18 CPU hours for a small office 6.9m by 4.75m by 2.88m containing four cubicles and four luminaires.

2.3.1.3 Ray tracing methods

The ray tracing approach includes parts of both finite element and Monte Carlo techniques and is capable of modelling a wide range of geometrically complex natural and artificial lighting installations. The various program algorithms are based on the technique of "backward ray tracing" in which a light ray is traced back from the point of measurement to the source. Each ray of light acts as a luminance value resulting either directly from an emitting source or indirectly from a surface using information on surface reflection properties. This has been much used in computer graphics to produce realistic, but not necessarily photometrically accurate images, but has been little used in lighting. *Ward and Rubinstein* adapted this technique for a particular application to compute luminance called Synthetic Imaging, which is a two-dimensional map of calculated luminance values as viewed from a selected point[18,19]. To determine direct illuminance, rays are traced to each light source and an intersection check, to test for any surfaces in the path of the ray, is performed. If the surface considered is unobstructed, the photometric characteristics of the source, the installation geometry and the surface properties are used to determine the outgoing luminance. If the surface is totally obstructed, the direct illuminance is zero, but in the case of partially obstructed surface a Monte Carlo method is used to determine the indirect illuminance by sampling the area around the source. The computation of indirect illuminance is also performed by sampling radiated luminance values over a hemisphere defined by the surface element position and normal direction. Both diffuse and specular surfaces may be dealt with in this manner. The Radiance computer program, incorporating these calculation methods, produces impressive images of the scene, but consumes enormous amounts of computation time. For example modelling an office scene lit by four fluorescent tubes, with a desk containing a number of objects and a chair took of the order of 20 CPU hours on a workstation to produce a high resolution image.

2.3.2 Computer based design methods

The last decade has seen three linked developments which together have done much to establish CAD as a major element of the lighting design process: improved hardware with the introduction of personal computers; the availability of comprehensive photometric data; and improved software. Little needs to be said here about developments in PC hardware. Photometric data became more readily available and standard formats (albeit different) were published in the UK, USA and elsewhere. The major improvements in software related to the user interface and improved program capabilities. The original lighting programs written for mainframe computers, often assumed a user knowledge of computing and were written with economy of machine time, rather than of designers' time, in mind. User interfaces consisting of text files have now largely been replaced by interactive input, usually based on a standardised operating systems such as Windows. This has greatly reduced designer learning time and widened the user base of such programs. Most contemporary CAD programs contain features other than a basic working plane illuminance calculations and some now include a consideration of the effects of objects, such as furniture and work stations, located in the room. Given the ever increasing importance of CAD in lighting, much of the basic research on obstruction will enter practice in this way. The purpose of this section is to review some of these applications in the context of both the research on obstruction that has been undertaken and the requirements of the tools needed by the designer.

Most commercial interior lighting software is mainly based on lumen/zonal cavity or point-by-point/finite element methods. Some programs combine these two types into modules of the same program, using the lumen method for "quick" calculations and finite element methods for more realistic calculations that include inter-reflected light.

Programs that are based on the lumen method are simple in operation and can operate efficiently on inexpensive equipment to predict the number of luminaires needed or average illuminance. Most suites of software offered for sale by software houses or consulting engineers include a program of this nature, but an ever increasing number of luminaire manufacturers distribute this type of program free to interested organisations. These programs are usually equipped with a database of the distributing manufacturers products. This development means that lighting design software of this type is reaching a wider range of users than previously. Non-lighting specialists, who are unlikely to buy software, may be tempted to use free software for design purposes possibly without realising the consequences.

The second type of program accurately simulates inter-reflected light between the various room surfaces and has been used as a research tool for a number of years, but is increasingly included in suites of purchased software or distributed as free software. Output for these types of program is by tabulated information, 2D or 3D contour plot, or visualisation routines and most have the capacity to define interior obstructions of varying degrees of complexity and to acknowledge their presence in the calculation process.

2.3.2.1 Obstruction in computer-aided lighting design

This section reviews some of the features of commercial software currently available to designers which are relevant to obstruction. In general, the majority of programs available to designers are lumen/zonal cavity based, mostly distributed free by manufacturers, but very few examples of this type handle obstructions. Programs purchased as part of a software package are generally more likely to address the problems of interior obstruction. Table 2.1 lists the main features of six examples of software that handle obstructions – four point-by-point/finite element based programs, of which one is currently distributed free of charge, and two programs which are intended primarily as research tools which have been included for comparison purposes only. Table 2.1 is not intended to be an exhaustive list of available programs, since this information is ephemeral and is available elsewhere (see for example the annual survey published by NAIES[20]). Most programs offer a multitude of features, but the four main variables relating to the way the software treats obstruction may be summarised as follows:

(i) Obstruction definition

The manner in which the individual obstructions are constructed, influences both input routines and calculation method. Most programs use rectangular planes to build up solid objects so that, for example, a cube may be defined as six single surfaces, each of which is treated as separate for calculation purposes. The alternative definition is of an obstruction as a pre-defined three-dimensional object which is then broken into appropriate planar surface areas by the calculation procedure. All of the programs in Table 2.1, with the exception of

	Lumen-Micro[38]	Luxicon[39]	Oasys-BEANS[40]	FACET[41]	Radiance 2.4	UoL Lighting Analysis
Hardware Platform	486DX PC 2Mb Ram	486DX-50 PC 12Mb Ram	486DX PC 2Mb Ram	486DX PC 2Mb Ram	UNIX workstation	UNIX workstation
Data Formats	IES/TM14	IES/Luxicon	TM14	IES/TM14/ASCII	radiance/IES	UoL/TM14
Maximum Obstructions	500	>500	50	>100	unlimited	100
Room types	rectangular	rectangular	complex	complex	complex	rectangular
Light sources	Artificial and natural	Artificial and natural	Artificial and natural	Artificial and natural	Artificial and natural	Artificial
Surface types and properties	diffuse reflecting solids	diffuse reflecting solids	diffuse reflecting solids or part transmitting	diffuse reflecting solids	specular, diffuse, dielectric, BRDF	diffuse reflecting solids
Obstruction types	single orthogonal surfaces	single orthogonal surfaces	complex orthogonal surfaces (up to 10 defining nodes	complex 3D boxes or surfaces	complex unlimited defining nodes	orthogonal 3D boxes
Calculation technique	Lumen/point-by-point and finite element techniques	Lumen/point-by-point and finite element techniques	Lumen/point-by-point and finite element techniques	Lumen/point-by-point and finite element techniques	hybrid combination of Monte Carlo and deterministic ray tracing	point-by-point and finite element techniques
types of output	report, contour plots, visualisation	report, contour plots, visualisation	numerical grids, contour plots	report, contour plots	photo-realistic visualisations	report

Table 2.1: Summary of some properties of lighting design computer programs that handle internal obstructions.

Radiance, construct the internal obstructions as a combination of horizontal or vertical orthogonal surfaces. Luxicon provides the user with a limited set of pre-constructed obstructions made up of combinations of basic surfaces, such as columns or furniture. In most programs room and obstruction surfaces must be aligned orthogonally and this clearly limits the degree of realism of an actual interior that can be modelled. Radiance users may construct furniture geometry made up from combinations of N-sided polygons, spheres, cones and discs. Complex surfaces, including curves, can also be defined using irregular areas defined by surface nodes.

(ii) Number of obstructions

The total number of obstructions that can be defined as input, also influences both the maximum size complexity and degree of realism to which an actual interior that can be modelled. Table 2.1 gives the maximum number of obstruction elements, which may be either three dimensional blocks or surfaces. For comparison, the contents of a typical office, having a room index of 1.6 and furnished with desks, chairs, VDTs and a small number of filing cabinets, could be modelled using some 240 vertical and 70 horizontal rectilinear surfaces. It is clear that some programs described in Table 2.1 are generally capable of modelling a room of this size, but that the maximum number of furniture items that can be accommodated depends on the degree of sophistication used in the modelling of the objects.

(iii) Calculation methods

The theoretical basis of the calculation methods, that have been implemented in the coding of the various examples, has been discussed in Section 2.3.1. The majority use a point-by-point calculation technique, combined with a check for light interception by obstructions, to determine the direct lighting contribution and a flux interchange routine for calculation of indirect illuminance. Linear and area light sources are generally modelled by subdivision into smaller portions, which are then treated as point light sources. The direct lighting contribution received on any surface element from each individual point source being the total from all sources the element can "see". The inter-reflected component is calculated using the "radiosity" or "finite element" method. The main difference between the programs in this process is the criterion for termination of the "bouncing" of light between surfaces which influences accuracy and run time. Most programs continue the process a set number of times (usually three), until all but a negligible proportion can be assumed to have been absorbed by the room surfaces, but some software (Oasys-BEANS for example) will allow the user to enter the number of bounces.

The Radiance program, based on the technique of backward ray tracing, has the advantage of being able to model a range of complex geometries and materials. Interior obstructions may be modelled to a high degree of accuracy. The output is in the form of photo-realistic images. However the program was developed as a research tool, for which it is used extensively worldwide, but its commercial use is limited by a user interface that requires large amounts of time consuming data input and by its large appetite for computer time. Whilst advances in computer technology may go some way towards overcoming these disadvantages, a more fundamental limitation is that, like all "analysis" methods, the Radiance user is required to input precise details of the installation and its contents. Such details are unlikely to be available at the time when most lighting schemes are undertaken.

(iv) Type of output

There are a number of common types of output, some of which are used in combination. Illuminance grids or contour plots in textual or graphical form and, increasingly as three dimensional plots, are features of all programs, although the practical use of the latter form of graphical contour plot is far from clear (see Figure 2.2). Three of the

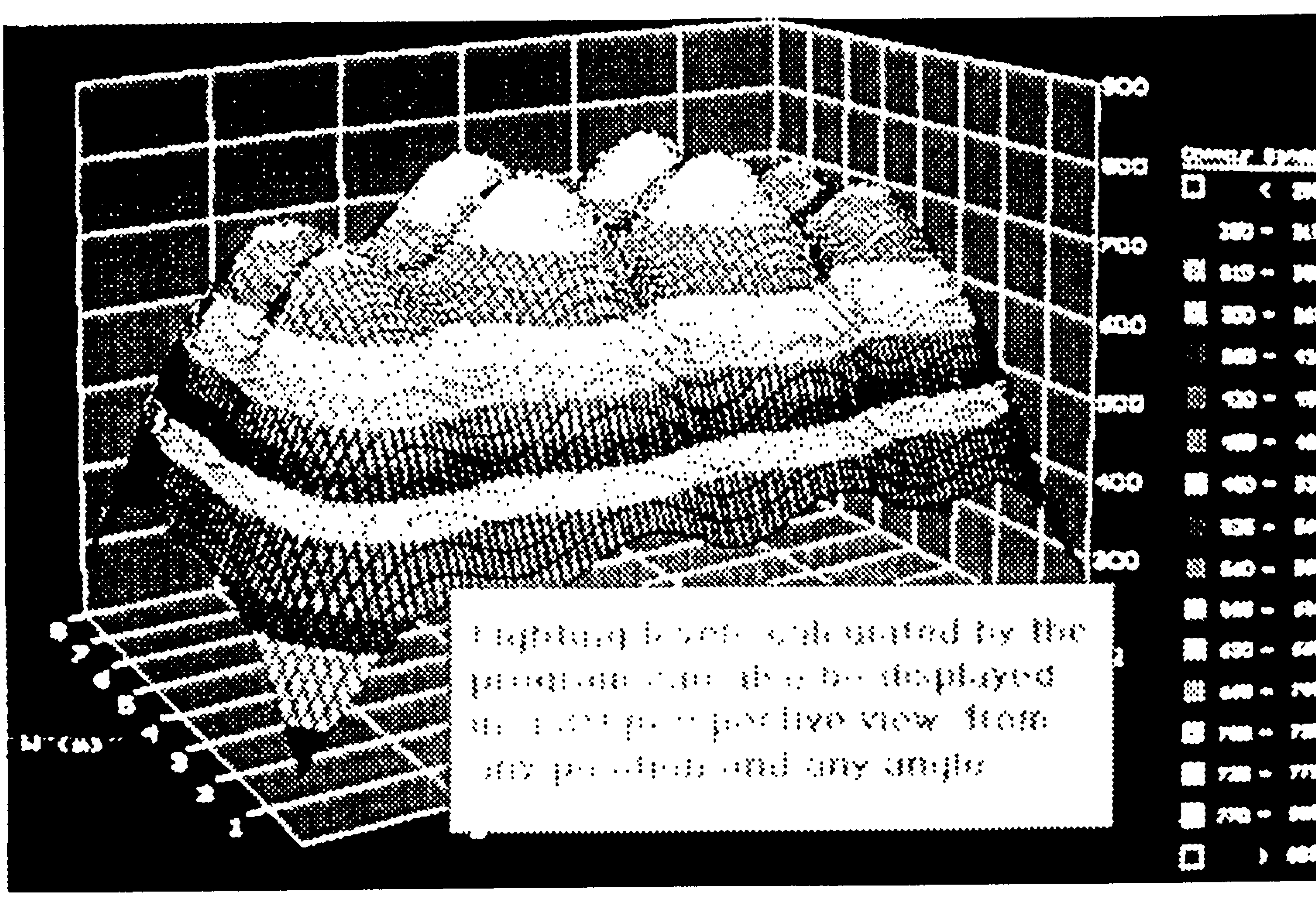
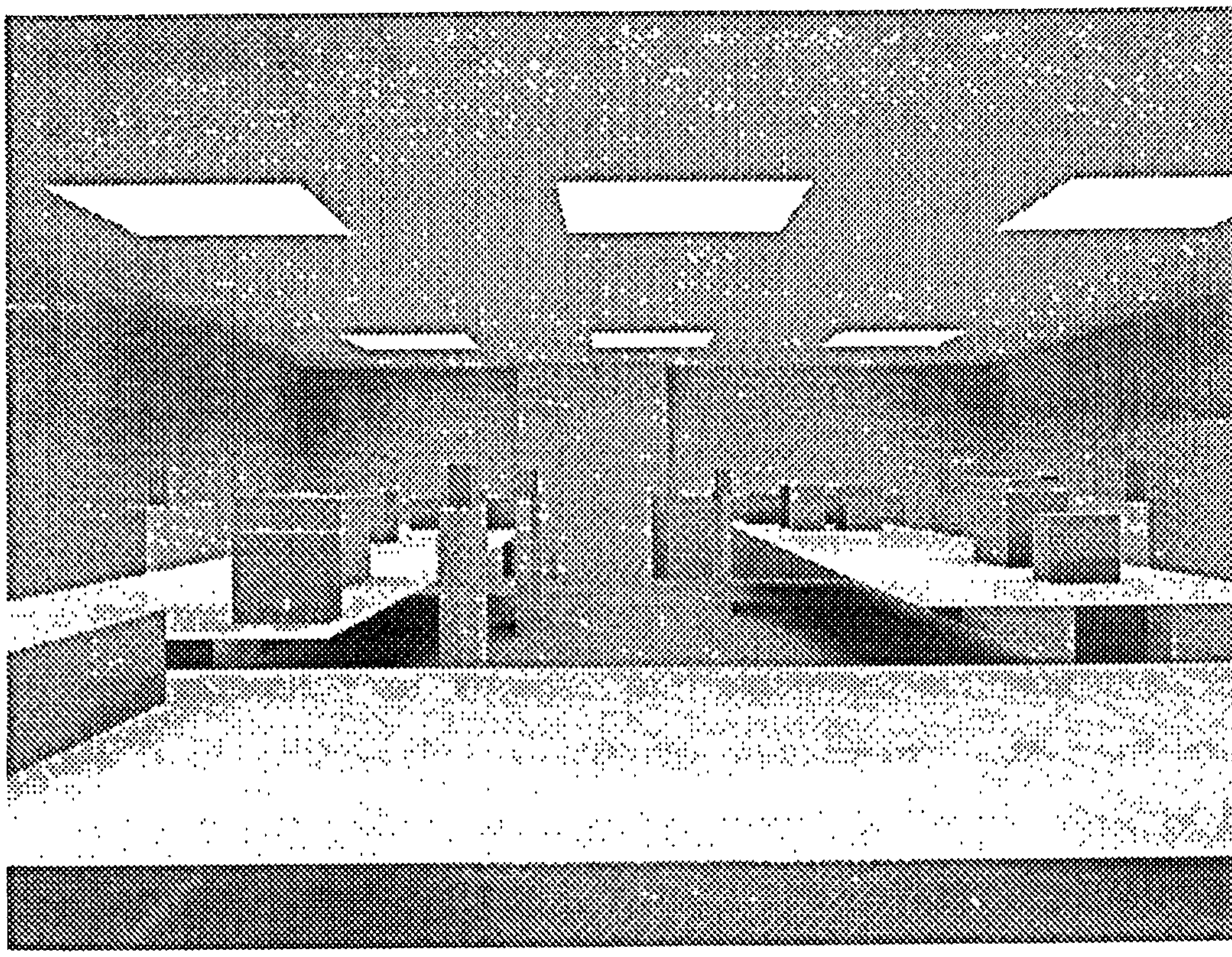


Figure 2.2: Example of 3D contour plot output from FACET lighting package



(a)

(b)

Figure 2.3: Examples of visualisation output from
(a) Lumen Micro and (b) Radiance 2.4

programs have the capacity for graphic visualisation output of which Figures 2.3a and 2.3b are examples. The Lumen Micro and Luxicon programs produce a monochromatic image from a fixed viewpoint and have the capacity to present a series of such images as a "walk through". Visualisation in the form of photo-realistic images, is the main form of output of Radiance. The generation of visualisation output is an major consumer of computer time – an image for a typical small office interior can take tens of hours for both data input and computation.

2.3.2.2 Program validation

Programs are increasingly used for appraisal of proposed designs. With the proliferation of programs and algorithms available there is a need for program validation so that they may be used with confidence by designers. Any validation process must include a review of the underlying assumptions of the program, including data used, and also testing of programs using standard "benchmark" data. Some work has already been done in this area to test programs based on the lumen method using, as standard conditions, an empty office lit by defined luminaires. The programs were evaluated against an acceptable range of limits of working plane illuminance parameters as the main validation device[21]. The results give provisional acceptability limits but further work is required to include the full range of types of program, a wider range of input conditions (e.g. luminaires other than direct downlighters) and alternative output criteria (e.g. vertical illuminance).

The test models used to date have all assumed an empty space, despite the fact that that a number of modern lighting design programs will now handle internal obstruction. The addition of obstructions to the input data must be considered as an essential modification to the test model. Currently, there exists no standard data for internal obstructions for test purposes and some representations of interior furnishings, suitable for this purpose are required. They will need to be simple enough to be created using the orthogonal geometry systems that are in common use in lighting design programs, yet capable of being used to predict light losses caused by room contents.

2.3.3 Simulation of lighting in non-empty interiors - design data

The various modelling techniques have been used, often in combination with some of the empirical techniques described in Section 2.4, to derive data that may be used in the design of lighting in non-empty spaces.

2.3.3.1 Work at the University of Liverpool

A number of researchers at the University of Liverpool have developed simulation methods for various aspects of lighting in non-empty interiors over the last ten years. The work has developed, firstly, a technique for spacing luminaires in general lighting installations at an appropriate distance to overcome the anticipated effects of light losses caused by obstructions on illuminance uniformity. Secondly, it developed a technique to predict and compensate for the magnitude of the likely light losses caused by obstructions.

The first study developed the idea of extending the existing design guidance for empty rooms by modifying the maximum spacing-to-mounting-height ratio to allow for some 'standard obstruction loss', which could be used by designers in addition to the normal maximum spacing-to-mounting-height ratio[22]. This work took, as a starting point, the standard UK method for calculation of SHR in empty rooms, which was then modified to take account of defined obstructions positioned within the central area of the 4x4 square luminaire array and was then implemented by means of a computer program. The obstructions, based ostensibly on the results of a survey carried out in an open plan office, represented a desk with either a partition or a filing cabinet at one

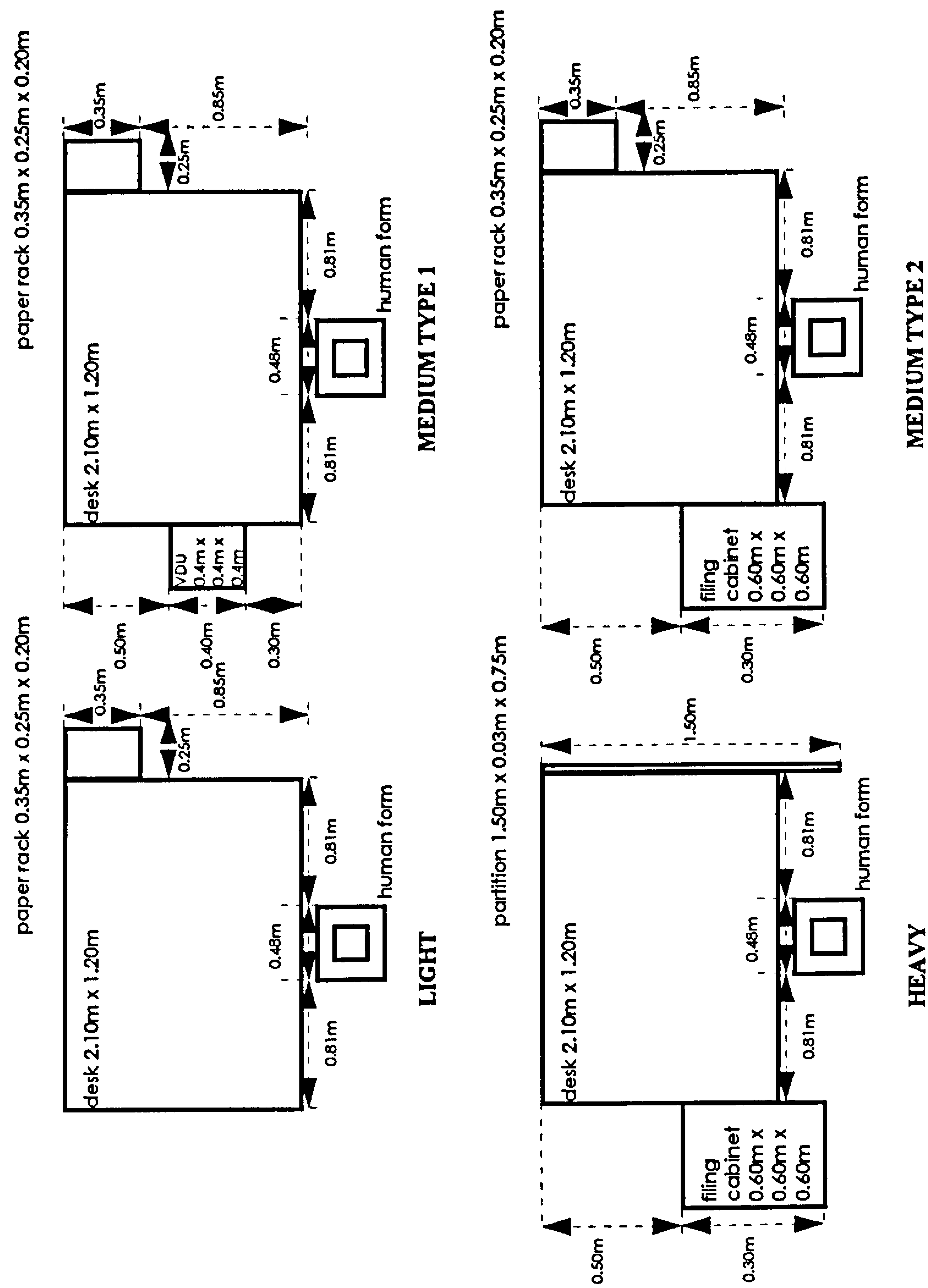


Figure 2.4: Diagram of standard obstruction layouts and sizes.

end, with a person seated at the desk. For each SHR value of the preferred series, the program calculated the illuminance conditions within the central area of the luminaires, taking into account the presence of the obstructions. The work went on to address the problem of the size and configuration of the elements of obstruction. A series of "light", "medium" and "heavy" obstructions were developed to represent the range of obstruction density in office interiors (see Figure 2.4). These "Standard Obstructions" were developed from analysis of data on room contents, collected by surveys of a limited number of office buildings and from information provided by two major office equipment manufacturers. The sizes of the elements of the Standard Obstructions are shown in Table 2.2. The elements are arranged into configurations set out below:

Light Standard Obstruction	-Person + Desk + Paper rack.
Medium Type 1 Standard Obstruction	-Person + Desk + VDT + Paper rack.
Medium type 2 Standard Obstruction	-Person + Desk + Filing cabinet + Paper rack.
Heavy Standard Obstruction	-Person + Desk + Filing cabinet + Partition.

Floor area per standard configuration may be 8, 10 or 12 square metres.

The representation of the human form was found to have a major influence on task illuminance conditions and the CIE standard for "body shadow" used in Contrast Rendering Factor computation was adopted, as this is capable of acknowledging the separate contributions of head and body to obstruction. The obstructed SHR program introduced the standard obstructions either parallel or perpendicular to the luminaire axis. For each SHR value of the preferred series, at each point on a 0.10*m* square grid over the task, the illuminance from each of the 16 luminaires was calculated taking into account the presence of obstructions. The uniformity ratio, based on the ratio of minimum/maximum illuminance over the task area, excluding a 0.10*m*

Element	Length (m)	Width (m)	Height (m)	Vertical Surface Area (m²)	Reflectance
Filing cabinet	*0.60*	*0.60*	*1.35*	*1.44*	*0.3*
Partition	*1.50*	*0.025*	*1.75*	*3.06*	*0.6*
VDT	*0.40*	*0.40*	*0.40*	*0.64*	*0.3*
Person - head	*0.20*	*0.20*	*1.30*	*0.53*	*0.3*
- torso	*0.48*	*0.48*	*1.09*	*0.72*	*0.4*
Desk	*0.76*	*1.41*	*0.75*	*N/A*	*0.3*

Table 2.2: Dimensions and reflectances of *Bougdahs* standard obstruction elements.

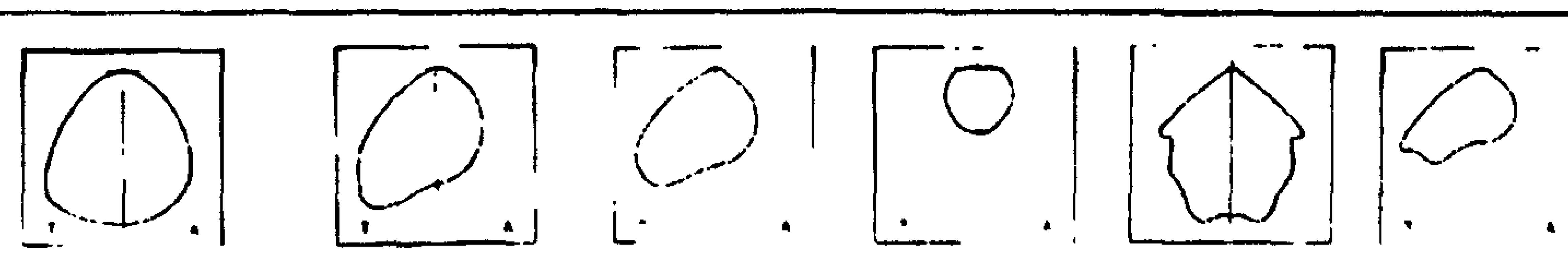
Configuration	Luminaire type								
	1 Prismatic panel diffuser		2 Surface mounted broadspan reflector		3 Recessed broad-span reflector		4 Surface mounted diffuser	5 Recessed diffuser	6 Recessed reflector
									
Position of workstation relative to luminaire axis	Perpen-dicular	Parallel	Perpen-dicular	Parallel	Perpen-dicular	Parallel	Perpendicular or parallel	Perpendicular or parallel	Perpendicular or parallel
Empty case	1 70	1.70	1.90	1.90	2.08	2.14	1.75	1.32	1.80
Light obstruction case	1 40	1.00	1.52	1 00	1.56	1.51	1.40	1.17	1.66
Medium ob- VDU	1.40	—	1.50	—	1.51	1.00	1.40	1.17	1.55
struction case FC	1.33	0.85	1.25	—	1.25	1.00	1.27	1.17	1.44
Heavy obstruction case	1.27	—	1.25	—	1.25	1 00	1.25	1 15	1.29

Table 2.3: SHR_{max} and SHR_{obs} for standard obstructed interiors lit by different types of luminaire

wide edge strip, was then calculated. The edge strip was excluded from the uniformity ratio calculation, since this would not, in practice, be used for visual tasks. The effect of obstructions was a major element in the illuminance calculation procedure and was assessed by separate consideration of how much of the luminaire, if any, may be "seen". For luminaires which were assumed to be point sources, they are either "seen" or "not seen" and for linear luminaires, checks were initially required to determine if a luminaire was partly or totally blocked by an obstruction. The illuminance was calculated using a point-by-point calculation.

To study the effects of the various standard obstructions, the uniformity ratios for the preferred series of SHR set out in CIBSE TM5 were calculated for a number of examples. The results are summarised in a series of graphs, similar to the examples shown in Figure 2.5, for both linear and symmetric point source luminaires. The examples include standard obstructions, positioned such that the axis of the work station is either parallel or perpendicular to those of the linear luminaires. Results for the Heavy standard obstruction configuration are denoted by "H", those for Medium standard obstruction configuration with VDT by "V", and with filing cabinet by "F", and those with the Light standard obstruction configuration by "L". To provide a reference for the obstructed cases, the uniformity ratios for the empty case identified by "E" are also shown. There were large differences in SHR_{max} (the maximum permitted spacing-to-mounting-height ratio) for the luminaires between empty and obstructed cases and smaller, but significant, differences between the various obstructed cases (see Table 2.3). The effect of an individual obstruction component was greater when perpendicular rather than parallel to a linear luminaire.

McEwan and Carter also developed a computer program capable of investigating the lighting conditions within spaces lit by any defined range of artificial lighting equipment[23]. *Bougdah* demonstrated

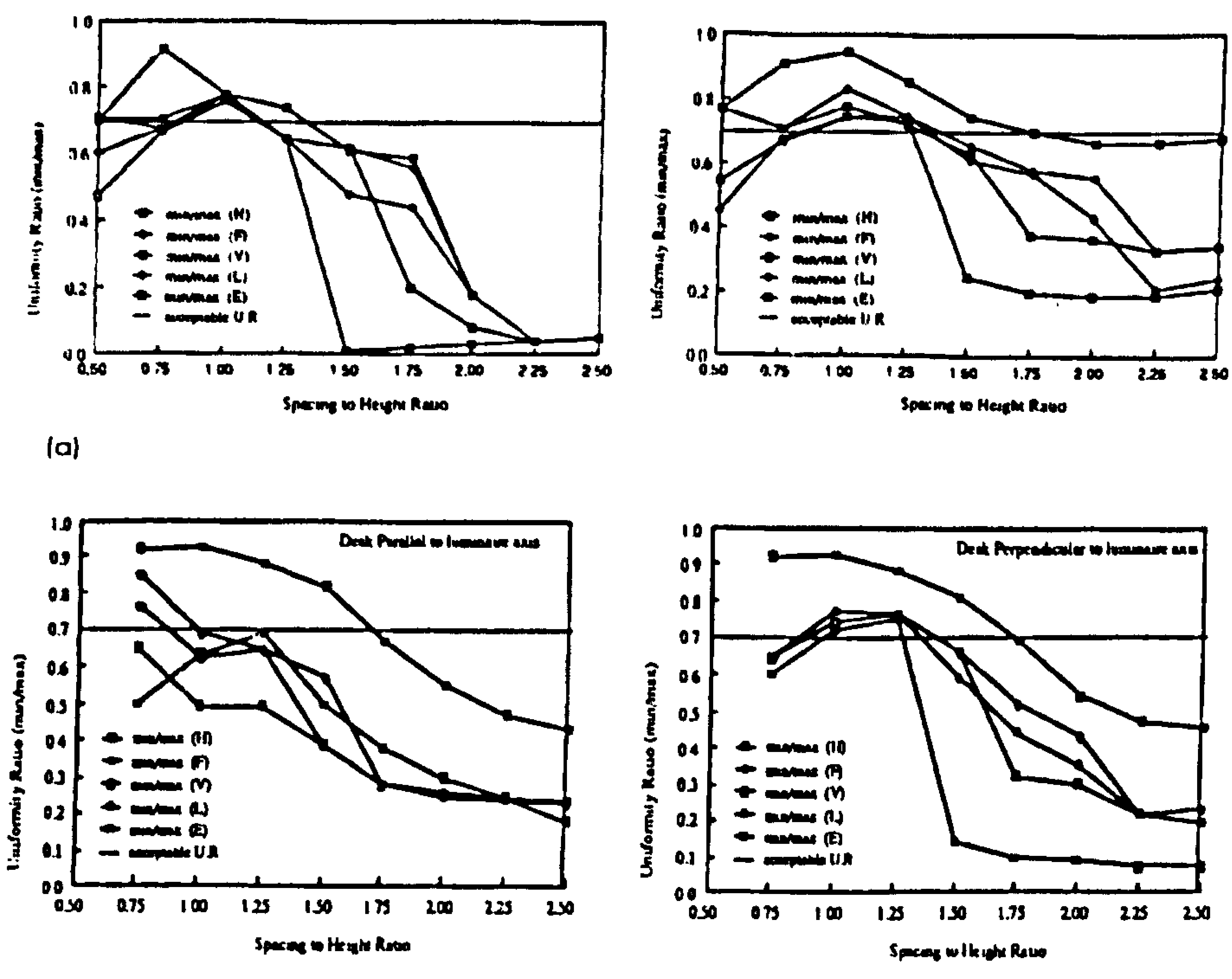


Figure 2.5: Variation of uniformity ratio as a function of luminaire spacing for (a) point source luminaires and (b) linear prismatic panel diffuser.

that this program could be used to investigate the influence of different luminaire types and spacings on the illuminance conditions within a space for known obstruction conditions, and using a larger dataset, attempted to develop some general rules regarding the behaviour of light in obstructed spaces[24]. The results showed that obstruction size and density had by far the greatest influence on reduction in average illuminance over the working plane (the 'OL') of up to up to 14%. The next most important factor was luminaire type, which caused losses of up to approximately 6%, depending on type of luminaire. Specifically, diffusing luminaires have a greater propensity for light loss than those which have more narrow downward light distributions. Variation of the reflectance of room and obstruction surfaces, room index and mounting height were thought to have a negligible effect on light loss.

A linear relationship between "obstruction density" (expressed in terms of Vertical surface area of obstruction above the working plane to Floor area Ratio – VFR) and light loss, was put forward for each of three luminaire types for a range of room sizes. Figure 2.6 is an example of this relationship for a surface mountea diffusing luminaire. The VFR values may be calculated for the proposed room contents by summing, for a typical workstation in the room, the total area of vertical surfaces above the working plane, including a human form, and dividing this by the floor area occupied by the workstation, including associated circulation space.

Raitelli and Carter extended the work of *Bougdah* in two different ways[25]. Firstly, the computer simulation was successfully carried out using general purpose, commercially available software to investigate the light loss characteristics of obstructions of different shapes and sizes. Additionally, rooms were modelled containing a regular grid of partitions, such that the working plane was covered by square "cells" or

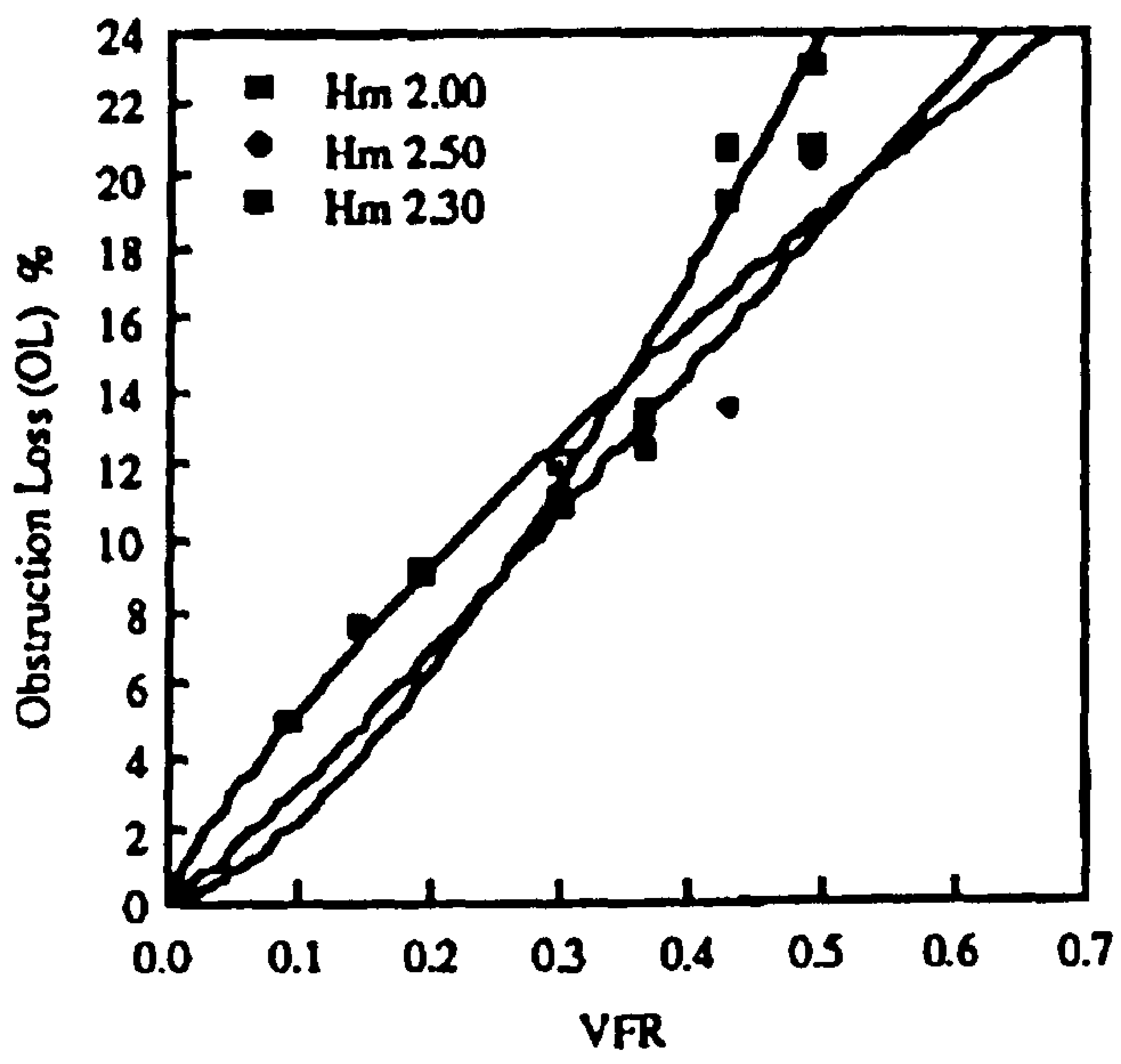


Figure 2.6: OL/VFR characteristic for surface mounted broadspread luminaire.

with "furniture like" obstructions. The results for the two types of obstruction were similar and confirmed the major influence of obstruction type on light loss.

2.3.3.2 *Choi and Mistrick*[26]

This work was a study of both working plane illuminance and task uniformity reduction in offices with uniform height cubicle partitions equipped with some furniture. The study is interesting in that although it only deals with this restricted range of room contents, it does examine the effects of different types and position of luminaires and provides information that could be of direct use to designers of open plan offices equipped with cubical partitions. The work was based on simulation of a 12.5m square room equipped with 25 cubicles. Detailed analysis was performed in the centre cubical only, the others being accounted for in the calculations by regarding their top surfaces as an imaginary surface. The results thus purport to represent conditions in the body of a room but do not consider, arguably, the worst case of the corner cubicles. A specially written computer program was used to investigate four luminaire layouts (a single luminaire over the centre of the cubical, a line of luminaires along the axis of the cubical, a single luminaire straddling the cubical walls and a line of luminaires straddling the cubical walls) and three luminaire distributions (direct, indirect and direct/indirect). Additionally three heights of partition and four partition reflectances were simulated.

The fraction of working plane average illuminance, relative to that for the empty room, was determined for a cubical with a desk only and also for a desk and overhead cabinet. For all types of luminaire, the obstructions caused light loss of up to the order of 50% on the desk only, and 65% on the desk with overhead cabinet - enough to require supplementary task lighting. In general, the loss increased with partition height and decreased with partition reflectance. Luminaires having a direct distribution had least light loss with low partitions but maximum with high partitions. Overall, the direct/indirect type had the least light loss. The luminaire layout also had an effect on the magnitude of light loss, with straddled layouts having least loss and centred luminaires the most. The Illuminance uniformity predictions were made, curiously, over the whole cubical, rather than just the desk (which was located at one side of the cubical) and thus, the results probably give an unreliable indication of uniformity over the task area. The values of uniformity are considerably affected by luminaire layout and type. The straddled layout and indirect luminaire giving the best uniformity, whereas centred layout and direct luminaires had the lowest uniformity.

2.4 Empirical approaches

The empirical approach to the problem of obstructed spaces has been adopted by a number of investigators. Detailed photometric measurements have been undertaken in both simulated and real obstructed interiors in order to better understand light distributions within such spaces and to form the start point for design methods. This section examines the results of the various photometric surveys, comments on their significance and describes design methods based on empirical data.

2.4.1 Measurement of light losses

The published investigations of lighting conditions in obstructed spaces have been undertaken for a variety of reasons. These may be as part of an assessment of interior environmental quality, to verify design criteria, for software validation or to act as the basis of a design method. Research of this nature has usually been undertaken by photometric survey, supplemented in some cases by computer simulation to expand the original data set.

Cook and Hill[27,28] investigated the influence of obstructions located in the floor cavity on the illuminance distribution on the working plane. The work describes illuminance surveys of a number of large rooms, firstly empty, and then furnished with tables and chairs. For each condition, values of floor cavity reflectance were calculated using standard techniques (CIBSE Code). In one room, furnished with a combination of desks and chairs, the reduction in average working plane illuminance was 14%, whilst in the second room, furnished only with leather backed chairs, showed no light loss. The authors attempted to derive a relationship between horizontal working plane illuminance and the effective reflectance of the floor cavity. It was concluded that no simple relationship existed and that the present methods of determining the influence of floor cavity obstructions on working plane illuminance did not necessarily produce predictable results using lumen calculations for some types of cavity obstruction. The nature of the cavity obstructions was found to influence flux transfer within the cavity. The relationship was more reliable when closed-sided or solid objects occupied the cavity, than for more open-sided obstructions such as desks.

Measurement of light losses has been undertaken at the University of Liverpool. Initially, four surveys of actual office interiors, before and after furnishing, were undertaken in order to obtain information on illuminance distributions over the working plane[29]. Detailed measurements of furniture configurations, room characteristics and horizontal working plane illuminance were made in each office. The results related the maximum and average reduction in working plane illuminance to a number of room variables (such as average reflectance of room and furnishings) and a number of indices, notably ratio of vertical obstruction surface area to floor area, ratio of height of obstruction to mounting height and area of working plane with a uniformity ratio lower than 0.8. Based on these results, tentative proposals regarding the relationships between light loss and furniture characteristics were put forward. Generally, it was noted that designers should be prepared for reductions in average working plane illuminance in the order of 10%, due to the introduction of office type room furnishings.

Secondly, *Raitelli and Carter* made a series of measurements to investigate the general trends indicated by the results of the earlier computer simulations[29]. The measurements were made in a room which allowed permutations of two luminaire types and two spacing-to-mounting-height ratios. It was furnished, in turn, by four different "furniture like" configurations, ranging from an empty room to a heavily furnished condition. The results confirmed the dominant roles of obstruction size and luminaire type over light loss, but in addition illustrated that reduction in luminaire spacing-to-mounting-height ratio could overcome some of the influence of the obstructions. Table 2.4 illustrates some typical predicted values of OL for installations with linear luminaires installed near maximum SHR.

Kajima et al undertook photometric measurements in a number of office buildings as part of an investigation of a variety of issues relating to the visual environment[30]. In one building, three offices, each lit by regular arrays of fluorescent 40W x 2 lamp batten open reflector luminaires, were surveyed both before and after the installation of furnishings. Reductions in average working plane illuminance of 22%, 21% and 19% respectively, were noted. The authors concluded that the reductions due to the furnishings were a significant design consideration. They proposed a correction factor (called the 'office furniture factor') to be applied to the 'lighting coefficient' (utilisation factor) as shown in Equation 2.1. On the basis of their measurements, a value of office furniture factor of 0.8 was put forward.

Luminaire type	Degree of Obstruction		
	Light VFR ≈ 0.1	Medium VFR ≈ 0.25	Heavy VFR ≈ 0.45
Diffuser	*2.5%*	*7%*	*14%*
Wide distribution reflector	*2%*	*5%*	*11%*
Narrow reflector	*1.5%*	*5%*	*10%*

Table 2.4: Some typical predicted values of OL for installations with linear luminaires installed near to their respective SHRmax.

actual mean illuminance	=	design mean illuminance of empty room	x	office furniture factor	—***Equation 2.1***

If some assumptions are made about the furnishing within each space, based upon the published plans of the rooms, it is possible to compare results of *Kajima et al* to those of the Liverpool researchers. The three rooms of *Kajima et al* have estimated VFRs of 0.44, 0.40 and 0.51 respectively and these compare well with *Bougdah's* predicted results for a surface mounted diffusing luminaire (see figure 2.6).

Siminovitch et al undertook a series of studies to investigate the luminous environment within enclosed workstations lit by general lighting systems, with the aim of developing geometric relationships between task and lighting layout such that good visual conditions were maintained[31,32]. The first study involved measurement in a scale model of a 13m x 13m interior, equipped with model workstation furniture and illuminated by a regular grid of scale model 600mm x 1200mm diffusing luminaires. Horizontal illuminance was measured at different viewing angles for four different workstation configurations. Reductions in average working plane illuminance of up to 36% for a 25 degree viewing angle and 70% in the 40 degree viewing angle were noted, when compared with similar measurements for the empty space.

A second investigation developed the initial work by the use of a full scale photometric simulation facility to investigate the effect of various obstruction configurations and orientations on both Contrast Rendering Factor and horizontal illuminance from the 2 x 2 array of fluorescent direct downlighter luminaires, as illustrated in Figure 2.7. A workstation with the four configurations (unobstructed desk; desk and person; desk, person and 1.2m partition; desk, person, and partition with a storage unit) was placed in the four orientations with respect to the luminaire array. Measurements of Contrast Rendering Factor and

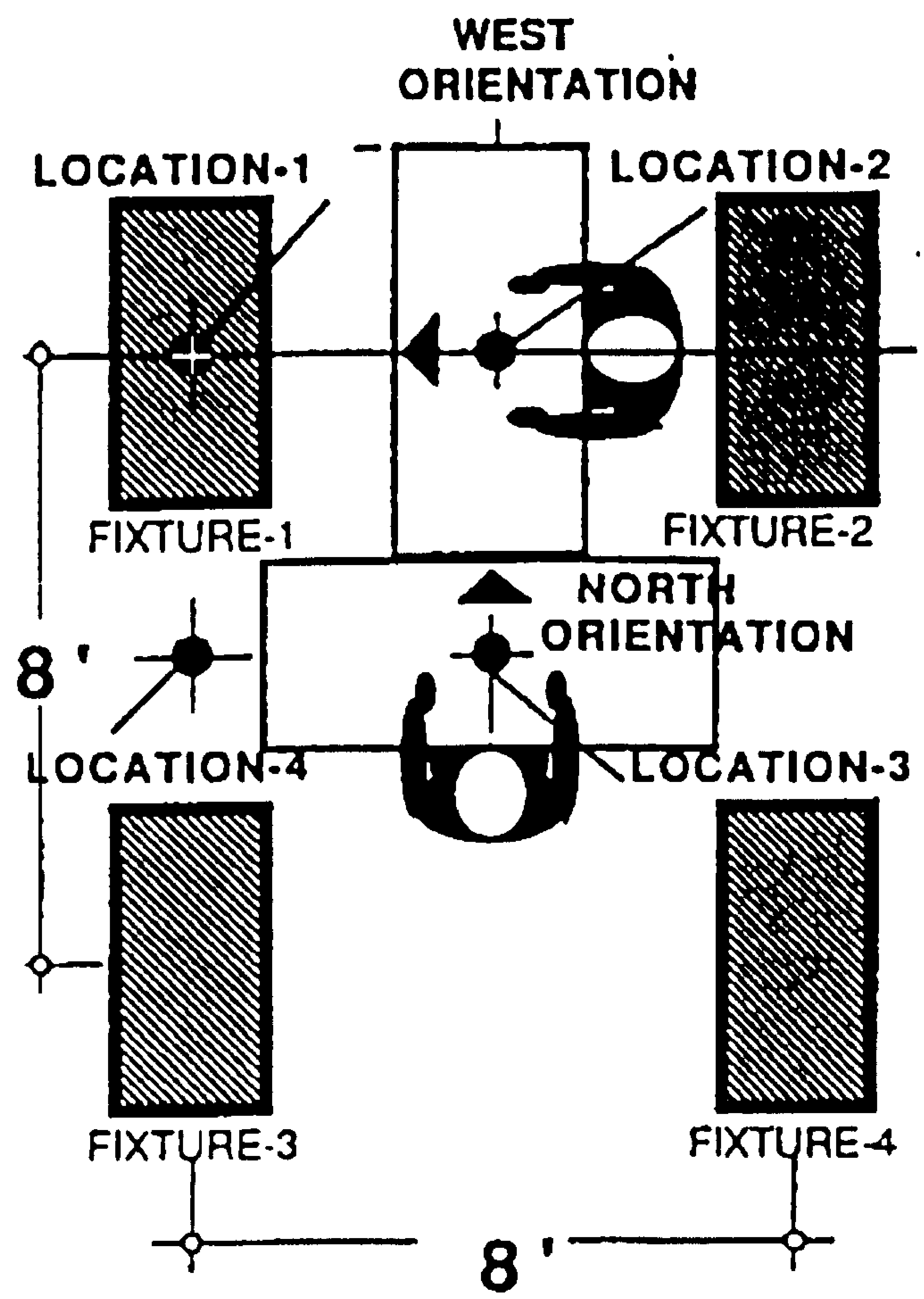


Figure 2.7: Layout of test suite used by *Siminovitch et al* in the evaluation of luminous environment within enclosed workstations.

illuminance were recorded at various points on the desk. Large variations of Contrast Rendering Factor were noted (with values as low as 40 recorded for some viewing angles) which may be explained by the degree to which the various obstructions were configured to partially or wholly occlude the luminaires. Horizontal illuminance was measured along the central axis of the desk at viewing angles of up to 45 degrees. Reductions for the obstructed cases compared with the empty case ranged from 40% to 80%. The authors found that the highest level of illuminance reduction occurs when the task plane is positioned between two luminaires located along the axis of viewing (see Figure 2.7 position 4). The lowest reductions occurred when the luminaire is located directly over the task plane and with the task between two luminaires located perpendicular to the line of sight (see Figure 2.7 positions 1 and 2).

These results are similar to the Liverpool simulations of task illuminance conditions made as part of the study of luminaire spacing-to-mounting-height ratio for obstructed spaces. *Siminovitch et al* put forward the concept of pre-defining interior lighting layouts and workstation task geometries, coupled with local task lighting, as methods of ensuring adequate illuminance and contrast and gave examples of suitable configurations. The major drawbacks of this approach are its lack of flexibility and its inapplicability to the design of interiors where detailed information on the furniture is unavailable.

2.4.2 Empirically based design methods

The Lumen or Zonal-Cavity method is the most widely used method of design of general lighting. It enables an average illuminance to be provided over the working plane of an empty interior whilst attempting to limit the variation of illuminance by control of the spacing of luminaires. The number of luminaires required to give the desired average illuminance is determined by rearranging Equation 2.2 and the subsequent luminaire layout set out using the appropriate spacing to height ratio (SHR).

$$E(s) = \frac{\text{UF(s) x N x F x MF}}{Area \quad of \quad Surface} \qquad \text{———— Equation 2.2}$$

where

UF(s) is the Utilisation Factor for the reference surface, S

N is the total number of lamps in the installation

F is the bare lamp flux

MF is the maintenance factor of the installation

There have been a number of proposals to modify the lumen method to account for the influence of room contents. These have usually involved the inclusion in Equation 2.2 of an additional term, a multiplier to the UF(s), which increases the initial installed flux to compensate for light absorbed by room contents and the adjustment of the SHR to acknowledge the presence of obstructions. This section examines these proposals.

Steffy[33] put forward a "partition factor", used as a multiplier to UF in Equation 2.2, to compensate for light absorbed by vertical, free-standing partitions and thus not reaching the working surface. No explanation is given as to the origin of the data. The partition factor, shown in Table 2.5, depends only on ceiling and partition height.

According to *Steffy*, the partition factor is "usually lower (worse) for direct, well-controlled luminaires and usually higher (better) for indirect, widespread distribution luminaires" but no magnitudes of these adjustments are quoted. This piece of advice is in general agreement with the results of *Choi and Mistrick* but, interestingly, is at variance with the results of the Liverpool work which was based on furniture

Ceiling Height (m)	Partition Height (m)	Approximate Partition Factor
Between 2.60 and 2.75	*Less than 1.05*	*1.0*
	1.05 to 1.35	*0.95*
	1.35 to 1.63	*0.85*
	1.63 to 2.0	*0.75*
Between 2.75 and 2.90	*Less than 1.05*	*1.0*
	1.05 to 1.35	*0.97*
	1.35 to 1.63	*0.90*
	1.63 to 2.0	*0.80*
Between 2.90 and 3.05	*Less than 1.05*	*1.0*
	1.05 to 1.35	*0.97*
	1.35 to 1.63	*0.95*
	1.63 to 2.0	*0.85*

Table 2.5: Partition Factors according to Steffy.

configurations that do not include cellular partitions. The major limitation of the partition factor is that it accounts only for height of partition and ceiling but not for number and location of partitions. The influence of luminaire type is also ignored. The results of the surveys of *Kajima et al* (described in Section 2.4.1) were also used to determine the value of a multiplier for the UF. The term, called the "office fu niture factor", had a value of 0.8 and appeared to be intended for use in the design of general lighting for offices only.

Ballman and Levin[34] put forward a number of calculation procedures for installations equipped with cellular partitions. The first estimates the value of a multiplier for the UF in order to calculate average illuminance over the whole floor area of such an installation. The multiplier, also known as the "Partition Factor", ranges from 0.6 to 0.8 depending on partition height, reflectance, cell size and ceiling height. The same authors devised a calculation method for total average illuminance in an individual cubicle, which employed the technique of separating the room into an upper cavity that extends from the top of the partitions to the luminaire plane, and an lower cavity that is the cavity within the partitioned space. The lumen method is used to calculate the average illuminance on the top of the partitions. Next, the UF for the area within a single cubical is determined assuming that the source (the top of the partitions) is a diffuse "virtual luminaire", using the appropriate surface reflectance and a zero effective ceiling reflectance. This technique may be extended to give the indirect illuminance at any point within the cubical by simply undertaking the calculation of the average illuminance on the plane of the top of the partitions twice, once as above to give total illuminance and secondly to give direct illuminance by assuming black walls and ceilings. A second lumen calculation gives average illuminance in the cubical. This method is included in the recommendations in the NAIES Handbook[6]. The final calculation method of interest is a graphic technique to check which luminaires in an installation contribute to the direct illuminance at a given point within a cubical. The magnitude of the direct illuminance is then calculated using the inverse square law.

Although there seems to be a consensus in a number of Codes that some adjustment of the SHR to acknowledge the presence of obstructions is necessary, there is little published quantitative advice. A number of 'rules of thumb' exist. CIBSE LG3 recommends a reduction of one third in the maximum SHR as suitable for most industrial applications. *Steffy* simply suggests more luminaires, spaced closer together in order to provide task illuminance from multiple sources. *Williams* describes an empirical method of adjusting manufacturers recommended spacing-to-mounting-height ratio for application for the design of lighting for areas with cubical partitions[35]. The modification to the published maximum spacing is shown in Equation 2.3.

$$Maximum\ Spacing = ((W_s - W_p) \div W_s)\ x\ SHR_{max}\ x\ (H_m + L_d)$$ — Equation 2.3

Where:

W_s = width of the smallest paneled workstation

W_p = vertical distance from working plane to top of panel

SHR_{max} = maximum spacing to height ratio

H_m = mounting height of luminaires above working plane

L_d = luminaire dimension (in same direction as SHR)

2.5 Subjective effects

Research over the past few years has given some clues as to which factors create subjective visual impressions of interiors. The work, notably by *Flynn*[36] and *Loe*[37], illustrated that luminance patterns on walls, ceilings and floors can influence how people perceive a given space. The research used an experimental mock-up room in which the lighting conditions were varied and a number of observers were asked to make subjective judgments. *Flynn* found five subjective impressions that were influenced by luminance patterns: visual clarity, spaciousness, relaxation, privacy and pleasantness. Design guidance to acknowledge these factors, can be framed in terms of luminance distribution on the room surfaces. *Loe et al* concentrated on the effect of the luminance pattern in the field of view and showed that people preferred a space to have lightness and interest. The lightness factor related to the average luminance of a horizontal band, 40 degrees wide and centred at eye height. The interest factor related to the non-uniformity of the luminance pattern which correlated well with the ratio of maximum to minimum luminance within the 40 degree band. The results of this work can, with some difficulty, be translated into design guidance for room surface luminance.

This work may be criticised for its concentration on the luminance conditions of the bounding surfaces of empty rooms, since large open spaces create an entirely different feeling from that of, say, partitioned workspaces. In a typical room which contains furniture or equipment, a view inside the room is likely to be a combination of room surface and horizontal and vertical surface of the room contents. The luminance patterns on room contents are likely to be influenced by factors other than just the lighting system within the space (for example: layout, shape, colour, texture) and the users' view of the obstructed interior may be completely different from that of the same installation in an empty state. Under these circumstances, even the modest amount of design guidance that exists in the form of preferred room surface luminance, is inappropriate except for the special case of rooms equipped with regular cubical workstations which take on many of the visual aspects of a small room. Since most working interiors contain a variety of objects, it is a matter of concern that little is known about how a view of room contents changes the subjective impressions of the whole interior and it is clear that some work is required in this area.

2.6 Discussion

Most of the recently published lighting Codes and Standards allude to the problems of light loss caused by interior obstruction and appear to recognise that this is of concern to designers. The empty room design assumptions are widely recognised as being misleading for interiors in their subsequent fully furnished state. The guidance they offer however is usually confined to general warnings about the dangers of light loss and shadowing caused by room contents and advice on overcoming these problems is typically in the form of a recommendation to use reduced luminaire spacing or increased installed flux in conjunction with traditional empty room design methods. The NAIES Handbook[6] on the other hand, offers detailed advice on calculation techniques for spaces equipped with partitions. This otherwise laudable attempt to address the problems suffers from two disadvantages, namely that its application is clearly very limited and that it requires more information in the form of precise furniture layouts than is arguably available at the design stage.

Most Codes give some guidance about the use of computers in lighting calculations, but none currently include any information on calculations that include interior obstruction. This is a matter of concern, since a wide range of software used for design includes such features. There is a need for techniques of validation of programs of this nature and guidance on accuracy and interpretation of results of such programs to be included in future codes.

Arguably the most important issue is that, having identified obstruction light loss as a problem, the various codes ignore the commercial implications. The nature of the problem is that absorption of light by contents must be compensated for by an increase in installed flux if it is necessary, for example to achieve a specified working plane illuminance. Under conditions of commercial competition, designers are attempting to achieve a solution within a cost limit, but there is little guidance in the codes on which to base design assumptions. Unlike other aspects of lighting design (such as utilisation factor and maintenance factor), there is little agreed numerical design data or design assumptions relating to obstructions and thus, the scope for commercial dispute is large.

Over the past decade no significant new techniques of modelling obstructed spaces have been developed. The main advances have been in improvements to the tried and tested finite element and ray tracing software largely to reduce run time. This, combined with the increase in power of computer hardware, has meant that there are now a large number of commercial software packages that are based on finite element techniques. There are few lighting design applications of Monte Carlo methods (forward ray tracing) but the Radiance program, which is based on backward ray tracing, has a number of applications as a research and design tool. The Fourier Series methods, that appeared to have much promise a decade ago, appear never to have been used in practice.

Over the last ten years, computer-aided-methods have become widely available in lighting. The available software ranges from lumen method to finite element and many programs offer some facility to include interior obstruction. Most of the programs permit definition of obstructions by combination of orthogonal surfaces, the degree of realism of the simulation depends on the variables of the program. The results of these programs may, in some cases, give only a crude indication of the effect of the obstructions, but it can be argued that even this is beneficial in that it causes the designer to think about the problems of obstruction at an early stage. As noted above, there is a need for agreed validation processes for programs and information in codes to enable the designer to interpret program output and relate it to code recommendations. All of the programs only permit analysis of an installation – i.e. the input data must include precise details of the room contents. Where the designer has no prior knowledge of the contents there is a need for some agreed obstruction configuration as input.

Several investigators have used computer simulation techniques to produce light loss data for combinations of installation and furniture configuration. The various pieces of work at Liverpool led to a proposal for a lumen method that allowed for both modified luminaire spacings and increases in installed flux to account for light absorbed by obstructions composed of partitions, VDTs, fling cabinets and human form. To use the method, the designer has to assess the degree of obstruction, select appropriate values of obstructed SHR and OL (the light loss multiplier to UF) and produce a luminaire layout in accordance with the normal conventions of the lumen method. The limitation of this work to date is the small number of luminaires for which the design data is available. *Choi and Mistrick* generated light loss data for spaces divided using cellular partitions and lit by a range of luminaires. These two pieces of work are the only two large scale data sets of light loss information using representative ranges of luminaires. They may be criticised for the non "designer friendly" nature of their data and the limitation of only applying to office interiors lit by a small range of luminaire types. Light loss is a major problem in industrial interiors and similar general light loss data is required for this application.

The various sets of photometric measurements that have been published are useful to understand the nature and magnitude of the light loss problem, to verify simulated design data and as the basis of empirical design methods. Measured data has only a limited use for design purposes since it only applies to one set of installation conditions and clearly, computer simulation is a more economic manner of generating large quantities of such data. The various empirical methods are used mainly for specialist applications, such as cubical partitions or enclosed work stations. To date the amount of measured data available for reference is severely limited and there is definitely scope for expanding this particular data set.

It is apparent that the two least researched aspects of obstructed interiors are luminaire spacing and subjective effects. Two approaches to the spacing problem have been put forward. Bougdah's proposed method, based on the CIBSE TM5 method of calculation of spacing-to-mounting-height ratio, required computer calculation for each luminaire and has not been adopted by the industry. The "rule-of-thumb" approach of *Williams* on the other hand, requires only a basic knowledge of height and arrangement of partitions. It is clear that neither method completely addresses the problem and that more work in this area is required.

The studies of subjective effects of lit interiors have yielded some clues about the impressions created by different luminance patterns on room bounding surfaces. The nature of obstructed interiors is such that some or all of the bounding surfaces may be obscured by the contents of the room and this would change the subjective impression of the space. This may be an important issue in some types of interior and some work is required to investigate this topic.

2.7 Conclusion - the next ten years?

It is clear that a large body of knowledge exists on the nature of obstruction loss in interior lighting design. The various factors that cause light loss have been identified and their relative importance established for a limited range of types of interior. Methods of analysis of illuminance in obstructed interiors have been developed and design methods which attempt to overcome the effects of obstruction loss, for a limited range of scenarios, put forward. However before the "empty room" assumption can be rendered invalid, there is a need for more development, better presentation and dissemination of the results of the work. Specifically effort is required in three areas.

The first is the continued development of appropriate calculation methods, not only of those mounted on computer software, but also of the hand calculation techniques which are arguably used for the majority of lighting design. Secondly, studies of the effects of obstruction should be extended to include interiors other than offices and commercial buildings. The problems of obstruction are of major importance in the lighting of industrial buildings for example and these contain a range of objects which could not be modelled using the existing techniques. Finally, the whole question of obstruction light loss and its consequences must be addressed more fully in Codes and Standards. It is desirable that such documents should include numerical data on light loss as a basis for design assumptions and advice on the available calculation methods including interpretation of results. They should also set out the commercial implications of obstruction light loss and the associated compensation factors.

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Chapter 3

The components of an obstructed interior

3.1 Introduction

Chapter 2 detailed the "state of the art" regarding the treatment of obstructions in the lighting design process, both at external institutions and at the University of Liverpool. This chapter discusses the elements of an obstructed space and their relationship and importance within the lighting design process. A definition of obstructions is put forward based upon this relationship. A historical review of the development of a set of "standard obstructions" is outlined and further modifications are proposed to broaden their range of possible applications. Several practical applications of the standard obstructions are proposed and discussed.

The second part of this chapter is concerned with two computer programs, developed at the University of Liverpool, suitable for research into, and design of, obstructed interiors. The development of, theoretical basis of and use of, the programs is reviewed. Finally, a number of modifications to both of the programs are introduced and justified. Example input and output for the modified programs is given in Appendix One.

In terms of lighting design, an obstruction can be defined as any object contained within the installation that influences the distribution of light and which does not feature in the same room in its empty condition. Within the scope of this research, the definition of obstruction is refined to include only those obstructions which project into the zone between the working plane and the luminaire plane. Research is being undertaken elsewhere to address the effect of obstructions below the working plane[1]. In a commercial building, typical obstructions may include visual display units, filing and storage cabinets, partitions for dividing offices into separate workstations and also the users of the office themselves, when seated at their desks.

In addition to defining obstruction, it is also necessary to determine how obstructions influence the lighting design process. Two of the criteria used in the design of artificial lighting schemes are the average illuminance over the working plane and the uniformity of the distribution of said illuminance. The Lumen Method[2] of lighting design is one popular technique that may be used to determine the number of a particular type of luminaire necessary to achieve a desired average illuminance level. To ensure the minimum uniformity standard is achieved, the design layout of the required number of luminaires should be planned using the constraints of the CIBSE maximum spacing-to-mounting-height ratio[3] technique. Both of these techniques fail to address the influence of obstruction on achieving the final criteria (as described in the previous chapter).

In addition to the obstructions themselves, the other components of an obstructed space involved in the lighting design process include the luminaire type installed, the size and shape of the installation and the photometric properties of each of these various components. Previous research has partially addressed the individual relationship of each of these components and obstruction light loss and the results form the basis of the methodology used in the generation of the design data detailed in chapter 5. A number of studies have demonstrated that size and disposition of obstructions has by far the greatest effect on the reduction in average working plane illuminance and a significant, but smaller, influence is due to the luminaire type. Room index and room and obstruction surface properties, on the other hand, were shown to cause a minimal effect on the reduction in average working plane illuminance[4].

3.2 Development of standard obstructions

A substantial research effort at the University of Liverpool has been directed into defining the most common configurations and components of office furniture. This endeavor has led to the evolution of a set of "standard obstructions". The standard obstructions were developed to be representative of typical office furnishings for use in lighting simulation computer software. Due to the limitations of the orthogonal geometry systems used by the majority of lighting software, this meant that the shapes of all the components of office furnishings had to be approximated to combinations of three dimensional blocks aligned with the major axes.

3.2.1 McEwans standard obstructions.

McEwan developed the rudimentary form of the standard obstruction, based upon a limited number of surveys of fully functioning commercial offices[5]. In these surveys, it was found that the main types of obstruction that adversely affected the task area illuminance on a desk were:

1. partitions.
2. filing cabinets.
3. the person occupying the desk.

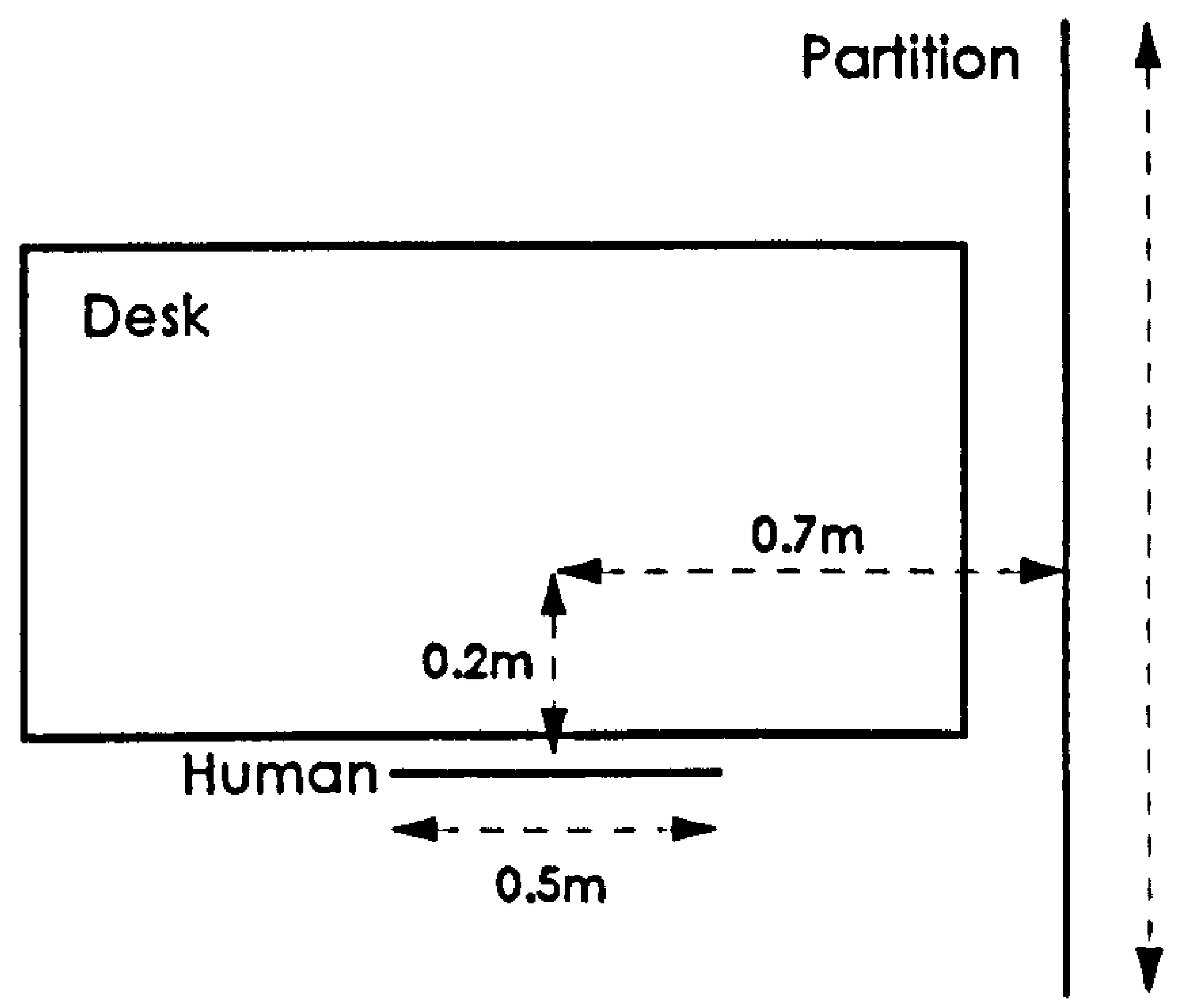

Figure 3.1: *McEwans* "partition" standard obstruction case.

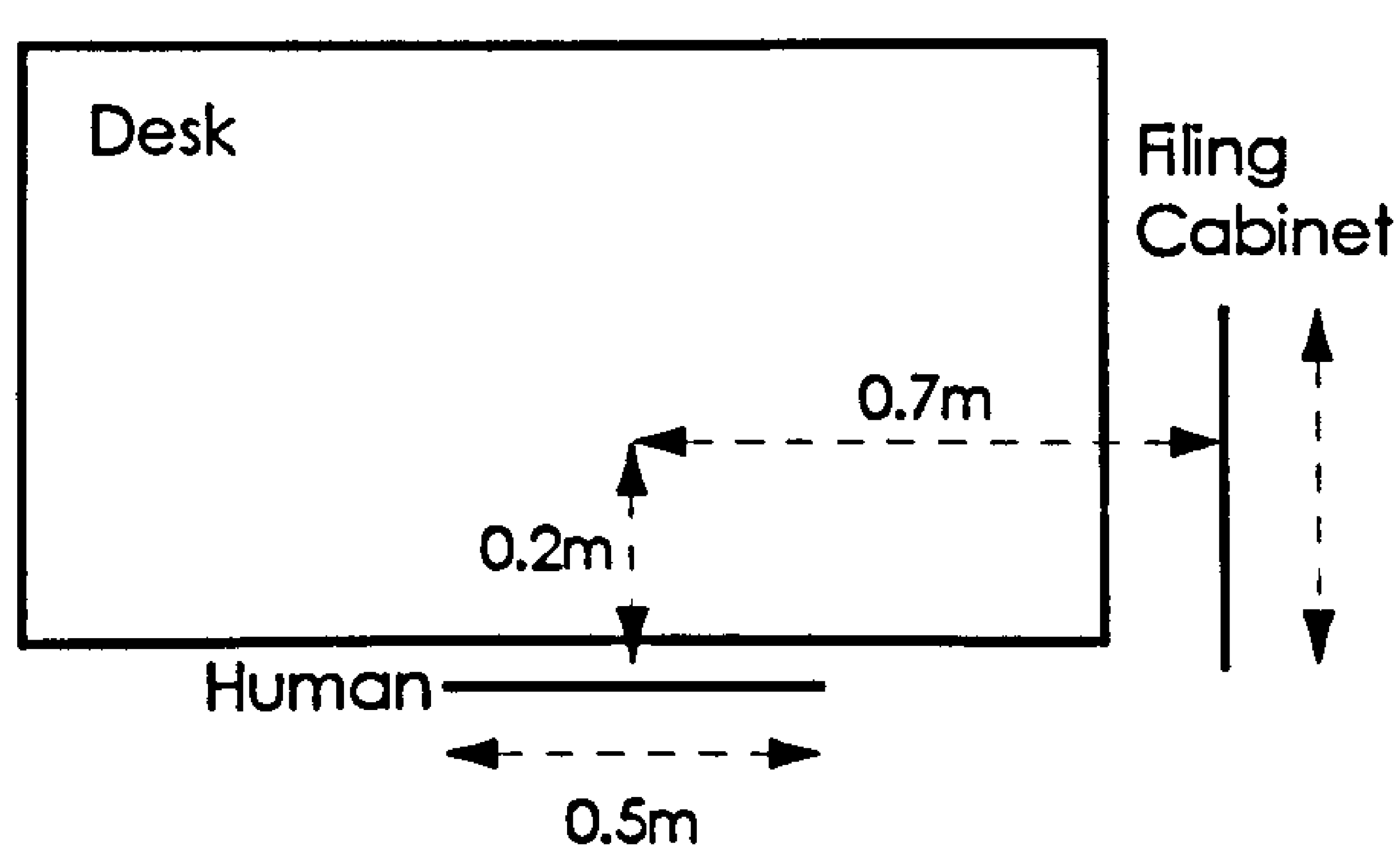

Figure 3.2 *McEwans* "filing cabinet" standard obstruction case.

From this information, two standard obstruction configurations were proposed and applied to research into the influence of furnishings on average working plane illuminance and the spacing-to-mounting-height ratio calculation for obstructed spaces. *McEwans* obstructions consisted of the combination of a desk and a seated person, with either a filing cabinet or partition at one end. The person, filing cabinet and partition were each represented by a single two dimensional surface. (see figures 3.1 and 3.2).

3.2.2 Bougdahs standard obstructions

Bougdah[4] noted that *McEwan's* two obstruction configurations were very similar in both shape and size of obstruction, and that the effect of either obstruction on the illuminance conditions on the desk was not noticeably different. There was also some doubt as to whether the two standard obstructions were capable of representing the range of contents typically found in offices.

To overcome the limitations of *McEwan's* obstructions *Bougdah* proposed several modifications to the standard obstructions. These modifications were based on *McEwan's* investigation into the relative importance of the influence of each of the individual obstruction components on the illuminance conditions on the desk and on an extensive survey of furniture data provided by two major furniture manufacturers.

McEwan demonstrated that the human form was an important obstruction as far as light loss was concerned. *Bougdah*, therefore, modified *McEwan's* rather simplistic human form to the CIE Body Shadow used in the Contrast Rendering Factor computation[6]. To determine the size and type of the most common office furnishings, *Bougdah* statistically analysed furniture data provided by two major European manufacturers – Steel Case Inc. and Herman Miller, to find the most common arrangements of office furnishing components. This analysis showed that furniture used in modern offices could generally be grouped in two main categories; those that project greater than 0.5m above the working plane and those less than 0.5m

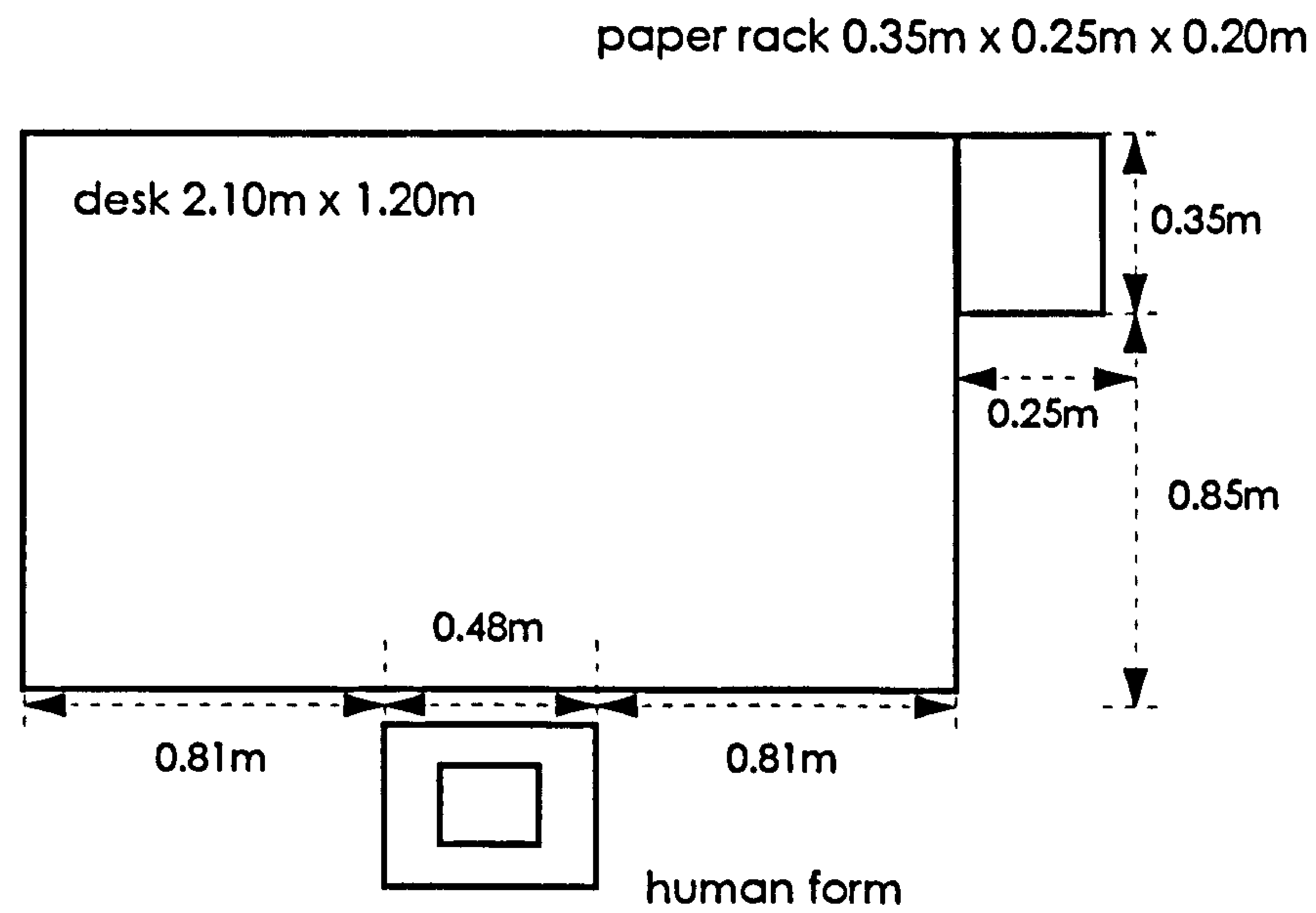

Figure 3.3: Bougdah's light standard obstruction case

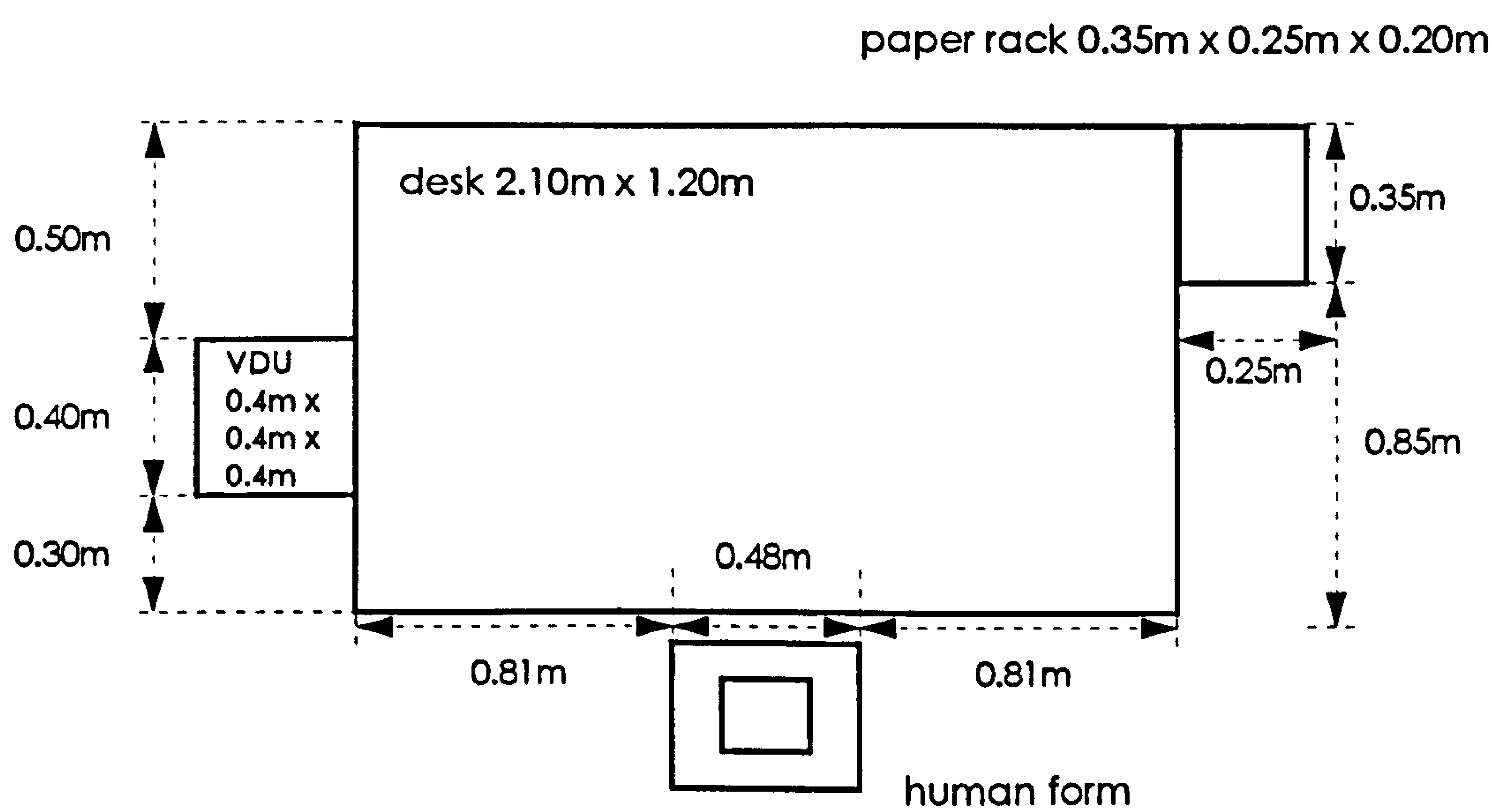

Figure 3.4: Bougdah's medium type 1 standard obstruction case

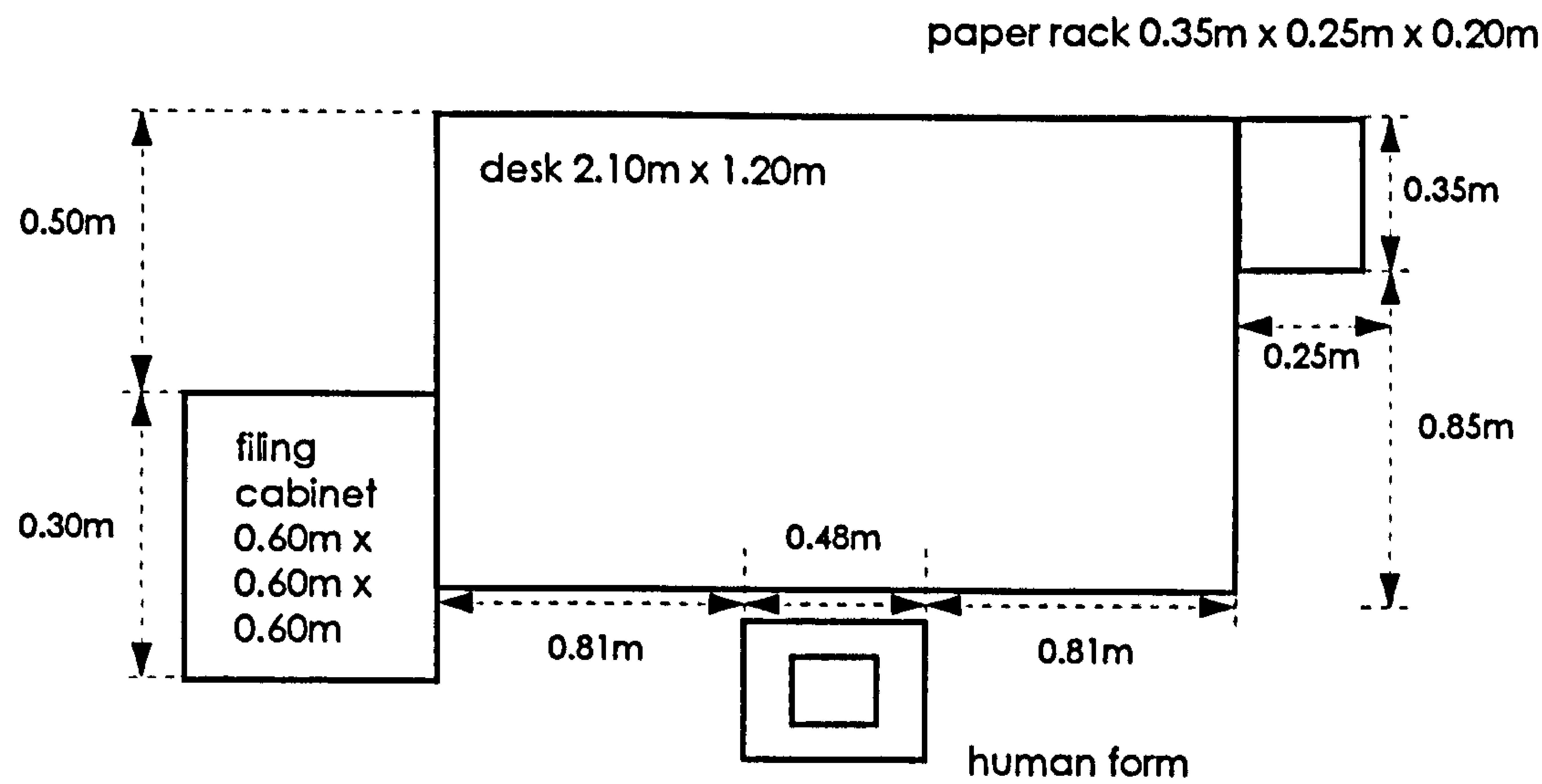

Figure 3.5: Bougdah's medium type 2 standard obstruction case

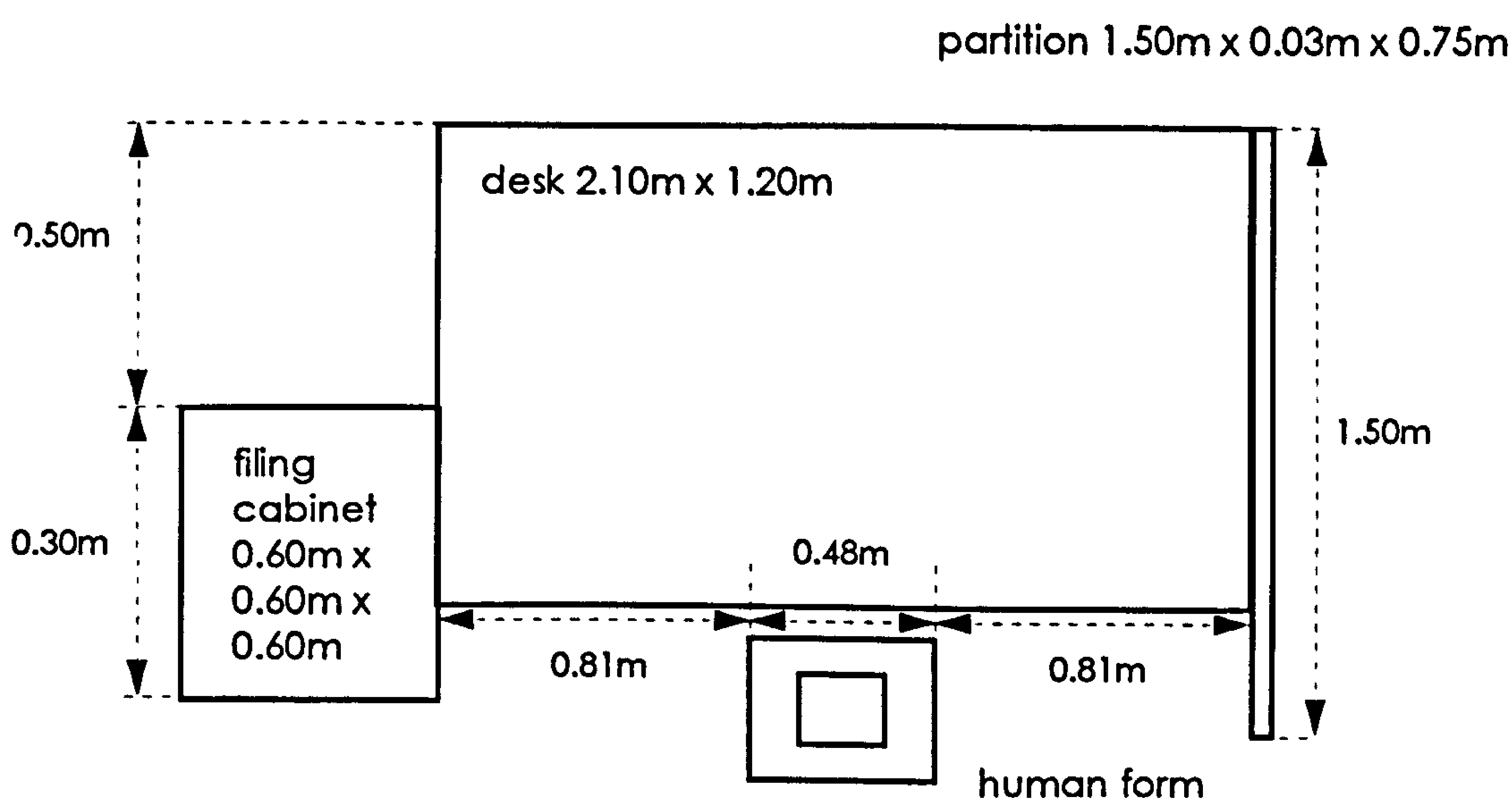

Figure 3.6: Bougdah's heavy case standard obstruction

above the working plane. Typical obstructions that fell into the first category, were items of furniture used for filing, storage and partitioning. The second group contained obstructions such as VDU's, paper racks and typewriters.

Based on these findings, new obstruction configurations were put forward with the density and size of obstruction used to identify the different cases. The configurations were:

1. *Lightly obstructed case* - human figure plus paper rack or typewriter type obstruction.
2. *Medium obstructed case (type 1)* - human figure plus VDU and paper rack.
3. *Medium obstructed case (type 2)* - human figure plus paper rack and filing cabinet.
4. *Heavily obstructed case* - human figure plus filing cabinet and dividing partition.

The obstructions were now represented more realistically using combinations of three dimensional blocks as opposed to a single surface for each component as used by *McEwan*. Figures 3.3, 3.4, 3.5 and 3.6 show *Bougdah's* obstruction sizes and components.

3.2.3 Modifications to Bougdah's standard obstructions

Bougdah's standard obstructions also contained several conceptual limitations. Firstly, the obstruction component that would realistically be located on the desk (VDU, typewriter and paper rack) were "floating" by the side of the desk. Secondly, the desk size of 2.1m by 1.2m was larger than desks commonly found in modern offices, as was the filing cabinet size of 0.6m by 0.6m. Thirdly, the two medium obstructions were essentially the same and hence one was unnecessary. Finally, *Bougdah's* interpretation of the CIE Body Shadow was incorrect.

To overcome the aforementioned restrictions, several modifications to the standard obstructions are proposed. These modifications would also allow the ability of standard obstructions to represent the behaviour of real office furnishings in field measurements, to be validated. The size and types of obstruction components developed by *Bougdah* were also verified against up to date versions of furniture data from the same two manufacturers. The proposed modifications are:

1. The alteration of the human form to a size and shape more accurately representing the CIE body shadow. The human form was also verified against the average size and shape of the researchers who would be the actual human forms when the obstructions were used in photometric surveys.
2. The movement of all components that required support onto the surface of the desk.
3. The reduction of the desk and filing cabinet dimensions to a size found to be more common in modern offices.
4. The amalgamation of the two medium standard obstruction cases into a single case.

As with *Bougdah's* obstructions the density of furniture was used as the delineating factor for determining each obstruction case. Based on this supposition and the above points, the following three obstruction cases have been put forward:

- Light Case Obstruction – person, desk and VDU.
- Medium Case Obstruction – person, desk, VDU and filing cabinet.
- Heavy Case Obstruction – person, desk, VDU, filing cabinet and partition.

The size, disposition and reflectance of the individual elements and obstruction cases are shown in figure 3.7 and table 3.1.

3.3 Quantifying obstruction density

The density of obstruction has been shown to be important in the distribution of light within furnished interiors. The standard obstructions, detailed in the previous section, have been shown to be a useful tool in investigating this relationship. If the results of any investigation carried out

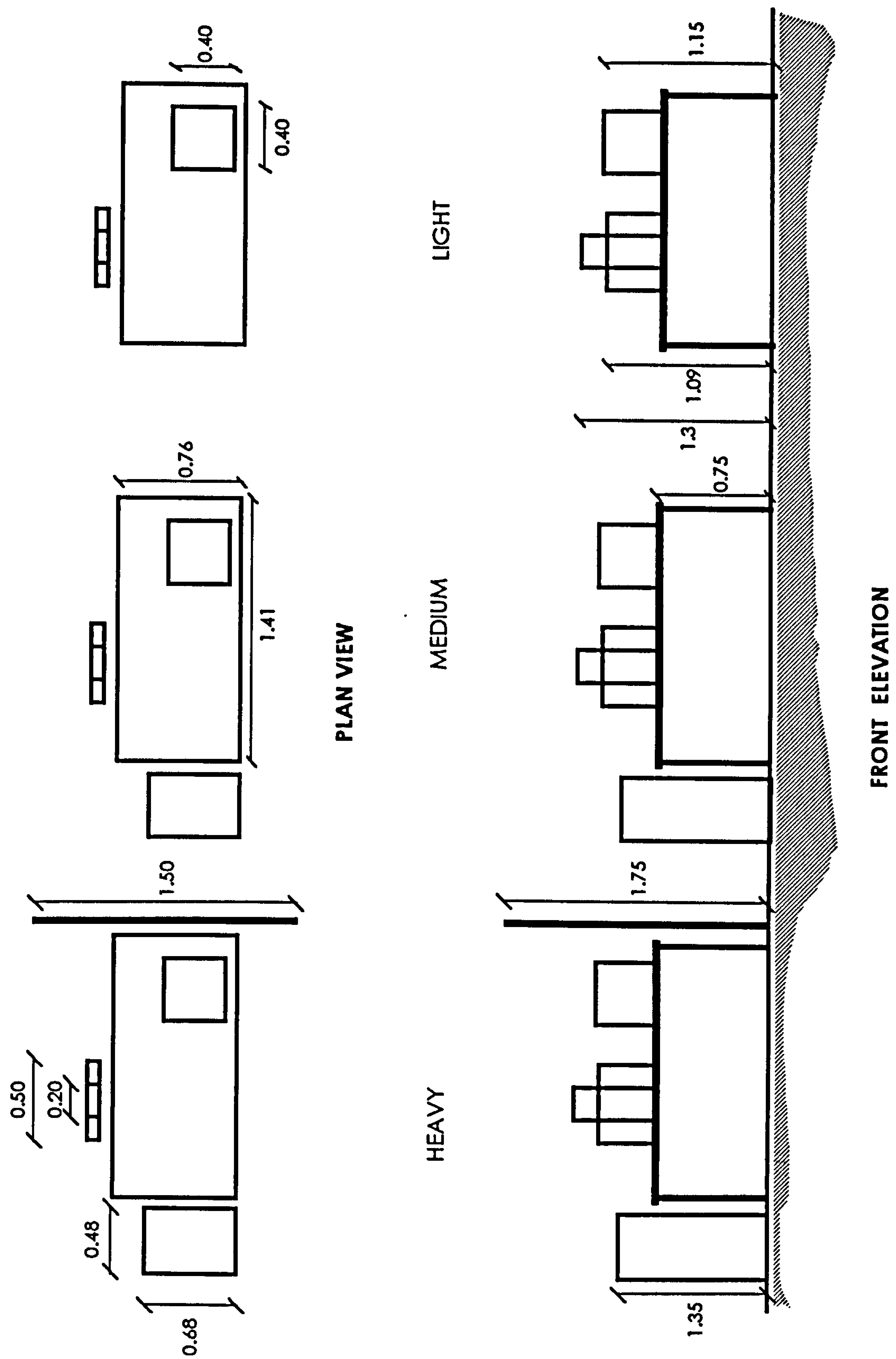

Figure 3.7: Diagram illustrating the new proposed standard obstruction configurations (all dimensions in metres)

Element	Length (m)	Width (m)	Height (m)	Vertical Surface Area (m^2)	Reflectance
Filing Cabinet	0.64	0.48	1.35	1.34	0.3
Partition	1.50	0.025	1.75	3.06	0.6
VDU	0.40	0.40	0.40	0.64	0.3
Person - head	0.10	0.20	0.55	0.53	0.3
- body	0.10	0.50	0.34	-	0.4
Desk	0.76	1.41	0.75	-	0.3

Table 3.1 – Elements of Standard Obstructions

Installation	Actual VFR
Shipping company general office	0.15
Health authority general office	0.28
Insurance company general office	0.34
Bank general office	0.34
Consulting engineers general office	0.38
Bank data processing office	0.42
University administration office	0.44
Insurance company general office	0.57
Consulting engineers design office	0.58
Electricity company general office	0.60
University accounts office	0.63
Transport authority engineering office	0.64
University computer unit	0.69

Table 3.2: VFR values for some actual furnished interiors.

using standard obstructions were to be applied to the behaviour of actual interiors, then some other method of expressing obstruction density is necessary, rather than the arbitrary light, medium and heavy descriptions used for standard obstructions. McEwan proposed two methods for assessing the density of furnishings in obstructed spaces, both of which take the form of ratios of obstruction area and another installation dependent quantity.

The first technique was the ratio of surface area of obstruction above the working plane to mounting height (OHR). This ratio was determined by calculating the total surface area of all obstructions within the installation projecting above the working plane and dividing this value by the mounting height of the luminaires.

The second tecnnique was known as the vertical surface area of obstruction to installation floor area ratio (VFR). This ratio was determined by calculating the total vertical surface area of obstruction projecting above the working plane and dividing this value by the floor area of the installation.

Bougdah also used these two classifications of obstruction in his analyses of obstructed space and he found the latter (vertical surface area to floor area ratio) to provide the most reliable means of assessing obstruction density.

To verify that these standard obstructions, described in Section 3.2.3, were representative of obstruction densities commonly found in commercial buildings, a number of surveys of room contents in offices were conducted. The surveys consisted of recording physical measurements of rooms and their contents, from which vertical surface area, floor areas and hence VFR values were calculated. The results, shown in table 3.2, indicate a range of VFR in actual interiors from 0.15 to 0.69, these being within the range that can be created by the standard obstructions. In terms of this measure of obstruction therefore, standard obstructions are capable of replicating conditions found in actual furnished interiors.

3.4 Practical applications of standard obstructions

Standard obstructions were originally developed for use in the calculation of luminaire spacing and light losses for use in the design of lighting for obstructed interiors. They may also have a use as benchmark validation tools for interior lighting analysis computer programs that have a capacity to handle internal obstructions. This section describes these various applications.

3.4.1 Measurement and prediction of light losses

To predict the obstruction light loss over the working plane, a specially written computer program was used to enable illuminance conditions for specific combinations of room size, room contents and light source to be determined (see section 3.6 for a detailed description of this program). Chapter 5 illustrates how this program was used to calculate the obstruction loss (OL), that is the percentage reduction in average working plane illuminance caused by uniformly distributed standard obstructions, for a range of interiors lit by point or linear source luminaires. The data generated by this analysis was used in the development of a modified lumen method capable of predicting and compensating for the obstruction light loss over the working plane. The dominant factor in interior light loss was the size and disposition of the room contents. Data was generated for a modified lumen method using standard obstructions as 'room contents' having a range of densities from 0 to 0.7, as classified using the VFR concept described earlier in section 3.3.

To verify the applicability of generating design data using standard obstructions, a series of field measurements of obstruction light loss were undertaken, in a range of interiors that contain lighting equipment that is representative of good modern practice. The measurements were made in the installations, firstly in their empty state, secondly filled with standard obstructions, and finally, in some cases, in their working state after occupation by the building users. Chapter 4 describes these surveys in more detail and shows that the trends and the magnitudes of the measured and simulated values are in good agreement.

On the evidence of the simulations and surveys of illuminance conditions within obstructed spaces, it appears that the standard obstruction concept appears to have potential as a predictive tool for overall light loss of an installation containing obstructions. Standard obstructions have also been used for measurement of effective floor cavity reflectance[7].

3.4.2 Computer program validation

Computer programs are increasingly used for appraisal of proposed designs. With the many programs and algorithms available, there is a need for a process of validation of the programs so that they may be used with confidence by designers. The validation process includes review of the underlying assumptions of the program, including data used, and also testing of programs using standard 'benchmark' data. Some work has already been done in this area to test programs based on the lumen method, using as standard conditions, an empty office lit by defined luminaires. The programs are evaluated against an acceptable range of limits of working plane illuminance parameters which acts as the main validation device[8]. The test models used to date have all assumed an empty space, despite the fact, as shown in Chapter 2, section 2.3.2.1, that many programs are available which have the capability to define internal surfaces such as partitions and to take account of these in the illuminance calculation process. There exists no standard data for internal obstruction for test purposes, and the standard obstructions put forward in this chapter are suitable for this purpose. Standard obstructions are simple enough to create using the orthogonal geometry systems that are common use in lighting design programs, yet are capable of being used to predict light losses caused by room contents.

3.5 Two computer programs for obstructed interiors

Through the course of research that was carried out into lighting design methods for obstructed interiors at the University of Liverpool, two types of computer program were developed to assist in both the research and design of obstructed spaces. The first program to be developed was a lighting analysis program capable of calculating illuminance conditions on room surfaces, taking into account the presence of obstructions between the luminaire plane and the working plane.

The second category of program developed was based on a modification to the current UK procedure for calculating the nominal and maximum spacing-to-mounting-height ratios (SHR_{nom} and SHR_{max}) of a luminaire. The SHR is intended for use by designers as a guide to permissible luminaire spacing that will achieve a set uniformity of illuminance criteria. The assumption of an empty space, in the SHR calculation, was found to be likely to cause reductions in illuminance uniformity when SHR_{max} was used as guidance to luminaire spacing in furnished spaces.

Both of the aforementioned computer programs were initially developed by *McEwan* and then further refined by *Bougdah*. The following sections describe this process of development and refinement. A further set of modifications are proposed and detailed.

3.6 A lighting analysis program for obstructed interiors

McEwan developed the lighting analysis program to be able to model all of the physical parameters present in an actual interior. The user was able to define all of the room dimensions and surface reflection factors, the luminaire photometric behaviour and obstruction dimensions, locations and surface reflection factors. The output consisted of a graphical model of the room showing the luminaire layout, the obstruction positions and the resulting illuminance conditions over the working plane. This enabled the program to be used as a design tool by allowing the designer to review the illuminance patterns and make informed decisions as to any necessary design changes. In addition to the graphical output, a detailed text-based output file was also generated which presented information such as obstructed and unobstructed, direct and indirect, and total illuminance on a grid of points. This form of output was particularly useful for detailed research into the components of obstructed spaces.

The analysis program could be divided into 3 main sections through which the working plane illuminance was calculated. The first section dealt with the input routines, in which all the user-specified data was transferred from external files into arrays ready for use. The second section, and main bulk of the program, dealt with the various calculation routines and the final section dealt with the output routine. The flow chart shown in figure 3.8 graphically describes this series of processes.

The first part of the program reads in the details of the space from external files. This includes information on the room size and photometric properties, obstruction sizes and photometric properties and luminaire photometric data. One of the preliminary calculations undertaken by the program was to determine the number of luminaires required according to the conventional lumen method and automatically position the luminaires using the specified SHR information. If linear luminaires were used then the program represented them by splitting each luminaire into point sources.

Once the luminaires are positioned and divided into their constituent components, the geometrical relationship between each component and all the surfaces within the room was assessed. This assessment determines whether the luminaire section and surface concerned can "see" each other. The model used for evaluation was the vector cosine technique. Normals of all surfaces are defined uniquely in relation to a consistent origin dependant upon their size and orientation. The use of vector cosines allows the line of sight between two points of interest (either luminaire and surface

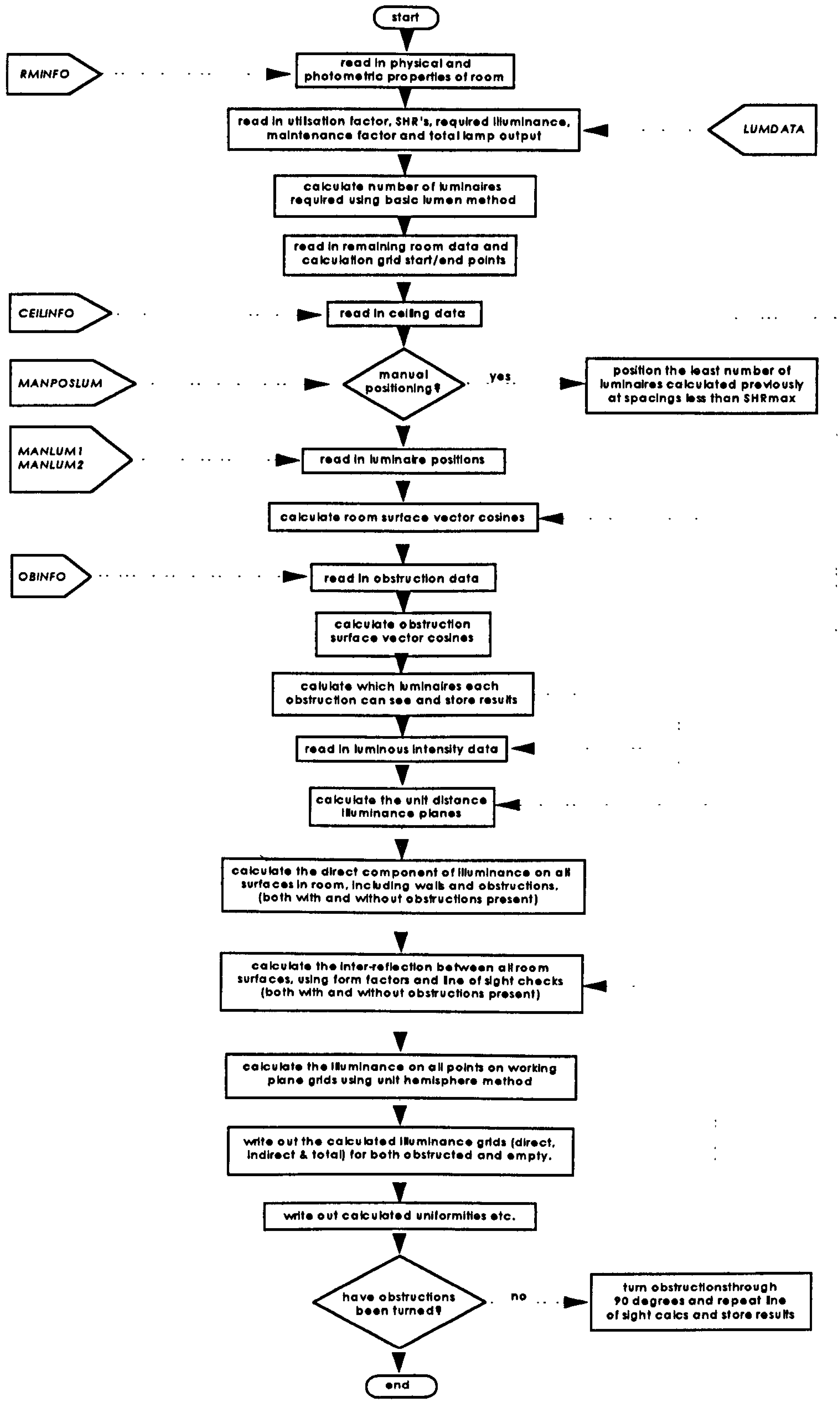

Figure 3.8: Flowchart showing the main procedures of the analysis program.

for the direct component or surface and surface for the indirect component) to be checked for intersection by an obstruction.

The direct component of the illuminance received on all the surfaces was calculated using the results of the vector cosine geometrical relationship as a guide to which surfaces receive direct light. A technique known as Unit Distance Illuminance Planes (UDIP), devised by *Bracket et al*[9], allows direct illuminance to be determined by hyperbolic interpolation of pre-calculated values. The pre-calculated values, or UDIP arrays, were computed on the following basis. Firstly the luminaire, if not a point source, was divided into sections small enough to be treated as a point source. Secondly, the luminaire was located at unit distance from the plane to be considered and illuminance was calculated over the surface, using the inverse square law, on a set of points located such that any two adjacent points are displaced by roughly 10°. This displacement allows effective use of all the intensity data. The third and final stage was to calculate the actual direct illuminance at any point in the room. This was done by interpolation amongst the UDIP array corresponding to the geometrical relationship between source and receiver, and by applying a correction factor based on the actual distance between the two points.

To calculate the indirect component, the technique of finite element analysis[10] was employed. The amount of flux received by a particular surface from any other surface is dependant upon the geometrical relationship between the two surfaces and the photometric properties of the emitting surface. The finite element technique involves dividing all room surfaces into discrete elements such that they may be considered to have uniform photometric behaviour. Each of the discrete elements was then analysed in turn and the overall contributions summed. The final stage involved in the indirect component calculation, was the determination and analysis of elements that contribute to the indirect illuminance on the working plane. A unit hemisphere was created above each calculation point (see figure 3.9) and using the vector cosine technique,

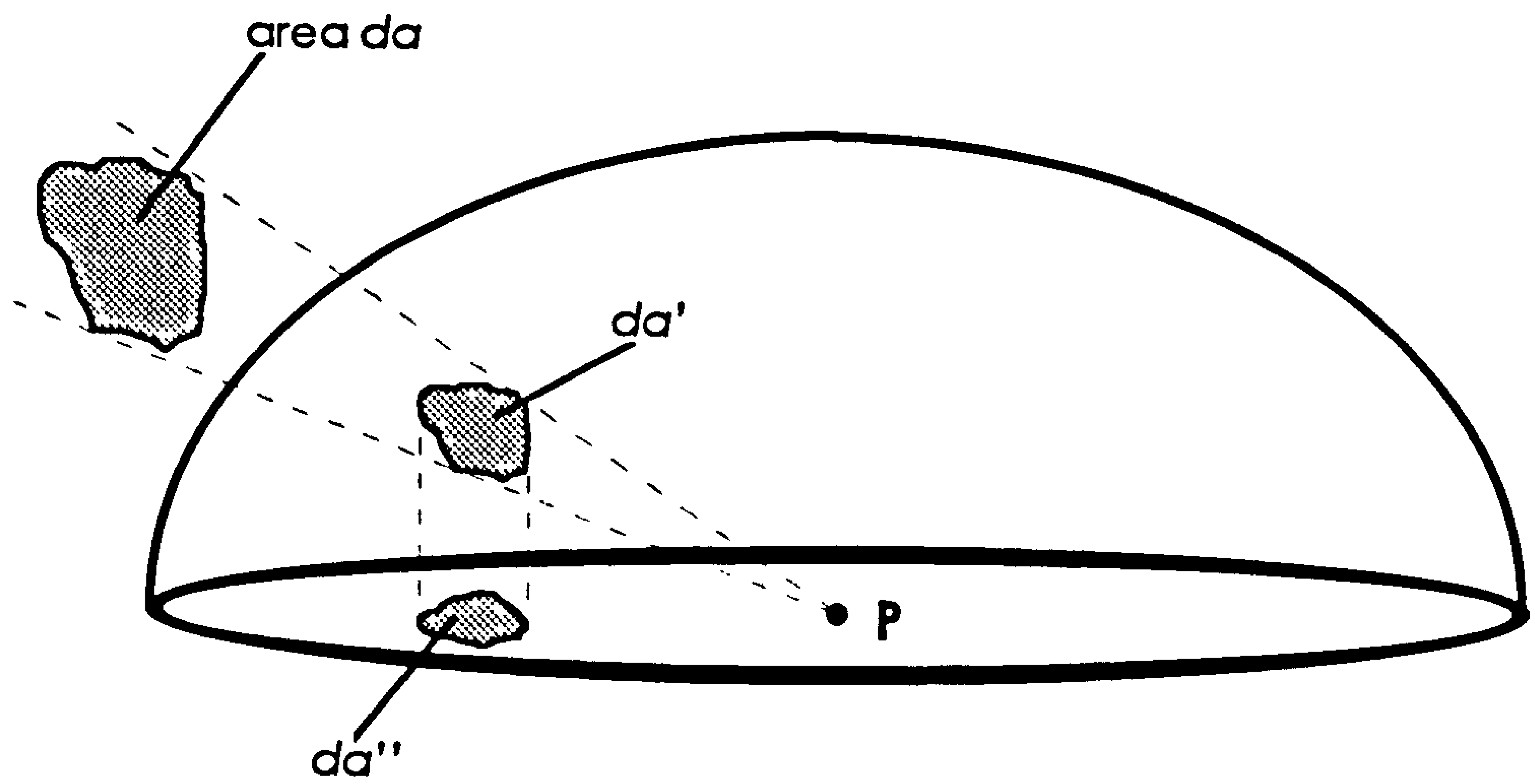

Figure 3.9: The unit hemisphere created above the point P to calculate the illuminance received at the point from a uniform diffuser.

the surfaces which intersect with lines passing through each equal area section of the hemisphere were determined. The excitance of the point intersected, which was obtained by interpolation amongst the stored excitance calculated over every surface, was then used to determine the excitance received on the calculation point.

McEwan intended the program to be used as a design tool and for this reason, included output in graphical form. The actual graphics were a plan view of the room, luminaire layout and obstructions, overlaid with isolux contours. The program was purposefully developed this way to create output suitable for conveying the results to non-technical parties. The program also created a text file as output, containing the input data, working plane illuminance grids for both empty and obstructed cases of direct, indirect and total illuminance.

In order to validate the results ot the lighting analysis program, *McEwan* compared the results of a series of office simulations to measurements of their actual working counterparts. The results showed that the program was capable of modelling illuminance conditions in obstructed spaces to within a 10% limit of the measured illuminance obtained using the CIBSE field survey method.

Bougdah found that the analysis program had several limitations that restricted both the range of sizes of spaces that could be modelled and their contents. The main limitations were, that the maximum allowable room size could not exceed 14m by 12m and similarly that the number of obstructions was restricted to a maximum of twenty-four. Also for each time the number of obstructions or room size was different from the previous simulation, the user had to redefine the various arrays within the software code.

An additional problem associated with the input data was the lack of flexibility available to the user. For instance, the user could not override the program's automatic positioning of the luminaires. A third problem concerned with the luminaire positioning routine was also discovered. The routine checked to satisfy SHR requirements but did not check whether the luminaires physically fitted into the room.

Bougdah redefined the arrays containing the obstruction and room size data as a function of certain variables within the code. Essentially this meant an increase in maximum permissible room size that could be modelled to 16m by 15m and similarly, the corresponding number of obstructions that could be modelled was increased to a maximum of 80. The limiting conditions of these values was imposed by the maximum array size allowable, which was in turn a condition imposed by the compiler and the computer memory available.

Concerning the problem with the luminaire positioning, *Bougdah* added a routine that checked whether the luminaires physically fitted into the room specified and automatically modified the spacings accordingly. The possibility of overriding the automatic luminaire positioning was also added, enabling the user to specify luminaire positions from an external file.

McEwan validated the analysis program by direct comparison of measured and simulated results. To further validate the software, *Bougdah* compared the same two sets of measured and simulated results using a statistical analysis method. *Bougdah* applied the Spearman rank correlation test and the results showed correlation coefficients ranging from 0.665 to 0.941, with 99% confidence levels. These results demonstrated that the analysis program was capable of simulating the lighting conditions in interiors where photometric and physical characteristics are known.

This was the state of the program when it was inherited by the author in 1992. Mounted on an IBM 3083 mainframe computer system, the program required an executive control program, which linked the programs algorithms to all related libraries and specified the location of the associated data files before it commenced the calculations. At this stage, a complex simulation would take several hours to complete and, due to the necessity of keyboard input, required the user to be present for at least the first few minutes. This was identified as a characteristic of the IBM version of Pascal used to write the program.

3.6.1 Transfer of software from mainframe to networked workstations

Around the time of the commencement of this project considerable advancements in computer hardware were appearing on the market. The use of mainframes was becoming an obsolete idea and being replaced by the use of networked groups of workstations. It was necessary to port the analysis program from the University of Liverpool IBM 3083, which was to be decommissioned, to its replacement, a UNIX based Sun workstation. This had the advantages of a potential increase in operating speed and batch processing possibilities. The difference between the syntax of the IBM Pascal compiler and the Sun Pascal Version 2.1 compiler required that several modifications had to be made to the program before it could be operate.

Amongst other modifications, this conversion required the removal of several obsolete external file handling commands and the removal of the graphics routines. These modifications offered several advantages; primarily, they allowed the program to run independently of any of the user interaction expected from the IBM version. The subroutines that constructed the graphics were developed with the original version of the program and were now considerably out of date. Additionally, the Sun system had several sophisticated graphics packages which were capable of presenting the results in a visual form. Hence, the removal of the graphics routines was not felt to be disadvantageous. Additionally, the program was intended to be used as a research tool, so as long as the relevant quantitative results were readily discerned, graphical presentation was a luxury, not a necessity.

The combination of Sun Pascal and a workstation offered several other options. Sun Pascal enabled the program to be compiled, with all of the necessary libraries statically linked to the executable file. This meant the program itself could be used on systems without a Pascal compiler and associated libraries. It also meant that only a single command was necessary to run the program. The Sun workstation allows extensive background processing and multitasking, which enabled the user to analyse a number of different situations at the same time. Additionally, once all the data files are defined and in place, the whole set could be processed overnight as a batch job. The time for the most complex analysis was also reduced from several hours to under one hour.

3.6.2 Modifications To The Input

The program requires input from external files describing the room, furniture and luminaires, as described earlier. There were no detailed descriptions of the contents of these input files available, so an exercise to assess this was undertaken by tracing the steps of the data input in the program code. The results of this exercise are contained in Appendix One, along with an example of the revised form of output from the program,. Some of the quantities being read into the program were found to be redundant and hence were removed from both the program itself and the input files.

The most significant modification to the input routine was the adaptation of the program to enable luminaire data to be read in from the file format accepted as the British Standard format for luminous intensity data, i.e. CIBSE TM14 format[11]. As the intention was to use the program to generate data for a large number of luminaires and this is the format used by the major British luminaire manufacturers, this was seen as a necessary step. As well as this, the option of including a more detailed description of the luminaire used and the analysis being carried out was included. To ensure that the intensity data was read into the correct array, two of the eight available label lines provided by the CIBSE TM14 data format were

CIBSE/1
<label line 2>
<label line 3>
<label line 4>
<label line 5>
<label line 6>
<label line 7> *(linear or point source indicator)*
<label line 8> *(luminaire group)*
<number of lamps><photometric type><width><length><height>
<ballast lumen factor><input power><input VA>
<design attitude>
<number of vertical angles><number of horizontal angles>
<vertical angles>
<horizontal angles>
<intensity values for all vertical angles at 1st horizontal angle>
<intensity values for all vertical angles at 2nd horizontal angle>
<.........>
<..etc..>
<.........>
<intensity values for all vertical angles at last horizontal angle>
<glare shape code><luminous area of base><luminous area of side><luminous area of end>

Notes: Apart from the specified modifications to label lines 7 and 8 the file remains completely as specified in CIBSE Technical Memorandum No. 14. The key to the identifiers used in label lines 7 and 8 is the same as the University of Liverpool format outlined in Appendix 1, where line 7 contains a 1 if the luminaire is a point source or a 2 if it is a linear source and line 8 contains the number of the luminaire characteristic group as outlined in the CIBSE Code for Interior Lighting.

Figure 3.10: Description of Modified CIBSE TM14 File Format Luminaire Photometric Data.

utilised to contain the variables, used in the old format, to identify source type and the number of the CIBSE luminaire characteristic luminaire group[12]. The modified TM14 data file is shown in figure 3.10.

The use of TM14 file also necessitated an extra input file containing additional lamp details. A second extra input file was used to contain data describing the simulation that was running, which was also written to the output file to enable easy identification of the results. This also ensured that when a large number of scenarios were processed as a batch job, the results were easily sorted.

3.6.3 Modifications to the calculation procedure

The intended use of the analysis program was for the generation of obstruction loss data for a range of luminaires, representative of modern lighting practices, installed in rooms with varying furniture conditions. The obstruction loss (OL) of an installation is defined as the percentage reduction in average working plane illuminance occurring when furniture is installed in a previously empty space. The calculation of OL had to be carried out by hand, once the program had determined the illuminance conditions. A routine to overcome this was developed and the calculated OL for the installation is now included as a standard part of the output. Additionally, routines were added to calculate the furniture density of the simulated interior in terms of its VFR (see section 3.3) and also the actual spacing-to-mounting-height ratio of the installed luminaires.

To generate a dataset that was large enough for practical purposes, it was necessary to simulate installations up to room index 5.0, furnished with modules of standard obstructions. This would necessitate a large increase in both the maximum number of obstructions that could be handled by the program and the maximum allowed room size. This required a major investigation into the techniques used to handle the data within the program structure. The arrays modified by *Bougdah* were further modified to increase the limits to those available using Sun Pascal and a workstation. The result of these modifications was an increase in the maximum number of obstructions to 110 and an increase in the maximum room size to 25 metres by 25 metres. The number of obstructions was still short of the required 360 needed for the largest rooms due to problems associated with the actual method of coding used in the initial program. The code was written bearing in mind the limitations of the original system and due to the complexity of the program, could not be greatly expanded outside these limits. After consultation with the University of Liverpool Computing Services Department it was decided that the ideal solution would have been to rewrite the program in a more flexible language (such as C++) but this would have delayed the work to such an extent that it was not a viable solution. An alternative solution to this problem was found and this is detailed in chapter 5 (data generation).

Finally, to reduce the number of mistakes due to operator error, expected in such a large project, additional error-check routines were added to the program. These routines were capable of detecting and alerting the user to any possible discrepancies in the input data. For instance, range checks were applied to luminaire data and also checks were applied to ensure the correct number of entries were contained in the intensity fields.

3.6.4 Modifications to the output

Bougdahs program output consisted of detailed illuminance grids for all combinations of direct and indirect illuminance and obstructed and unobstructed conditions. Whilst this is ideal for using the program for a limited number of investigations and making detailed checks of the output to trace errors, the majority of the output is superfluous to the requirements of the data generation involved in this project. For this reason, the output was completely restructured and streamlined to include only what was necessary, plus the additional quantities such as

VFR and Obstruction Loss. The long format data, however, was not totally removed and can easily be reinstated by changing a single variable in the code and recompiling the program. An example output file is included in Appendix One.

All of the modifications to the input, output and calculation procedures resulted in a streamlining of the programs operation that corresponded to a 15% reduction in operating time for each individual simulation.

3.7 A computer program for the calculation of obstructed spacing-to-mounting-height ratio.

McEwan[13] developed a second computer program to address a limitation of the standard UK method of calculating maximum permissable spacing-to-mounting-height ratio. The limitation was the lack of treatment of obstruction. The program used the standard UK method, described in CIBSE Technical Memorandum No. 5[3], as its basis. This method involves calculating the illuminance in the central area of an array of 16 luminaires, the spacing of which is increased in a preferred series of steps. The ratio of minimum to maximum illuminance at each step is determined and the process stops when this ratio falls below 0.7. The exact value of the SHR at the point of failure is the maximum permissable spacing-to-mounting-height ratio (SHR_{max}), and the value of the step below this is known as the nominal spacing-to-mounting-height ratio (SHR_{nom}). This information is calculated and published for all luminaires by the manufacturer and intended for use by the designer in planning his luminaire layout. The CIBSE Code for Interior Lighting recommends that an installed luminaire spacing less than the quoted SHR_{max}, for that particular luminaire, should ensure that the required uniformity standard will be achieved, but this will only hold true if the room remains unfurnished. The Code also suggests that the presence of obstructions within the room will adversely effect the uniformity and suggests smaller spacings, but it does not give any guidance as to the magnitude of the spacings or the main factors influencing the spacing.

The obstructed SHR program and concept was developed to overcome this limitation. It achieves this by introducing a "standard obstruction" into the calculation zone at the centre of the luminaire array and repeating the SHR calculation described for the empty room. The program calculates the illuminance received directly on a grid of points over the desk top. The effect of the obstructions is determined by a line of sight check between each point on the desk and the luminaires, or part thereof.

McEwan developed two programs – one for linear sources and one for point sources – in which a combination of either human figure and partition or human figure and filing cabinet were introduced into the calculation process.

Bougdah[14] critically evaluated *McEwan's* SHR programs and found certain areas needed further development and modification. The first problem that needed addressing was the size of the grid of points across which the uniformity was assessed. In *McEwan's* model the grid size increased as the luminaire spacing increased and this was leading to an inaccurate assessment of uniformity. *Bougdah* decided to implement a fixed grid of points, 0.1m apart in both directions, covering the whole desk top except a 10 cm edge strip.

A second conceptual error was found in the routine that checked for obstruction in the line of sight between points on the grid and the luminaire. This routine compared two incompatible angles and hence was fundamentally flawed. *Bougdah* rewrote this section of the program to eliminate this error.

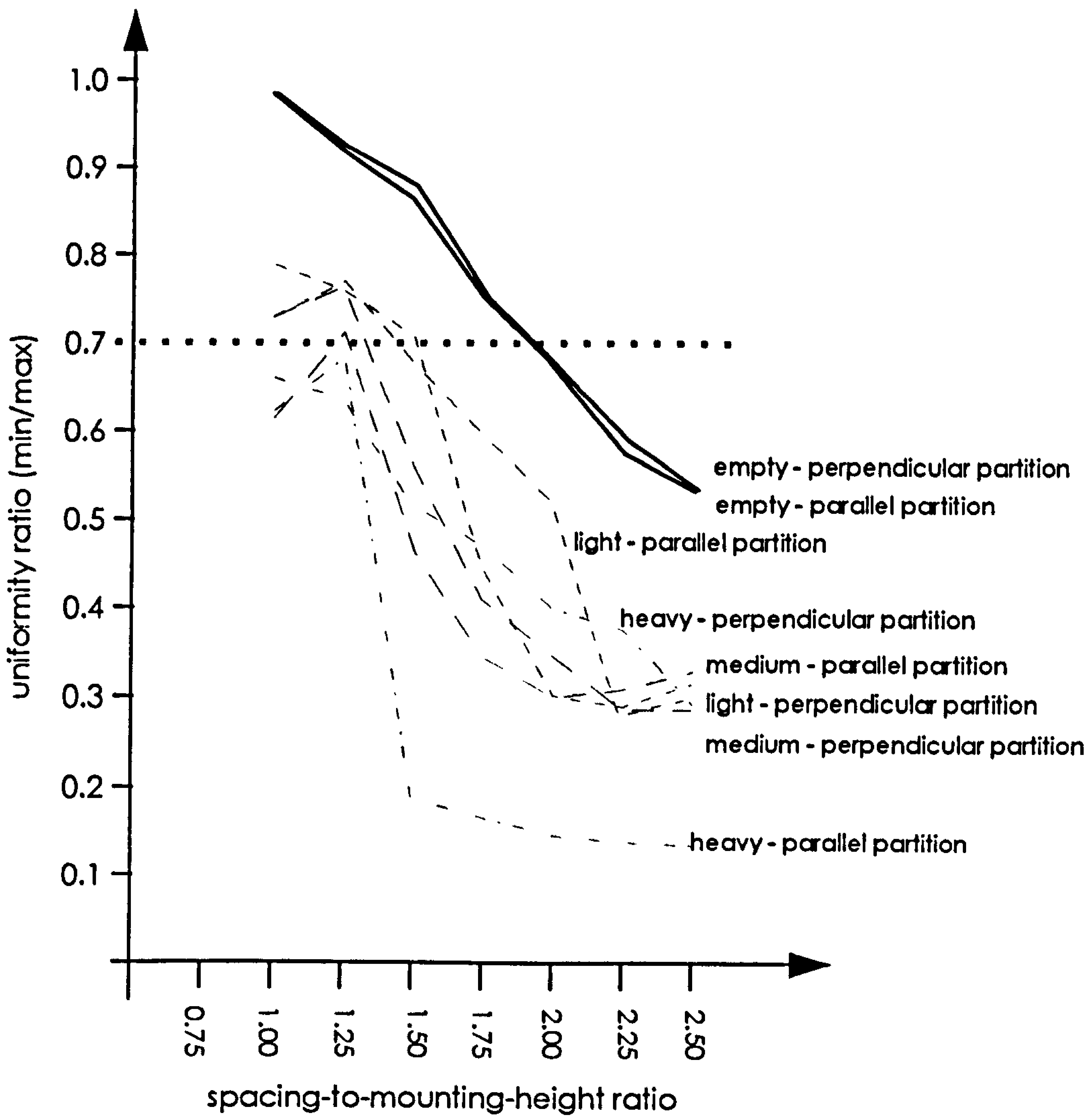

Figure 3.11 - SHR_{obs} curve example

Bougdah's most significant modification to the SHR_{obs} program was to introduce new standard obstruction configurations (detailed in section 3.3) into the program algorithms. This resulted in a suite of eight programs, one for each of *Bougdah's* three proposed obstruction cases (light, medium and heavy) plus the empty case and each of these versions had two variations - they either considered a point or linear source.

The output from the SHR_{obs} programs takes the form of illuminance grids and uniformity ratios for a series of steps of spacing to mounting height ratio. Once converted to graphical form, (see figure 3.11) the results are readily interpreted. The obstructed SHR value for each particular standard furnishing case, is the point were the uniformity ratio falls below 0.7. The results of a number of SHR_{obs} simulations are discussed elsewhere[5,6] and a detailed investigation into the performance and use of the SHR_{obs} concept is given in chapter 7.

3.7.1 Modifications To The SHR_{obs} Programs.

As with the analysis program, it was necessary to convert the SHR_{obs} program from IBM Pascal to Sun Pascal and again this involved the transformation of the program syntax to suit the new Pascal version. This conversion offered the same improvements in operating speed and batch processing options and the program is now fully developed and proven ready for use for the generation of SHR_{obs} data for a large body of luminaires.

3.8 Conclusion

All the previous research related to the design of artificial lighting installation for obstructed interiors has shown that the role of obstruction needs to be included in the lighting design process. The difficulties associated with quantifying and predicting the density of obstruction have led to the development of a set of standard obstructions and the concept of VFR as a measure of obstruction density. The proposals in this chapter detailed modifications to the standard obstruction capable of redefining them into a form in which they could be proposed to the lighting community as a useful design tool. Other uses for the standard obstruction are suggested, such as, data generation and a benchmark validation tool.

The development of two computer programs for obstructed interiors is also detailed in this chapter. The lighting analysis program now has a proven track record and is ready to be used in conjunction with the standard obstructions to generate design data. The obstructed spacing-to-mounting-height ratio computer program is now in a form whereby it can be used as an aid to the lighting design process. It is also ready to be used to generate design data.

3.9 References

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Chapter 4

Measured light losses in commercial interiors

4.1 Introduction

Previously, the main approach to the investigation of light loss due to room furnishings has been through the use of computer simulation. There are several advantages to the use of computer simulation, primarily there is the speed and ease at which different room configurations can be constructed and analysed. The use of photometric surveys to assess the relationship between light loss and room furniture is inefficient and impractical, particularly if the aim is the generation of design data. Gaining access to and measuring a large number of different room and furniture combinations would be a much too lengthy and complicated process to efficiently generate design data. Photometric surveys however, are a valuable aid in assessing the validity of computer generated design data. Additionally, some knowledge of the practical range of installation configurations, commonly found in commercial interiors, would be useful for devising the limits of data needed for design purposes.

This chapter is concerned with the field measurement of the amount of light absorbed by room contents in commercial interiors. The furniture, equipment and personnel that occupy a working office will cause light loss in terms of both local variation of illuminance uniformity across working areas and an overall reduction in average working plane illuminance. Extensive simulation studies to investigate the theoretical values, by other institutions, are described in chapter 2 and whilst chapter 5 describes a new, wider ranging, simulation technique used to generate light loss data for design purposes, previously little work has been undertaken to measure light absorption. A series of photometric surveys of illuminance within modern office buildings are described in this chapter, which were undertaken for an installation firstly in its empty condition; secondly, furnished with simulated standard obstructions; and finally, in its actual working state. The installations were selected so as to include examples of common types of luminaire and different types of room furniture systems. The results show typical magnitudes of light loss and give an insight into the relative importance of the various parameters that influence light absorption – notably obstruction type and size and luminaire type. The influence of the results on current practice are indicated.

4.2 Review of previous field measurements

Photometric surveys have been undertaken by a small number of researchers to investigate both lighting conditions in particular furniture configurations and overall light loss within a furnished space. Additionally, surveys have been carried out to investigate the effect of room furnishings on effective floor cavity reflectance. These surveys are described fully in chapter 2, section 2.4.1 "Measurement of light losses".

The surveys reported by *Briggs*[1] described a series of measurements primarily intended as the basis of a new NAIES calculation technique for predicting illuminance levels in spaces equipped with uniformly distributed cellular partitions. *Siminovitch et al*[2,3] analysed the reduction in working plane illuminance due to a number of different work station geometries using firstly a scale model of an office interior and secondly a full scale photometric simulation facility. The results indicated local light losses of up to 70% on task areas and put forward some general advice regarding the positioning of workstations in relation to the luminaire layout. *Kajima et al*[4] and *McEwan and Carter*[5] reported the results of surveys of measurements across the whole working plane of modern offices in empty and furnished conditions. The former reported losses of 20% in one room, the latter losses of between 8% and 10% in four different installations. *Cook and Hill*[6,7] used a series of photometric surveys to investigate the influence of obstructions located in the floor cavity on the illuminance distribution on the working plane. Light losses of up to 14% were found and the authors attempted to derive a relationship between horizontal working plane illuminance and effective floor cavity reflectance.

Losses of the magnitudes quoted above have clear implications for the lighting designer, particularly when using the maintained illuminance concept. Surveys to investigate light losses are however, time consuming and are only able to address a limited range of geometric and photometric variables. Computer simulation overcomes this problem but designers need to be confident that data produced in this way is capable of representing real conditions.

4.3 Field measurement in modern commercial interiors

Any modifications to lighting design methods to take account of obstruction depends critically on the assumptions made. The modifications proposed in this document (chapter 6) are based on calculated values of OL for installations assumed to be occupied by standard obstructions. The field measurements described in this chapter were undertaken in order to assess light losses due to standard obstructions, which would enable comparison to be made with the calculated values, or to relate them to losses in actual interiors.

Measurements of these values are thus important for three reasons. The first is to add to the sparse information on the magnitude of measured light losses in commercial buildings. The second is the need to verify that the simulated and measured values of OL are of the same order of magnitude, and the third is to check whether illuminance conditions in actual installations in their working state can be replicated using the various standard obstruction configurations.

The surveys investigated illuminance levels in a range of interiors that contained lighting equipment that is representative of good modern practice. Three of the installations were equipped with surface mounted diffusers, two with luminaires specifically intended for areas with VDT's, one with uplighters and one with a wall-washing luminaire system. The rest of the installations were lit using surface mounted or recessed wide distribution reflector luminaires with either wedge or cross-blade louvres, which are classified in the CIBSE Code[8] as "surface modular" or "recessed modular". The surface reflection factors for all installations were within the CIBSE Code recommendations. The measurements were made in the installations firstly in their empty state, secondly furnished with standard obstructions and finally, in some cases, in their working state after occupation by the building users. A total of 24 surveys are reported in this chapter.

4.4 Standard obstructions

In general lighting terms an obstruction can be defined as an object which is between the luminaire plane and working plane. In an office this can be taken as VDT's, filing and storage cabinets, panels and screens used for dividing offices into work stations and users of the office when seated at desks. Work described in chapter 3 addressed the problem of the size and configuration of the elements of office obstruction and a series of "light", "medium" and "heavy" standard obstructions were put forward to represent the range of obstruction density in office interiors. The sizes of the standard obstruction elements to be used for the simulation of OL data and for the photometric surveys are described in chapter 3, section 3.2.3. Figure 3.7 and table 3.1 shows the size, disposition and reflectance of the individual elements and obstruction cases. These standard obstructions can be used to represent obstruction densities having ratios of vertical surface area to floor area (VFR – see chapter 3, section 3.3) from 0 to 0.7. Typical values of VFR for modern offices were within the range 0.15 to 0.69 and thus the standard obstructions should be capable of simulating obstruction densities within most working interiors. For the purposes of the surveys the standard obstructions were constructed of painted cardboard, polystyrene, wood and were designed for ease of transport in small sections.

4.5 Survey Locations

Gaining access to suitable installations for measurement purposes was a major task. The problem was not only one of selecting suitable installations in terms of size and equipment content but also one of persuading building designers, owners and users to allow access at the various stages of the surveys. Information on the survey locations is given below and in table 4.1.

Installations 1 to 4

The single room, that was used in different configurations, to form the first four installations was a general purpose room located in the School of Architecture at the University of Liverpool. The room dimensions were 7.7m by 6.8m by 3.0m high and it was furnished with four standard obstructions. The room was lit by a regular array of ceiling mounted luminaires, switched such that two luminaire configurations could be used with different transverse spacing-to-mounting height ratios – 0.89 or 1.79. A choice of two different luminaire types was also available; a prismatic base, opal sided diffuser and a modular louvred reflector luminaire. These surveys formed part of research carried out by *Raitelli and Carter*[9] and have been included in with the results in a form suitable for comparison with the rest of the data set.

Installations 5, 6 and 7

A demonstration area owned by a luminaire manufacturer was used for installations 5 to 7. The room was 9.5m by 6.8m by 2.7m high. Only half of the room was used for an installation and each half was furnished by with four standard obstructions. Each room half could be lit in turn by regular arrays of three different types of luminaire - LG3 Cat 1, LG3 Cat 2 and recessed modular reflector, all having spacing-to-mounting-height ratios of 1.2 axial and 0.75 transverse.

Installations 8 and 9

A Medical Records Centre and a general purpose office, both equipped with recessed modular louvred luminaires, served as installations 8 and 9 respectively. Installation 8 measured 9.3m by 5.6m by 2.6m high and was lit by a regular 2 by 3 array of luminaires installed at an SHR_{trans} of 1.6. For the second stage of the survey installation 8 was furnished with 4 standard obstructions, in its actual working conditions the room functioned as a medical file/record store and hence was equipped with three 2m high by 3m long file stacks. Installation 9 was 8.4m by 8.5m by 2.6m high and lit by a 3 by 3 array of luminaires, again installed at an SHR_{trans} of 1.6. This installation was furnished with six standard obstructions. In its working conditions installation 9 was a general purpose office used by approximately eight people. It contained general filing equipment and VDT's, but no dividing partitions. (See figure 4.1). The calculated furniture density, expressed in terms of the VFR, for installation 9 was 0.28, which falls just below the average density of furnishing expected in modern offices.

Installations 10 and 11

Installations 10 and 11 were representative sections of two very large open plan offices belonging to a national insurance company. The section of the first room, used as installation 10, measured 7.2m by 13.1m by 2.7m high. Installation 11 was a 11.2m by 8.9m by 3.1m high

Figure 4.1: Installation 9 in its working condition.

Figure 4.2: Installation 11 in its working condition.

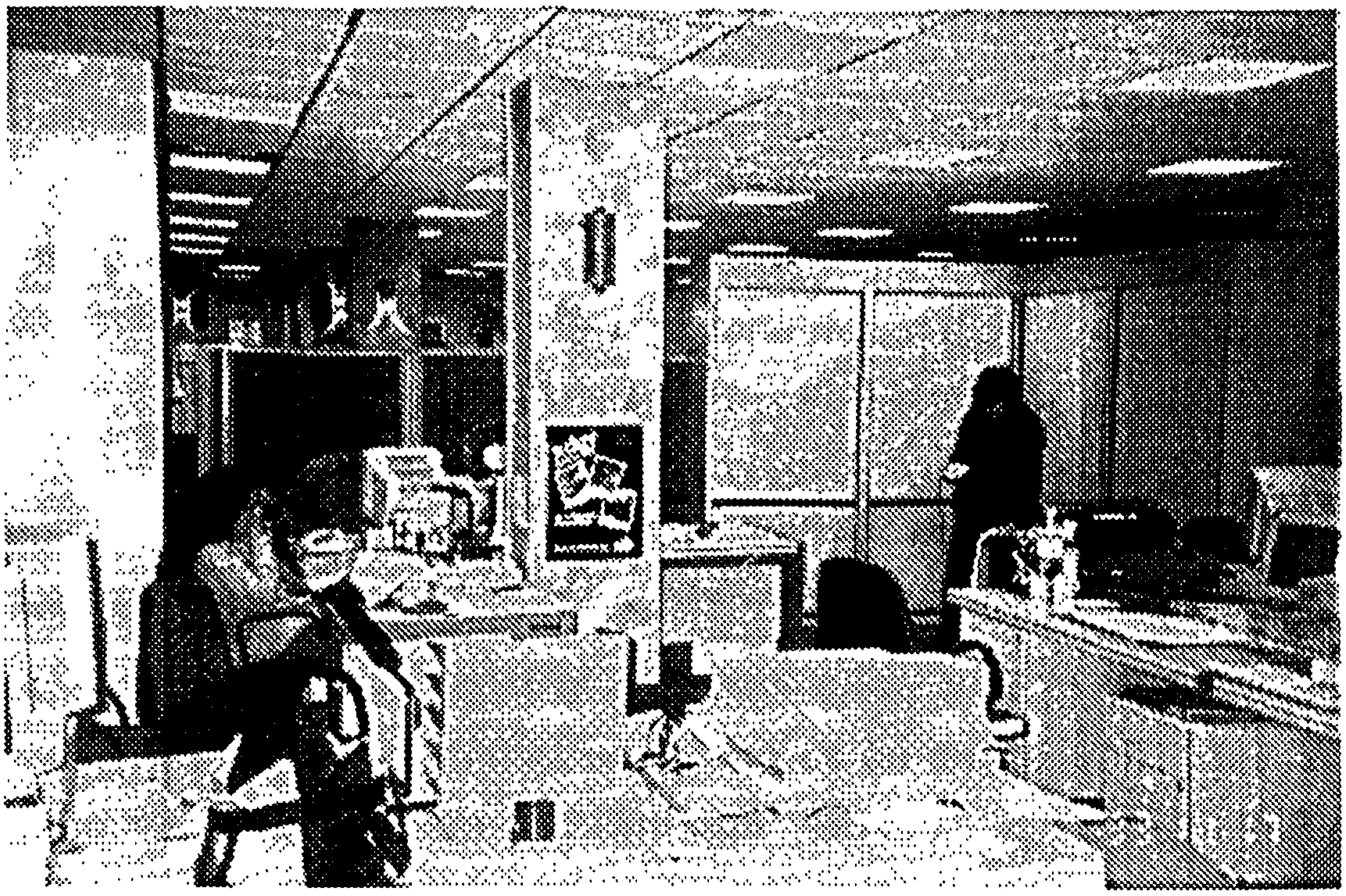


Figure 4.3: Installation 12 in its working condition.

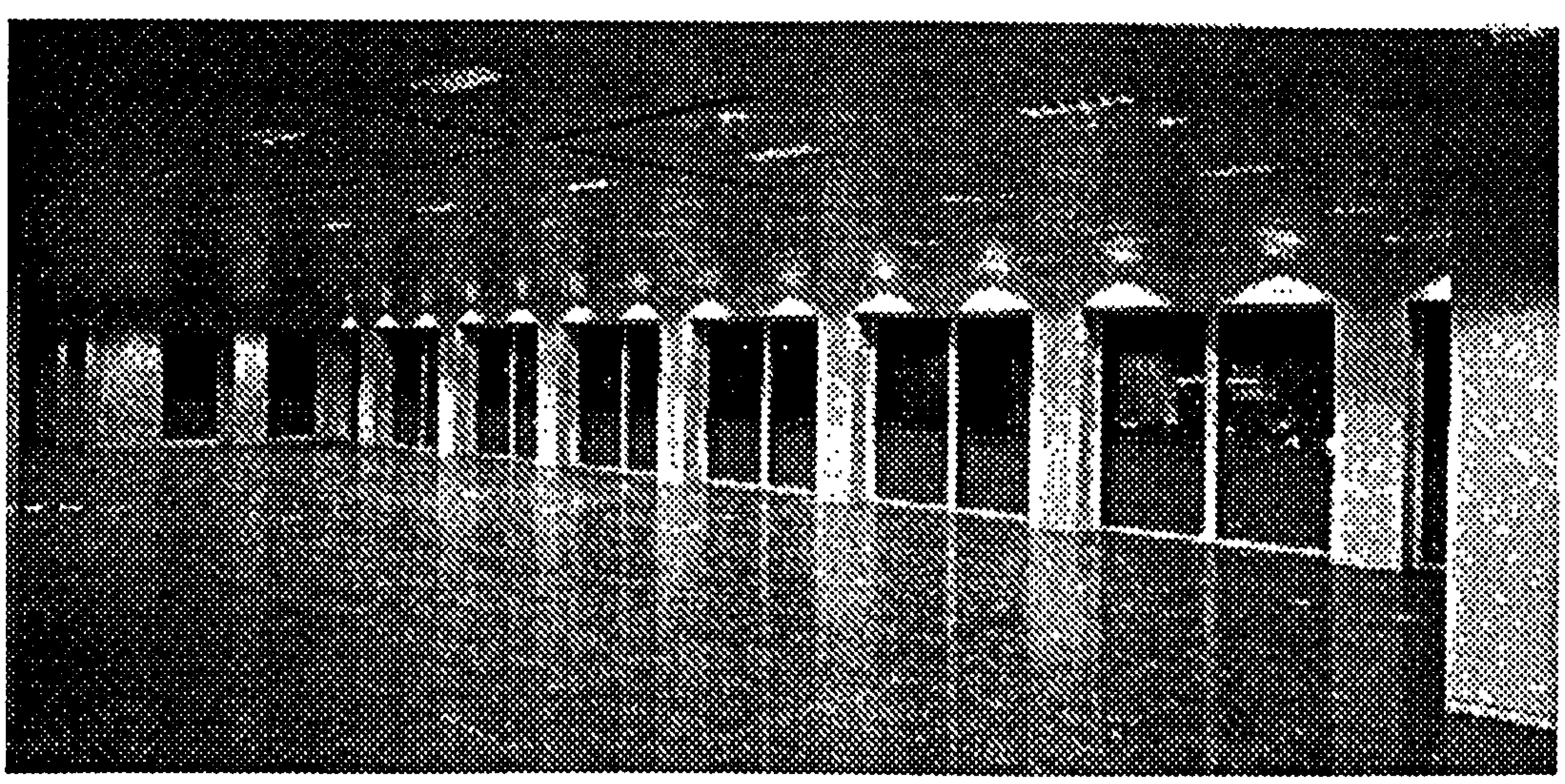


Figure 4.4: Installation 13 in its empty condition.

section of the second room. In both cases the spaces were furnished with ten standard obstructions and in the working conditions both were busy administrative offices, with calculated VFR's of 0.57 and 0.34 respectively. Installation 10 was lit by a 7 by 3 regular array of recessed modular reflector luminaires installed at an SHR_{trans} of 1.1. Installation 11 was lit by a 3 by 3 regular array of surface mounted modular luminaires (SHR_{trans} = 1.0) suspended between timber trusses at 3.8m centres below a white plastered void. (See figure 4.2).

Installation 12

Installation 12 was a ground floor office suite belonging to a Transport Authority and intended for use as an engineering office. It measured 13.5m by 7.4m by 2.75m high. The room was lit by a 6 by 4 regular array of recessed modular louvred luminaires installed at SHR_{trans} of 1.0. The room contained two permanent supporting columns and, to simulate working conditions, was furnished with nine standard obstructions. In its working state the room contained a number of large obstructions – such as dividing partitions and large storage cabinets – providing a relatively high VFR of 0.64. (See figure 4.3)

Installations 13 and 14

Installations 13 and 14 were two rooms in the Show Suite of a new office development. Installation 13 was a representative section of the main open plan office area measuring 9m by 4.5m by 2.8m high. Installation 14 was a smaller (5.45m by 5.9m by 2.8m high) adjoining conference room. Both installations were lit by a 1.5m square array of recessed profiled reflectors with a 24W PL lamp (See figure 4.4). Four standard obstructions were used in each space to simulate working conditions, but the office was a show suite and it could, therefore, not be surveyed in its actual working condition.

Installation 15

Installation 15 was a representative section of a large open plan office, occupied by an international shipping company. The section used for the survey measured 8.5m by 9m by 2.7m high and was lit by a regular array of semi-recessed prismatic base, opal sided diffusing luminaires, installed at SHR_{trans} of 1.33. To simulate working conditions the empty room was furnished with nine standard obstructions. In its actual working condition the room contained only a few large storage units and the furnishings consisted mainly of desks and visual display units. This is reflected in the relatively low measured VFR value of 0.15.

Installations 16,17 and 18

These three installations were part of a refurbished office building in the University of Liverpool. Installation 16 was a single person, executive type office; installation 17 was a general purpose filing area and installation 18 was a four person general administrative office. The ceiling height in all three of the installations was 3.9m and the plan dimensions were 7.4m by 5.4m, 8.2m by 4.5m and 7.5 by 5.4m respectively. All installations were lit by surface mounted louvred reflector luminaires and each installation was furnished with four standard obstructions. The transverse SHR of the three installations were 1.02, 0.91 and 1.03 respectively. In their working conditions installations 16 and 17 had relatively low VFR's of 0.21 and 0.19 respectively, whilst installation 18 had a VFR of 0.37, which is approximately the average VFR for modern commercial interiors.

Installations 19, 20 and 21

This room was the full scale experimental office space at the Lighting and Applied Vision section of the Building Research Establishment at Garston, UK. The room is a windowless space 6.8m by 6.7m by 2.6m high. The room could be lit by three independent lighting systems: a regular 4 by 4 array of ceiling mounted twin lamp mirrored luminaires; four free standing uplighters and an arrangement of wall-washing luminaires. These three luminaire types formed the three different installations and measurements were made under each system furnishing the room with four standard obstructions. As this is an experimental area the actual working conditions could not be measured.

Installations 22, 23 and 24

These three installations were separate teaching and computer rooms in the refurbished Television Centre at the University of Liverpool. Installation 22 was a teaching room 7.6m by 5.5m on plan and 3.5m high. Installations 23 and 24 were computer rooms of the same plan area as installation 22 but with a floor to ceiling height of 2.9m. All three installations were lit by surface mounted louvred reflector luminaires. Installation 22 was surveyed furnished with four standard obstructions and installations 23 and 24 furnished with five standard obstructions.

4.6 Survey Methods

The first part of each survey consisted of gathering physical and photometric details of the installation and its lighting equipment. In the working case, the dimensions of all room furnishing were taken to enable the VFR of the installation to be calculated. Each survey consisted of measuring horizontal working plane illuminance on a square grid of points (usually 0.5m centres) over the whole room whilst empty, again when furnished with the three standard obstruction cases and finally in its actual working condition. All daylight was excluded during measurement by a combination of shielding windows and delaying the commencement of the surveys until after sunset. The cosine and colour corrected photcell of a LMT Pocket Lux illuminance meter was mounted on a tripod and positioned over the grid points at desk top height (approximately 0.75m above the floor). The average working plane illuminance was calculated as an area weighted arithmetic average of the grid point illuminance. The obstruction loss (OL) was calculated as the percentage reduction in average working plane illuminance of the

installation	luminaire type	room index	SHR transverse maximum	SHR transverse actual	obstruction type and VFR		obstruction loss (%)
1	diffuser	1.60	1.70	0.89	light	0.10	1.00
					medium	0.19	3.80
					heavy	0.50	7.70
2	surface modular louvred reflector	1.60	1.80	0.89	light	0.10	1.20
					medium	0.19	3.70
					heavy	0.50	7.00
3	diffuser	1.60	1.70	1.79	light	0.10	4.00
					medium	0.19	6.40
					heavy	0.50	11.5
4	surface modular louvred reflector	1.60	1.80	1.79	light	0.10	1.30
					medium	0.19	2.90
					heavy	0.50	7.70
5	VDT Cat 1	0.90	1.26	0.75	medium	0.34	9.20
					heavy	0.95	9.80
6	VDT Cat 3	0.90	1.67	0.75	medium	0.34	12.8
					heavy	0.95	17.0
7	recessed modular louvred reflector	0.90	1.62	0.75	medium	0.34	15.8
					heavy	0.95	19.0
8	recessed modular louvred reflector	1.80	1.87	1.30	light	0.11	4.00
					medium	0.23	8.00
					heavy	0.53	14.0
					actual	1.64	30.0
9	recessed modular louvred reflector	2.20	1.87	1.60	light	0.09	3.00
					medium	0.21	7.00
					heavy	0.47	12.0
					actual	0.28	10.0
10	recessed modular louvred reflector	2.30	1.25	1.10	light	0.12	0.00
					medium	0.27	2.00
					heavy	0.56	3.00
					actual	0.57	11.0
11	recessed modular louvred reflector	2.10	1.25	1.00	light	0.12	0.00
					medium	0.25	3.00
					heavy	0.54	8.00
					actual	0.34	8.00
12	recessed modular louvred reflector	1.74	1.25	1.00	light	0.10	0.00
					medium	0.23	5.00
					heavy	0.50	10.0
					actual	0.64	12.0
13	recessed modular louvred reflector	1.30	1.70	0.80	light	0.12	1.00
					medium	0.25	2.00
					heavy	0.55	8.00
14	recessed modular louvred reflector	1.20	1.50	0.80	light	0.15	5.00
					medium	0.31	5.00
15	semi-recessed opal side, prism. base	1.60	1.60	1.33	light	0.14	4.90
					medium	0.30	11.6
					heavy	0.66	20.0
					actual	0.15	6.60
16	surface mounted louvred reflector	0.88	1.80	1.02	light	0.10	0.00
					medium	0.23	5.00
					heavy	0.50	10.0
					actual	0.21	9.00
17	surface mounted louvred reflector	0.99	1.80	0.91	light	0.12	3.00
					medium	0.26	12.0
					heavy	0.57	11.0
					actual	0.19	4.50
18	recessed modular louvred reflector	0.88	1.80	1.03	light	0.12	3.00
					medium	0.25	4.00
					heavy	0.56	12.0
					actual	0.37	9.00
19	up-lighters	1.80	-	-	light	0.10	-2.80
					medium	0.22	5.50
					heavy	0.48	10.2
20	twin lamp mirrored	1.80	1.50	0.90	light	0.10	-2.60
					medium	0.22	-2.02
					heavy	0.48	1.00
21	wall washers	1.80	-	-	light	0.10	0.00
					medium	0.22	5.20
					heavy	0.48	5.30
22	recessed modular louvred reflector	1.20	1.25	0.60	light	0.11	0.00
					medium	0.24	5.00
					heavy	0.53	9.00
23	recessed modular louvred reflector	1.50	1.25	0.60	light	0.15	0.00
					medium	0.32	3.50
					heavy	0.69	13.0
24	recessed modular louvred reflector	1.50	1.25	0.60	light	0.15	0.00
					medium	0.32	7.50
					heavy	0.69	17.0

Table 4.1 Measured Obstruction Loss (OL) and installation characteristics.

furnished cases compared with the empty case. Table 4.1 shows the OL for each of the installations in the three standard obstruction cases and in the actual working case.

4.7 Discussion of results

The results for all installations show the same general pattern in that OL rises as VFR increases. Figures 4.5, 4.6 and 4.7 show a statistical analysis of the light loss data in terms OL/VFR for increasing room index for modular louvred luminaires. The results were processed using the same method employed in chapter 5 to analyse the large simulated data set, a linear regression technique assuming a true zero. These trends and the average OL values of 1.52%, 6.25% and 12.01% for the light, medium and heavy standard obstruction cases are comparable to the average values predicted using the computer simulated design data described in chapter 5. Table 4.2 shows the predicted values. For the eight interiors measured in their actual working conditions the average measured OL was 8.76%. (Installation 8 was excluded on the grounds that it was a storage room, furnished solely with large shelf units and hence out of the VFR range typically found in commercial interiors). It thus appears that the methods of simulation and prediction of light losses for obstructions described in chapter 5 could be the source of realistic design data for actual interiors.

The results also agree with the trends found in previous research[10], which showed that different luminaires have varying propensity for light loss for a similar degree of obstruction. It is apparent from the results for installations 1 to 4 that the diffusing luminaires have higher OL for a given VFR than the modular louvred luminaires and similarly that the LG3 Cat 3 and modular louvred luminaires have higher light loss than the LG3 Cat1 luminaire (installations 7 to 9). The results for installation 15 also support this conclusion. The reason for this is presumably that light from luminaires with direct light distribution is not intercepted to the same

Regression Summary
SURVEY RESULTS / ROOM INDEX 1 vs. V.F.R.

Count	13
Num. Missing	0
R	.944
R Squared	.891
Adjusted R Squared	.882
RMS Residual	3.606

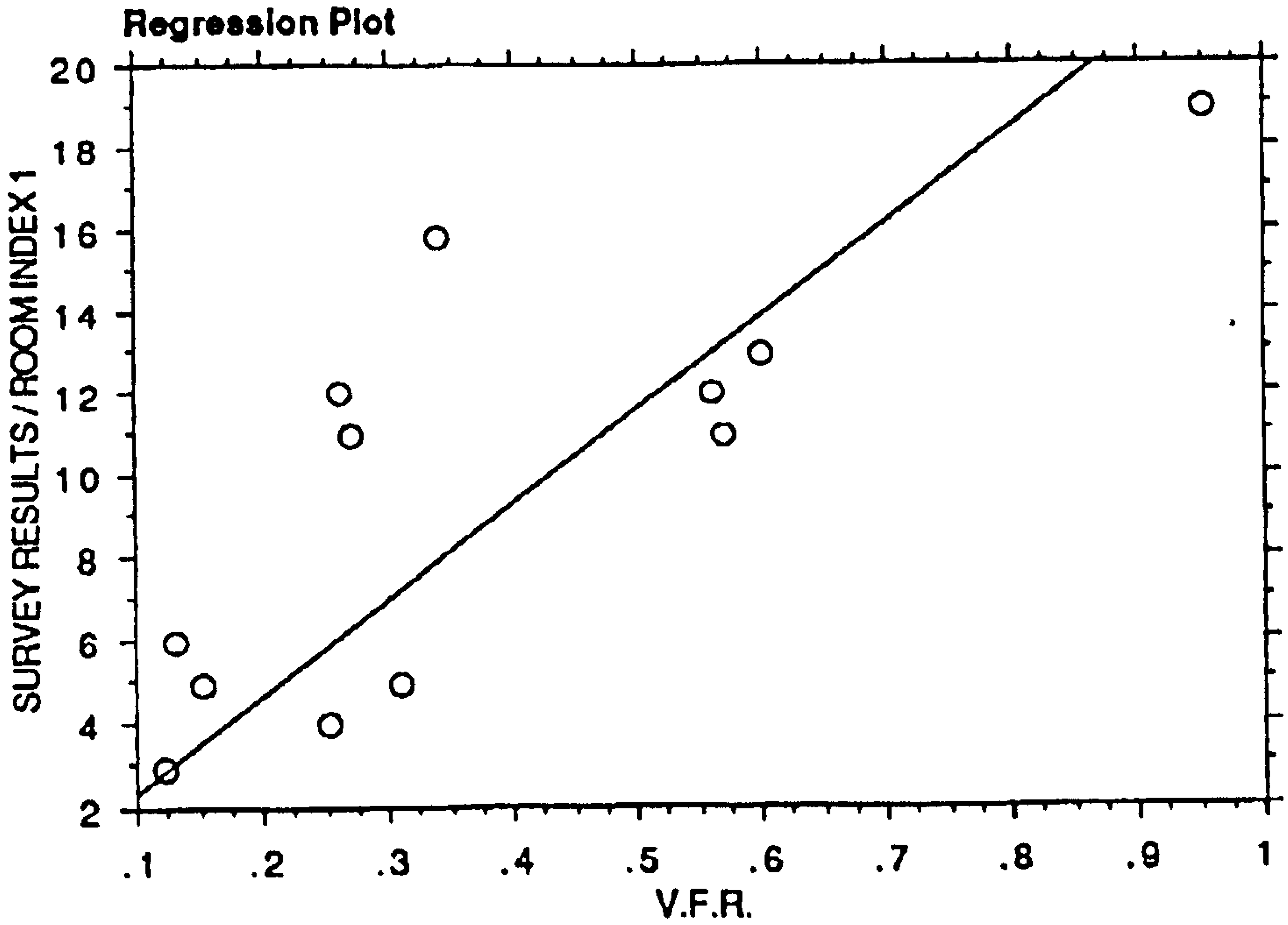
ANOVA Table
SURVEY RESULTS / ROOM INDEX 1 vs. V.F.R.

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1273.640	1273.640	97.972	<.0001
Residual	12	156.000	13.000		
Total	13	1429.640			

Regression Coefficients
SURVEY RESULTS / ROOM INDEX 1 vs. V.F.R.

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
V.F.R.	23.114	2.335	1.098	9.898	<.0001

Regression Plot



Y = 0 + 23.114 * X; R^2 = .891

Figure 4.5: Linear regression of survey results for room index 1.0

Regression Summary
SURVEY RESULTS / ROOM INDEX 1.5 vs. V.F.R.

Count	9
Num. Missing	0
R	.989
R Squared	.978
Adjusted R Squared	.976
RMS Residual	.742

ANOVA Table
SURVEY RESULTS / ROOM INDEX 1.5 vs. V.F.R.

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	198.114	198.114	359.744	<.0001
Residual	8	4.406	.551		
Total	9	202.520			

Regression Coefficients
SURVEY RESULTS / ROOM INDEX 1.5 vs. V.F.R.

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
V.F.R.	14.280	.753	.912	18.967	<.0001

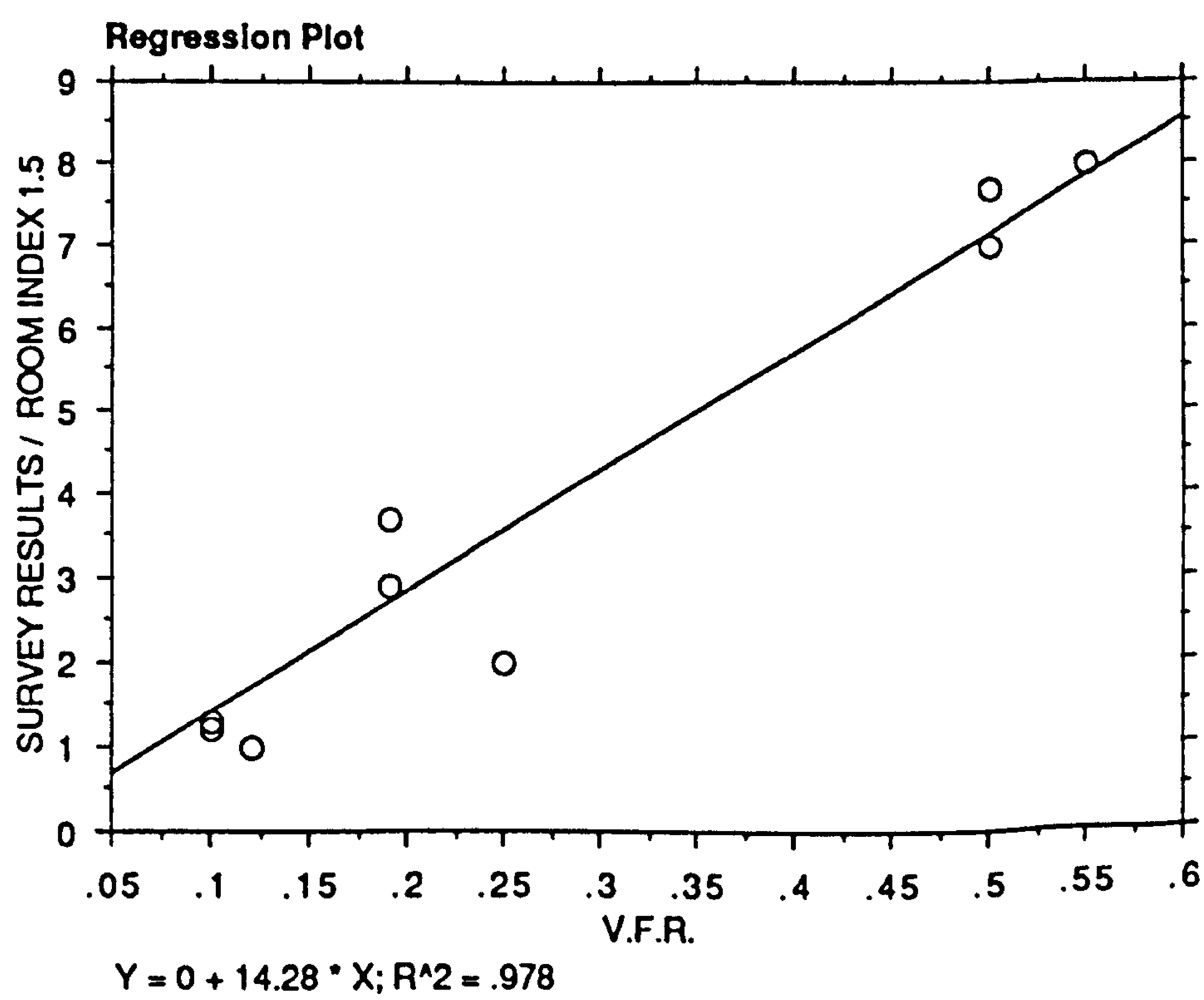


Figure 4.6: Linear regression of survey results for room index 1.5

Regression Summary
SURVEY RESULTS / ROOM INDEX 2 vs. V.F.R.

Count	16
Num. Missing	0
R	.952
R Squared	.906
Adjusted R Squared	.900
RMS Residual	3.306

ANOVA Table
SURVEY RESULTS / ROOM INDEX 2 vs. V.F.R.

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1585.053	1585.053	145.021	<.0001
Residual	15	163.947	10.930		
Total	16	1749.000			

Regression Coefficients
SURVEY RESULTS / ROOM INDEX 2 vs. V.F.R.

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
V.F.R.	18.569	1.542	.948	12.042	<.0001

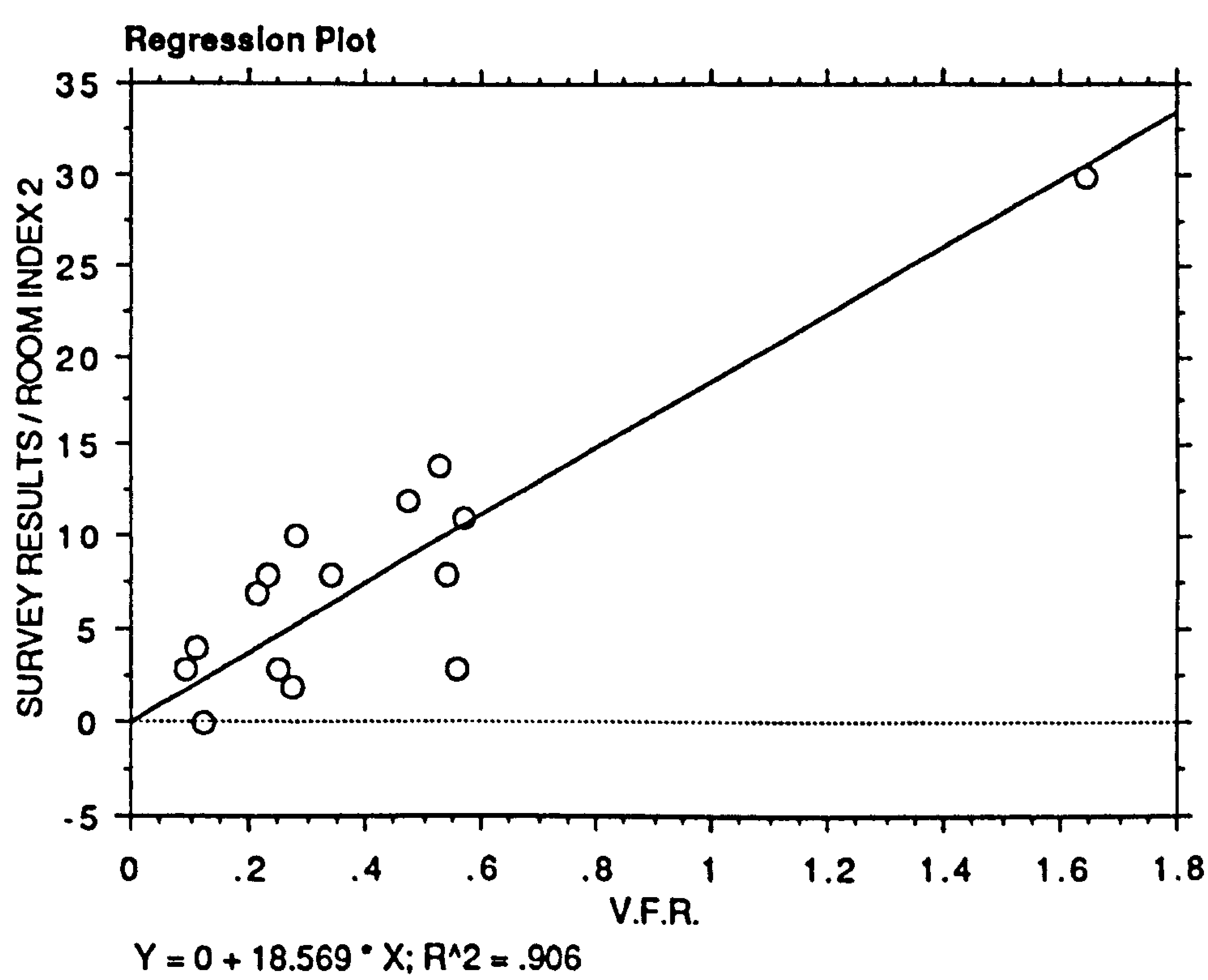


Figure 4.7: Linear regression of survey results for room index 2.0

Luminaire Type	Degree of Obstruction		
	light (VFR = 0.1)	Medium (VFR = 0.25	Heavy (VFR = 0.45)
Diffusing luminaire	3.6	9.0	16.2
Modular Louvred Luminaire	3.1	7.8	13.9
VDT Luminaire	2.7	6.8	12.2

Table 4.2: Predicted OL values for installations with linear luminaires.

extent by vertical obstruction than that from luminaires with pronounced sideways intensity distributions.

The results for installations 19, 20 and 21 (the BRE experimental office space) illustrate a number of interesting points. The first is that in some cases (light and medium standard obstruction with twin lamp mirrored downlighters and light standard obstruction with uplighters) the addition of obstructions causes a net increase in average working plane illuminance. There are a number of possible explanations for this. The downlighter luminaires are under-spaced relative to their maximum permitted SHR. The uplighters were positioned in the room in their most favourable location, namely adjacent to the partition element of the standard obstruction. Under these circumstances the vertical obstructions would be expected to intercept little downward direct light and in both cases the high reflectance partitions act to channel light at a glancing angle downwards onto the measurement points leading to higher values of point illuminance than would be expected in the empty room. In general the magnitudes of light losses are greater for the uplighter and wall-washer system than for the downlighters. In the uplighter and wall-washer systems a large proportion of the total working plane illuminance is indirect via the room surfaces. Where light reaches the working plane from directions other than the downward vertical the various obstructions will act to intercept this light and cause higher light losses than for the downlighter systems, where the main component of working plane illuminance is direct downward light.

There also appears to be some evidence that OL varies with SHR. The results for installations 1 to 4 indicate that higher OL values occur when the luminaires are spaced nearer to their SHR_{max} and that under spacing the luminaires reduces obstruction light loss. Installations 13 and 14, which are equipped with a large number of small lumen output luminaires installed at well below their SHR_{max}, had lower than average

OL values. The relationship between luminaire spacing and OL requires further research and chapter 7 attempts to undertake this investigation.

Some indication of the effect of room index can also be seen from figures 4.5, 4.6 and 4.7 which show linear regressions of the OL/VFR relationships, with each graph representing an increased room index, for modular louvred luminaires. From the graphs it can be determined that a room with a VFR of 0.35, exhibits an OL of 8% at room index 1.0, decreasing to 5% at room index 1.5 and increasing to 6% for room index 2.0. OL is a function of luminaire type and it is possible that the effect of room index on OL could also be a function of luminaire type, but more data is required before this can be fully investigated. Chapter 5 uses the ranges of room index and luminaire type to generate a large set of data intended for design purposes. The effect of luminaire type and room index will be further examined at this stage.

The magnitude of OL for installations 5 to 8 is higher than for the other installations and a number of factors may be responsible. It is unlikely that the luminaires account for the differences since installations 7 and 8 are photometrically similar to other installations lit by modular louvred luminaires, but give very different results in terms of OL. The rooms used to create installations 5 to 7 are, however, smaller than the rest of the installations and the smaller floor area per workstation gave higher VFR values. Additionally, installation 8 contained the medical record racks. There was thus not only more obstruction vertical surface area in these rooms which served to intercept light but also a greater proximity of the room wall surrounded each work station which also served to absorb light. Luminaires in installations 5 to 7 were all greatly under spaced and it is conceivable that the OL values could have been higher had they been spaced nearer their maximum SHR. On the other hand, those room with room indices of greater than 2 (installations 9 to

12) generally had lower than average values of OL. Clearly, there is a need for further evidence to determine the influence of room index.

The extent of VFR values created for the measurements using standard obstructions, ranged from 0.09 to 0.95. Results of the surveys of modern office buildings cited earlier, indicated that typical values of VFR for room contents ranged from 0.15 to 0.64. Hence the measurements could be considered to be made under conditions that ranged from the current design condition of an empty room, through that of the actual finished state for a typical office, to that of a grossly over obstructed space which is unlikely to occur intentionally in a commercial building, but which could occur in an industrial environment. On the limited evidence of eight surveys of real interiors, it may be concluded that the VFR and OL for offices in their working state could best be represented by the Medium Standard Obstruction. OL values of up to 15% might reasonably be expected in commercial interiors, given a particular combination of luminaire and contents. Losses of this magnitude have clear implications for the lighting designer when trying to meet a specification written in terms of average working plane illuminance.

4.8 Conclusion

It would be foolish to attempt to draw up general rules based upon the results of a limited number of surveys but the results of the work do point to some tentative conclusions, which could be useful in the generation of design data and the derivation of a new design technique. The range of the magnitude of the measured values are generally similar to those of the predicted values produced using the University of Liverpool Lighting Analysis program described in the previous chapter. Simulation of design data for real interiors is thus feasible and chapter 5 describes the process through which this has been undertaken. It may also be worth noting that the range of luminaires in the surveyed installations is limited, in that the majority of luminaires were some form of modular louvred reflector downlight. There is a clear need for surveys in rooms illuminated by a wider range of luminaires to provide additional information to support the surveys detailed in this chapter.

The major factor influencing OL is size and density of obstructions. Luminaire type is the next most important factor but there are differences in performance between types of luminaire in obstructed interiors. The room index also appears to be of influence, with large rooms generally displaying higher OL values than small rooms, although this is an area which requires further investigation before a conclusive answer regarding the effect of room index can be ascertained.

The maximum influence of obstructions on OL appears to be when luminaires are spaced nearer their SHRmax and light loss can be reduced by under spacing the luminaires, although this effect appears to be more prominent for certain luminaires. It may be tentatively concluded that the medium standard obstructions are capable of replicating illuminance conditions in office interiors.

4.9 References

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Chapter 5

Computer synthesis of obstructed spaces

5.1 Introduction

One of the main conclusions that can be drawn from the review of published literature on lighting design methods for obstructed interiors, discussed in chapter 2, is the need for a general design method capable of predicting and compensating for obstruction light loss for a practical range of design conditions. This method must be capable of being employed by a designer, quickly and easily, to estimate the effect of obstruction on light loss at the initial stage of the design process.

Previous research has demonstrated the relative importance of the different factors influencing light loss. A detailed investigation was carried out by *Bougdah*[1], using an early version of the analysis program described in chapter 3, in order to isolate the relative effect of each of a range of parameters, viz. – room index, room surface reflection factor, obstruction density, obstruction reflection factor, luminaire type and luminaire spacing.

The results of this research showed that obstruction density had by far the largest influence on light loss and the second most important factor was the luminaire type, which had a smaller, but significant, effect on obstruction light loss. The effect of room and obstruction surface reflectance caused a negligible effect on the reduction in average working plane illuminance. The variation in average working plane illuminance attributable to changes in room index proved to be impossible for *Bougdah* to interpret from the number of cases investigated. Following this investigation *Bougdah* concluded that it would be possible to use the trends he found as the basis to generate data for a general lighting design method for obstructed interiors, but the results of his work formed a data set that was too big to be conveniently used by designers, even though it only applied to a limited number of cases. Some form of reduced dataset based on the trends found by *Bougdah* was therefore necessary.

Another investigation by *Raitelli*[2] demonstrated, using commercially available lighting design software, that the OL/VFR relationship found for standard obstructions held good for a limited range of other obstruction sizes and shapes. This further reinforced the belief that VFR (section 3.3) could be used as part of a general design method to assess furniture density and hence to predict obstruction light loss. The research detailed in chapters 3 and 4 has already shown the applicability of the use of the standard obstruction concept to represent the range of furnishings found in modern commercial offices. Both *Raitelli's* investigation and the results of photometric surveys described in chapter 4, therefore, reinforce the belief that standard obstructions are suitable for use in generating OL/VFR data.

Raitelli also further investigated the relationship between luminaire characteristics and obstruction loss by simulation and measurement. Firstly, a series of computer simulations were carried out using nine different luminaires. The simulated interiors were lit by three examples of batswing, narrow beam and diffusing luminaires installed at or near their maximum SHR values. Secondly, a series of field measurements were undertaken. The measurements utilised a room switched in such a way that permutations of two luminaire types (batswing or diffusing) and two magnitudes of transverse spacing-to-mounting-height ratio (0.89 or 1.79) could be made. The simulated and measured results were comparable and also enforced the hypothesis, previously presented by *Bougdah*, which stated that luminaires having similar physical and photometric properties have a similar OL/VFR relationship.

Assuming that *Bougdah*'s hypothesis regarding luminaire type and OL is correct and the OL/VFR relationship is valid over the whole range of practical room sizes and room surface reflection factors, then a large set of OL/VFR data can be generated on this basis. From this dataset it will hopefully be possible to devise some general techniques that will enable the designer to reliably predict OL.

This chapter describes the process through which the aforementioned dataset was generated. The results are verified against the trends and magnitudes of simulated OL/VFR data found by *Bougdah* and *Raitelli*, against the measured values found by McEwan and against the measured data detailed in chapter 4. The large set of results was then converted to a form suitable for use by designers via a statistical analysis technique. The OL/VFR data was generated using the analysis program described in chapter 3 for a representative range of luminaires, obstruction densities and room indices.

5.2 Factors influencing light loss

In section 5.1 previous research was cited that investigated the effect of the various design parameters on light loss. The most significant parameters were found to be obstruction density and luminaire type.

The effect of room index was undetermined. The results of a series of photometric surveys (chapter 4) indicate that room index may be also a significant factor. To investigate the room index effect fully and to ensure the data is applicable to the range of room sizes commonly found in lighting design, it was necessary to generate data over a practical range for all of these three variables. The design method is intended primarily for use in commercial interiors and the range of the primary variables was selected to be representative of modern practice in commercial interiors.

5.2.1 The effect of obstruction density

Obstruction density has been shown to be the primary factor influencing the reduction of average working plane illuminance. The surveys in chapter 4 indicate that the furniture conditions in modern commercial offices will typically have densities in the range 0.15 to 0.69, when classified using the VFR concept. Combinations of standard obstructions were distributed evenly across the floor areas of the rooms to create VFR's ranging from 0 (empty) to 0.7 (heavy). To make the large obstruction dataset, requirea as input to the simulation, easier to create, the standard obstruction configurations were arranged in modules. Three modules, each with a different floor area, were used and this enabled three different VFR's for each standard obstruction configuration (light, medium and heavy) to be created. Table 5.1 shows the VFR for each of the modules when furnished with a single standard obstruction.

5.2.2 The effect of luminaire type

A selection of generic luminaire groups, based on physical and photometric characteristics, was made using the classification system detailed in the CIBSE Code for Interior Lighting, section 3.3.2 "Luminaire characteristics" [3] as this was the most up to date published data on the classification of commonly used luminaires. Eighteen categories of interior luminaire were identified using this method and a selection of examples were made for each category, from four multinational manufacturers (Toshiba, Thorn Moorlite and Philips). In most cases there were at least two examples in each class but in class 6 there was only a single example. The class 6 luminaire was essentially a Japanese type of luminaire that is very popular in Japan, but not so in the UK. (The data was provided by Toshiba Lighting and Technology). Where shortfalls in the number of luminaires in each group occurred, the gaps were filled with data from other manufacturers Care was taken to ensure that the luminaires selected from each category, had similar luminous intensity distributions and spacing characteristics. Table 5.3 shows the division and names of the luminaires used the investigation.

The OL/VFR calculations were undertaken for sixteen out of the eighteen classes. The full OL/VFR calculation was not undertaken for classes 13 (high bay) and 14 (low bay) since these are luminaires intended for industrial applications and hence would not be used with office type obstructions.

5.2.3 The effect of room index

The effect of room index has not yet been fully determined, but other research (chapter 4) indicates that it may be a significant influence. To further investigate the effect of room index data was generated for the full range of room indices over which Utilisation Factor is calculated – that is up to room index 5.0. The modules described in section 5.2.1, each containing a single standard obstruction, were combined into "rooms" of different sizes to vary room index. Table 5.2 shows the range of room indices and sizes that could be created under the current limitations implied by the use of the analysis program. The range of room indices was limited to a maximum of 2.0. This problem is discussed and a solution proposed in section 5.3.

Obstruction Case	Module type		
	8m² module	*10m² module*	*12m² module*
Light	0.15	0.12	0.10
Medium	0.31	0.26	0.21
Heavy	0.70	0.56	0.46

Table 5.1: VFR's created using single module standard obstructions

Room Index	Room Size		
	8 m² module (L x W x H)	*10 m² module (L x W x H)*	*12 m² module (L x W x H)*
1.00	4m x 6m x 3.15m	4m x 5m x 2.97m	4m x 6m x 3.15m
1.25	4m x 6m x 3.15m	8m x 5m x 3.21m	8m x 6m x 3.49m
1.50	8m x 8m x 3.41m	8m x 7.5m x 3.33m	12m x 6m x 3.41m
2.00	12m x 12m x 3.15m	12m x 7.5m x 3.06m	12m x 9m x 3.32m

Table 5.2: Room index and room sizes for single module standard obstructions.

CIBSE Code classification	1 bare batten	2 batten with opal diffuser	3 batten with prismatic controller	4 batten with opal side & prismatic base	5 batten with industrial reflector	6 recessed batten (reflector shape and UF similar to 5)
TOSHIBA	single FT41001K + FLR40SW	Concord lighting Opal diffusier 36W/MCF Cat no. - 736236	none	none	single trough reflector. FTX41124K twin trough reflector FT42105	twin FR42540 P38 data on sheet and disc
MOORLITE	single trimpak PS/S/1555 (TM14) twin trimpak PS/S/ 1555 (TM14)	Fitzgerald lighting twin deluxe light pack prismatic controller Cat no. LPT236/TPC4	none	single trimpack diffuser PSD. cat 106 PSD/S/1558 twin trimpack diffuser PSD. cat 106 PSD/S/1558	single target reflector TAT. cat 100 TAT/M/1558 twin target reflector TAT. cat 100 TAT/M/2558	none
THORN	PP single batten. data p5:01 cat p 1.2.3 twin PP narrow twin batten cat 1.2.3 no data PP wide twin batten cat 5.03	single clipper 2 diffuser data P 8.1 cat P 1.2.26 twin clipper 2 diffuser data P 8.13 cat p.1.2.26	single and twin clipper 2 prismatic controller. cat 1.2.25 data 8.07, 8.09	single clipper opal sided prismatic base. cat 1.2.27 data 8.15 twin clipper opal sided prismatic base. cat 1.2.27 data 8.15	single clipper dispersive reflector. cat 1.2.31 data 8.21 twin clipper dispersive reflector. cat 1.2.31 data 8.23	none
PHILIPS	single streamlite 1 lamp w/o attachments cat P6 IRN 6019 (PACKS)	single streamlite with narrow opal diffuser cat P9 IRN 6036 twin streamlite 2 with wide opal diffuser cat P9	single streamlite prismatic. cat P10 No data twin streamlite prismatic. cat P10 IRN 6060	none	single streamlite trough reflector. cat P8 no data twin streamlite trough reflector. cat P8 IRN 6028	none

Table 5.3a: Luminaire classification groups.

CIBSE Code classification	7 batten with VDT reflector	8 surface modular	9A modular (louvre)	9B modular (prismatic)	9C modular (opal)	10 modular VDT CIBSE CATS
TOSHIBA	twin battens with VDT reflector FT42756K	twin opal. FT42502K twin prismatic. FT42505K	FR42558K cat P46 data on sheet & disc FR427713 cat P130 data on sheet	twin flat sheet prismatic lens FR42563K	FR4256FK flat opal FR42564K dished	FR42553K (J cat I) on disk FR42555K (J cat III) on disk FR42557K (J cat II) on disk
MOORLITE	none	twin MPR surface modular. 12/MPR/M/2558/W P 80 single rap.er surface. RSM/M/1558/Ar P92	none	twin MFA recessed modular. 300/MFA/M/2436 P 82 see also MM range 300/MM/M/2436 p 88	none	recessed twin 300/B13RT/W1/M/2436 page 14 cat 1 300/B13RT/W2/M/2436 page 16 cat 2 300/B13RT/W3/M/2436 page 20 cat 3
THORN	single clipper 2 VDT louvre.	single and twin diffuser pack. cat 1.3.3 data 6.03 (prismatic side and base)	twin low brightness reflector FTX/FTXN. cat 1.4.8 data 14.05	twin troffer pack flat prismatic controller. cat P145. data P1403 quattro prismatic controller FRE dished cat P1413 data 10.05	twin troffer pack flat opal diffuser. cat P14.4 data 14.01 quattro opal diffuser FRD dished P14.11 data 10.01	cat 2 recessed twin quattro FRAZ236 + FRV2312 cat 3 FRAZ236 + FRW2312
PHILIPS	none	single and twin lux pack TCS058 cat p30 TM4502 prismatic only INR2065 side and base	single and twin TBS 300 B4 mirror. P73 (also VDT 2) IRN2385 (indoor)	twin TBS 300 prismatic controller dished. P47 INR2150 or TM2101 twin standard recessed flat opal P90 INR 2120	none	cat 2 recessed twin TBS222 HMS INR2321 cat 3 TBS 222 MMS INR 2309 (not on disk)

Table 5.3b: Luminaire classification groups (cont.).

CIBSE Code classification	11 direct-indirect VDT	12 proof fluorescent	13 high bay	14 low bay	15 downlighter	16 general diffusing compact
TOSHIBA	Concord lighting LT90 direct/indirect diffuser 36W/T8/T26?MCF/G13 Cat no. 22383+22920	none	concentrating reflector SN-4042A medium spread reflector SN-4044A batwing reflector M300/L-J/BUP	none	DD - 1042 P 439 FLD - 1890 (V)	FLD - 3742 P 378
MOORLITE	cat 2 or 3, vector 300/VEC/W/S/1436 without top reflector P 30 file: 14455014	twin YB/M/2558 P 118 file: 8097MB25	simplex hibay series 1 B400SW/HBSR (1 x 400W SON-T)	simplex lowbay plus (no attachments) LPY 250 S (1 x 250W SON-T)	compact source M/FL100 P 114	G-line compact source GX 2D/16 P 116
THORN	Concord lighting LT90 direct/indirect VDU mod + Silver louvre 36W/T8/T26/MCF/G13 Cat no. 22683+22420	twin invisible LUS 236 P 8.03	narrow DHS 250/N P501 medium DHS 250/M P523 wide DHS 250/W P523 also a 400W version	batwing reflector DLS 250 P611 B/W reflection & transverse louvre DLS 250+DLL P613 eggcrate louvre DLS 250+DLE P615	surface chalice P 2.3.15	2D nova glassware p 2.4.14
PHILIPS	none	fortress twin P108 for 236 IRN 5212	hermes narrow 150W SON post 3 P117 medium 150W SON post 7 P117 wide HPI/BUS post 7 P119	batwing reflector lowbay 250W SON/T P124 INR 5202 lowbay louvre 250W SON/T+louvre P124 INR 5203	145 range FBS 145-118IP54 P 15	none

Table 5.3c: Luminaire classification groups (cont.).

5.3 Data generation technique

The analysis program, discussed in chapter 3, was used to generate OL/VFR data for the sixteen classes of luminaire, over the full range of room indices and obstruction configurations – a total of 7644 cases. For each room index an installation was constructed using a combination of modules of 8 m^2, 10 m^2 or 12 m^2 floor area. This gave three different installations for each room index. Figure 5.1 shows an typical room constructed from 4m by 3m modules, furnished with heavy standard obstructions. This technique required rooms containing up to 360 obstructions. Under the limitations of the analysis program the maximum number of obstructions permissible is 110. This meant it was only possible to generate OL/VFR data up to room index 2.0 for the single obstruction module (see table 5.2).

To overcome this problem the concept of the double standard obstruction was introduced. In this case either 20m², 22m² or 24m² floor area modules were furnished with two standard obstructions positioned back-to-back. This double standard obstructions module could be constructed from only seven individual obstructions as opposed to the ten individual obstructions required to construct two single standard obstructions (see figure 5.2). Using this new combination of double standard obstruction and module size enabled data to be generated for room indices up to 5.0. Tables 5.4 and 5.5 show the range of VFR's, room indices and room sizes created using the double module standard obstructions. The use of this technique also had the advantage of generating an additional set of data for the smaller, and arguably more common, range of room indices (i.e. from 1.0 to 2.0), which could then be combined with the data generated using the single standard obstructions.

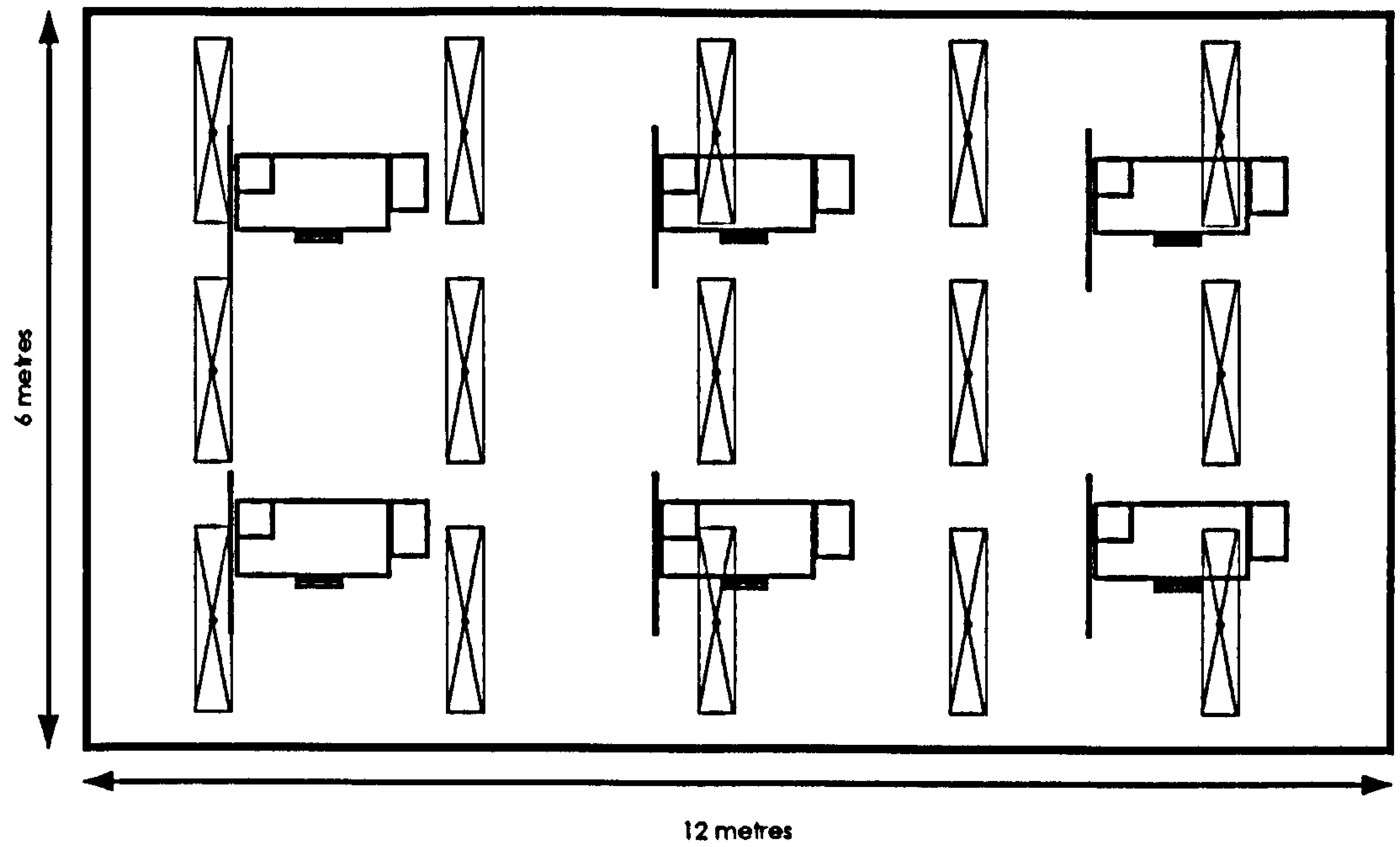


Figure 5.1: Typical room configuration used for generation of OL/VFR data. (Room index 1.50, furnished with heavy standard obstructions arranged in 4*m* by 3*m* modules).

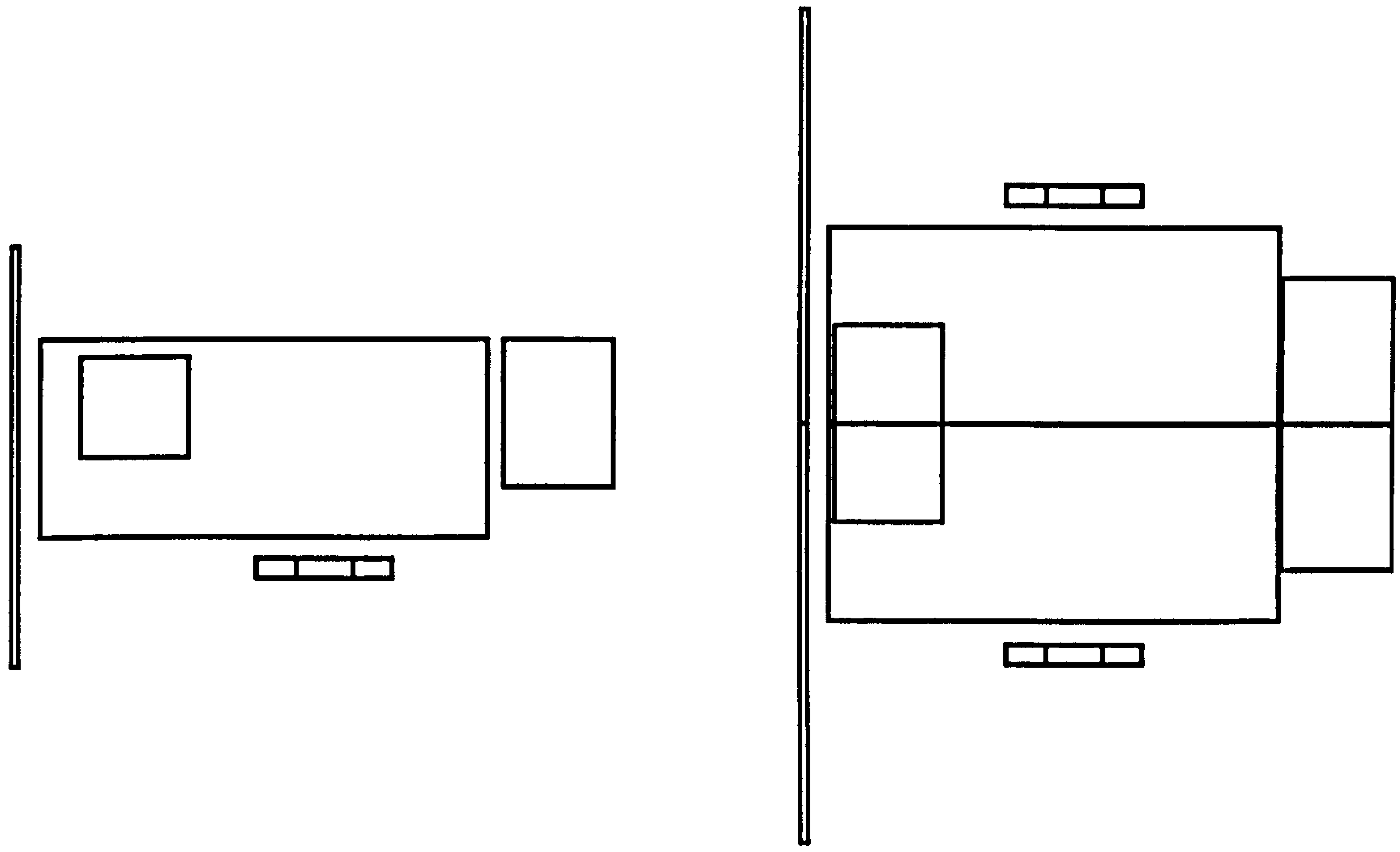


Figure 5.2: Illustration of single and double standard obstructions.

The OL/VFR results for the lower range of room indices , generated using the single standard obstructions, were also used to validate the results in the same range of room indices found using the double standard obstructions. The two sets compared favourably and hence the use of the double standard obstructions was proven. The two sets of results were combined for use in the final statistical analysis and derivation of general rules. Table 5.6 shows a comparison of the OL/VFR characteristics for the single and double obstruction modules for class 1 and class 10 luminaires.

5.3.1 Use of the analysis program

Before each run of the analysis program, several thousand input files had to be created. These included room data files, obstruction data files and a luminaire data file. In each room case, the number of luminaires required and their spacing was determined, using the conventional lumen method and calculated to give an average horizontal illuminance of 500 lux on the working plane. For each luminaire used in the simulation (table 5.1) the necessary files were created to enable all room variations (63) for that luminaire to run as a batch process, controlled by a macro program. To eliminate any effect of luminaire orientation relative to the obstructions, each simulation was undertaken for two different luminaire orientations - parallel and perpendicular to the partitions.

Obstruction Case	Module type		
	20 m² module	22 m² module	24 m² module
Light	0.10	0.09	0.08
Medium	0.20	0.18	0.17
Heavy	0.54	0.49	0.45

Table 5.4: VFR for double standard obstructions.

Room Index	Room Size		
	20 m² module (L x W x H)	22 m² module (L x W x H)	24 m² module (L x W x H)
1.00	4m x 5m x 2.97m	4m x 5.5m x 3.06m	4m x 6m x 3.15m
1.25	8m x 5m x 3.21m	8m x 5.5m x 3.36m	8m x 6m x 3.49m
1.50	12m x 5m x 3.10m	12m x 5.5m x 3.26m	12m x 6m x 3.42m
2.00	8m x 10m x 2.97m	8m x 11m x 3.06m	8m x 12m x 3.15m
3.00	12m x 10m x 2.56m	16m x 11m x 2.92m	12m x 12m x 2.75m
4.00	16m x 15m x 2.67m	16m x 11m x 2.78m	12m x 18m x 2.55m
5.00	20m x 15m x 2.46m	20m x 16.5m x 2.56m	4m x 6m x 3.15m

Table 5.5: Room index and room sizes for double module standard obstructions.

Room Index	Obstruction Loss Characteristic			
	Class 1 Luminaire		Class 10 Luminaire	
	single	double	single	double
1.00	31.4	34.3	27.7	28.9
1.25	31.5	35.9	22.2	26.6
1.50	34.2	39.6	23.9	27.8
2.00	38.7	40.0	24.7	26.7

Table 5.6: Comparison between simulated OL/VFR characteristics using single and double standard obstructions for class 1 and class 10 luminaires.

The OL/VFR data from this analysis was initially collated, in table form (see table 5.7). Each room index had nine variations of VFR, each with two variations of luminaire orientation and this was repeated for four variations of luminaire manufacturer. The dataset was then analysed using a linear regression technique, assuming a true zero – i.e. no obstruction (VFR) implies no light loss (OL). The results of this analysis confirmed that a straight line passing through the origin could be fitted to the data with a measure of fit (r^2) in the order of 0.98. The trends and implications of the results of this analysis are discussed in the following section.

5.4 Discussion of the results of the simulation

OL/VFR relationships were analysed in terms of luminaire type and room index. Figures 5.3 to 5.8 are samples of the OL/VFR regression for group 1 (bare batten) luminaires and group 10 (VDT) luminaires. The full set of regression analyses are contained in Appendix Two. From these graphs it can been seen that it is possible to translate the OL/VFR relationship into a mathematical expression of the form $y = mx + c$. It has already been established that the point of intercept (c) is zero. This means that the OL/VFR (or y/x) relationship in its simplest form is purely a function of the slope of the graph (m).

The greater the slope of the linear regression graphs the greater the value of OL for a given value of VFR and hence the greater the propensity for light loss. Table 5.8 shows a summary of the slopes of the graphs for all luminaire types and room indices. The slopes of the graphs vary considerably for the different luminaire types and room indices. From the results in figures 5.3 to 5.8 and table 5.8 a number of points of interest can be noted.

Luminaire - Toshiba Class 9A

Room Index	Obstruction Case	Average Illuminance		OL	VFR
		(empty)	(obstructed)		
1.00	light	718	693	3.48%	0.08
1.00	medium	718	651	9.33%	0.17
1.00	heavy	718	628	12.53%	0.45
1.25	light	628	604	3.82%	0.59
1.25	medium	628	574	8.60%	0.78
1.25	heavy	628	542	13.69%	0.96
1.50	light	637	617	3.14%	1.14
1.50	medium	637	569	10.68%	1.32
1.50	heavy	637	541	15.07%	1.50
1.75	light	699	659	5.72%	1.68
1.75	medium	699	646	7.58%	1.86
1.75	heavy	699	616	11.87%	2.04
2.00	light	736	698	5.16%	2.22
2.00	medium	736	688	6.52%	2.40
2.00	heavy	736	663	9.92%	2.58
2.25	light	961	911	5.20%	2.76
2.25	medium	961	889	7.49%	2.94
2.25	heavy	961	814	15.30%	3.13
2.50	light	942	895	4.99%	3.31
2.50	medium	942	876	7.01%	3.49
2.50	heavy	942	804	14.65%	3.67

PARALLEL

Room Index	Obstruction Case	Average Illuminance		OL	VFR
		(empty)	(obstructed)		
1.00	light	711	681	4.22%	0.08
1.00	medium	711	644	9.42%	0.17
1.00	heavy	711	606	14.91%	0.45
1.25	light	627	607	3.19%	0.59
1.25	medium	627	578	7.81%	0.78
1.25	heavy	627	535	14.67%	0.96
1.50	light	638	613	3.92%	1.14
1.50	medium	638	590	7.52%	1.32
1.50	heavy	638	536	15.99%	1.50
1.75	light	700	657	6.14%	1.68
1.75	medium	700	645	7.86%	1.86
1.75	heavy	700	588	16.00%	2.04
2.00	light	736	695	5.57%	2.22
2.00	medium	736	685	6.93%	2.40
2.00	heavy	736	621	15.63%	2.58
2.25	light	960	912	5.00%	2.76
2.25	medium	960	892	7.08%	2.94
2.25	heavy	960	824	14.17%	3.13
2.50	light	940	896	4.68%	3.31
2.50	medium	940	879	6.49%	3.49
2.50	heavy	940	810	13.83%	3.67

PERPENDICULAR

Table 5.7: Sample results from OL/VFR simulation for Toshiba class 9A luminaire, 4m x 6m modules.

Regression Summary
group 1 OL (room index 1.00) vs. VFR

Count	108
Num. Missing	0
R	.982
R Squared	.965
Adjusted R Squared	.965
RMS Residual	2.177

ANOVA Table
group 1 OL (room index 1.00) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	14002.500	14002.500	2953.602	<.0001
Residual	107	507.268	4.741		
Total	108	14509.768			

Regression Coefficients
group 1 OL (room index 1.00) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.368	.632	1.179	54.347	<.0001

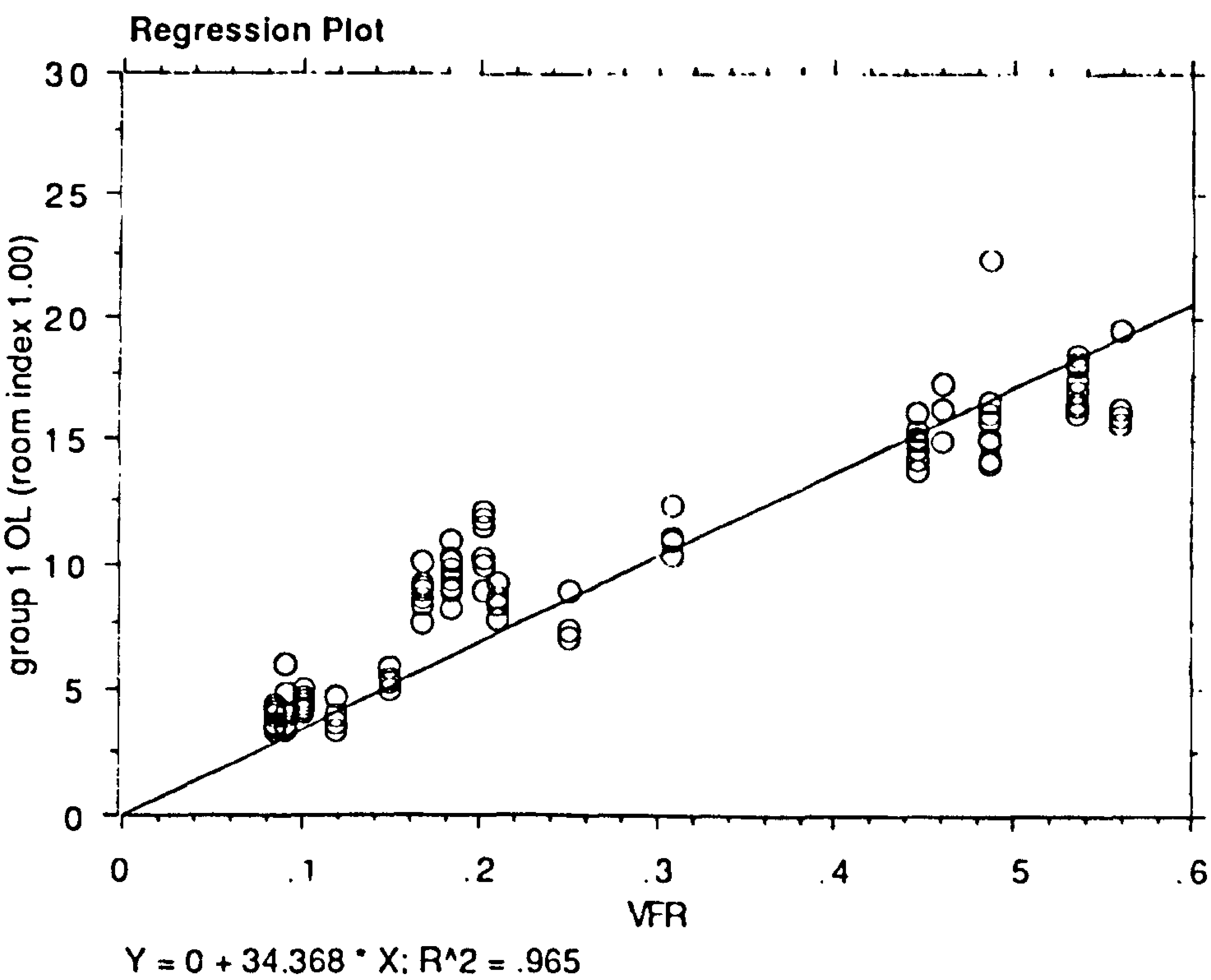


Figure 5.3: OL/VFR linear regression for class 1 luminaires, room index 1.0

Regression Summary
group 1 OL (room index 1.5) vs. VFR

Count	108
Num. Missing	0
R	.983
R Squared	.966
Adjusted R Squared	.966
RMS Residual	2.480

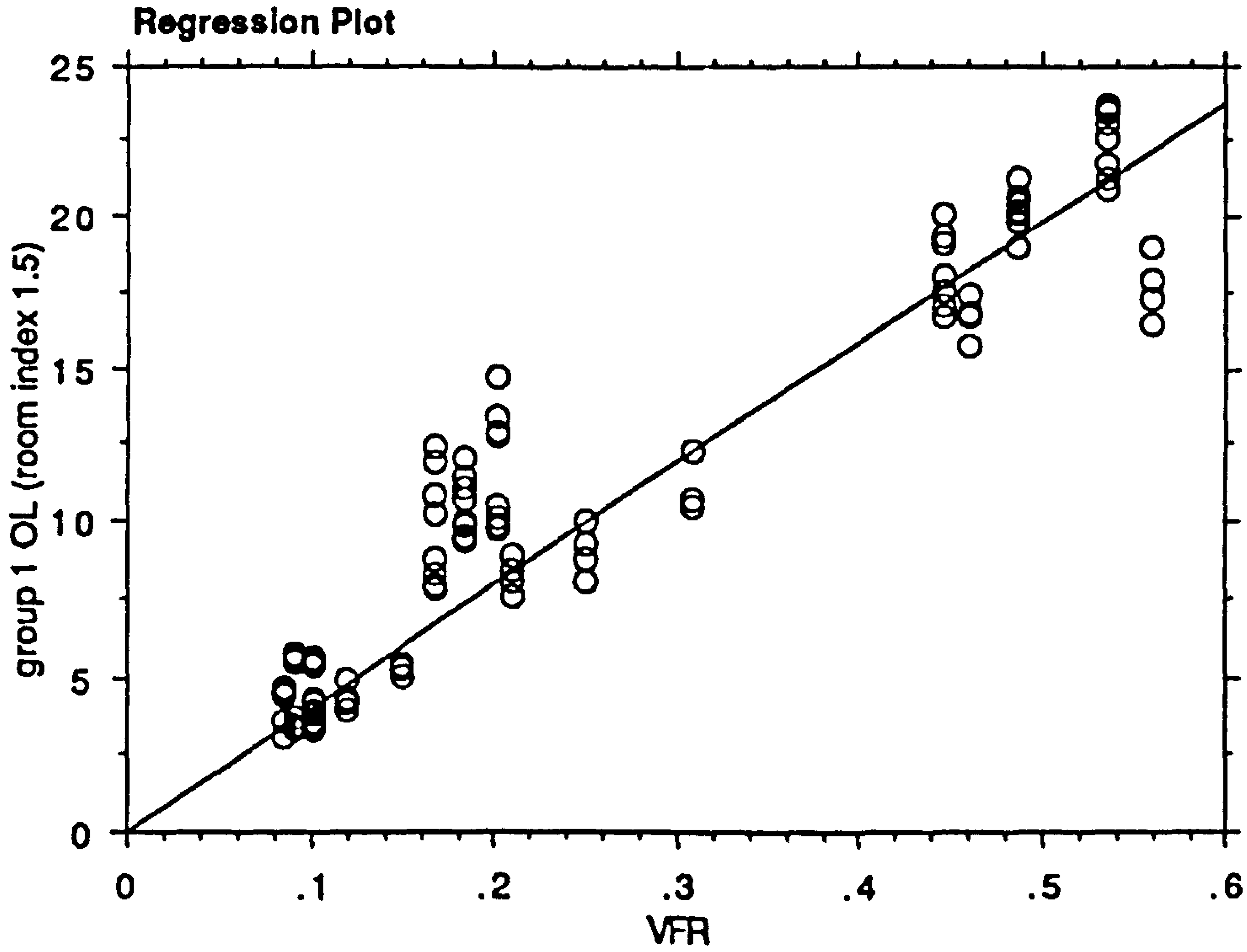
ANOVA Table
group 1 OL (room index 1.5) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	18623.217	18623.217	3028.493	<.0001
Residual	107	657.979	6.149		
Total	108	19281.195			

Regression Coefficients
group 1 OL (room index 1.5) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.636	.720	1.095	55.032	<.0001

Regression Plot



Y = 0 + 39.636 * X; R^2 = .966

Figure 5.4: OL/VFR linear regression for class 1 luminaires, room index 1.50

Regression Summary
group 1 OL (room Index 5.0) vs. VFR

Count	64
Num. Missing	8
R	.989
R Squared	.978
Adjusted R Squared	.978
RMS Residual	1.860

ANOVA Table
group 1 OL (room Index 5.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9638.341	9638.341	2786.090	<.0001
Residual	63	217.945	3.459		
Total	64	9856.286			

Regression Coefficients
group 1 OL (room Index 5.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	45.253	.857	1.132	52.783	<.0001

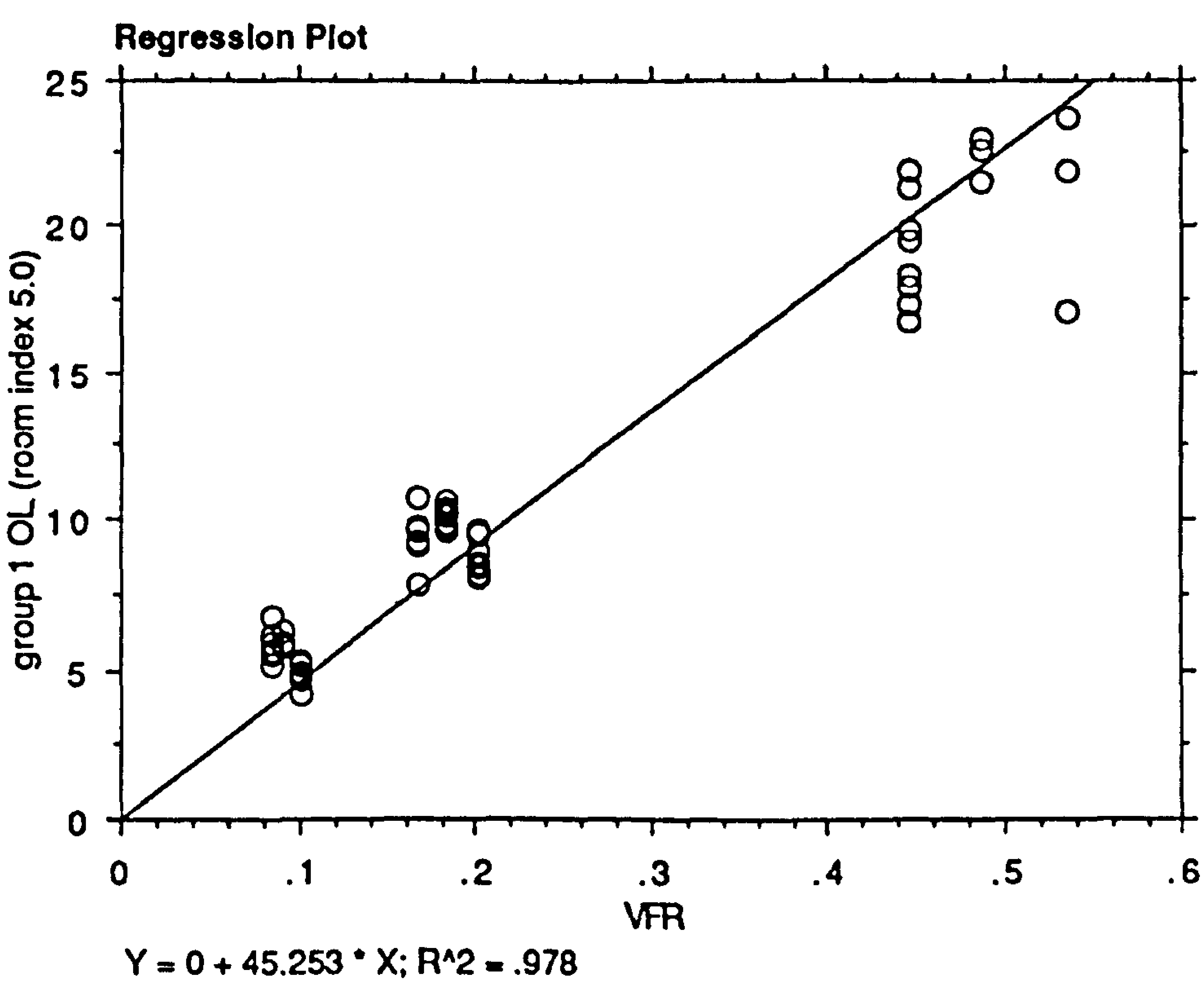


Figure 5.5: OL/VFR linear regression for class 1 luminaires, room index 5.0

Regression Summary
group 10 OL (room index 1.00) vs. VFR

Count	108
Num. Missing	0
R	.968
R Squared	.938
Adjusted R Squared	.937
RMS Residual	2.478

ANOVA Table
group 10 OL (room index 1.00) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9908.584	9908.584	1613.742	<.0001
Residual	107	656.994	6.140		
Total	108	10565.578			

Regression Coefficients
group 10 OL (room index 1.00) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.911	.720	1.050	40.171	<.0001

Regression Plot

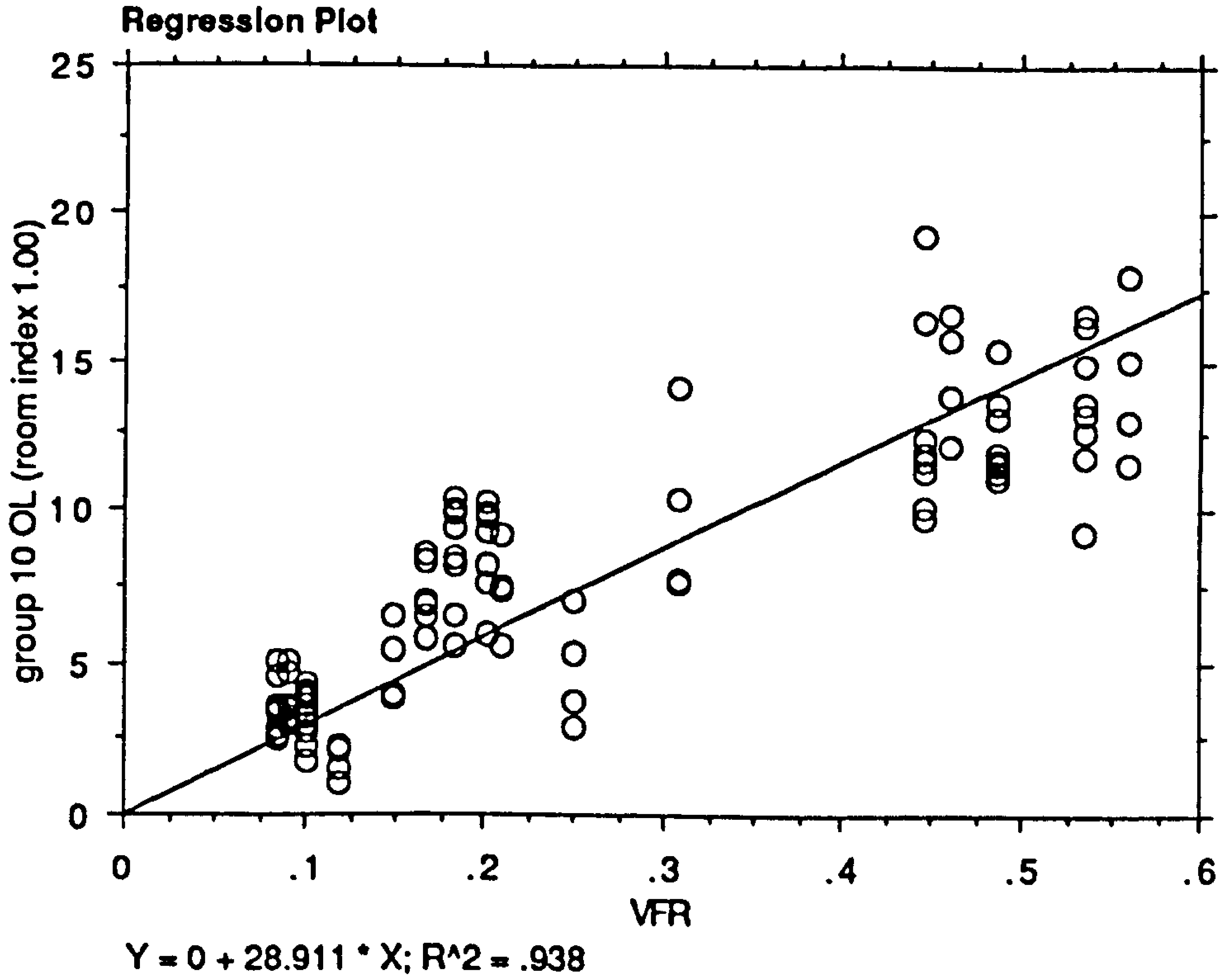


Figure 5.6: OL/VFR linear regression for class 10 luminaires, room index 1.0

Regression Summary
group 10 OL (room index 1.5) vs. VFR

Count	108
Num. Missing	0
R	.972
R Squared	.945
Adjusted R Squared	.944
RMS Residual	2.236

ANOVA Table
group 10 OL (room index 1.5) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9161.729	9161.729	1832.053	<.0001
Residual	107	535.086	5.001		
Total	108	9696.815			

Regression Coefficients
group 10 OL (room index 1.5) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	27.800	.649	1.043	42.802	<.0001

Regression Plot

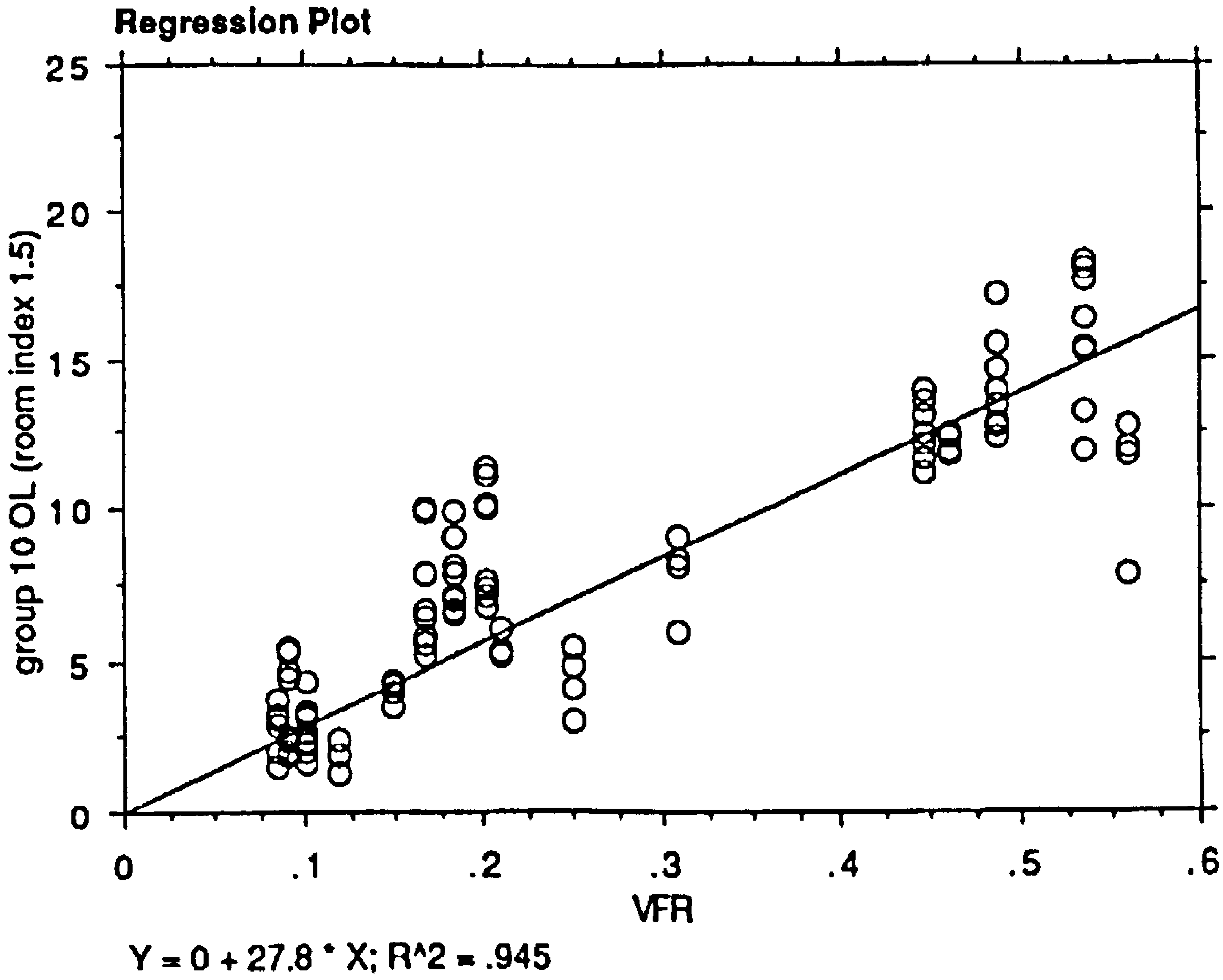


Figure 5.7: OL/VFR linear regression for class 10 luminaires, room index 1.5

Regression Summary
group 10 OL (room Index 5.0) vs. VFR

Count	56
Num. Missing	16
R	.955
R Squared	.912
Adjusted R Squared	.911
RMS Residual	2.008

ANOVA Table
group 10 OL (room Index 5.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2309.768	2309.768	573.101	<.0001
Residual	55	221.667	4.030		
Total	56	2531.435			

Regression Coefficients
group 10 OL (room Index 5.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.490	1.107	.963	23.940	<.0001

Regression Plot

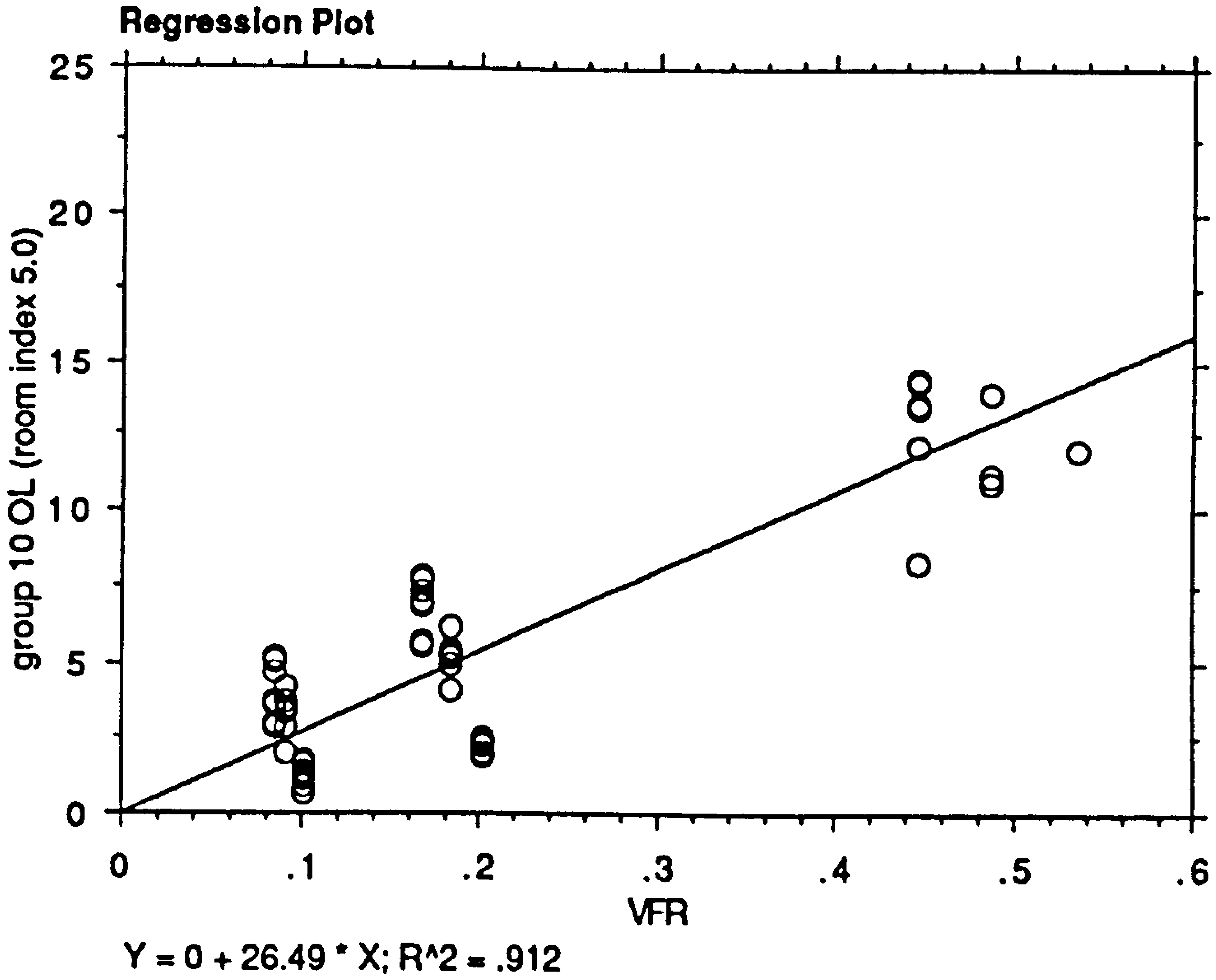


Figure 5.8: OL/VFR linear regression for class 10 luminaires, room index 5.0

The first point of interest is the difference between the two extremes of OL/VFR slope. This is between the bare batten luminaires (group 1), which have the greatest slope and hence highest propensity for light loss, and the VDT luminaires (group 10), which have the lowest slopes. Translating this into actual magnitudes of OL from figure 5.4 (group 1 luminaire, room index 1.50) and figure 5.7 (group 10 luminaire, room index 1.50) for a VFR of 0.25 the following OL's can be predicted. For a group 1 luminaire an OL of approximately 10% will be expected, but for a group 10 luminaire an OL around 7% will be expected. The reason for this is that light from luminaires with direct light distributions is not intercepted to the same extent by vertical obstructions than that from luminaires which have a more pronounced sideways intensity distribution. This trend is reproduced by similar luminaires in other groups. For instance, the modular louvered luminaires in group 9A behave similarly to the group 10 luminaires, whereas the bare batten with opal diffuser group 2 luminaires behave similarly to the group 1 luminaires. The rest of the luminaires investigated, which have an OL/VFR slope between the extremes of battens and VDT, are semi-direct luminaires that have a degree of optical control using prismatic controllers or painted reflectors.

The effect of room index on the magnitude of OL can be more easily discerned from table 5.8 than from the limited range of results previously generated by *Bougdah*. It can be seen that the effect of room index is also dependent upon luminaire type and it was only due to the large number of cases analysed that this effect can be finally determined. Broadspread luminaires, such as those in groups 1, 2 and 8, exhibit an OL/VFR characteristic significantly influenced by room index. However, the OL/VFR characteristics of luminaires with a direct downward light distribution, such as groups 7, 9A and 10, are not significantly affected by room index. In fact for the latter luminaire type OL tends to decrease slightly for an increase in room index.

Room Index	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9A
1.00	34.7	33.4	33.2	33.9	33.7	32.6	25.6	32.1	28.8
1.25	35.9	34.4	34.3	34.6	33.9	35.1	25.0	33.1	28.9
1.50	39.6	38.0	35.9	36.3	34.6	38.6	26.3	37.1	30.5
2.00	40.0	39.9	35.7	35.6	39.1	38.1	21.9	36.6	27.3
3.00	43.2	42.1	39.5	37.0	36.8	39.6	22.6	39.9	28.2
4.00	42.3	42.4	39.8	36.9	35.4	38.1	21.5	39.3	28.3
5.00	45.3	45.8	41.2	37.8	35.3	39.9	22.8	40.6	27.0
Room Index	**Class 9B**	**Class 9C**	**Class 10**	**Class 11**	**Class 12**	**Class 13**	**Class 14**	**Class 15**	**Class 16**
1.00	28.9	32.3	28.9	31.7	33.5	-	-	29.7	33.9
1.25	29.8	33.9	26.6	31.7	34.7	-	-	28.0	35.2
1.50	31.4	36.4	27.8	33.9	38.4	-	-	30.2	39.1
2.00	31.7	35.5	26.7	32.7	40.1	-	-	26.9	38.6
3.00	31.3	38.1	28.5	36.8	39.0	-	-	28.5	41.7
4.00	31.9	36.5	25.9	32.6	40.5	-	-	26.5	39.5
5.00	33.0	38.4	26.5	36.8	42.2	-	-	26.5	42.4

Table 5.8: Summary of slopes of regression analysis for all luminaires classes up to room index 5.0

To illustrate the effect of room index, some magnitudes of OL for the two extremes of room index can be predicted using figures 5.3, 5.5, 5.6 and 5.8. For a group 1 luminaire and a furniture density VFR of 0.2, an OL in the order of 7% can be expected for an installation of room index of 1.0; whereas an OL of around 9% can be expected for the same combination of luminaire and VFR for an installation of room index of 5.0. In the case of a group 10 luminaire under the same conditions, OL's in the order of 6% and 5.5% respectively could be expected.

5.5 Validation of results

Both the magnitude and trend of all the OL/VFR relationships found in this simulation, agree with the results found in the photometric surveys detailed in chapter 4. Table 5.9 compares some values of measured with predicted results for actual installations. The results also compare well to the magnitudes and trends found by previous researchers, *Bougdah*[1] and *Raitelli*[2]. Table 5.10 compares the OL/VFR characteristic found by *Bougdah* and *Raitelli* for a surface mounted diffusing luminaire, with the results for the same luminaire type found in this investigation.

Installation	Obstruction Loss (%)	
	Predicted	Measured
Health authority general office	10	11
Insurance company general office	11	14
Insurance company general office	8	8
Transport authority engineering office	12	16
Shipping company general office	7	5

Table 5.9: Comparison of measured and predicted results.

Bougdah's Results		**Raitelli's Results**		**New Results**	
VFR	OL	VFR	OL	VFR	OL
0.1	3	0.1	5	0.1	3.7
0.2	6	0.2	9	0.2	7.3
0.3	11.5	0.3	12	0.3	11
0.4	15.5	0.4	14	0.4	14.6
0.5	18.5	0.5	16.5	0.5	18.3

Table 5.10: Comparison of Bougdah's, Raitelli's and new OL/VFR results for room index = 2.00, mounting height = 2.5m, surface mounted diffuser (class 8) luminaire.

5.6 Conclusion

Using the results of this series of simulations, it has been possible to deduce some general trends regarding the OL/VFR relationship and the factors influencing that relationship. It was also possible to use the results to predict the magnitude of expected light losses, based upon a knowledge of furniture density. The dataset generated is extensive enough to form the basis of a lighting design method for obstructed interiors covering the practical range of cases encountered in modern commercial interiors. In its present form, however, it is too voluminous for this purpose. Some form of presentation of the results, of practical use by designers to predict OL for a given VFR, is required.

The following chapter proposes and critically discusses several methods through which this presentation and dissemination of the design data can be achieved. The most viable of the proposed solutions is then developed into a fully fledged design method.

5.7 References

1. *Bougdah H*, "The design of lighting installations for obstructed interiors", *Ph.D. Thesis*, University of Liverpool, pp. 139–164 (1991).

2. *Raitelli M R and Carter D J*, "A designers guide for electric lighting in obstructed interiors", *Proc. Lux Europa 1993*, Edinburgh, UK, pp. 220–232 (1993).

3. *CIBSE Code for interior lighting*, "Section 3.3.2 luminaire characteristics", *Chartered Institution of Building Services Engineers*, pp. 108–124 (1994).

Chapter 6

An average illuminance lighting design method for obstructed interiors

6.1 Introduction

The likely effect of obstructions on the distribution and absorption of light is acknowledged in such documents as the CIBSE Code for Interior Lighting [1]. This acknowledgment, however, only appears in the form of a warning that reductions in illuminance due to room furnishings may occur – no numerical guidance is offered to enable the designer to predict these reductions and hence to make an informed design decision.

This chapter presents a modification to the lumen design method, as described in the CIBSE Code for Interior Lighting, that takes account of the likely losses under working conditions caused by the contents of a room. In office buildings, typical room contents may include furniture or partitions, which project above the working plane and may cause the measurable illuminance levels in the installation to be lower than those predicted, using the "empty room" assumption. To overcome this limitation, the modified lumen method includes a multiplier to the Utilisation Factor (UF), which increases the installed flux to compensate for light absorbed by typical room contents.

The Obstruction Factor was based upon the results of the extensive computer simulation described in chapter 5. The Obstruction Factor (OF) data is general enough to acknowledge the range of luminaire types, room sizes and obstruction configurations likely to be found in modern commercial interiors. It is also in a form suitable for development into a design method.

In addition to detailing the development and use of the modified lumen method, this chapter also acknowledges and discusses the commercial implications of the results. Additionally, the problems associated with the use and dissemination of the method are critically reviewed.

6.2 Data presentation

The dataset developed in the previous chapter consists of a measure of the OL/VFR relationship for a generic group of luminaires over a range of room indices. This measure of the OL/VFR relationship was termed the Obstruction Loss Characteristic (OLC) of the luminaire and may be transformed into an expected light loss by multiplication by obstruction density. It was also shown in chapter 5 that the intensity distribution of the luminaire is the primary influence on the Obstruction Loss Characteristic. It was found that luminaires with a large downward intensity component (e.g. VDT luminaires) had a lower propensity for light loss (and hence OLC) than luminaires with a pronounced sideways intensity distribution (e.g. bare batten).

However, in its present state the dataset is in a form not suitable for use as a design tool. A simplified form of presentation is required to enable designers to quickly and easily deduce Obstruction Loss (OL) using information readily available. It was decided that some graphical form of presentation would probably be the optimal solution.

One initially attractive solution, was to reduce the dataset to a manageable size by grouping the luminaires based on their propensity for light loss. The results indicated that three separate groups were the optimum number and the classifications of these three groups enabled all the 16 classes of luminaire to be described as high, medium or low light loss luminaires. The luminaire types contained in each group are shown in table 6.1. The corresponding graphical presentation of these results is shown in figure 6.1. Included in this presentation method was an indication of the ranges of furniture densities likely to be encountered in typical commercial interiors and also for the standard obstruction configurations.

To use this graph, the designer must first decide to which group the design luminaire belonged. This would necessitate reference to either the CIBSE Code for Interior Lighting and table 6.1, or the provision of a list of typical luminaire types and their respective light loss groups with the graph. The next stage is the determination of the correct VFR value. The problems associated with the calculation and interpretation of VFR are dealt with in section 6.3. Once the correct VFR is determined, however, the designer can read the correct Obstruction Factor from the graph. The Obstruction Factor can then be used as a direct multiplier to the Utilisation Factor in the standard lumen method.

Although this is one possible solution to the presentation and use of the data generated in chapter 5 for lighting design in obstructed spaces, it is not ideal. Its use requires the designer to refer to other documents to make a decision as to which light loss classification group the luminaire belongs. Additionally the groupings and divisions of the

	Typical average slope of graph (OLC)	Type of luminaire
High loss	38 – 40	1, 2, 6, 12, 16
Medium loss	34 – 37	3, 4, 5, 8, 9c, 11
Low loss	24 – 28	7, 9a, 9b, 10, 15

Table 6.1: Division and contents of high, medium and low loss luminaire groups

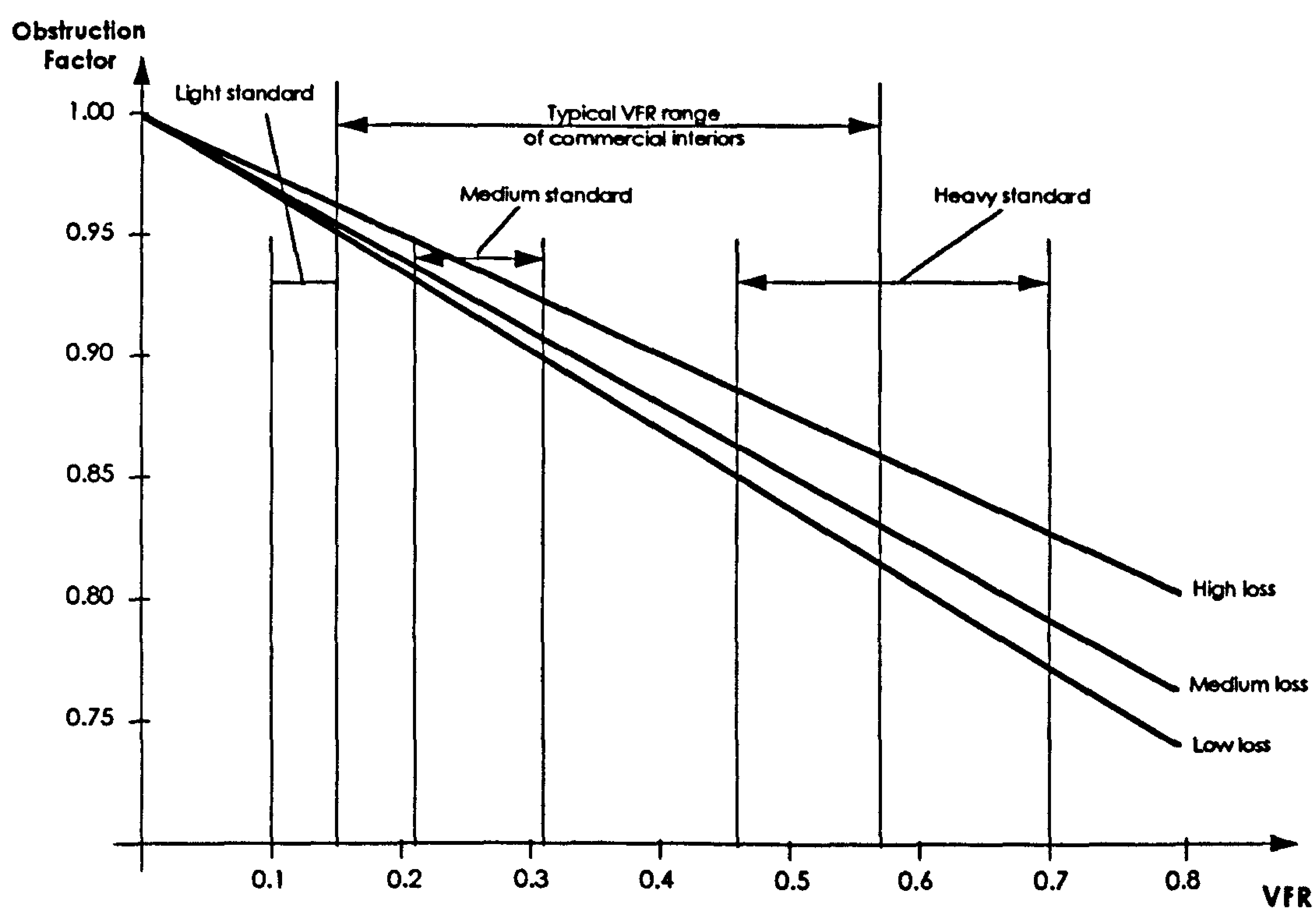


Figure 6.1: Linear plot of obstruction factor for high, medium and low loss luminaires and VFR, with an indication typical commercial range of VFR.

three groups were essentially arbitrary and thus open to debate as to where the limits should fall.

A much more advantageous method of grouping luminaire photometric characteristics was to use the maximum spacing-to-mounting-height ratio. By its nature this is a quantity unique to each individual luminaire, dependent upon the intensity distribution of the particular luminaire. All the luminaires used in the data generation had their own particular SHR_{max} and in the final presentation of the data each luminaire group was classified as a numerical average of the SHR_{max} for the actual luminaires in the group, as used in the data generation (see table 6.2). This technique of classification had a further advantage in that manufacturers provide SHR_{max} information as a standard part of the published luminaire data. Hence the need for the designer to refer to other documents, to determine the light loss group of any particular luminaires, was eliminated.

An additional advantage of using this method of presentation was the ease at which it could be converted for inclusion into the relevant codes of practice in other countries. For instance to convert the data to IESNA format the only modification necessary would be conversion factors between the IESNA spacing criterion and CIBSE SHRmax and between CIBSE Room Index and IESNA Room Cavity Ratio.

The most expedient method of presenting the data in table 6.2, in graphical form, was to derive a contour plot of Obstruction Loss Characteristic (OLC) for the various room indices and spacing-to-mounting-height ratios. Figure 6.2 shows the data presented in this manner. To determine Obstruction Loss from figure 6.2, the designer requires knowledge of three variables: the room index of the installation, the maximum SHR of the design luminaire and the density of the room contents. Two of these variables, the room index and the maximum SHR, are necessary to determine the OLC from figure 6.2 and these two

Room Index	SHR$_{max}$							
	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.75	26.1	27.9	29.9	31.8	33.5	35.0	36.0	36.8
1.00	25.9	27.7	29.9	31.9	33.8	35.3	36.4	37.3
1.25	25.6	27.6	29.9	32.0	34.1	35.8	36.9	37.8
1.50	25.4	27.3	29.9	32.1	34.5	36.2	37.4	38.3
2.00	25.1	27.2	29.9	32.3	34.9	36.8	38.0	39.0
3.00	24.2	26.8	30.0	33.2	36.6	39.0	40.8	42.0
4.00	23.9	26.6	30.1	33.9	37.4	40.3	42.2	43.6
5.00	23.9	26.7	30.3	34.2	38.0	40.9	42.9	44.3

Table 6.2: Obstruction Loss Characteristic as a function of Room Index and maximum spacing-to-mounting-height ratio.

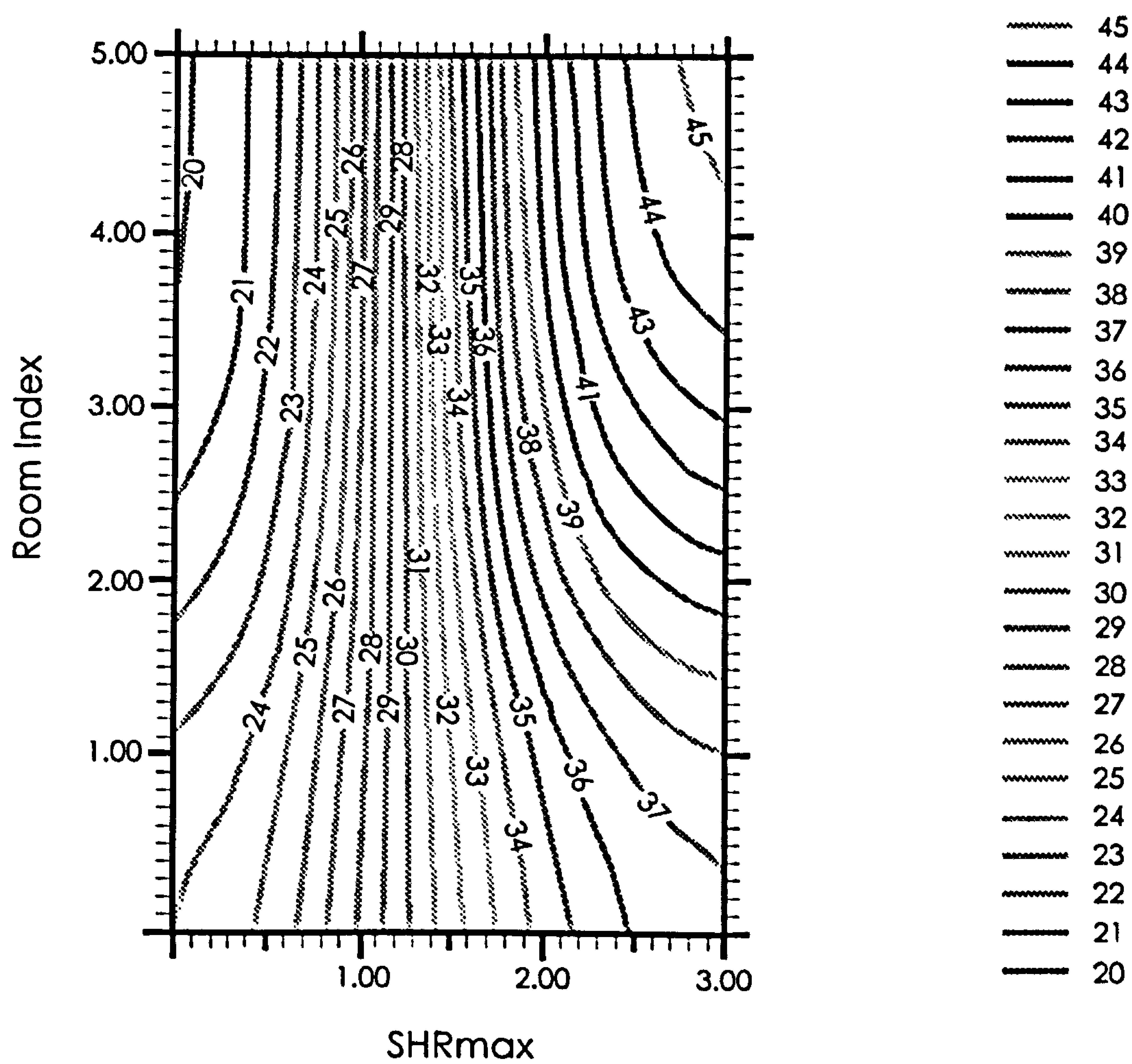


Figure 6.2: Contour plot of obstruction loss characteristic for typical range of SHRmax and room indices

variables are readily found. The third variable, the density of room contents, could have proven to give an unfavourable impression of the design method unless straight forward guidance was set out for calculating and estimating obstruction density.

6.3 Estimation of furniture density

In the case of some design schemes the size, nature and layout of furniture may be known. However for most lighting designs knowledge of the room contents is at best speculative and for design purposes a number of assumptions must be made. In either case the contents or furnishings must be quantified in terms of their 'density' in the room. This can be achieved by expressing the vertical surface area of furniture and other room contents above the working plane as a ratio of the floor area of the room, a ratio termed the **V**ertical surface area to **F**loor area **R**atio – VFR.

Generally for offices, or other commercial buildings, interiors may be described as falling into one of three categories of obstruction density; light, medium or heavy.

Light obstruction density – a typical commercial interior in the light category would contain mainly desks equipped with computer terminals (VDT's), with approximately 12m² of floor space per workstation. Each workstation would have a minimum of other equipment and the office as a whole would contain few filing cabinets and partitions. Executive and financial offices using computer terminals are good examples of a lightly obstructed office. (Figure 4.1, chapter 4, shows an office with a light density of obstructions and a measured VFR of 0.15).

Medium obstruction density – in this case each individual user of the office would typically have one or more computer terminals. The office may also contain a small number of movable partitions, filing cabinets, drawing boards or other large pieces of equipment. Most modern offices fall into this category. (Figure 4.2, chapter 4 shows an office with a medium desnity of obstructions and a measured VFR of 0.34).

Heavy obstruction density – an office in this category would typically be divided into individual workstations by the use of partitions and each person would generally have a filing cabinet and VDT at their workstation. Examples which fall into this category include drawing office and densely populated administrative offices. (Figure 4.3, chapter 4, shows an office with a heavy density of obstructions and a measured VFR of 0.57).

In the case where there is no information available regarding the ultimate use of the room, default values of VFR may be assumed. For example, a VFR of 0.35 will apply to most office interiors in the UK, as long as they do not contain cellular dividing partitions. This is the VFR of the medium case standard obstruction, which was shown by the field measurements described in chapter 4, to be most represenative of furniture density in modern commercial interiors.

6.4 Use of obstruction factor in a modified lumen method

The standard lumen method formula, equation 6.1, enables the designer to predict average working plane illuminance or, by rearranging, the number of a particular type of luminaire necessary to achieve a desired illuminance. The core of this method is the Utilisation Factor, which is the ratio of flux received by the working plane (both directly and reflected) to the total lamp flux installed, taking into account properties such as luminaire optics and room surface reflectance. For design purposes, the UF is determined from tables supplied by luminaire manufacturers, which cover a standard range of room dimensions and surface reflectances.

$$E_{(s)} = (UF.\ N.F.MF) \div (\text{Area of surface, } s) \quad \text{———Equation 6.1}$$

where:

$E_{(s)}$ is the average planar illuminance, for the working plane, s.

UF is the utilisation factor.

N is the total number of lamps in the installation.

F is the bare flux of each lamp.

MF is the maintenance factor of the installation.

In order to compensate for reduction in average working plane illuminance attributable to room furnishings, an additional Obstruction Factor, OF, must be introduced into equation 6.1. Using the maximum permitted luminaire spacing and room index for the proposed installation the Obstruction Loss Characteristic (OLC) for the design luminaire may be determined from figure 6.1. The OLC can then be converted to Obstruction Factor by applying knowledge of the expected furniture density, VFR, in equation 6.2:

$$OF = 1-((VFR \times OLC) \div 100) \quad \text{———— Equation 6.2}$$

The resultant obstruction factor may then be used as multiplier to the Utilisation Factor in equation 6.1.

6.5 Modified lumen method lighting design examples

The following example calculations illustrate the procedure used to calculate VFR and OL for some typical commercial offices, using real or speculative contents as appropriate.

Design Example 1 - A company is relocating their general administrative office to a newly built office. The complete contents of the old accommodation are to be moved into the new premises and thus the quantity and size of the furnishings is known.

Design Details:

Room Size - 8m x 10m x 3m high.

Working Plane Hieght - 0.75m.

Reflectance - ceiling 70%, walls 50%, floor 20%.

Furniture Details - 8 desks, 12 filing cabinets, 7 VDT's, 2 large bookcases adjacent to walls, 13 paper trays, 5 dividing partitions, 3 printers, 8 occupants.

Luminaire information - VDT LG3 Cat 2 luminaire, SHR_{max} = 1.23 (1.0 nom), twin lamp, lamp lumen output 3700, recessed, 1.5m x 0.297m.

Design Illuminance = 500 lux.

Design Solution:

Step 1: Quantifying furniture density.

No. Of	Furniture Item	Length (m)	Width (m)	Hieght (m) above w.p.	Vertical Surface Area (m²)
8	Desk	1.41	0.8	0	0
12	Filing Cabinet	0.64	0.48	0.60	16.128
7	V.D.T.'s	0.38	0.35	0.37	3.7814
2	Bookcases*	0.90	0.30	0.95	2.85
13	Paper trays	0.38	0.26	0.10	1.664
5	Partitions	1.50	0.025	1.00	15.25
3	Printers	0.36	0.38	0.15	0.666
8	Occupants**				4.24

Total Vertical Surface Area - *44.57 m²*

Installation Floor Area - *80 m²*

V.F.R. - *44.57 ÷ 80* = **0.56** (heavy category)

Step 2: Determine UF, MF & OF.

Mounting Height, H_m = 3.0 - 0.75 = **2.25m**

Room Index, k = (L x W) ÷ ((L + W) x H_m) = **1.98**

From Figure 6.2; using SHR_{max} = 1.23, k= 1.98; **OLC = 30**

* One side of each bookcase is against the wall and therefore does not figure in the VFR calculation.

** Assuming a V.S.A. of 0.53 m² for a typical person.

Equation 6.2 : OF = 1- ((VFR x OLC)/100) = 1 - ((0.56 x 30) +100) = **0.83**
From manufacturers information; UF = **0.64**, Operating factor, Z = **0.85**
As office is air conditioned a MF of **0.85** is assumed.

Step 3: Determine number of luminaires required.

Equation 6.1: E		= (UF(s) x Z x N x F x OF x LLF) + Floor Area
	500	= (0.64 x 0.85 x N x 3700 x 0.83 x 0.85) + 80
	N	= (500 x 80) + (0.64 x 0.85 x 3700 x 0.83 x 0.85)
	N	= **28 lamps (or 14 luminaires)**

Design Example 2 - Relocation and expansion of an international shipping company to a new office building. Designers have a general knowledge of projected number of occupants and some details of likely working methods and equipment.

Design Details:

Room Size - 12m x 10m x 3m high.
Working Plane height - 0.75m.
Reflectance - ceiling 70%, walls 50%, floor 20%.
Furniture Details - approx. 13 occupants, main office function - data processing and filing.
Luminaire information - VDT LG3 Cat 2 luminaire with PLL lamp, SHR_{max} = 0.97 (0.75 nom), 2 x 36W PLL lamps, lamp lumen output 2900, recessed, 0.5m x 0.5m.
Design Illuminance - 500 lux.

Design Solution:

Step 1: Quantifying furniture density.

Assumptions - one VDT terminal per person, two filing cabinets per person, four shared printers, two paper trays per person.

No. of	Furniture Item	Length (m)	Width (m)	Height (m) above w.p.	Vertical Surface Area (m^2)
26	Filing Cabinet	0.64	0.48	0.60	34.95
13	V.D.T.'s	0.38	0.35	0.37	7.02
26	Paper trays	0.38	0.26	0.10	3.33
4	Printers	0.36	0.38	0.15	0.89
13	Occupants**				6.89

Total Vertical Surface Area - *53.08 m^2*

Installation Floor Area - *120 m^2*

V.F.R. - *53.08 ÷ 120* = ***0.44*** (medium category)

<u>Step 2</u>: Determine UF, MF & OF.

Mounting Height, H_m = 3.0 - 0.75 = **2.25m**

Room Index, k = (L x W) ÷ ((L + W) x H_m) = **2.42**

From Figure 6.2; using SHR_{max} = 0.97, k = 2.42; **OLC = 27.4**

Equation 6.2: OF = 1-((VFR x OLC)÷100) = 1-((0.44 x 27.4) ÷ 100) = **0.88**

From Manufacturers info.; **UF = 0.61** , Operating factor, **Z = 0.85**

Air Conditioned Office; **MF = 0.85.**

<u>Step 3</u>: Determine number of luminaires required.

Equation 6.1: E = ($UF_{(S)}$ x Z x N x F x OF x LLF) ÷ Floor Area

500 = (0.61 x 0.85 x N x 2900 x 0.88 x 0.85) ÷ 120

N = **53 lamps (or 27 luminaires)**

<u>Design Example 3</u> - Speculative office building. No details of likely tenants or ultimate use available.

<u>Design Details:</u>

Room Size - 6m x 7m x 3.2m high.

Working Plane height - 0.75m.

Reflectance - ceiling 70%, walls 50%, floor 20%.

** Assuming a V.S.A. of 0.53 m^2 for a typical person.

Furniture Details - not available.

Luminaire information - Twin lamp prismatic luminaire, SHR_{max} = 1.78 (1.75 nom), lamp lumen output 5000, surface mounted, 1.55m x 0.21m x 0.01m.

Design Illuminance - 500 lux.

Design Solution:

Step 1: Quantifying furniture density.

Assumptions - No data available so assuming the default value for UK commercial interiors, (see section 6.3), **VFR = 0.35.**

Step 2: Determine UF, MF & OF.

Mounting Height, H_m = 3.1 - 0.75 = **2.35m**

Room Index, k = (L x W) ÷ ((L + W) x H_m) = **1.38**

From Figure 6.2; using SHR_{max} = 1.78, k = 1.38; **OLC = 36.0**

Equation 6.2: OF = 1-((VFR x OLC) ÷ 100) = 1-((0.30 x 34.5) ÷ 100) = **0.9**

From Manufacturers info.; **UF = 0.52** , Operating factor, **Z = 0.85**

Air Conditioned Office; **LLF = 0.85** .

Step 3: Determine number of luminaires required.

Equation 6.1: E		= ($UF_{(S)}$ x Z x N x F x OF x LLF) ÷ Floor Area
	500	= (0.52 x 0.85 x N x 5000 x 0.9 x 0.85) ÷ 42
	N	= **12 lamps (or 6 luminaires)**

6.6 Dissemination of the new design method

Although there is some scope for dissemination of this design method via the distribution of an in-house document, detailing the use of the new technique, this could only be implemented on a limited scale. However, this limited method of dissemination would be ideal for gaining feedback on the practical use of the technique. Following this, the publication of the method in a relevant peer-reviewed journal or conference proceedings would be the ideal second stage. Due to the associated commercial implications, the eventual goal, however, has to be the inclusion of the modified lumen method into the relevant codes of practice, such as the CIBSE Code for Interior Lighting.

Another method of dissemination that could be considered useful would be the inclusion of the obstruction factor into the various average illuminance computer packages, such as those distributed freely by luminaire manufacturers. This would ensure the problem was given some acknowledgment by the large body of designers who use the aforementioned software. The data in the form of table 6.2 would probably be the most suitable for inclusion in this type of software.

6.7 Commercial Implications

One of the main points of contention regarding the new method of design is that the inclusion of the obstruction factor may place the designer at a commercial disadvantage since the method involves the specification of more luminaires, which usually means higher initial and operating costs. Three things need to be borne in mind relating to the commercial implications of this new design method:

i. It is hoped that the results of this research will, in time, be included in interior lighting Codes and Standards and will thus be available to designers, manufacturers and users. Once this information is in the public domain, it is likely to become the *de facto* standard and thus no commercial disadvantage will accrue.

ii. All room furnishings absorb light. Installations designed using the conventional "empty space" assumption and subsequently filled with furniture will have lower than predicted average working plane illuminance and areas of local shadow which may cause user dissatisfaction. To maintain a specified average illuminance level under these circumstances requires increased installed flux, distributed to make good the effects of the obstructions, with an accompanying increased load. The quality of lighting has long been linked to user productivity, satisfaction and visual comfort. The use of the method could be "sold" on the grounds of contributing significantly to lighting quality, particularly since staff costs far exceed any other operating costs within a typical commercial building.

iii. With careful planning and design, the costs of an installation designed using this method increase roughly in line with the level of light loss. In the course of the research, it has been established that certain types of luminaire perform better than others in terms of obstruction loss. By exploiting this fact, alternative design solutions are possible.

6.8 Validation of design method

The validation of the techniques used for the generation of this design data has been carried out as an integral part of the work (see for instance: chapter 3, section 3.2 "Development of standard obstructions"; chapter 3, section 3.6 "A lighting analysis program for obstructed interiors" and chapter 5, section 5.5 "Validation of results"). Therefore the validation of the design, by any of the methods used previously, would be ambiguous, as all the individual components have been validated during their development. An alternative method of validation is by comparison of the University of Liverpool design method with other published techniques. Both of the design methods that follow operate under the limitation that the rooms are furnished with a uniform distribution of single height partitioned workstations. The new design method is able to handle this special case in the same way as a complex distribution of variable size room contents.

6.8.1 Comparison with Steffey

In his text "Architectural Lighting Design" [2] Steffey describes a series of partition factors that can be used in a similar fashion to the obstruction factor. In order to validate the use of the modified lumen method, a test situation was used and the resultant "furniture" factors from the two techniques were calculated and compared. The test installation was a simple rectilinear room 4 metres by 2.5 metres by 3 metres high, lit by a luminaire with SHRmax of 1.50 and furnished with a single partitioned workstation. The workstation partitions are 1.524 metres high and have a VFR of 0.271. Table 2.5, in chapter 2, shows Steffeys partition factors and according to this table a partition factor of 0.95 is required.

To calculate the obstruction factor using the new design method the designer needs to determine the obstruction loss characteristic from figure 6.2. Using room index 0.7 and SHRmax 1.50, figure 6.2 gives an OLC of 25.4, which enables an obstruction factor of 0.915 to be calculated using equation 6.2 and the aforementioned VFR.

6.8.2 Comparison with IESNA

The IESNA Handbook [3] describes a calculation strategy that can be used to take account of light losses and shadowing caused by uniformly distributed partitions. The procedure is illustrated by an example, of which the main points are set out below. The units used are converted into metric values and to enable comparison with the modified lumen method the luminaire used in the IESNA example luminaire was replaced with a twin lamp luminaire with a lumen output of 3700 and SHRmax of 1.23, although for ease of calculation the original UF table specified in the IESNA Handbook was still assumed to be correct for this fictitious luminaire.

An office of 11 metres by 9.15 metres with a 2.9 metre floor-to-ceiling height is furnished with workstations 3.7 metres by 3.7 metres floor area, surrounded by 1.525m high partitions. The room is shown in plan in figure 6.4. The IESNA calculation technique involves treating the zone

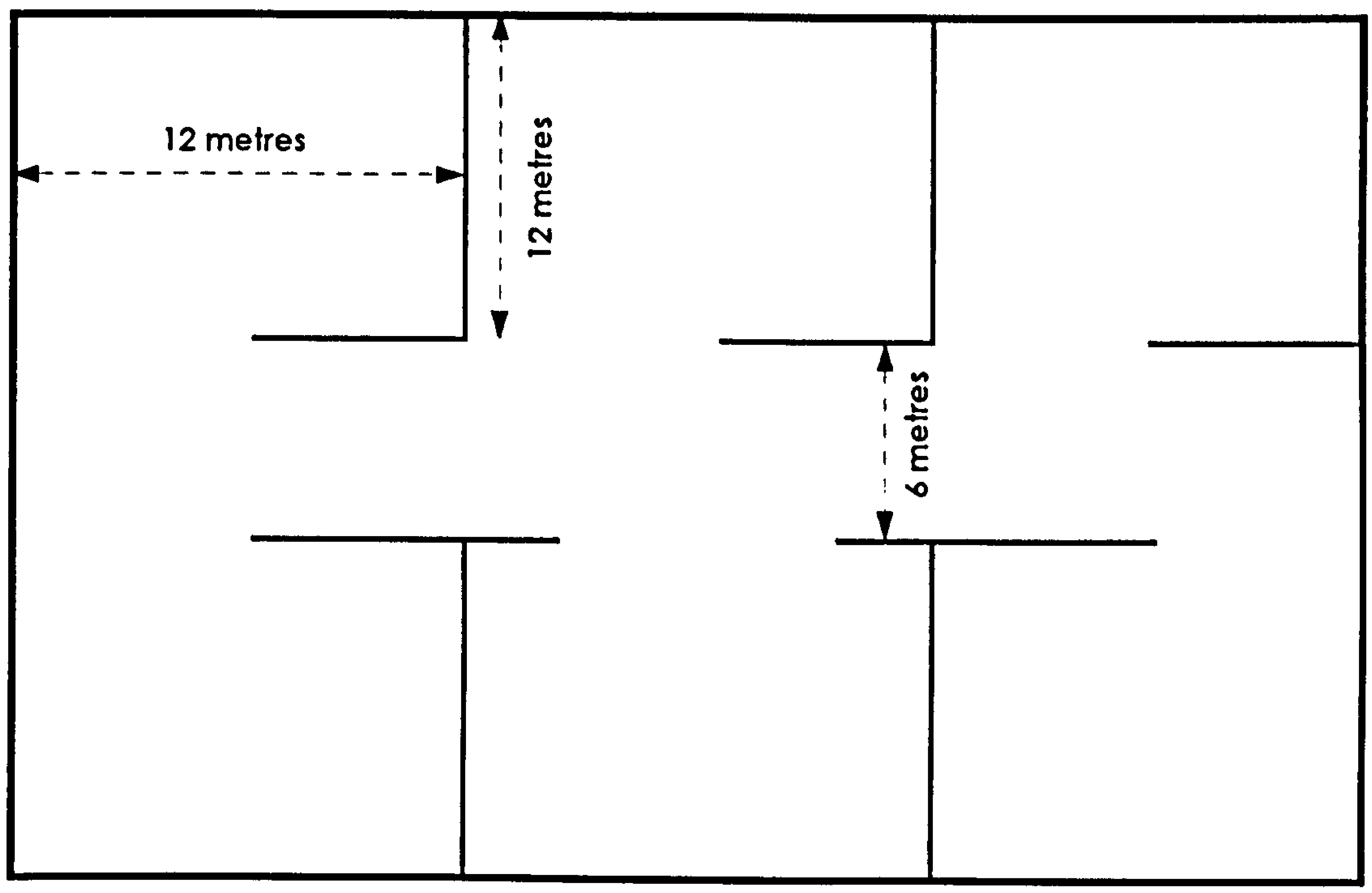


Figure 6.3: Plan of installation used in IESNA lighting calculation for partitioned spaces example.

between the top of the partitions and luminaire plane as well as the zone between the working plane and the top of the partitions as individual cavities. The technique was fully explained in chapter 2, section 2.4.2, "Empirically based design methods".

The results of the example outlined in the IESNA Handbook, with the aforementioned modifications, are:

No. of luminaires = (E_{ave} x A_{wp}) ÷ (N x LLO x CU x LLF)

where:

E_{ave}	= average working plane illuminance
A_{wp}	= area of working plane
N	= number of lamps
LLO	= lamp lumen output
CU	= coefficient of utilisation
LLF	= light loss factor

∴ No. of luminaires = (500 x 11 x 9.15) ÷ (2 x 3700 x 0.72 x 0.771)
= 12.3 luminaires

Performing the same calculation with the modified lumen method gives the following results:

Room Index = 2.3 and SHRmax = 1.23.

From figure 6.2 OLC = 30

VFR = 0.229

From equation 6.2; OF = 0.93

Using equation 6.1;

No. of lums = (500 x11 x9.15) ÷ (2 x 3700 x 0.71 x 0.771 x 0.93)
= 13.4 luminaires

The agreement between both of the two published calculation techniques and the modified lumen method outlined in this chapter is encouraging. This validation exercise augments the validation exercises carried out at the various stages of development of this design method, all of which have indicated that the new design method is capable of predicting OL for a variety of installations.

6.8.3 Validation of design method by Industry

To further validate the design data and the use of the design method, two national luminaire manufacturers were approached and asked to assess, use and validate the design method. The two manufacturers were Thorn Lighting Limited and Moorlite Electric Limited.

6.8.3.1 Moorlite Electrical Limited

Moorlite Electrical Limited used the Obstructed design method to devise a "shadow" design for a live project, that was to be designed using the empty room assumption. The project was a 29.2 metre by 10.2 metre section of a large open plan office intended for occupation by a financial organisation (See figure 6.4).

Using conventional techniques it was determined that 42.4 luminaires were the required minimum needed to achieve an average working plane illuminance of 500 lux. The spacing constraints of the installation necessitated that a 4 by 12 array of luminaires was required and it was predicted that this would result in an average working plane illuminance of 567 lux. The design used a 600mm x 600mm LG3 Cat 3 recessed louvred luminaire with two compact fluorescent lamps. (See figure 6.5).

Using the obstructed design method, the designer assumed a VFR for a typical commercial interior, i.e. 0.35. Based on the Room Index, SHRmax of the luminaire and the assumed value of VFR the designer predicted that an obstruction loss of 13% was likely and hence an OF of 0.87 was included in the conventional lumen calculation. The result of using the obstruction factor indicated that 48 of the same type of fittings used in the initial design were required to give an average illuminance of 500 lux. Hence, the same number of luminaires were used in the conventional and obstructed design schemes. In this case the obstructed design method was used to devise a lighting scheme that incurred no penalties in cost or energy use compared with conventional techniques, but the designer could specify the illuminance that may be measured by the client, in the final furnished interior, with greater confidence.

6.8.3.2 Thorn Lighting Limited

Thorn assessed the validity of the design data by comparing predicted values of obstruction loss found using figure 6.1 with simulated values of obstruction loss found using their in-house computer program, the Lighting Visualisation System (LVS). This program can include any specified object into a space and calculate the illuminance distribution over all surfaces. The program then generates a pictorial visualisation to which the calculated values of illuminance can be linked.

To generate OL data that could be used to compare with the results detailed in Chapter 5, Thorn Lighting Limited set up, in LVS, a series of rooms furnished with heavy, medium and light standard obstructions. The analysis was undertaken using three different levels of subdivision of room surface – firstly "adaptive" subdivisions, i.e. according to the luminance gradient, and secondly two fixed subdivisions of 0.25m by 0.25m and 1m by 1m elements respectively. Table 6.5 shows the results of the simulations compared with the predicted OL values for the same installations found using figure 6.1. The results found using the adaptive subdivision method compare most favourably with the results predicted using the obstructed design method, with the difference increasing as the number of subdivisions decreased. The level of agreement between the Thorn results and the design method results is very encouraging and

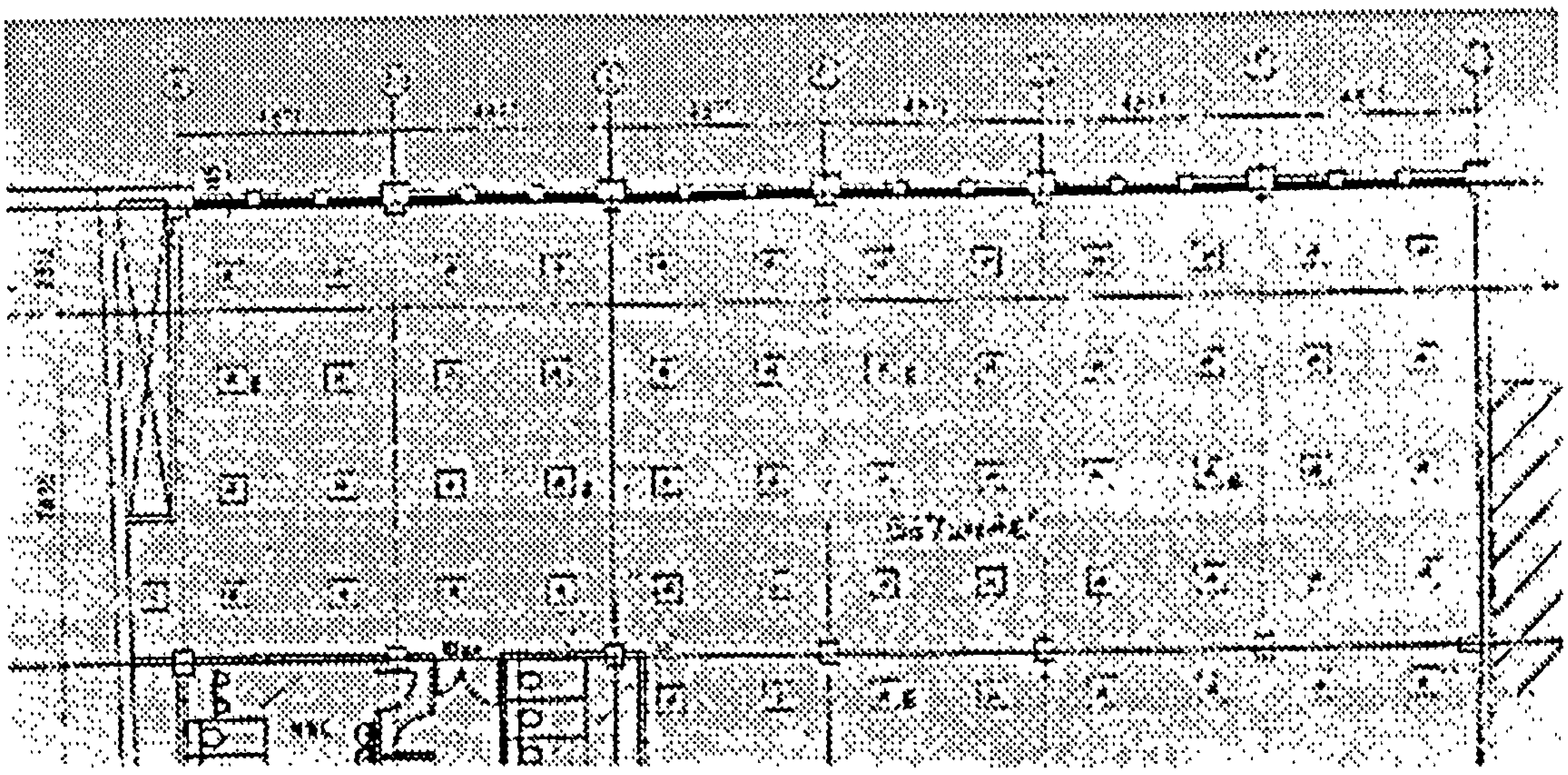


Figure 6.4: Installation floor plan and proposed luminaire layout for Moorelite electric "empty room" design scheme.

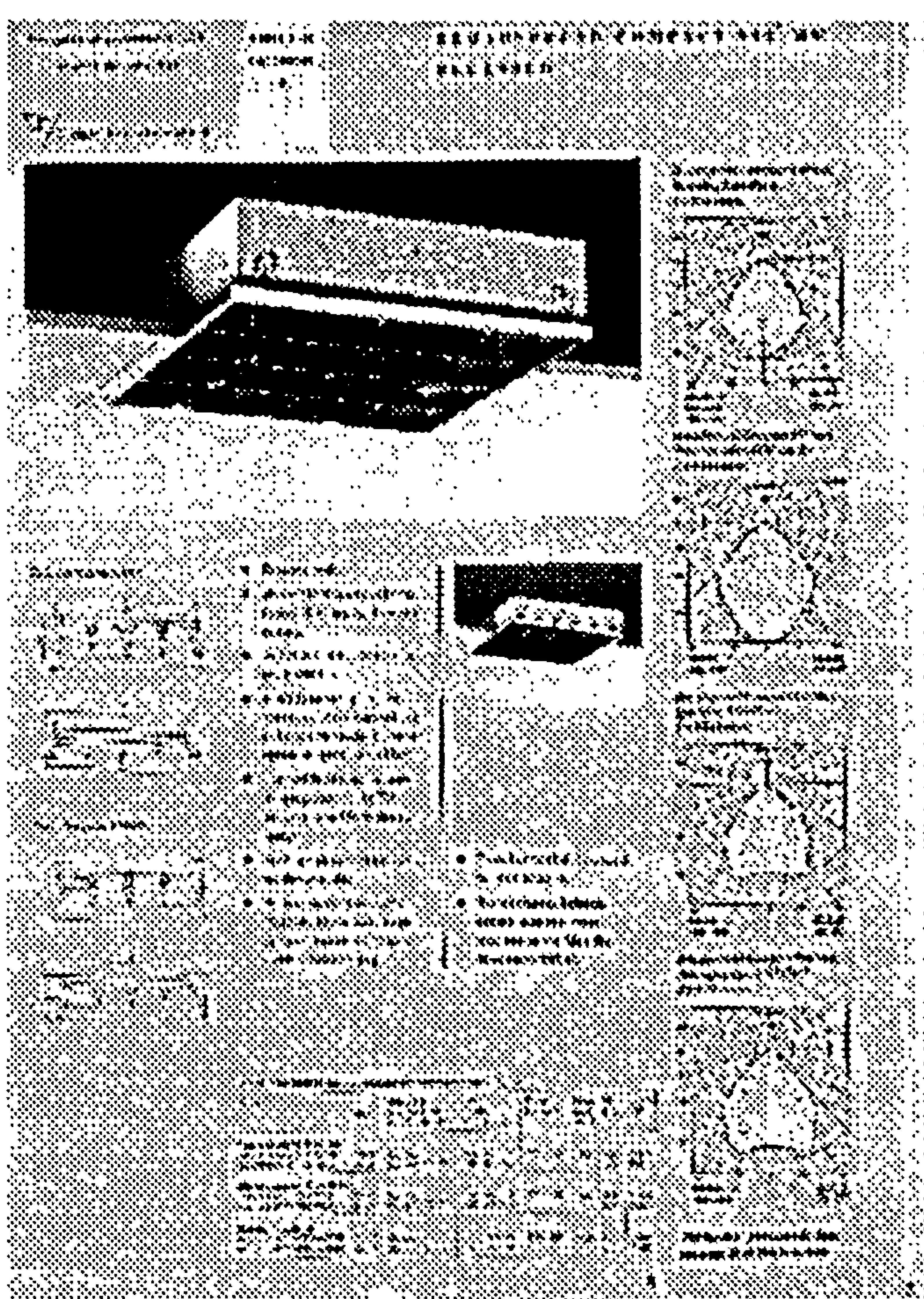


Figure 6.5: Moorlite design luminaire - 600 x 600 LG3 Cat 3 recessed louvred luminaire.

Furniture Density	***Design Method Prediction***	**LVS Simulated Values**		
		Adaptive sub-division	*Fixed sub-division (0.25 x 0.25)*	*Fixed sub-division (1.0 x 1.0)*
High	0.82	0.77	0.73	0.70
Medium	0.85	0.83	0.77	0.75
Low	0.94	0.94	0.88	0.87

Table 6.5: Comparison of Thorn Lighting Limited LVS simulated obstruction factors and obstructed design method predicted obstruction factors.

appears to reinforce the applicability of the use of this method as valid design tool.

6.9 Conclusion

The research detailed in this chapter has described the development of an easily implemented method for the prediction of light loss for a representative range of interior luminaires for installations of different sizes and containing varying degrees of interior obstruction. There was encouraging evidence that the results of this new method and other similar methods give comparable results. Validation exercises undertaken by industry also demonstrated the practicality and applicability of the new design method as a useful lighting design tool for obstructed interiors.

The main areas of this work requiring further development is the field testing of the method and the successful dissemination of the new technique. The dissemination and field testing will hopefully result in the inclusion of this method in the relevant documents, such as the CIBSE Code for Interior Lighting. The inclusion of the new method in the code is particularly pertinent due to the associated commercial penalties, discussed in section6.7. The new design method allows the designer to devise a lighting design which provides higher quality visual conditions, albeit at an increased financial cost.

6.10 References

1. *CIBSE Code for Interior Lighting*, "Section 2.4.3 Illuminance variation", *Chartered Iinstitution of Building Services Engineers*, pp. 29, 1994.

2. *Steffey G R*, "Architectural lighting design", *Van Nostrand Reinhold*, New York, 1990.

3. *IESNA Lighting Handbook Reference and Application*, "Chapter 12: Basic Lighting Calculations", *Illuminating Engineering Society of North America*, 8th edition, PP 484–487, 1993.

Chapter 7

The influence of SHR on illuminance conditions in obstructed interiors

7.1 Introduction

One of the criteria set out in lighting standards, which must be adhered to in order to achieve a "satisfactory" lighting design, is the correct spatial distribution of illuminance over the working plane. In a commercial environment, this usually means a limit to the diversity of illuminance distribution over the working plane throughout the entire space. This not only effects the user perception of the space, but also the number and location of luminaires that must be installed and hence the energy consumption of the installation. Recent research into illuminance variation has shown that excessive variations in illuminance between desks can contribute to user dissatisfaction[1] and it has addressed the limits of acceptability of the various measures of uniformity[2]. The results of this research support the CIBSE code for interior lighting, which states that *"excessive variations of illuminance within an interior may affect comfort levels and visual performance by causing transient adaptation problems"*. This statement is further enforced by the IESNA Handbook, which states that *"in general, the more uniform the light distribution in the visual field, the better one sees the visual task".*

There are two measures recommended in the CIBSE Code for Interior Lighting[3] that can be used to quantify and assess the illuminance variation in an installation. They are the Uniformity Ratio and the Illuminance Diversity. The CIBSE code recommends that the Uniformity Ratio, when calculated as the ratio of minimum to average illuminance over the task area, should not fall below 0.8 and states that this is normally achieved if the ratio of minimum to maximum direct illuminance is greater than 0.7. The diversity is defined as the ratio of the maximum to minimum illuminance over the "core area" of the installation, excluding any point within 0.5m of obstructions or walls. The limiting value of this variable is 5:1.

In an unfurnished room, the spatial distribution of horizontal illuminance is primarily a function of the luminaire layout and the photometric distribution of the individual luminaires. To enable the lighting designer to quickly judge whether his choice of luminaire and layout will satisfy the uniformity requirements, he compares the actual luminaire spacing-to-mounting-height ratio (SHR) to the maximum SHR recommended by the luminaire manufacturer. If this limiting value is not exceeded, the designer is assured that his design will satisfy uniformity requirements.

Unfortunately, the process by which the SHR for a particular luminaire is derived, contains one assumption which could influence the uniformity achieved in a fully functioning commercial installation. As with the Lumen Method for lighting design, the SHR calculation procedure (set out in CIBSE Technical Memorandum No. 5[4]) assumes the volume between the luminaire plane and the working plane is empty. Therefore, the SHR can only give a indication of uniformity performance of a particular arrangement of luminaires when they are installed in an empty room. The likely effects of obstructions are acknowledged in standards such as the Illuminating

Engineering Society of North America Handbook[5] and CIBSE Lighting Guide: The Industrial Environment[6]. The CIBSE Code for Interior Lighting[7] suggests that some reduction in luminaire spacing may be necessary to achieve the required uniformity in heavily obstructed spaces. There is no guidance to magnitude of this reduction, nor information regarding the principal variables influencing this reduction. These could include luminaire type and furniture size and disposition.

The problem of working plane uniformity reduction can only become more significant when one considers the current awareness of the need for energy efficient designs. One superficially attractive solution to reducing energy use is to use broadspread distribution luminaires at wide spacings to replace a larger number of conventional luminaires. SHRmax describes the maximum spacing at which luminaires can be installed to achieve acceptable uniformity, so that the nearer luminaires are installed to SHRmax the closer the uniformity of illuminance will be to the lower end of the scale of acceptability. This move to towards the lower end of the scale of acceptability will be further affected by the introduction of furnishings. Some numerical guidance is required to assist the designer in ensuring the proposed luminaire layout will give the required uniformity of horizontal illuminance in an obstructed space.

One method to overcome this problem has been proposed to the lighting community – the concept of obstructed spacing-to-mounting-height ratio (SHR_{obs})[8]. This chapter attempts to assess the relative performance of conventional SHR and obstructed SHR in a furnished interior. It will also address the problems associated with SHRobs and discuss why the technique has yet to gain wide acceptance by the industry. Finally, it will use the data generated to develop guidance that can be used by designers to predict modifications in luminaire spacing required in obstructed interiors.

7.2 Calculation of SHR for empty interiors

The current UK procedure for calculating conventional SHR is detailed in CIBSE Technical Memorandum No. 5[4]. Briefly, the method involves calculating the illuminance in the central area of an array of 16 luminaires, the spacing of which is increased in a preferred series of steps starting at an SHR of 0.75 and moving apart in increments of 0.25 SHR. Only the direct component of the illuminance is considered. The ratio of minimum to maximum illuminance at each step is determined and the process stops when this ratio falls below 0.7. The luminaires are assumed to be installed in an empty space. The central area is at working plane height and varies in size as the luminaire spacing changes, with the outer corners remaining always below the centres of the four innermost luminaires. This procedure yields two spacing-to-mounting-height ratios: the maximum spacing-to-mounting-height ratio, the point at which the uniformity ratio falls below 0.7 and the nominal spacing-to-mounting-height ratio, which is the value of SHR in the preferred series of steps before failure occurs.

The main point of contention about this method is the empty room assumption. Other standard techniques to calculate similar ratios – such as the IESNA Spacing Criteria[9] and the Japanese spacing-to-height ratio[10] – also contain the same assumption. The basis of these American and Japanese methods are outlined in section 7.2.1 and 7.2.2. The "empty room" assumption, inherent in all three of the aforementioned spacing techniques, could lead an inexperienced designer, unaware that there will be an influence on the illuminance due to the presence of obstructions, to base his design around empty SHR values without considering the obstruction effect.

7.2.1 The IESNA spacing criterion

The IESNA Handbook[9] describes the luminaire spacing criterion as the maximum luminaire spacing at which horizontal illuminance will be reasonably uniform. The spacing criterion is intended to be informative, rather than prescriptive, in the lighting design process. It is recommended that luminaires must be installed at some spacing-to-mounting-height ratio less than the luminaire spacing criterion, particularly when other criteria such as shadowing and luminaire overlap are considered. In installations where uniformity is particularly important, the IESNA Handbook suggests that a value of 1.5 be assigned as the luminaire spacing criterion for any luminaire. The handbook also notes that any spacing-to-mounting-height ratio recommended by the luminaire manufacturer, supersedes the IESNA spacing criterion. It is the responsibility of the manufacturer, however, to determine and specify the procedure through which this value is decided.

7.2.2 The Japanese spacing-to-height ratio

The Japanese equivalent of CIBSE SHR is the spacing-to-height ratio (S/H ratio) and can be calculated by the following method. A single luminaire is mounted at height 'H' above the working plane (see figure 7.1). The horizontal illuminance is calculated on the working plane firstly for a C-angle of 0° (i.e. the transverse plane). This determines the distance, 'd_a', where the illuminance 'E_a' is half of the illuminance 'E_0'. A similar calculation is performed in the axial (C = 90°) plane to find the distance 'd_b', the point where 'E_b' is half of 'E_0'. The transverse S/H ratio is determined as 2 x d_a ÷ H and similarly the axial S/H ratio is determined as 2 x d_b ÷ H. In Japan, some luminaire manufacturers adopt the above-mentioned definition and provide the S/H ratio for their luminaire range, but, the use of the S/H ratio to determine luminaire spacing is not included in the code of practice.

7.3 Obstructed spacing-to-mounting-height ratio

The obstructed SHR (SHR_{obs}) has been proposed as an alternative to the conventional SHR. SHRobs takes as its basis, the conventional SHR calculation procedure and introduces some modifications. The most important of which is the addition of obstructions into the central task area. The procedure for calculating obstructed SHR is fully documented and published by *Bougdah et al*[8] and also outlined in chapter 3. A computer

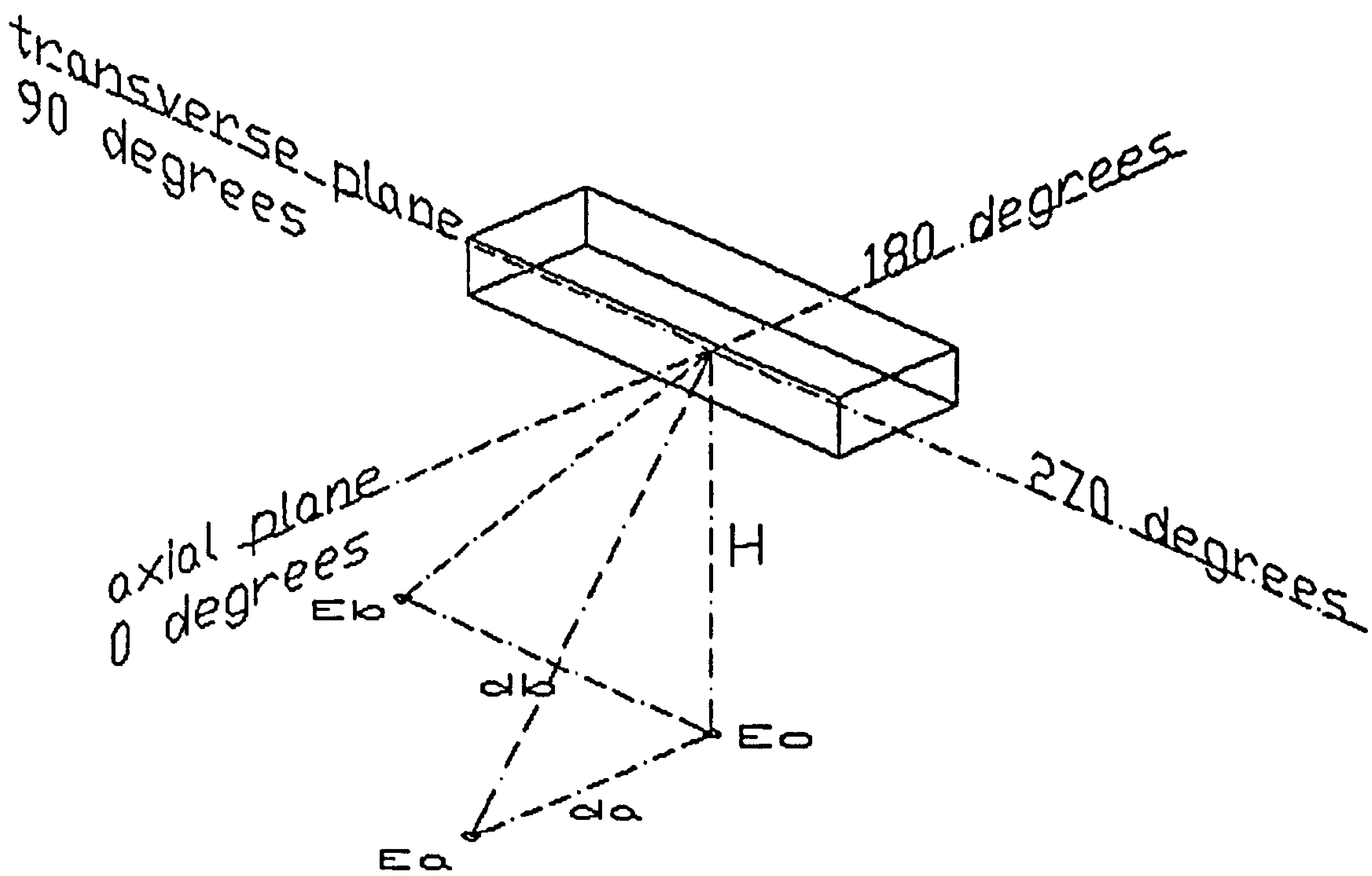


Figure 7.1: Illustration of Japanese spacing-to-height ratio

program has been developed to calculate SHR for luminaires for use in installations with various degrees of internal obstruction and the results highlight a significant difference between the empty and furnished cases. See section 3.7 for a detailed description of SHR_{obs} concept and program.

The industry has not accepted this technique as the standard which could be due to several factors. Firstly, there is the problem of providing designers with SHR_{obs} data. One solution could be for the luminaire manufacturers to generate SHR_{obs} data for their luminaires. This, however, would require a considerable amount of expense for the manufacturers, as all existing data would need to be processed as well as any new data. Add to this the commercial implications should some manufacturers decide not to proceed with the generation of SHR_{obs} data, and it is quite easy to see why this option has nol been used. An alternative solution would be for the designer to generate the SHR_{obs} data for the luminaire they were considering before including them in their design, but this would necessitate all designers having access to a copy of the relevant computer software. The outstanding reason for the non-implementation of the SHR_{obs} method is its lack of inclusion in the relevant codes of practice and hence, the lack of awareness of the existence of the problem. In order for either of these proposals to become the *defacto* standard in the UK, CIBSE would have to incorporate obstructions into documents such as Technical Memorandum No. 5[4] and the Code For Interior Lighting[7].

Guidance available to date indicates that there may be a problem but does not provide a solution that is suitable for designers. Some recommendations need to be developed which the designer can readily apply to a number of situations.

The limited amount of numerical guidance that is available regarding luminaire spacing and illuminance conditions in obstructed spaces is usually limited to special cases. For instance, the CIBSE Lighting Guide for the

Industrial Environment[6] recommends that "typically a one-third reduction in the maximum spacing-to-mounting-height ratio is required". *Steffey*[11] and *Williams*[12] have also addressed this area and attempted to provide some general guidance, apparently developed using the authors' practical experience. Both *Williams* and *Steffey's* techniques are detailed in chapter 2, section 2.4.2. However, neither *Steffey* nor *Williams* provide any evidence to either support the improved illuminance conditions achieved, nor do they validate the use of their respective techniques.

7.4 Experimental Method

To ensure that any general rules regarding the relationship between the variation in horizontal illuminance and luminaire spacing are applicable to a wide range of situations encountered in modern commercial interiors, an investigation based on of a significant number of cases is necessary. To this end, a series of computer simulations were decided to be the most expedient means of achieving this goal. A computer simulation would allow single variables to be changed and the results of the changes assessed individually. More importantly, the use of a computer simulation meant a large number of cases could be investigated with considerably less effort than with other techniques, such as scale models or field measurement. A commercially available computer package - Lumen Micro from Lighting Technologies Inc. - was used to compute horizontal working plane illuminance in an installation over a large 'core area' and two smaller task area's. This computer package had several advantages over the other software available. Firstly, illuminance could be calculated over the three areas (two tasks and the core area) without the need to run the program three times. Also, luminaire spacing and type was easily varied within the program.

The modelled space was intended to represent a typical open plan office. From its empty condition, it was furnished with several arrangements of standard obstructions which have been proven capable of simulating actual working conditions[13]. To streamline the model and reduce computation time to within practical limits, several assumptions were applied to the model. Firstly, to eliminate the influence of the walls on the lighting calculation and to prevent the need for the room size to be increased with each increase in luminaire spacing, an oversized room was used with only the core area, as shown in figure 7.2, considered in the illuminance calculations. To ensure consistency throughout the investigation, the task area grids and core area grids remained in the same position and the same size during the simulation. However, the luminaire grid increased to facilitate the change in SHR, although the luminaires always remained symmetrical around the centre axes of the room.

To reduce the calculation time for each of the 544 cases (by a factor of three to an average of 1 hour per case, on a 486DX-33 PC) only direct light was considered. This could give rise to a slight underestimation of the uniformity. It is reasonable to assume however, that the inter-reflected component may be the same for the points of maximum illuminance as well as for the points of minimum illuminance. If this is accepted then this small underestimation in uniformity could be justified on the grounds of engineering safety. Additionally, it meant that the results were calculated under the same basis as both the conventional TM5 SHR and the University of Liverpool obstructed SHR described earlier.

The task and core area horizontal illuminance was calculated for 6 different types of luminaire (classes 1, 4, 8, 9a, 9b and 10 as specified in the CIBSE code[14] and chapter 5). These groups were selected as being representative of luminaires used in modern office lighting practice. To avoid the influence of any particular characteristic associated with a single manufacturer on the results, data was taken from three major manufacturers (see table 7.1 and figure 7.3). Task illuminance was calculated on a 0.25m^2 grid, as recommended by the CIBSE Code, at two

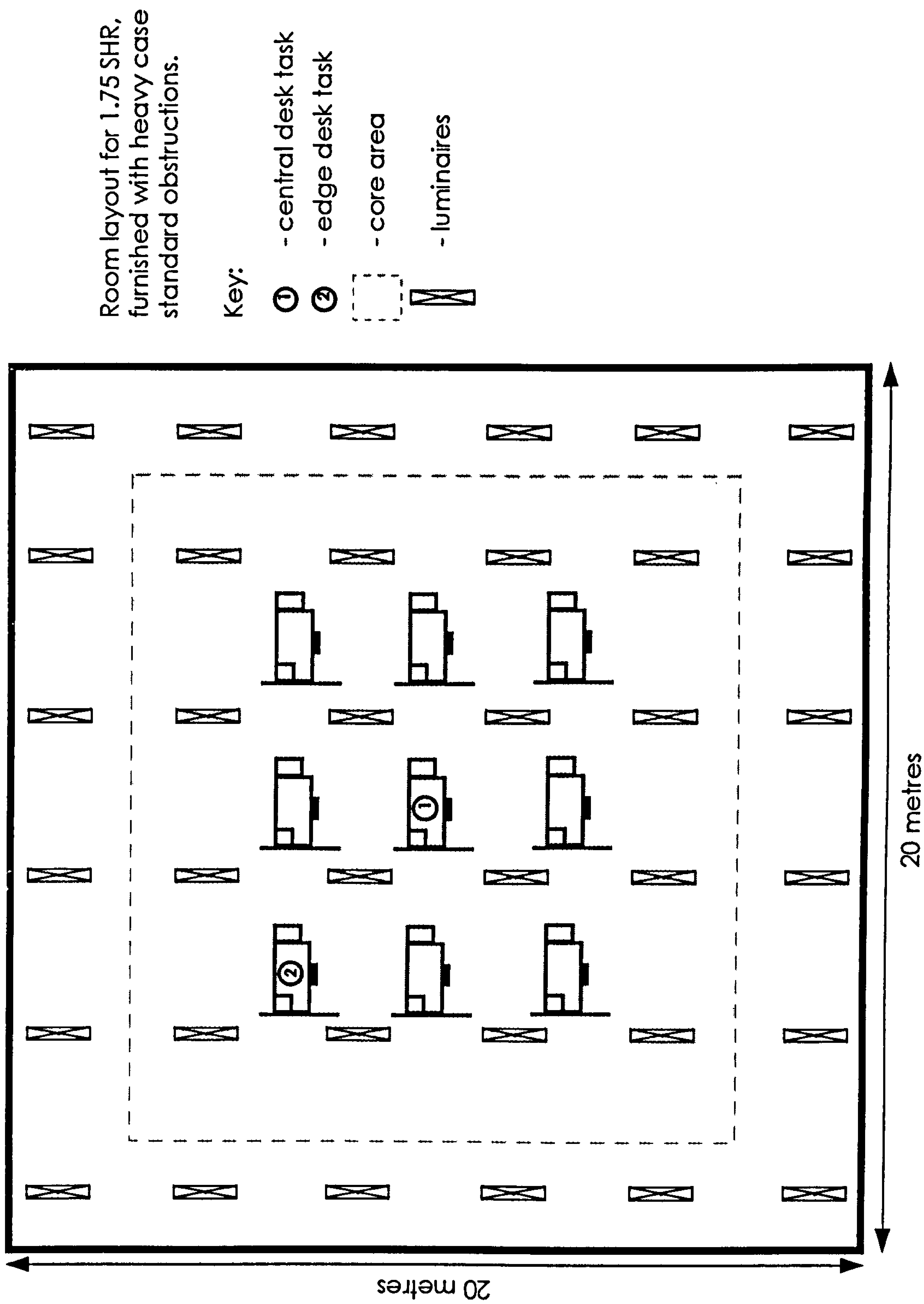


Figure 7.2: Experimental Room Layout (for 1.75 SHR, furnished with heavy case standard obstructions).

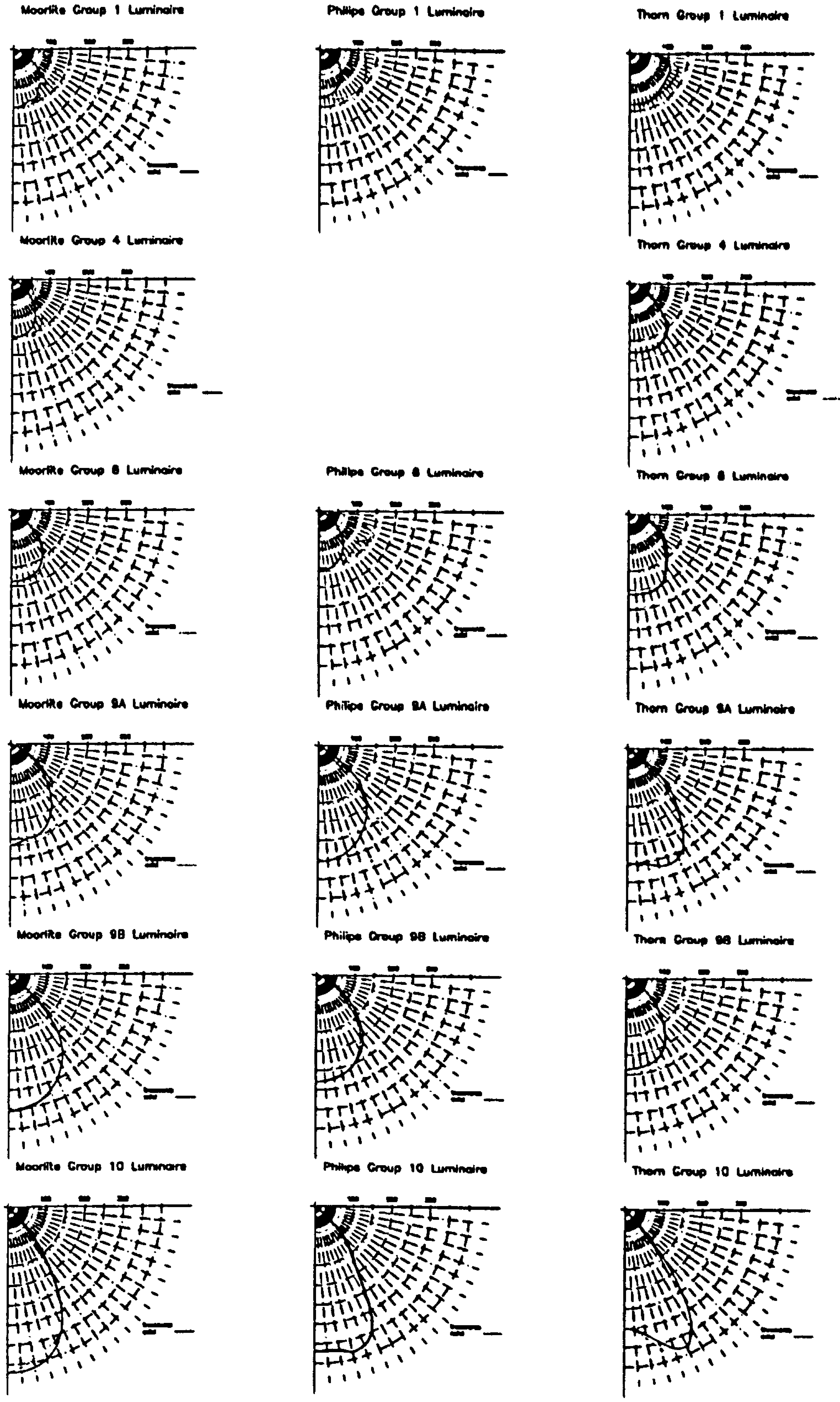


Figure 7.3: Polar curves of intensity distributions for all luminaires used in the simulation.

locations in the room. One on a desk located centrally in relation to the luminaire layout and one on an edge desk (also shown on figure 7.2). This served to ascertain the influence of task position in relation to the luminaire layout.

The CIBSE Code states that when calculating diversity, the grid of points should "*normally be at a spacing of 1 metre*" but also that "*a calculation grid size of less than 1 metre may be necessary for installations where abrupt variations in working plane illuminance may occur, for instance those using luminaires with batwing or narrow distributions. Care must also be taken to ensure that the luminaire and calculation grid do not coincide and this may also necessitate a small change in the size of the calculation grid*". To this end, a 0.75m spaced grid was used, with points within 0.5m of obstructions ignored, which ensured that all points that in reality would not be used as a task location (i.e. close to partitions or filing cabinets) were not included in the calculation.

Using the horizontal illuminance results, several quantities could be calculated and assessed. Uniformity Ratio for the task illuminance for the two positions was calculated as the ratio of minimum-to-maximum illuminance, because this measure of uniformity closely resembles the Mid Area Ratio (MAR) specified for when considering direct light only in the CIBSE CODE For Interior Lighting and Technical Memorandum Number 5. This quantity gives a good indication of the results likely to be achieved in the final installation when inter-reflected light is taken into account. By not assuming the same degree of symmetry implied in the use of the MAR and the empty room assumption, the ratio of minimum to maximum illuminance as the uniformity criteria can be applied to this situation. Additionally, all previous research at Liverpool related to obstructed SHR[8,13] had used minimum to maximum as the measure of uniformity and hence the new results would be comparable with all previous research.

Luminaire	SHRnom	SHRmax axial	SHRmax transverse	SHRobs		
				Light	Medium	Heavy
Philips single batten (INR 6019) - class 1	1.75	1.99	2.77	1.70	1.30	
Philips surface modular (INR 2060) - class 8	1.5	1.66	1.66	1.32	1.29	
Philips recessed mod. louvre (INR 2385) - class 9a	1.25	1.36	1.75	1.50	1.30	
Philips recessed mod. prismatic (INR 2150) - class 9b	1.5	1.52	1.52	1.20	0.95	
Philips twin VDT (INR 2321) - class 10	1.0	1.22	1.26	1.12	1.07	
Thorn twin batten (pp236) - class 1	1.75	1.85	2.47	1.38	1.31	
Thorn twin opal prismatic (fclz258 + fcle25) - class 4	1.5	1.73	2.00	1.51	1.37	1.26
Thorn single diff. pack (fpp 158) - class 8	1.5	1.65	2.16	1.42	1.33	
Thorn modular louvred-(fta236 + ftx2312) class 9a	1.25	1.3	1.39	1.25	1.25	
Thorn modular prism. (fta236 + ftp312)-class 9b	1.50	1.69	1.97	1.29	1.29	
Thorn twin VDT (fraz236 + frv2312) - class 10	1.00	1.40	1.40			
Moorlite trimpak twin batten (ps/s/155)-class 1	1.75	1.79	2.24	1.50	1.35	
Moorlite twin opal prismatic (psd/s) - class 4	1.50	1.64	1.89	1.40	1.28	
Moorlite surface modular prismat. (12/mrp) - class 8	1.50	1.61	1.80	1.32	1.27	
Moorlite rec. mod louvred (300/b13rt) - class 9a	1.50	1.59	1.79	1.30	1.26	
Moorlite rec. prismatic (300/mm) - class 9b	1.50	1.71	1.95	1.37	1.34	
Moorlite twin VDT - class 10	1.25	1.31	1.35	1.12	1.12	

Table 7.1: Luminaire descriptions and derived photometric data.

Diversity was calculated as the ratio of maximum to minimum illuminance in the core area, excluding all ineligible points. Additionally, the average reduction in illuminance, due to the introduction of furnishings into a previously empty space, was determined for the two task areas and the core area.

7.5 Results

Tables 7.2 to 7.7 show the complete set of results obtained for each of the luminaires used in the investigation. The results of the various simulations were analysed in graphical form, with the dependant variable plotted against SHR, which increased in the CIBSE TM5 preferred series of steps. On each of the graphs the following points of interest are indicated:

1. The nominal and maximum SHR's of the luminaires.
2. The obstructed SHR.
3. The CIBSE limiting value for the dependant variable.

To determine the obstructed SHR for each luminaire, the University of Liverpool SHR_{obs} computer program was used[15]. The SHR_{obs} values are also shown in table 7.1. To rationalise the large dataset to some extent, the results from luminaires in the same classification group were expressed as an numerical average of the three manufacturers.

Luminaire Group 1

Manufacturer	SHR	Empty						Light					
		Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
		URe	*Eave*	*Div*	*Eave*	*URc*	*Eave*	*URe*	*OL*	*Div*	*OL*	*URc*	*OL*
Moorlite	0.75	0.99	2210	1.20	2150	0.99	2280	0.67	16.3%	1.2	2.8%	0.70	15.8%
Philips	0.75	0.99	1200	1.24	1170	0.99	1230	0.66	16.8%	1.2	3.4%	0.69	16.3%
Thorn	0.75	0.99	1380	1.23	1330	0.99	1410	0.66	17.4%	1.3	3.0%	0.71	16.3%
Average		0.99		1.22		0.99		0.66	16.8%	1.23	3.1%	0.70	16.1%
Moorlite	1.00	0.98	1250	1.20	1320	1.00	1270	0.70	15.2%	1.2	9.1%	0.71	15.0%
Philips	1.00	0.98	678	1.20	671	0.99	699	0.66	16.7%	1.2	3.1%	0.69	15.6%
Thorn	1.00	0.98	777	1.20	767	0.99	797	0.67	16.5%	1.2	3.0%	0.70	15.4%
Average		0.98		1.20		0.99		0.68	16.1%	1.21	5.1%	0.70	15.3%
Moorlite	1.25	0.97	832	1.30	790	0.98	785	0.68	18.4%	1.3	3.5%	0.64	14.8%
Philips	1.25	0.98	453	1.30	429	0.98	440	0.68	19.0%	1.3	3.7%	0.66	15.5%
Thorn	1.25	0.97	519	1.30	491	0.98	495	0.67	19.3%	1.3	3.9%	0.65	15.4%
Average		0.97		1.30		0.98		0.68	18.9%	1.30	3.7%	0.65	15.2%
Moorlite	1.50	0.94	536	1.50	528	0.97	512	0.65	19.4%	1.4	3.8%	0.61	15.7%
Philips	1.50	0.94	301	1.40	287	0.98	291	0.66	19.9%	1.4	4.2%	0.62	15.5%
Thorn	1.50	0.93	333	1.50	327	0.98	321	0.65	20.4%	1.5	4.0%	0.55	15.6%
Average		0.94		1.47		0.98		0.65	19.9%	1.43	4.0%	0.53	15.4%
Moorlite	1.75	0.92	364	1.65	407	0.97	360	0.73	14.3%	1.7	2.7%	0.47	16.7%
Philips	1.75	0.94	206	1.50	221	0.98	208	0.69	15.0%	1.5	2.7%	0.47	16.8%
Thorn	1.75	0.92	227	1.70	253	0.97	226	0.71	15.4%	1.7	2.8%	0.43	17.3%
Average		0.93		1.62		0.97		0.71	14.9%	1.61	2.7%	0.46	16.9%
Moorlite	2.00	0.89	247	2.40	290	0.97	244	0.64	12.6%	2.2	2.8%	0.39	17.2%
Philips	2.00	0.94	132	2.30	155	0.97	142	0.62	13.6%	2.3	2.6%	0.39	17.6%
Thorn	2.00	0.92	148	2.40	179	0.98	152	0.62	14.2%	2.4	2.8%	0.38	17.8%
Average		0.92		2.37		0.97		0.63	13.5%	2.30	2.7%	0.38	17.5%
Moorlite	2.25	0.82	208	2.40	244	0.97	180	0.62	12.0%	2.4	2.9%	0.36	18.3%
Philips	2.25	0.83	111	2.40	132	0.97	107	0.61	12.7%	2.1	3.0%	0.35	19.0%
Thorn	2.25	0.79	128	2.50	151	0.97	114	0.59	13.3%	2.5	2.6%	0.36	19.3%
Average		0.81		2.43		0.97		0.61	12.7%	2.33	2.8%	0.36	18.9%
Moorlite	2.50	0.70	204	3.20	195	0.96	135	0.59	8.8%	3.2	2.6%	0.35	19.3%
Philips	2.50	0.75	109	2.76	107	0.97	81	0.60	10.8%	2.9	2.8%	0.35	19.5%
Thorn	2.50	0.70	130	3.20	121	0.98	87	0.58	10.8%	3.3	2.5%	0.33	19.9%
Average		0.72		3.05		0.97		0.59	10.1%	3.13	2.6%	0.34	19.6%
								average	15.4%	average	3.3%	average	16.9%
								minimum	8.8%	minimum	2.5%	minimum	14.8%
								maximum	20.4%	maximum	9.1%	maximum	19.9%

Key:

Div	Diversity Ratio
URe	Uniformity Ratio (edge desk)
URc	Uniformity Ratio (central desk)
Eave	Average Illuminance
OL	Obstruction Loss (%)

Table 7.2a: Illuminance, uniformity, diversity and obstruction loss results for group 1 luminaires, empty and light cases.

Medium						Heavy					
Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
URe	OL	Div	OL	URc	OL	URe	OL	Div	OL	URc	OL
0.69	24.0%	1.2	7.4%	0.70	23.7%	0 66	28.1%	1.2	11.6%	0.67	30.3%
0.67	24.6%	1.2	8.5%	0.69	23.8%	0.63	28.6%	1.3	12.8%	0.65	30.6%
0.68	24.6%	1.2	7.5%	0.70	23.4%	0.64	28.5%	1.3	12.0%	0.68	29.8%
0.68	24.4%	1.21	7.8%	0.70	23.6%	0.64	28.4%	1 28	12.2%	0 67	30.2%
0.70	22.3%	1.3	13.6%	0.71	21.3%	0.67	25.8%	1.3	17.4%	0.69	25.6%
0.66	23.3%	1.2	8.0%	0.70	22.2%	0.64	27.0%	1.5	12.4%	0.68	26.5%
0.67	22.9%	1.2	8.0%	0.71	21.7%	0.64	26.5%	1.5	12.4%	0 68	25.8%
0.68	22.8%	1.23	9.9%	0.71	21.7%	0.65	26.4%	1.43	14.1%	0.68	26.0%
0.59	26.9%	1.3	8.1%	0.66	19.5%	0.53	34.6%	1.6	12.7%	0.63	22.4%
0.59	27.4%	1.4	8.6%	0.66	20.2%	0.53	35.3%	1.6	13.3%	0.63	23.4%
0.59	27.4%	1.4	8.6%	0.66	20.0%	0.52	34.7%	1.6	13.4%	0.64	23.0%
0.59	27.2%	1.37	8.4%	0.66	19.9%	0 53	34.9%	1.60	13.1%	0.63	23.0%
0.47	29.1%	1.4	8.1%	0.53	19.9%	0.45	31.7%	1.8	13.1%	0.40	27.5%
0.48	29.6%	1.4	8.7%	0.53	20.6%	0.45	32.2%	1.7	13.9%	0.41	28.9%
0.48	29.7%	1.5	8.6%	0.57	19.6%	0.45	32.4%	1 8	13.8%	0.46	28.3%
0.48	29.5%	1.43	8.5%	0.54	20.1%	0.45	32.1%	1.77	13.6%	0.42	28.3%
0.56	25.0%	1.6	7.1%	0.48	23.1%	0.55	26.6%	2.0	11.1%	0.37	36.7%
0.55	25.2%	1.6	7.7%	0.48	23.1%	0.54	27.2%	2.0	11.8%	0.38	37.5%
0.56	25.1%	1.7	7.5%	0.45	23.0%	0.55	26.9%	2.1	11.5%	0.32	36.7%
0.56	25.1%	1.63	7.4%	0.47	23.0%	0.55	26.9%	2.02	11.4%	0.36	37.0%
0.54	25.9%	2.4	7.2%	0.39	24.6%	0.44	49.0%	3.3	11.7%	0.35	39.3%
0.58	26.9%	2.2	7.7%	0.40	23.9%	0.41	47.8%	2.5	12.3%	0.35	39.2%
0.57	27.7%	2.4	7.3%	0.36	24.3%	0.40	48.2%	3.3	12.3%	0.29	38.7%
0.56	26.8%	2.33	7.4%	0.38	24.3%	0.42	48.3%	3 03	12.1%	0.33	39.1%
0.36	26.4%	2.8	6.6%	0.37	26.1%	0.29	37.5%	3.9	11.9%	0.29	41.1%
0.40	27.1%	2.6	6.8%	0.36	26.1%	0.33	37.7%	3.3	12.1%	0.29	41.4%
0.38	27.8%	3.2	6.6%	0.35	25.9%	0.32	37.9%	3.4	11.9%	0.29	40.9%
0.38	27.1%	2.87	6.7%	0.36	26.0%	0.31	37.7%	3.54	12.0%	0.29	41.1%
0.17	17.2%	3.9	7.2%	0.35	27.3%	0.16	21.6%	6.1	12.3%	0.29	41.7%
0.21	18.7%	3.4	7.3%	0.34	26.7%	0.20	23.5%	5.1	12.3%	0.29	41.1%
0.55	15.4%	4.0	7.4%	0.33	26.7%	0.60	20.0%	5.9	12.4%	0.30	40.9%
0.31	17.1%	3.77	7.3%	0.34	26.9%	0.32	21.7%	5.70	12.3%	0.29	41.2%
average	25.0%	average	7.9%	average	23.2%	average	32.1%	average	12.6%	average	33.2%
minimum	15.4%	minimum	6.6%	minimum	19.5%	minimum	20.0%	minimum	11.1%	minimum	22.4%
maximum	29.7%	maximum	13.6%	maximum	27.3%	maximum	49.0%	maximum	17.4%	maximum	41.7%

Table 7.2b: Illuminance, uniformity, diversity and obstruction loss results for group 1 luminaires, medium and heavy cases.

Luminaire Group 4

Manufacturer	SHR	Empty						Light					
		Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
		URe	Eave	Div	Eave	URc	Eave	URe	OL	Div	OL	URc	OL
Moorlite	0.75	0.98	1690	1.10	1650	1.00	1700	0.68	13.0%	1.2	2.4%	0.74	12.9%
Thorn	0.75	0.99	2050	1.10	2020	1.00	2070	0.70	12 2%	1.1	2 0%	0.77	12.1%
Average		0 99		1.10		1 00		0 69	12 6%	1.15	2.2%	0.76	12.5%
Moorlite	1.00	0.98	937	1.10	939	0.99	952	0.71	12.4%	1.2	2.2%	0.72	11.6%
Thorn	1 00	0.99	1140	1.09	1150	0 99	1160	0 72	11.4%	1.1	2 6%	0.75	10 3%
Average		0.99		1.10		0.99		0.72	11.9%	1.15	2.4%	0.74	10.9%
Moorlite	1.25	0.95	647	1.30	601	0.97	580	0.59	16.2%	1.2	3.0%	0.65	12.2%
Thorn	1.25	0.99	767	1.20	733	0.98	726	0.61	15.9%	1.2	2.9%	0.67	10.5%
Average		0.97		1.25		0.98		0.60	16.1%	1.20	2.9%	0.66	11.4%
Moorlite	1.50	0.87	406	1.60	405	0.95	358	0.50	18.5%	1.6	3.2%	0.50	13.4%
Thorn	1.50	0.92	504	1.40	499	0.97	467	0.52	17.3%	1.4	2.6%	0.50	12 0%
Average		0.90		1.50		0.96		0.51	17.9%	1.50	2.9%	0.50	12.7%
Moorlite	1.75	0.83	244	2.10	307	0.94	233	0.70	13.1%	2.1	2.3%	0.46	15.5%
Thorn	1.75	0.88	313	1.80	374	0.96	302	0 69	10.9%	1.9	1.9%	0.46	13.9%
Average		0.86		1.95		0.95		0.70	12.0%	2 00	2.1%	0.46	14.7%
Moorlite	2.00	0.83	157	3.20	230	0.94	147	0.54	11.5%	3.3	2.2%	0.37	16.3%
Thorn	2.00	0.85	205	2.70	283	0.93	186	0.52	8 8%	2 8	1.8%	0.35	15 6%
Average		0.84		2.95		0.94		0.53	10.1%	3.03	2.0%	0.36	16.0%
Moorlite	2.25	0.66	146	3.80	189	0.95	103	0.51	8.9%	3.9	1.6%	0.34	18.0%
Thorn	2.25	0.68	187	3.75	232	0.93	119	0.52	7 0%	3 8	1.7%	0.30	17.6%
Average		0 67		3.78		0 94		0 52	7 9%	3 85	1.7%	0.32	17 8%
Moorlite	2.50	0.60	168	5.40	146	0.96	76	0.53	6.5%	5.4	2.1%	0.34	19.4%
Thorn	2.50	0.63	211	6.00	177	0.93	78	0 56	4 7%	6 0	1.7%	0.32	18.6%
Average		0.61		5.70		0.94		0 54	5.6%	5.70	1.9%	0.33	19.0%
								average	11.6%	average	2.3%	average	14.4%
								minimum	4.7%	minimum	1.6%	minimum	10.3%
								maximum	18 5%	maximum	3.2%	maximum	19.4%

Key:

Div	Diversity Ratio
URe	Uniformity Ratio (edge desk)
URc	Uniformity Ratio (central desk)
Eave	Average Illuminance
OL	Obstruction Loss (%)

Table 7.3a: Illuminance, uniformity, diversity and obstruction loss results for group 4 luminaires, empty and light cases.

Medium						Heavy					
Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
URe	OL	Div	OL	URo	OL	URe	OL	Div	OL	URo	OL
0.70	20.1%	1.2	6.7%	0.74	19.4%	0.67	23.1%	1.2	10.3%	0.71	24.7%
0.72	19.0%	1.2	5.9%	0.77	19.8%	0.68	22.0%	1.2	9.4%	0.71	25.1%
0.71	19.6%	1.20	6.3%	0.76	19.6%	0.68	22.5%	1.20	9.9%	0.71	24.9%
0.73	17.8%	1.2	6.6%	0.74	16.8%	0.70	20.6%	1.5	10.1%	0.72	20.1%
0.74	16.8%	1.1	6.1%	0.77	15.9%	0.71	19.5%	1.5	9.6%	0.73	19 0%
0.74	17.3%	1.15	6.3%	0.76	16.4%	0.71	20.0%	1.50	9 8%	0.73	19.5%
0.60	22.9%	1.5	7.0%	0.67	16.0%	0.54	29.1%	1.6	11.1%	0.65	18.3%
0.63	23.5%	1.4	6.5%	0.69	14.0%	0.56	30.6%	1.4	10.6%	0.66	16.0%
0.62	23.2%	1.45	6.8%	0.68	15.0%	0.55	29.8%	1.50	10.9%	0.66	17.1%
0.43	26.4%	1.6	6.9%	0.51	17.0%	0.41	28.6%	1.7	11.4%	0.40	25.1%
0.45	25.8%	1.4	6.2%	0.51	15.2%	0.43	27.8%	1.6	10.4%	0.40	23.1%
0.44	26.1%	1.50	6.6%	0.51	16.1%	0.42	28.2%	1.66	10.9%	0.40	24.1%
0.52	23.0%	2.2	5.9%	0.47	21.9%	0.50	24.6%	2.6	9.1%	0.35	35.6%
0.50	21.4%	1.9	5.3%	0.47	19.5%	0.49	22.7%	2.2	8.0%	0.34	33.1%
0.51	22.2%	2.05	5.6%	0.47	20.7%	0.50	23.6%	2.40	8.6%	0.35	34.4%
0.50	26.8%	3.4	5.7%	0.39	23.1%	0.35	50.4%	4.9	9.1%	0.33	37.8%
0.44	24.9%	3.0	4.9%	0.37	22.0%	0.26	52.6%	4.4	8.5%	0.30	36.0%
0.47	25.8%	3.20	5.3%	0.38	22.6%	0.31	51.5%	4.65	8.8%	0.32	36.9%
0.26	26.7%	3.9	5.3%	0.34	25.0%	0.19	36.3%	6.5	9.0%	0.27	39.9%
0.22	22.5%	3.8	4.7%	0.33	24.7%	0.13	34.2%	6.9	8.6%	0.24	38.2%
0.24	24.6%	3.85	5.0%	0.34	24.9%	0.16	35.3%	6.70	8.8%	0.26	39.1%
0.50	11.3%	5.4	6.2%	0.33	26.5%	0.52	14.9%	1.9	11.0%	0.28	40.6%
0.48	10.0%	5.9	5.6%	0.32	25.9%	0.51	14.2%	12.6	9.6%	0.25	38.9%
0.49	10.6%	5.65	5.9%	0.33	26.2%	0.52	14.5%	7.25	10.3%	0.27	39.7%
average	21.2%	average	6.0%	average	20.2%	average	28.2%	average	9.7%	average	29.5%
minimum	10.0%	minimum	4.7%	minimum	14.0%	minimum	14.2%	minimum	8 0%	minimum	16.0%
maximum	26.8%	maximum	7.0%	maximum	26.5%	maximum	52.6%	maximum	11.4%	maximum	40.6%

Table 7.3b: Illuminance, uniformity, diversity and obstruction loss results for group 4 luminaires, medium and heavy.

Luminaire Group 8

Manufacturer	SHR	Empty						Light					
		Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
		URe	Eave	Div	Eave	URc	Eave	URe	OL	Div	OL	URc	OL
Moorlite	0.75	0.99	1160	1.10	1150	1.00	1180	0.73	9.5%	1.1	1.7%	0.80	10.2%
Philips	0.75	0.99	1150	1.20	1120	0.99	1170	0.70	15.0%	1.3	2.7%	0.75	14.6%
Thorn	0.75	0.99	1110	1.13	1090	0.99	1120	0.69	12.3%	1.2	1.8%	0.75	12.0%
Average		0.99		1.14		0.99		0.71	12.3%	1.20	2.1%	0.77	12.2%
Moorlite	1.00	0.99	652	1.07	651	0.99	658	0.76	9.2%	1.1	1.7%	0.76	7.8%
Philips	1.00	0.98	649	1.16	643	0.99	655	0.67	15.3%	1.3	2.5%	0.75	13.7%
Thorn	1.00	0.99	624	1.10	622	0.99	630	0.72	11.5%	1.1	2.1%	0.73	11.0%
Average		0.99		1.11		0.99		0.72	12.0%	1.17	2.1%	0.75	10.8%
Moorlite	1.25	0.97	436	1.20	417	0.98	401	0.62	14.9%	1.2	2.4%	0.68	9.2%
Philips	1.25	0.93	439	1.30	413	0.97	392	0.56	18.0%	1.3	3.4%	0.61	14.5%
Thorn	1.25	0.95	420	1.20	399	0.97	380	0.59	15.7%	1.2	3.0%	0.65	11.6%
Average		0.95		1.23		0.97		0.59	16.2%	1.23	2.9%	0.65	11.8%
Moorlite	1.50	0.86	272	1.60	283	0.94	237	0.45	17.6%	1.6	2.5%	0.53	11.8%
Philips	1.50	0.90	269	1.70	276	0.95	246	0.49	20.8%	1.7	3.6%	0.45	15.4%
Thorn	1.50	0.88	264	1.60	269	0.95	234	0.49	17.8%	1.6	2.6%	0.49	12.8%
Average		0.88		1.63		0.95		0.48	18.8%	1.63	2.9%	0.49	13.4%
Moorlite	1.75	0.75	153	2.60	212	0.91	137	0.62	10.5%	2.5	1.4%	0.40	14.6%
Philips	1.75	0.86	178	1.90	212	0.95	172	0.64	14.0%	2.0	2.6%	0.39	16.9%
Thorn	1.75	0.82	160	2.10	203	0.94	151	0.69	11.9%	2.2	2.0%	0.45	14.6%
Average		0.81		2.20		0.93		0.65	12.1%	2.23	2.1%	0.41	15.3%
Moorlite	2.00	0.70	101	4.50	166	0.88	75	0.40	8.1%	4.7	1.2%	0.34	15.8%
Philips	2.00	0.90	122	6.35	154	0.99	123	0.63	13.1%	3.0	2.6%	0.28	17.9%
Thorn	2.00	0.83	104	3.10	154	0.94	98	0.54	10.6%	3.1	1.9%	0.37	15.7%
Average		0.81		4.65		0.94		0.52	10.6%	3.60	1.9%	0.33	16.4%
Moorlite	2.25	0.54	103	6.60	133	0.89	46	0.44	5.3%	6.6	0.8%	0.32	17.9%
Philips	2.25	0.73	106	2.99	128	0.99	96	0.53	12.1%	3.0	2.3%	0.28	18.6%
Thorn	2.25	0.64	97	3.80	126	0.94	68	0.50	8.3%	3.8	1.6%	0.33	17.5%
Average		0.64		4.46		0.94		0.49	8.6%	4.47	1.6%	0.31	18.0%
Moorlite	2.50	0.54	132	10.50	99	0.92	31	0.50	3.0%	10.5	1.5%	0.30	19.5%
Philips	2.50	0.62	112	3.90	101	0.98	74	0.53	7.1%	3.8	2.6%	0.27	19.0%
Thorn	2.50	0.57	112	5.52	96	0.95	48	0.51	4.5%	5.6	1.9%	0.33	18.6%
Average		0.58		6.64		0.95		0.51	4.9%	6.63	2.0%	0.30	19.1%
								average	11.9%	average	2.2%	average	14.6%
								minimum	3.0%	minimum	0.8%	minimum	7.8%
								maximum	20.8%	maximum	3.6%	maximum	19.5%

Key:

Div	Diversity Ratio
URe	Uniformity Ratio (edge desk)
URc	Uniformity Ratio (central desk)
Eave	Average Illuminance
OL	Obstruction Loss (%)

Table 7.4a: Illuminance, uniformity, diversity and obstruction loss results for group 8 luminaires, empty and light cases.

Medium						Heavy					
Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
URe	OL	Div	OL	URo	OL	URe	OL	Div	OL	URo	OL
0.74	16.7%	1.2	5.2%	0.80	16.9%	0.71	19.0%	1.3	8.7%	0.76	21.4%
0.74	21.2%	1.3	7.1%	0.78	20.4%	0.71	24.1%	1.3	10.7%	0.75	25.4%
0.71	18.9%	1.2	6.4%	0.75	18.3%	0.68	21.5%	1.2	9.4%	0.72	23.1%
0.73	19.0%	1.23	6.3%	0.78	18.6%	0.70	21.5%	1.25	9.6%	0.74	23.3%
0.77	13.7%	1.1	5.5%	0.78	12.2%	0.75	15.8%	1.2	8.0%	0.75	14.4%
0.69	19.9%	1.3	7.0%	0.77	18.8%	0.65	22.5%	1.6	10.4%	0.74	21.7%
0.74	16.3%	1.1	6.3%	0.74	15.6%	0.71	18.8%	1.5	9.3%	0.79	18.3%
0.73	16.6%	1.17	6.3%	0.76	15.5%	0.70	19.0%	1.43	9.2%	0.76	18.1%
0.62	20.9%	1.5	6.0%	0.69	12.2%	0.56	26.1%	1.5	9.4%	0.67	14.0%
0.58	24.6%	1.5	7.7%	0.62	17.9%	0.48	31.4%	1.7	11.4%	0.61	19.6%
0.60	21.9%	1.5	6.8%	0.66	14.7%	0.55	27.9%	1.6	10.5%	0.64	41.1%
0.60	22.5%	1.50	6.8%	0.66	14.9%	0.53	28.5%	1.61	10.4%	0.64	24.9%
0.40	24.6%	1.5	5.3%	0.54	15.6%	0.38	26.1%	2.2	9.2%	0.43	22.4%
0.45	29.0%	1.6	7.6%	0.46	18.7%	0.43	30.9%	2.0	12.0%	0.28	27.2%
0.43	25.8%	1.6	6.3%	0.50	16.2%	0.41	27.7%	2.1	10.4%	0.40	23.9%
0.43	26.5%	1.57	6.4%	0.50	16.9%	0.41	28.2%	2.12	10.5%	0.37	24.5%
0.46	20.3%	2.4	4.2%	0.42	21.2%	0.45	22.2%	2.8	6.6%	0.27	33.6%
0.50	22.5%	2.0	6.6%	0.40	20.9%	0.49	23.6%	2.5	9.9%	0.27	34.3%
0.50	21.3%	2.2	5.4%	0.47	20.5%	0.49	22.5%	2.6	7.9%	0.35	34.2%
0.49	21.3%	2.20	5.4%	0.43	20.9%	0.48	22.8%	2.64	8.1%	0.30	34.0%
0.33	26.9%	4.9	4.2%	0.37	22.7%	0.17	54.2%	6.9	6.6%	0.24	36.0%
0.56	24.4%	3.1	6.5%	0.28	22.2%	0.47	44.7%	4.4	10.4%	0.28	26.8%
0.50	25.8%	3.3	5.2%	0.38	22.2%	0.35	49.5%	4.9	8.4%	0.33	36.7%
0.46	25.7%	3.77	5.3%	0.34	22.4%	0.33	49.4%	5.40	8.5%	0.28	33.2%
0.15	26.5%	6.7	3.8%	0.34	25.8%	0.09	34.5%	11.6	6.8%	0.24	39.5%
0.33	26.3%	3.9	5.5%	0.28	24.0%	0.27	35.0%	5.1	10.2%	0.27	36.8%
0.24	25.7%	4.1	4.8%	0.33	24.7%	0.18	34.9%	6.7	8.7%	0.26	38.7%
0.24	26.2%	4.90	4.7%	0.32	24.8%	0.18	34.8%	7.80	8.6%	0.26	38.3%
0.46	9.1%	10.4	5.2%	0.28	27.7%	0.47	11.4%	21.3	9.4%	0.26	41.0%
0.17	16.0%	5.0	6.6%	0.27	25.2%	0.17	18.8%	7.7	10.8%	0.25	37.3%
0.49	9.8%	6.3	5.7%	0.32	25.7%	0.51	12.6%	11.6	9.9%	0.26	38.9%
0.37	11.6%	7.24	5.8%	0.29	26.2%	0.38	14.2%	13.52	10.0%	0.26	39.1%
average	21.5%	average	5.9%	average	20.0%	average	27.3%	average	9.4%	average	29.4%
minimum	9.1%	minimum	3.8%	minimum	12.2%	minimum	11.4%	minimum	6.6%	minimum	14.0%
maximum	29.0%	maximum	7.7%	maximum	27.7%	maximum	54.2%	maximum	12.0%	maximum	41.1%

Table 7.4b: Illuminance, uniformity, diversity and obstruction loss results for group 8 luminaires, medium and heavy cases.

Luminaire Group 9A

Manufacturer	SHR	Empty						Light					
		Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
		URe	Eave	Div	Eave	URc	Eave	URe	OL	Div	OL	URc	OL
Moorlite	0.75	1.00	2610	1.0	2600	1.00	2610	0.72	7.3%	1.1	1.5%	0.80	7.3%
Philips	0.75	0.98	1860	1.0	1870	0.96	1840	0.70	7.0%	1.1	1.1%	0.85	6.5%
Thorn	0.75	0.98	1820	1.1	1770	0.98	1780	0.73	8.2%	1.1	1.7%	0.81	7.9%
Average		0.99		1.03		0.98		0.72	7.5%	1.08	1.4%	0.82	7.2%
Moorlite	1.00	0.99	1470	1.1	1470	0.99	1430	0.75	6.1%	1.1	1.4%	0.78	4.2%
Philips	1.00	0.96	997	1.2	1050	0.94	1030	0.72	7.4%	1.2	1.0%	0.80	3.5%
Thorn	1.00	0.97	950	1.1	998	0.96	984	0.76	8.1%	1.1	1.3%	0.75	6.1%
Average		0.97		1.12		0.96		0.74	7.2%	1.15	1.2%	0.78	4.6%
Moorlite	1.25	0.95	1010	1.2	938	0.97	672	0.60	12.9%	1.3	2.1%	0.67	5.7%
Philips	1.25	0.88	755	1.4	670	0.90	659	0.62	14.6%	1.4	2.1%	0.59	4.9%
Thorn	1.25	0.95	699	1.3	636	0.95	600	0.53	13.4%	1.3	2.2%	0.67	7.3%
Average		0.93		1.30		0.94		0.58	13.6%	1.32	2.1%	0.64	6.0%
Moorlite	1.50	0.84	652	1.5	649	0.90	515	0.42	15.3%	1.5	2.0%	0.45	9.1%
Philips	1.50	0.87	496	1.5	467	0.94	423	0.39	15.9%	1.5	2.6%	0.37	8.5%
Thorn	1.50	0.84	431	0.7	437	0.97	371	0.45	16.5%	1.5	2.1%	0.54	10.2%
Average		0.85		1.23		0.94		0.42	15.9%	1.50	2.2%	0.45	9.3%
Moorlite	1.75	0.71	322	2.6	471	0.85	283	0.52	7.6%	2.7	1.1%	0.39	11.0%
Philips	1.75	0.85	259	2.2	339	0.98	257	0.39	5.4%	2.3	1.2%	0.27	12.1%
Thorn	1.75	0.81	241	2.4	323	0.94	223	0.60	7.9%	0.4	1.5%	0.39	13.0%
Average		0.79		2.48		0.92		0.50	7.0%	1.81	1.3%	0.35	12.0%
Moorlite	2.00	0.70	191	5.5	386	0.84	146	0.35	5.2%	5.5	0.8%	0.33	13.0%
Philips	2.00	0.77	169	4.0	273	0.96	147	0.38	4.1%	4.1	1.1%	0.18	15.0%
Thorn	2.00	0.80	162	4.1	256	0.90	128	0.42	5.6%	4.1	1.2%	0.33	14.8%
Average		0.76		4.53		0.90		0.38	5.0%	4.56	1.0%	0.28	14.3%
Moorlite	2.25	0.47	203	9.9	307	0.83	69	0.38	2.5%	9.9	0.7%	0.23	15.0%
Philips	2.25	0.62	166	6.3	218	0.95	74	0.45	4.2%	6.3	0.5%	0.15	15.7%
Thorn	2.25	0.60	160	6.2	205	0.90	73	0.46	5.0%	6.2	1.0%	0.27	16.7%
Average		0.56		7.48		0.89		0.43	3.9%	7.47	0.7%	0.22	15.6%
Moorlite	2.50	0.47	287	27.6	220	0.80	30	0.46	0.3%	24.0	0.9%	0.22	15.8%
Philips	2.50	0.54	200	16.0	158	0.89	32	0.50	1.0%	15.0	0.6%	0.13	16.2%
Thorn	2.50	0.57	195	11.61	150	0.93	43	0.52	3.1%	11.4	0.7%	0.24	18.3%
Average		0.53		18.40		0.87		0.49	1.5%	16.79	0.7%	0.20	16.6%
								average	7.7%	average	1.3%	average	10.7%
								minimum	0.3%	minimum	0.5%	minimum	3.5%
								maximum	16.5%	maximum	2.6%	maximum	18.3%

Key:

Div	Diversity Ratio
URe	Uniformity Ratio (edge desk)
URc	Uniformity Ratio (central desk)
Eave	Average Illuminance
OL	Obstruction Loss (%)

Table 7.5a: Illuminance, uniformity, diversity and obstruction loss results for group 9A luminaires, empty and light cases.

Medium						Heavy					
Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
URe	OL	Div	OL	URo	OL	URe	OL	Div	OL	URo	OL
0.72	12.3%	1.2	4.6%	0.80	11.9%	0.70	13.0%	1.2	6.5%	0.77	14.6%
0.72	12.9%	1.2	4.3%	0.85	12.5%	0.73	14.5%	1.3	7.0%	0.82	16.8%
0.75	15.4%	1.2	5.1%	0.82	15.7%	0.71	18.1%	1.3	7.9%	0.78	20.2%
0.73	13.5%	1.20	4.7%	0.82	13.4%	0.71	15.2%	1.26	7.1%	0.79	17.2%
0.75	8.2%	1.1	4.8%	0.78	6.3%	0.75	8.8%	1.2	6.1%	0.78	7.0%
0.73	11.1%	2.2	3.8%	0.82	7.5%	0.71	12.3%	1.5	6.6%	0.83	8.6%
0.77	13.3%	1.2	4.9%	0.78	11.2%	0.74	15.8%	1.2	7.1%	0.76	13.5%
0.75	10.9%	1.49	4.5%	0.79	8.3%	0.73	12.3%	1.33	6.6%	0.79	9 7%
0.61	16.4%	1.6	5.0%	0.67	6.2%	0.56	20.5%	1.7	7.4%	0.66	6.3%
0.63	21.1%	1.8	5.1%	0.60	5.8%	0.56	27.4%	2.0	7.9%	0.59	5.9%
0.64	20.2%	1.7	5.3%	0.69	10.3%	0.57	26.6%	1.7	8.3%	0.67	11.7%
0.63	19.2%	1.70	5.1%	0.65	7.4%	0.56	24.8%	1.80	7.9%	0.64	8.0%
0.36	20.2%	1.5	4.8%	0.46	10.5%	0.36	20.6%	2.3	7.6%	0.35	16.3%
0.36	22.4%	1.5	5.4%	0.37	9.9%	0.37	22.8%	2.1	8.1%	0.28	17.5%
0.37	24.1%	1.6	5.0%	0.55	13.2%	0.37	26.0%	2.4	8.5%	0.44	19.9%
0.36	22.3%	1.53	5.1%	0.46	11.2%	0.37	23.1%	2.26	8.1%	0.36	17.9%
0.39	16.5%	2.9	3.4%	0.43	15.5%	0.39	16.5%	3.3	4.5%	0.30	27.9%
0.35	14.7%	2.2	3.5%	0.27	14.8%	0.35	14.7%	2.6	5.0%	0.19	26.1%
0.41	18.7%	2.4	4.0%	0.41	17.9%	0.41	19.5%	2.7	5.9%	0.26	30.5%
0.38	16.6%	2.49	3.7%	0.37	16.1%	0.38	16.9%	2.86	5.1%	0.25	28.2%
0.26	25.1%	5.8	3.1%	0.36	19.2%	0.06	56.6%	8.2	4.4%	0.23	31.5%
0.27	22.5%	4.0	3.3%	0.18	18.4%	0.03	58.6%	7.2	5.1%	0.18	28.6%
0.32	24.1%	4.1	3.5%	0.34	20.3%	0.09	56.7%	6.5	5.9%	0.20	33.4%
0.28	23.9%	4.63	3.3%	0.29	19.3%	0.06	57.3%	7.28	5.1%	0.20	31.2%
0.04	25.1%	9.9	2.9%	0.26	21.4%	0.01	30.5%	26.2	4.6%	0.16	32.0%
0.04	24.7%	6.3	2.8%	0.15	19.9%	0.01	36.1%	37.0	5.5%	0.16	28.8%
0.13	25.6%	6.2	3.4%	0.26	22.7%	0.02	37.5%	13.9	6.3%	0.18	34.7%
0.07	25.1%	7.47	3.0%	0.22	21.3%	0.01	34.7%	25.70	5.5%	0.17	31.8%
0.45	5.2%	27.6	3.6%	0.23	22.2%	0.45	5.6%	100.0	6.8%	0.12	31.6%
0.01	11.0%	15.0	3.8%	0.13	20.6%	0.01	12.5%	300.0	7.0%	0.14	28.7%
0.45	8.2%	8.7	4.0%	0.20	24.3%	0.47	11.3%	43.0	8.0%	0.19	35.4%
0.30	8.1%	17.10	3.8%	0.19	22.4%	0.31	9.8%	147.67	7.3%	0.15	31.9%
average	17.5%	average	4.1%	average	14.9%	average	24.3%	average	6.6%	average	22.0%
minimum	5.2%	minimum	2.8%	minimum	5.8%	minimum	5 6%	minimum	4.4%	minimum	5.9%
maximum	25.6%	maximum	5.4%	maximum	24.3%	maximum	58.6%	maximum	8.5%	maximum	35.4%

Table 7.5b: Illuminance, uniformity, diversity and obstruction loss results for group 9A luminaires, medium and heavy cases.

Luminaire Group 9B

Manufacturer	SHR	Empty						Light					
		Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
		URe	Eave	Div	Eave	URc	Eave	URe	OL	Div	OL	URc	OL
Moorlite	0.75	1.00	1660	1.1	1650	0.99	1680	0.72	9.6%	1.1	1.8%	0.80	10.1%
Philips	0.75	0.99	1760	1.1	1740	0.99	1760	0.68	8.5%	1.1	1.1%	0.86	8.5%
Thorn	0.75	0.99	1420	1.1	1400	1.00	1430	0.73	9.9%	1.1	2.1%	0.80	9.8%
Average		0.99		1.07		1.00		0.71	9.3%	1.09	1.7%	0.82	9.5%
Moorlite	1.00	0.99	929	1.1	931	1.00	939	0.75	9.4%	1.1	1.6%	0.76	9.9%
Philips	1.00	0.98	982	1.1	983	0.99	977	0.77	8.6%	1.1	1.3%	0.80	7.0%
Thorn	1.00	0.99	790	1.1	792	0.99	791	0.76	9.4%	1.1	1.6%	0.75	6.5%
Average		0.99		1.07		0.99		0.76	9.1%	1.10	1.5%	0.77	7.8%
Moorlite	1.25	0.95	629	1.2	597	0.97	562	0.60	14.5%	1.3	2.5%	0.67	8.9%
Philips	1.25	0.91	656	1.3	632	0.98	579	0.61	14.5%	1.3	2.2%	0.65	8.5%
Thorn	1.25	0.94	540	1.3	508	0.96	467	0.61	14.4%	1.3	2.6%	0.67	9.4%
Average		0.93		1.27		0.97		0.61	14.5%	1.30	2.4%	0.66	8.9%
Moorlite	1.50	0.87	393	1.6	406	0.93	334	0.46	17.0%	1.6	2.2%	0.52	11.4%
Philips	1.50	0.89	384	1.8	427	0.93	339	0.44	17.7%	1.8	2.6%	0.38	11.2%
Thorn	1.50	0.85	326	1.7	344	0.94	279	0.47	17.5%	1.7	2.3%	0.53	11.8%
Average		0.87		1.70		0.93		0.46	17.4%	1.68	2.4%	0.48	11.5%
Moorlite	1.75	0.76	220	2.5	302	0.91	199	0.62	9.5%	2.4	1.3%	0.38	13.0%
Philips	1.75	0.74	228	2.8	321	0.93	201	0.46	8.3%	5.3	1.6%	0.30	14.4%
Thorn	1.75	0.78	187	2.6	258	0.93	172	0.64	9.6%	2.5	1.6%	0.40	14.5%
Average		0.76		2.64		0.92		0.57	9.2%	3.41	1.5%	0.36	14.2%
Moorlite	2.00	0.75	143	4.1	237	0.89	116	0.45	7.7%	4.2	1.3%	0.34	15.0%
Philips	2.00	0.72	162	4.8	253	0.92	118	0.40	6.2%	4.8	1.6%	0.22	15.7%
Thorn	2.00	0.77	125	4.0	201	0.93	104	0.47	7.2%	4.1	1.0%	0.35	15.1%
Average		0.75		4.31		0.91		0.44	7.0%	4.37	1.3%	0.30	15.3%
Moorlite	2.25	0.56	142	5.8	191	0.89	71	0.43	5.6%	5.8	1.0%	0.30	16.8%
Philips	2.25	0.56	166	6.4	201	0.93	74	0.42	5.4%	6.5	1.0%	0.22	17.5%
Thorn	2.25	0.58	123	5.5	162	0.93	67	0.44	5.7%	5.5	1.2%	0.30	17.4%
Average		0.56		5.90		0.92		0.43	5.6%	5.92	1.1%	0.27	17.2%
Moorlite	2.50	0.53	179	10.0	142	0.92	45	0.48	3.4%	10.0	1.4%	0.27	18.0%
Philips	2.50	0.53	209	10.7	147	0.93	48	0.48	3.3%	10.4	1.4%	0.22	18.7%
Thorn	2.50	0.53	154	8.74	120	0.94	45	0.47	3.9%	8.7	0.8%	0.29	18.7%
Average		0.53		9.79		0.93		0.48	3.5%	9.67	1.2%	0.26	18.5%
								average	9.5%	average	1.6%	average	12.9%
								minimum	3.3%	minimum	0.8%	minimum	7.0%
								maximum	17.7%	maximum	2.6%	maximum	18.7%

Key:

Div	Diversity Ratio
URe	Uniformity Ratio (edge desk)
URc	Uniformity Ratio (central desk)
Eave	Average Illuminance
OL	Obstruction Loss (%)

Table 7.6a: Illuminance, uniformity, diversity and obstruction loss results for group 9B luminaires, empty and light cases.

Medium						Heavy					
Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
URe	OL	Div	OL	URc	OL	URe	OL	Div	OL	URc	OL
0.74	16.3%	1.2	5.5%	0.80	16.7%	0.70	18.7%	1.2	8.5%	0.76	20.8%
0.69	16.5%	1.2	4.6%	0.85	15.9%	0.71	18.8%	1.3	8.0%	0.84	21.0%
0.75	17.6%	1.2	5.7%	0.81	16.8%	0.71	19.7%	1.2	8.6%	0.76	21.7%
0.73	16.8%	1.20	5.3%	0.82	16.5%	0.71	19.0%	1.23	8.4%	0.79	21.2%
0.76	14.0%	1.1	5.3%	0.78	12.2%	0.73	16.0%	1.1	7.5%	0.75	14.4%
0.79	13.7%	1.1	5.3%	0.81	12.1%	0.75	16.2%	1.5	8.2%	0.80	14.3%
0.78	14.6%	1.1	5.4%	0.78	13.5%	0.74	17.1%	1.2	8.0%	0.75	16.2%
0.78	14.1%	1.10	5.3%	0.79	12.6%	0.74	16.4%	1.27	7.9%	0.77	16.0%
0.61	20.7%	1.6	5.9%	0.67	11.6%	0.56	26.1%	1.6	8.9%	0.65	12.8%
0.62	21.8%	1.8	5.4%	0.66	11.6%	0.53	28.2%	1.6	8.9%	0.64	13.1%
0.62	21.1%	1.7	5.9%	0.68	13.1%	0.56	27.0%	1.6	9.3%	0.66	14.8%
0.62	21.2%	1.68	5.7%	0.67	12.1%	0.55	27.1%	1.60	9.0%	0.65	13.6%
0.41	23.7%	1.6	5.4%	0.54	14.1%	0.39	25.2%	2.3	8.9%	0.42	21.0%
0.41	25.3%	1.8	5.4%	0.39	14.7%	0.39	27.1%	2.6	8.7%	0.29	22.4%
0.40	25.5%	1.7	5.5%	0.55	15.4%	0.38	27.3%	0.4	9.0%	0.43	22.2%
0.41	24.8%	1.69	5.4%	0.49	14.7%	0.39	26.5%	1.77	8.8%	0.38	21.9%
0.43	19.1%	2.5	4.3%	0.41	19.1%	0.21	81.3%	9.1	58.6%	0.15	89.2%
0.41	18.4%	2.8	4.0%	0.31	18.9%	0.39	19.3%	2.8	6.2%	0.20	30.3%
0.44	20.3%	2.6	4.7%	0.42	20.3%	0.43	21.4%	3.0	7.0%	0.28	33.1%
0.43	19.3%	2.63	4.3%	0.38	19.4%	0.34	40.7%	4.95	23.9%	0.21	50.9%
0.38	24.5%	4.5	3.8%	0.36	21.6%	0.20	52.7%	6.4	6.3%	0.23	34.7%
0.33	23.5%	4.8	4.0%	0.22	20.9%	0.15	53.5%	8.1	6.7%	0.21	31.9%
0.39	24.6%	4.3	4.0%	0.37	21.8%	0.20	52.7%	6.4	7.0%	0.24	35.4%
0.37	24.2%	4.53	3.9%	0.32	21.4%	0.18	53.0%	6.97	6.7%	0.23	34.0%
0.18	26.1%	5.9	3.7%	0.28	24.0%	0.10	36.1%	10.5	6.8%	0.22	36.4%
0.11	25.9%	6.5	3.5%	0.22	23.5%	0.06	36.7%	12.6	7.0%	0.21	34.5%
0.19	25.9%	5.5	3.7%	0.30	24.5%	0.10	36.4%	10.2	7.4%	0.23	37.6%
0.16	25.9%	5.97	3.6%	0.27	24.0%	0.09	36.4%	11.10	7.1%	0.22	36.1%
0.46	8.9%	10.0	4.9%	0.25	25.4%	0.47	11.7%	20.2	9.2%	0.23	37.2%
0.03	13.4%	10.7	4.8%	0.22	25.2%	0.03	16.7%	24.2	8.8%	0.22	35.8%
0.45	9.1%	8.7	5.0%	0.26	26.3%	0.46	12.3%	19.2	9.2%	0.24	38.5%
0.31	10.5%	9.78	4.9%	0.24	25.6%	0.32	13.6%	21 20	9.1%	0.23	37.2%
average	19.6%	average	4.8%	average	18.3%	average	29.1%	average	10.1%	average	28.7%
minimum	8.9%	minimum	3.5%	minimum	11.6%	minimum	11.7%	minimum	6.2%	minimum	12.8%
maximum	26.1%	maximum	5.9%	maximum	26.3%	maximum	. 81.3%	maximum	58.6%	maximum	89.2%

Table 7.6b: Illuminance, uniformity, diversity and obstruction loss results for group 9B luminaires, medium and heavy cases.

Lumen Micro SHR Investigation
Luminaire Group 10

Manufacturer	SHR	Empty						Light					
		Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
		URe	Eave	Div	Eave	URc	Eave	URe	OL	Div	OL	URc	OL
Moorlite	0.75	0.98	697	1.0	707	0.98	715	0.76	3.7%	1.1	1.1%	0.87	2.8%
Philips	0.75	0.95	1840	1.1	1730	0.95	1860	0.68	3.8%	1.1	0.6%	0.89	4.3%
Thorn	0.75	0.97	1580	1.0	1530	0.97	1550	0.75	4 4%	1.1	1.3%	0.85	4 5%
Average		0.97		1.05		0.97		0.73	4 0%	1.10	1.0%	0 87	3.9%
Moorlite	1.00	0.99	393	1.1	398	0.97	390	0.86	2.8%	1.1	1.0%	0.76	2.3%
Philips	1.00	0.95	905	1.2	976	0.95	974	0.83	4.0%	1.2	0.7%	0.76	2.2%
Thorn	1.00	0.93	754	1.4	869	0.91	901	0 80	4.5%	1 4	0.9%	0.73	2.9%
Average		0.96		1.20		0.94		0 83	3 8%	1.22	0 9%	0.75	2 4%
Moorlite	1.25	0.86	278	1.7	256	0.88	196	0.59	8.6%	0.4	1.6%	0.61	5.6%
Philips	1.25	0.83	672	1.5	625	0.88	506	0.64	10.6%	1.5	1.4%	0.60	5.3%
Thorn	1.25	0.92	605	1.3	550	0.94	532	0.67	11.7%	1.3	1.8%	0.66	5.6%
Average		0.87		1.52		0.90		0 63	10.3%	1 07	1 6%	0 62	5 5%
Moorlite	1.50	0.67	138	3.4	173	0.76	82	0.24	18.1%	3.4	1.7%	0.43	7.9%
Philips	1.50	0.77	296	2.2	424	0.88	260	0.30	17.2%	2.2	1.7%	0.30	9.2%
Thorn	1.50	0.80	345	1.7	380	0.96	287	0.33	17.1%	1.7	1.6%	0.50	9.4%
Average		0.74		2.42		0 87		0.29	17.5%	2 43	1.7%	0.41	8 8%
Moorlite	1.75	0.34	48	12.5	128	0.65	28	0.33	9.3%	8.7	0.8%	0.27	10.6%
Philips	1.75	0.54	179	4.6	318	0.90	135	0.33	7.3%	4.6	0.6%	0.22	12.6%
Thorn	1.75	0.63	175	3.7	281	0.92	136	0 47	8.6%	3.7	0.7%	0.37	12 5%
Average		0.50		6 90		0 82		0 38	8 4%	5 65	0 7%	0 29	11 9%
Moorlite	2.00	0.37	28	46.9	111	0.54	8	0.14	4.3%	25.6	0.0%	0.15	11.3%
Philips	2.00	0.49	147	9.0	263	0.92	67	0.22	4.1%	9.8	0.4%	0.15	15.0%
Thorn	2.00	0.61	134	9.2	231	0.84	55	0 27	5.2%	17.2	0.4%	0.29	14 1%
Average		0.49		21.70		0.77		0.21	4 6%	17.60	0.3%	0.20	13 5%
Moorlite	2.25	0.23	44	113.0	85	0.49	2	0.20	0.5%	73.0	0.4%	0.14	12.4%
Philips	2.25	0.45	170	18.2	204	0.89	30	0.36	2.4%	18.2	0.5%	0.14	15.6%
Thorn	2.25	0.49	147	21.3	181	0.74	19	0 40	2.0%	21.3	0.6%	0.20	14.7%
Average		0.39		50.85		0.71		0.32	1.6%	37 50	0.5%	0.16	14 3%
Moorlite	2.50	0.30	85	475.0	57	0.69	1	0.30	0.0%	100.0	0.4%	0.16	15.2%
Philips	2.50	0.50	234	53.9	140	0.85	11	0.50	0.0%	26.8	0.7%	0.12	14.9%
Thorn	2.50	0.53	197	94 81	126	0.66	6	0 52	0.5%	69.3	0.8%	0.15	15.2%
Average		0.44		207.92		0.73		0 44	0.2%	65 38	0.6%	0.14	15.1%
								average	6.3%	average	0.9%	average	9.4%
								minimum	0.0%	minimum	0.0%	minimum	2.2%
								maximum	18 1%	maximum	1 8%	maximum	15 6%

Key:

Div	Diversity Ratio
URe	Uniformity Ratio (edge desk)
URc	Uniformity Ratio (central desk)
Eave	Average Illuminance
OL	Obstruction Loss (%)

Table 7.7a: Illuminance, uniformity, diversity and obstruction loss results for group 10 luminaires, empty and light cases.

Medium						Heavy					
Edge Desk		Whole Room		Centre Desk		Edge Desk		Whole Room		Centre Desk	
URe	OL	Div	OL	URo	OL	URe	OL	Div	OL	URo	OL
0.76	7.9%	1.2	4.0%	0.86	5.3%	0.83	7.9%	1.2	5.5%	0.85	6.0%
0.68	9.8%	1.2	3.5%	0.86	9.7%	0.69	10.3%	1.4	5.8%	0.86	12.9%
0.76	10.1%	1.2	3.9%	0.85	9.7%	0.75	10.8%	1.3	5.9%	0.83	12.9%
0.73	9.3%	1.20	3.8%	0.86	8.2%	0.76	9.7%	1.27	5.7%	0.85	10.6%
0.86	3.3%	1.1	4.0%	0.77	2.6%	0.86	3.3%	1.7	5.5%	0.76	2.8%
0.85	6.0%	1.2	4.3%	0.78	4.4%	0.84	6.3%	1.2	6.5%	0.78	4.8%
0.81	6.9%	1.4	4.1%	0.75	4.8%	0.80	7.4%	1.4	5.5%	0.74	5.2%
0.84	5.4%	1.22	4.2%	0.77	3.9%	0.83	5.7%	1.40	5.8%	0.76	4.3%
0.59	9.4%	2.5	3.9%	0.61	5.6%	0.58	10.1%	2.2	5.9%	0.61	5.6%
0.64	15.5%	1.5	3.8%	0.60	5.5%	0.58	19.9%	1.7	6.4%	0.60	5.7%
0.68	15.7%	1.8	4.5%	0.67	5.8%	0.62	19.5%	1.8	6.9%	0.67	5.8%
0.64	13.5%	1.94	4.1%	0.63	5.7%	0.59	16.5%	1.91	6.4%	0.63	5.7%
0.23	19.6%	3.4	3.5%	0.44	8.9%	0.23	19.6%	4.5	5.2%	0.36	16.2%
0.32	23.3%	2.2	3.5%	0.31	10.4%	0.31	23.6%	3.5	5.7%	0.23	17.7%
0.30	21.7%	1.7	3.7%	0.51	10.5%	0.29	22.0%	2.7	6.3%	0.42	16.7%
0.28	21.5%	2.44	3.6%	0.42	9.9%	0.28	21.7%	3.56	5.7%	0.34	16.9%
0.21	14.7%	12.5	2.3%	0.32	14.4%	0.21	14.7%	6.4	2.3%	0.15	24.6%
0.31	15.6%	3.8	2.2%	0.23	15.6%	0.30	16.2%	4.5	3.1%	0.16	25.9%
0.33	18.3%	3.7	2.5%	0.38	15.4%	0.33	18.3%	3.4	3.2%	0.20	27.5%
0.28	16.2%	6.66	2.3%	0.31	15.1%	0.28	16.4%	4.79	2.9%	0.17	26.0%
0.06	29.3%	16.7	1.8%	0.18	16.7%	0.01	55.4%	64.7	2.7%	0.08	25.5%
0.15	22.4%	9.8	2.3%	0.15	18.3%	0.01	57.1%	17.7	3.8%	0.16	27.8%
0.15	26.0%	10.6	2.6%	0.30	18.1%	0.01	58.6%	16.7	3.9%	0.11	29.3%
0.12	25.9%	12.38	2.2%	0.21	17.7%	0.01	57.1%	33.03	3.5%	0.12	27.5%
0.01	28.6%	113.0	1.9%	0.17	18.0%	0.01	29.7%	300.0	3.2%	0.09	26.7%
0.02	25.3%	18.2	2.5%	0.14	19.7%	0.01	31.2%	95.3	4.9%	0.15	28.1%
0.03	25.9%	21.3	2.8%	0.23	19.5%	0.01	31.3%	174.0	5.0%	0.10	28.4%
0.02	26.6%	50.85	2.4%	0.18	19.0%	0.01	30.7%	189.75	4.3%	0.11	27.8%
0.32	5 6%	100.0	3.2%	0.19	20.8%	0.32	5.6%	600.0	6.4%	0.12	29.5%
0.01	10.7%	50.7	4.3%	0.12	19.7%	0.01	10.7%	297.0	7.1%	0.13	27.5%
0.47	5.1%	89.0	4.0%	0.15	20.0%	0.47	5.6%	300.0	7.1%	0.10	28.3%
0.27	7.1%	79.90	3.8%	0.15	20.2%	0.27	7.3%	398 99	6.9%	0.12	28.4%
average	15.7%	average	3.3%	average	12.5%	average	20.6%	average	5.2%	average	18.4%
minimum	3.3%	minimum	1.8%	minimum	2.6%	minimum	3.3%	minimum	2.3%	minimum	2.8%
maximum	29.3%	maximum	4.5%	maximum	20.8%	maximum	58.6%	maximum	7.1%	maximum	29.5%

Table 7.7b: Illuminance, uniformity, diversity and obstruction loss results for group 10 luminaires, medium and heavy cases.

7.5.1 Variation of task area uniformity with SHR

Tables 7.8 and 7.9 show the spacing at which task uniformity fell below the 0.7 acceptance level for each of the luminaires. Table 7.8 shows the results for the edge desk and table 7.9, the results for the central desk. Figures 7.4, 7.5 and 7.6 are a graphical representation of the UR/SHR relationship for three photometrically different luminaires (CIBSE classes 1, 4 and 10) for the edge desk. Figures 7.7, 7.8 and 7.9 present the equivalent results for the centre desk. For both task locations it can be seen that the uniformity ratio (UR) decreases as SHR increases. Although the spacing was the primary influence on uniformity, the presence of furniture was also very significant. The density of the furniture however, has a much smaller influence. For the empty case, the uniformity requirements are comfortably satisfied within the constraints of the maximum permitted spacings for the luminaires concerned, for both task locations. The edge desk shows considerably lower uniformity than the central desk for a given SHR (only group 10 comes close to failure on the central desk – see figure 7.6) and this was due to the symmetrical layout of luminaires around the central desk. The importance of the task location becomes negligible once an amount of furniture is introduced into the space. The variation in uniformity was small for each of the different furniture cases, but the difference between the furnished cases and the empty cases was substantial and this was the case for all luminaire types and task locations, as can be seen from figures 7.4 to 7.7.

Luminaire	SHRmax	SHR at 0.7 Uniformity			
		Empty	Light	Medium	Heavy
Class 1	2.50	>2.50	1.75	/	/
Class 4	1.95	2.20	1.75	1.13	1.05
Class 8	1.87	2.15	1.08	1.10	1.00
Class 9A	1.77	2.10	1.08	1.10	1.04
Class 9B	1.74	2.12	1.11	1.13	1.09
Class 10	1.07	1.54	1.07	1.15	1.10

Table 7.8: Uniformity Ratios for Edge Desk

Luminaire	SHRmax	SHR at 0.7 Uniformity			
		Empty	Light	Medium	Heavy
Class 1	2.50	>2.50	1.00	1.10	/
Class 4	1.95	>2.50	1.20	1.11	1.10
Class 8	1.87	>2.50	1.12	1.13	1.12
Class 9A	1.77	>2.50	1.12	1.13	1.13
Class 9B	1.74	>2.50	1.13	1.14	1.13
Class 10	1.07	>2.50	1.10	1.13	1.12

Table 7.9: Uniformity Ratios for Central Desk

The relationship between the position of the luminaire and the task was also influential in the resultant variation in uniformity. This can be seen from the results for the edge desk (figures 7.4, 7.5 and 7.6). For the first four steps of SHR the illuminance on the task was mostly made up from contributions from either a symmetrical array of luminaires or luminaires directly overhead and the UR/SHR relationship here is similar to that of the central task. At SHR 1.75, the illuminance on the task was a contribution from four luminaires, but the two luminaires on the partition side were slightly more influential. This explains the sharp rise in UR for the light case, as once the partition was introduced a substantial amount of the direct illuminance was blocked. This effect was more obvious for the broadspread luminaires. From SHR 2.00 onwards, the major illuminance contribution was from one luminaire located on the filing cabinet side of the task, moving closer to the task as SHR increases. This explains the increase in uniformity and also the reason for the apparently small difference between the medium and heavy cases.

The photometric characteristics of the luminaire (and hence the CIBSE classification group) are implicitly linked to the uniformity, but this relationship seemed to hold mainly for the empty and light furniture cases, for some of the broadspread luminaires only. This suggests that the presence of furnishing was a more important influence on the uniformity than the type of luminaire used. One possible explanation for this similarity in behaviour of photometrically different luminaires was the exclusion of the inter-reflected component, as this would, to some extent, make all the luminaires behave similarly once furnishings are introduced to the space. Evidence to support this can be gleaned from the characteristic shape of all the uniformity curves. Looking at the UR/SHR curves for two photometrically different luminaires, a class 4 (figures 7.5 and 7.8) diffusing luminaire and a class 10 VDT luminaire (figures 7.6 and 7.9), reveals the following information. For the class 10 luminaire, the majority of light is distributed directly

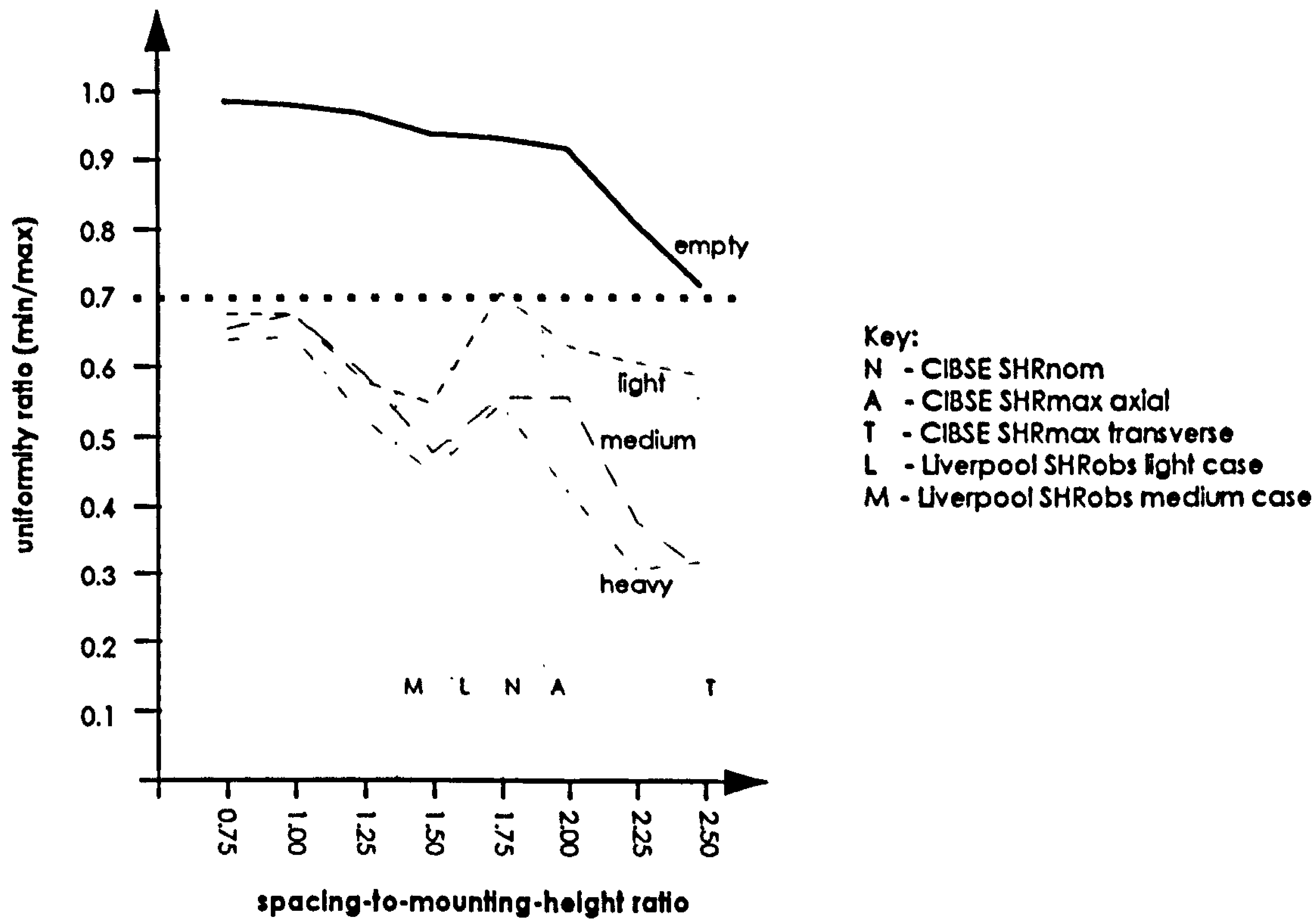


Figure 7.4: Edge desk UR/SHR relationship for class 1 luminaire

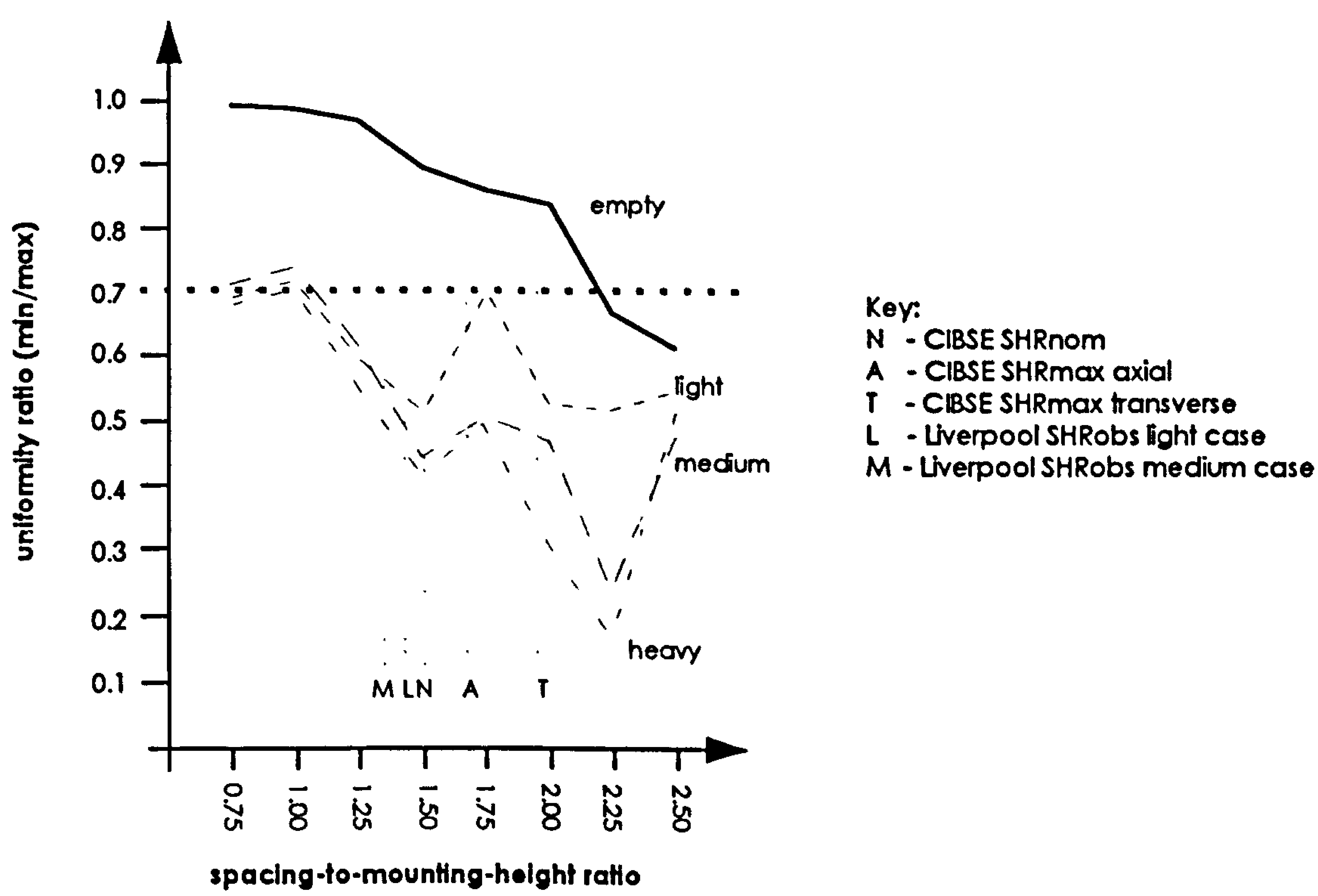


Figure 7.5: Edge desk UR/SHR relationship for class 4 luminaire

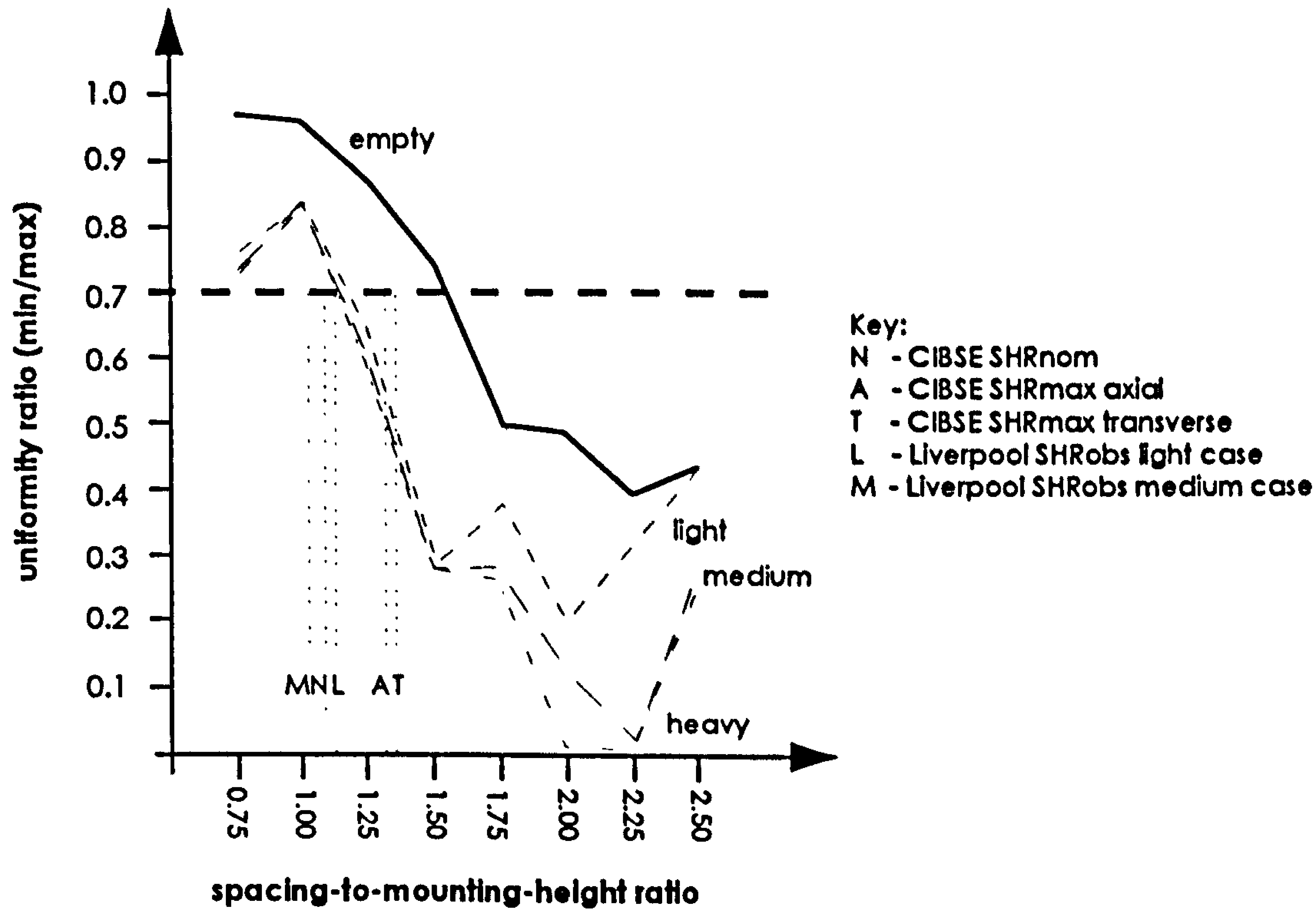


Figure 7.6: Edge desk UR/SHR relationship for class 10 luminaire

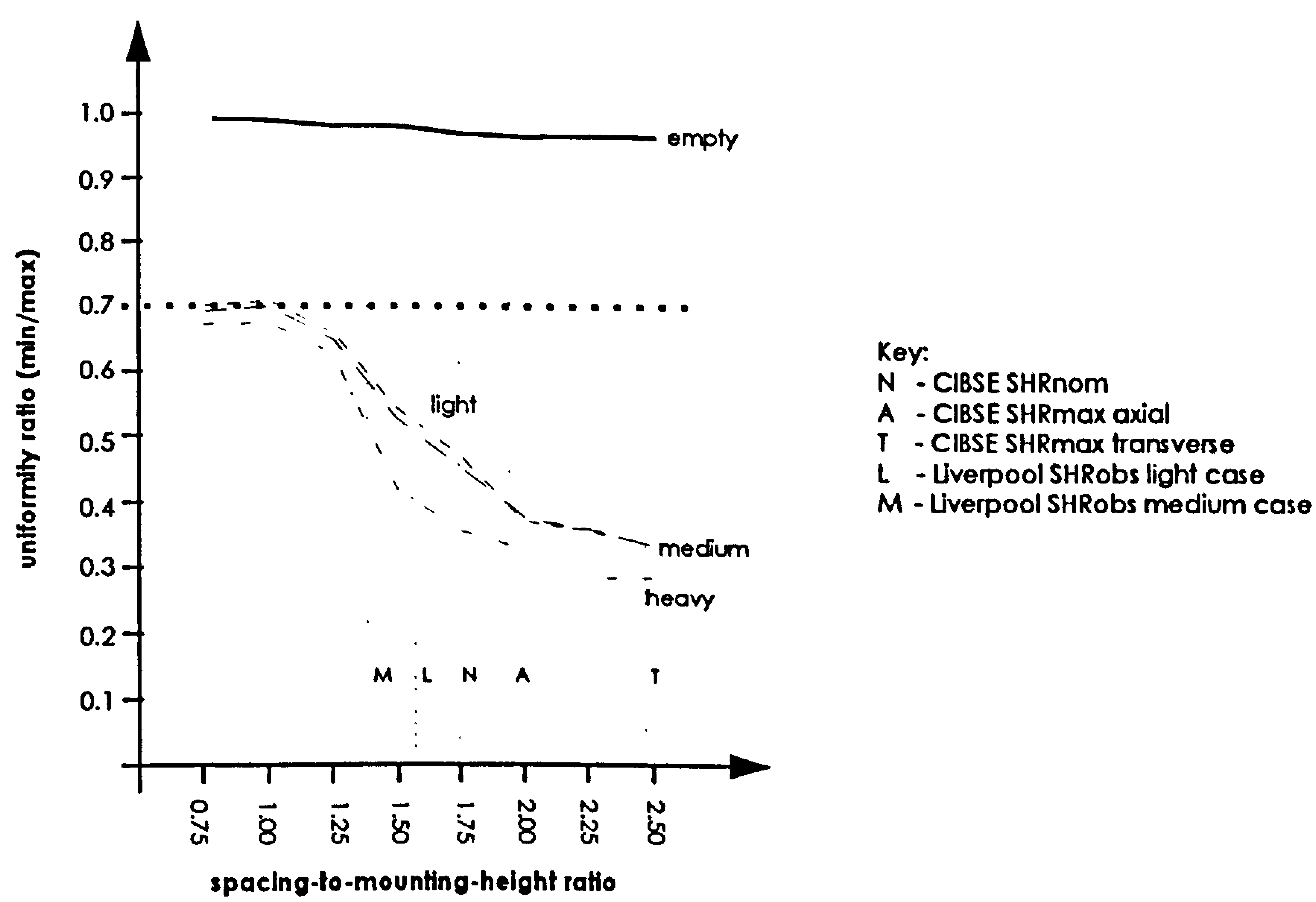


Figure 7.7: Central desk UR/SHR relationship for class 1 luminaire

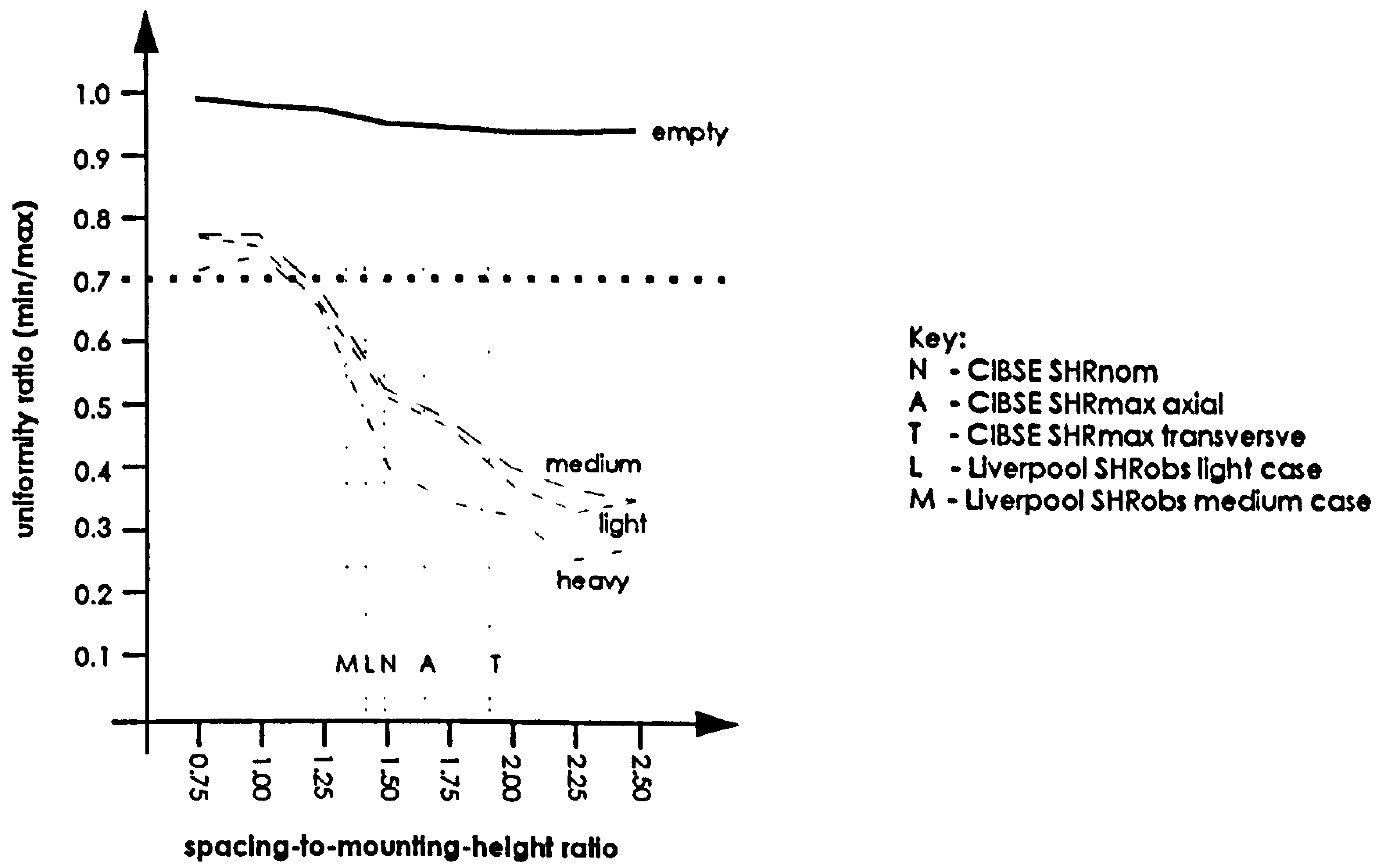


Figure 7.8: Central desk UR/SHR relationship for class 4 luminaire

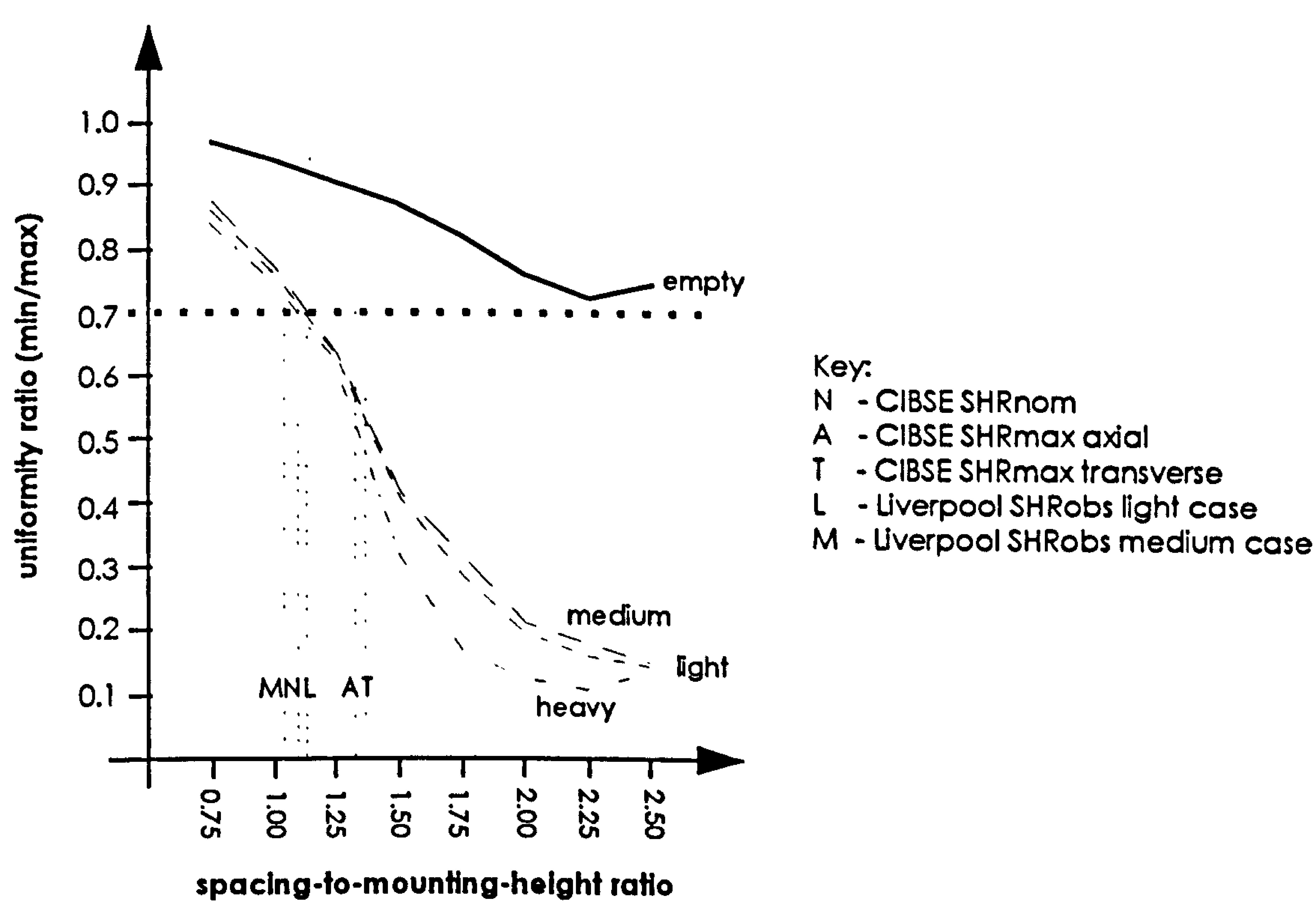


Figure 7.9: Central desk UR/SHR relationship for class 10 luminaire

downwards and hence received without inter-reflection, the UR started high (around 0.8) and decreased rapidly with increasing SHR to a low point of 0.02, as expected. The class 4 luminaire, however, where a quantity of light would be likely to be received via inter-reflection, the UR started around the 0.7 mark and decreased with SHR, but to a lesser extent than degree of the class 10 luminaire (only as far as 0.25). This seems to indicate that for broadspread luminaires, with a large component of light likely to be distributed via inter-reflection, UR is significantly underestimated around the lower SHR values.

For most of the luminaires, the UR had fallen below the CIBSE limiting value, close to, but usually before the SHR_{nom} and SHR_{obs} limits. However, bearing in mind that we are only considering direct light and that uniformity will, therefore, be underestimated, it is reasonable to assume that if indirect illuminance were included, SHR_{nom} and SHR_{obs} would satisfy the uniformity requirements.

7.5.2 Variation of core area diversity with SHR

The diversity increased directly with SHR, but VFR and luminaire type were also influential. The increase in diversity with VFR was greater for broadspread (classes 1 and 4) luminaires, falling to an almost negligible amount for luminaires with a high downward component (classes 9A and 10 for example). The rate of increase of diversity with SHR can also be linked to luminaire type, although with an opposite trend to the previous relationship. Luminaires with a high downward component exhibited a much more rapid rise in diversity with SHR than broadspread luminaires. Table 7.10 shows the actual point of failure of each of the luminaire types and figures 7.10, 7.11 and 7.12, show SHR diversity characteristic curves for classes 1, 4 and 10 luminaires, respectively.

From these graphs it can be seen that, only when using broadspread luminaires (classes 1 and 4) under heavily obstructed conditions, must the designer take care to ensure diversity conditions are satisfactory. In all other cases, as long as SHR_{max} is not exceeded, the diversity does not fall below the recommended limits.

7.5.3 Variation of obstruction light loss with SHR

The illuminance over the core area and each task area, was calculated as an area-weighted arithmetic average of the illuminance at each of the relevant grid points. The results in chapters 4 and 5, and those found by previous researchers[16], have investigated the reduction in the average working plane illuminance that is likely to occur with the introduction of furnishings into a previously empty space. For each luminaire spacing arrangement, the three aforementioned average illuminance values were used to calculate the obstruction loss (OL) for the three different furniture cases. For the task and each core area, the OL is calculated as the percentage reduction in average illuminance in the furnished case, compared with the empty case. The three different areas (two tasks and the core area) are considered individually.

Luminaire	SHRmax	SHR at 5:1 Diversity Ratio			
		Empty	Light	Medium	Heavy
Class 1	2.50	>2.50	>2.50	>2.50	2.38
Class 4	1.95	2.38	2.38	2.38	2.05
Class 8	1.87	2.27	2.27	2.25	1.90
Class 9A	1.77	2.05	2.05	2.05	1.88
Class 9B	1.74	2.11	2.10	2.07	1.75
Class 10	1.07	1.60	1.70	1.60	1.75

Table 7.10: Value of SHR for diversity of 5:1

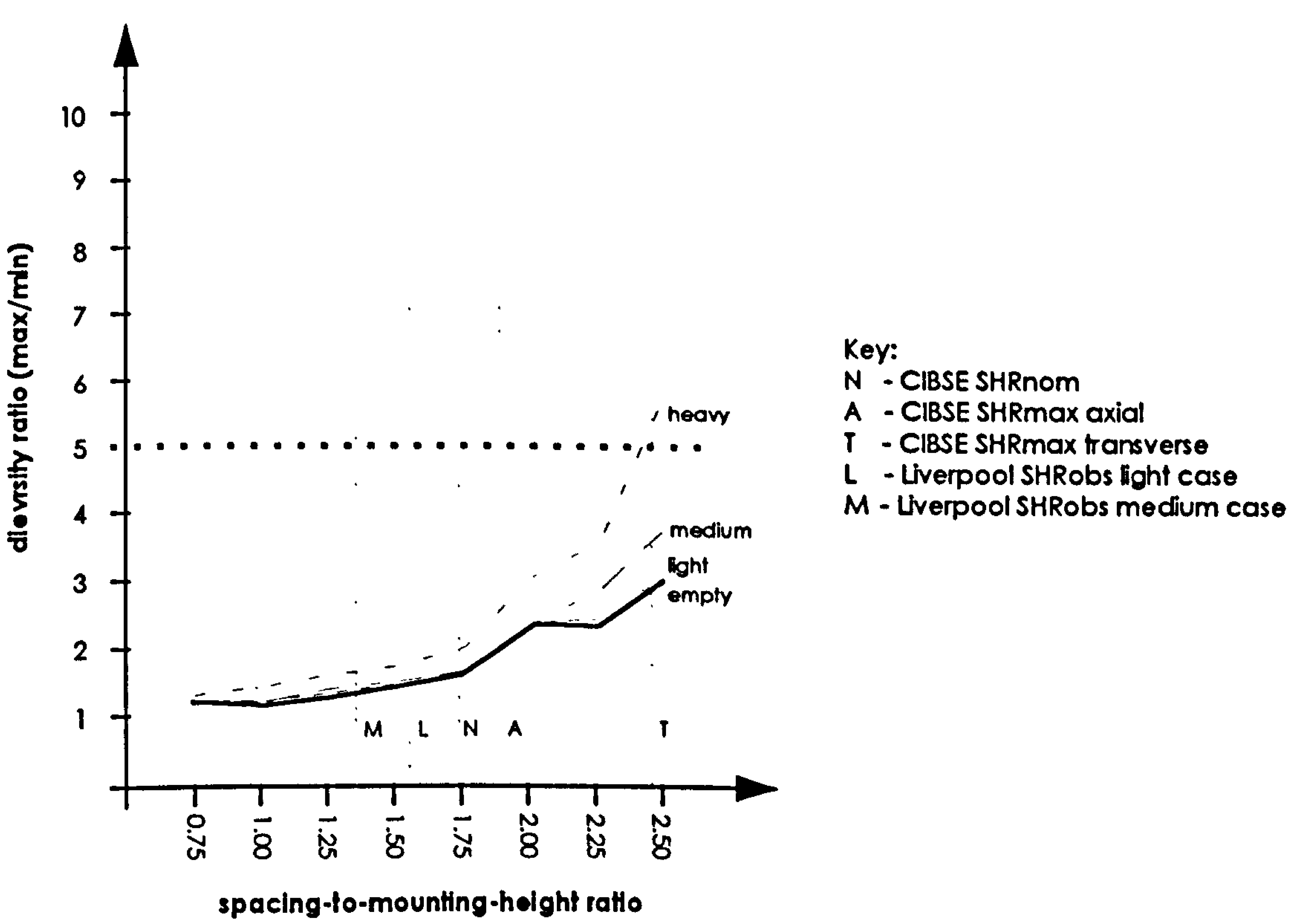


Figure 7.10: Variation of diversity with SHR for class 1 luminaire

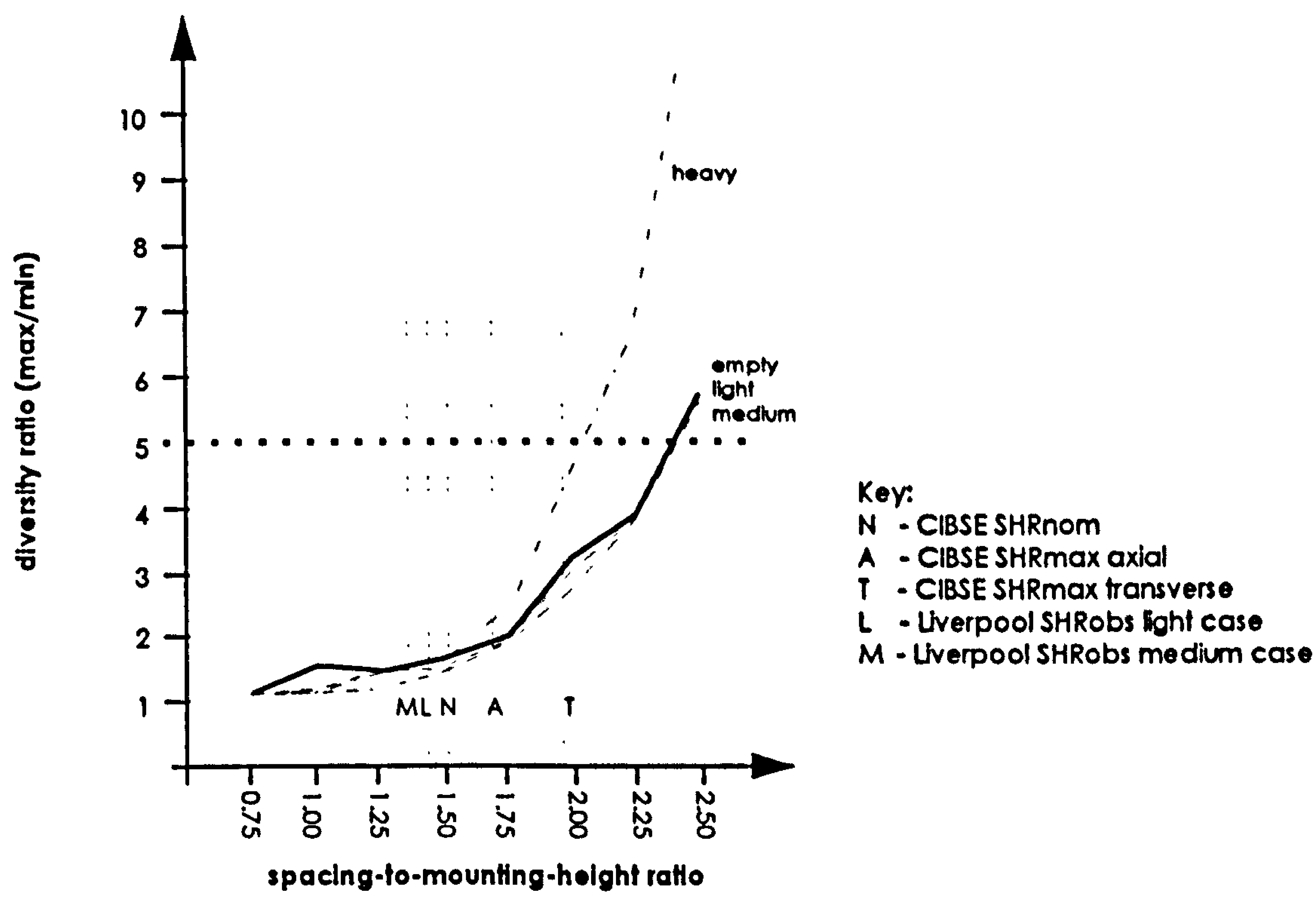


Figure 7.11: Variation of diversity with SHR for class 4 luminaire

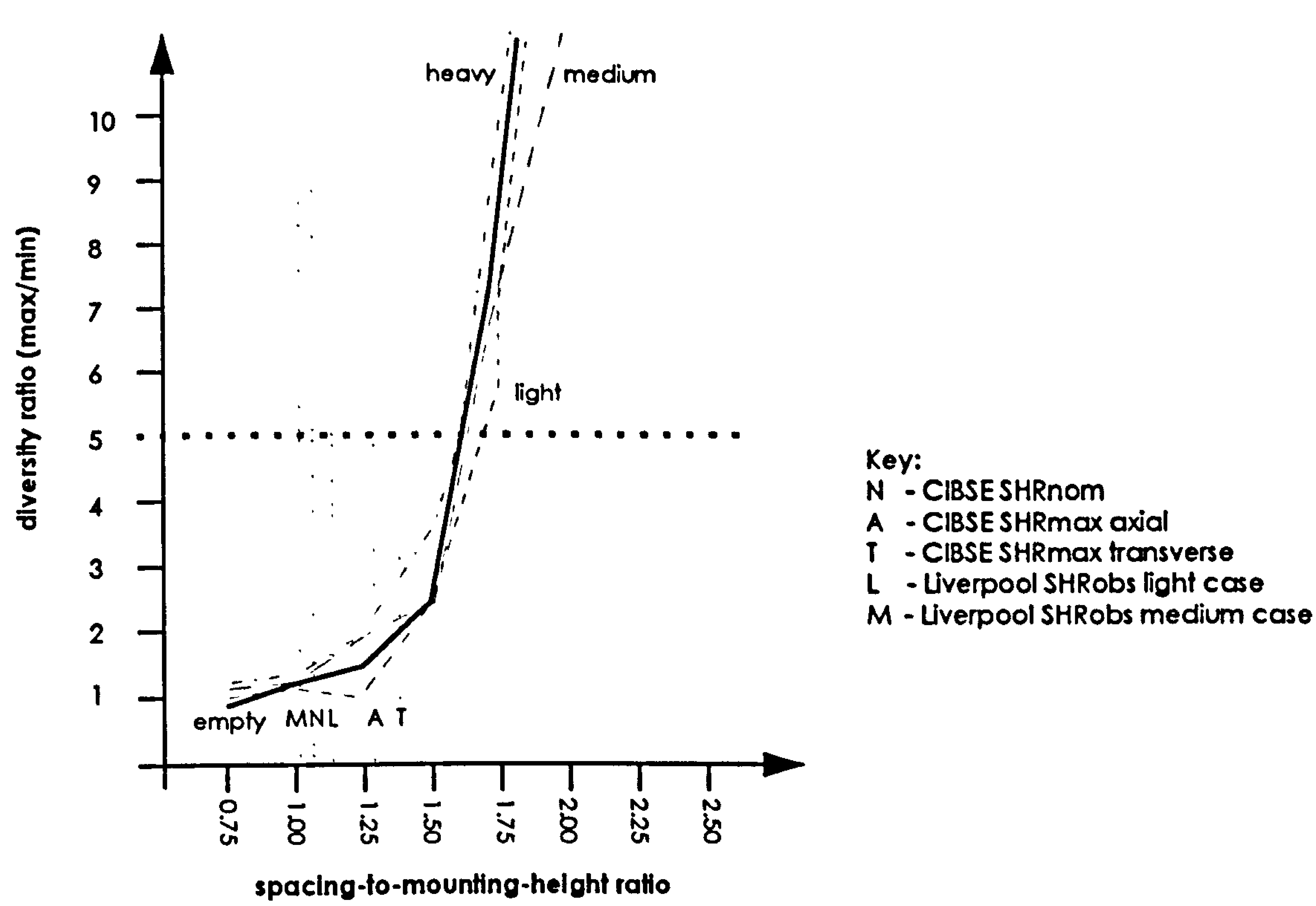


Figure 7.12: Variation of diversity with class 10 luminaire

7.5.3.1 Whole room

The average magnitude of OL values, across the range of SHR's, are given in table 7.11, and examples of the variation characteristics for the class 1, 4 and 10 luminaires are shown in figures 7.13, 7.14 and 7.15. For all the luminaire types, the variation of OL over the core area was almost constant for increasing values of SHR. In all the cases the primary factor was the VFR of the installed furniture. Also notable was the influence of luminaire type on OL (see table 7.11). The average value of OL across the range of SHR's reinforced the results found in chapter 5. Luminaires with a high SHR_{max} exhibit, in general, a larger OL than those with a lower SHR_{max}.

7.5.3.2 Individual tasks

The average illuminance on the actual tasks ($0.25m^2$ grid on desks) at the two positions, exhibits slightly different OL characteristics compared to the whole room. OL was calculated on the same basis as earlier (i.e. percentage reduction in average illuminance between the empty and furnished cases), but this time the average illuminance was calculated over the task area alone. The OL/SHR variation for class 1 and class 10 luminaires over edge and centre tasks are shown in figures 7.16, 7.17, 7.18 and 7.19. In both cases the magnitude of the OL were significantly higher. The general trend of the magnitude of OL was the same as for the case of the whole room, i.e. luminaires with a higher SHR_{max} exhibit a general larger OL than those with a lower SHR_{max}.

Luminaire Class	SHRmax	Average OL across the range of SHR's (%)		
		Light	Medium	Heavy
Class 1	2.50	3.3	7.9	12.6
Class 4	1.95	2.3	6.0	9.7
Class 8	1.87	2.2	5.9	9.4
Class 9A	1.77	1.3	4.1	6.6
Class 9B	1.74	1.6	4.8	10.1
Class 10	1.07	0.9	3.3	5.2

Table 7.11: Average OL variation for SHR's in the range of 0.75 to 2.50

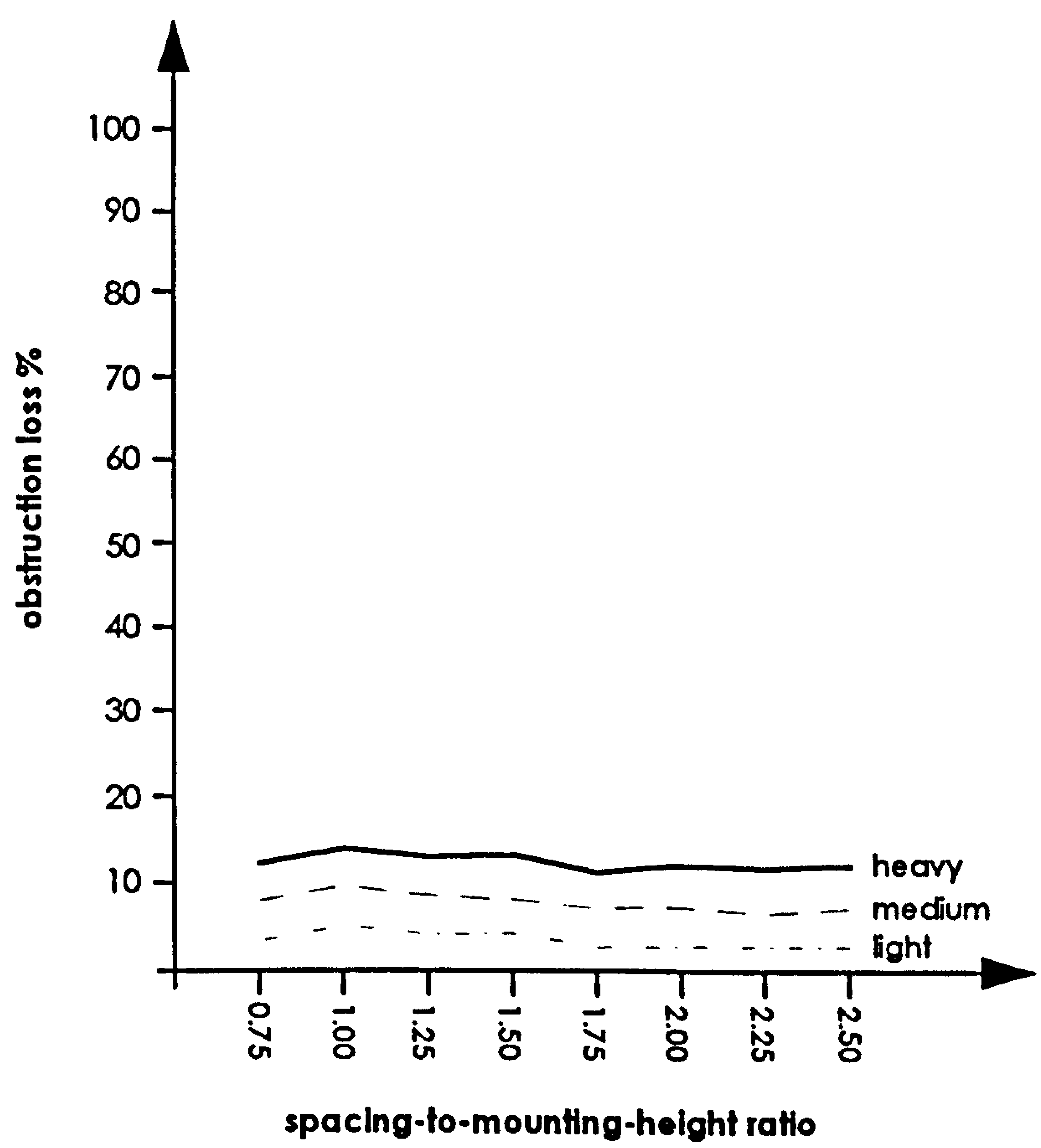


Figure 7.13: Variation of OL over core area with SHR for class 1 luminaire.

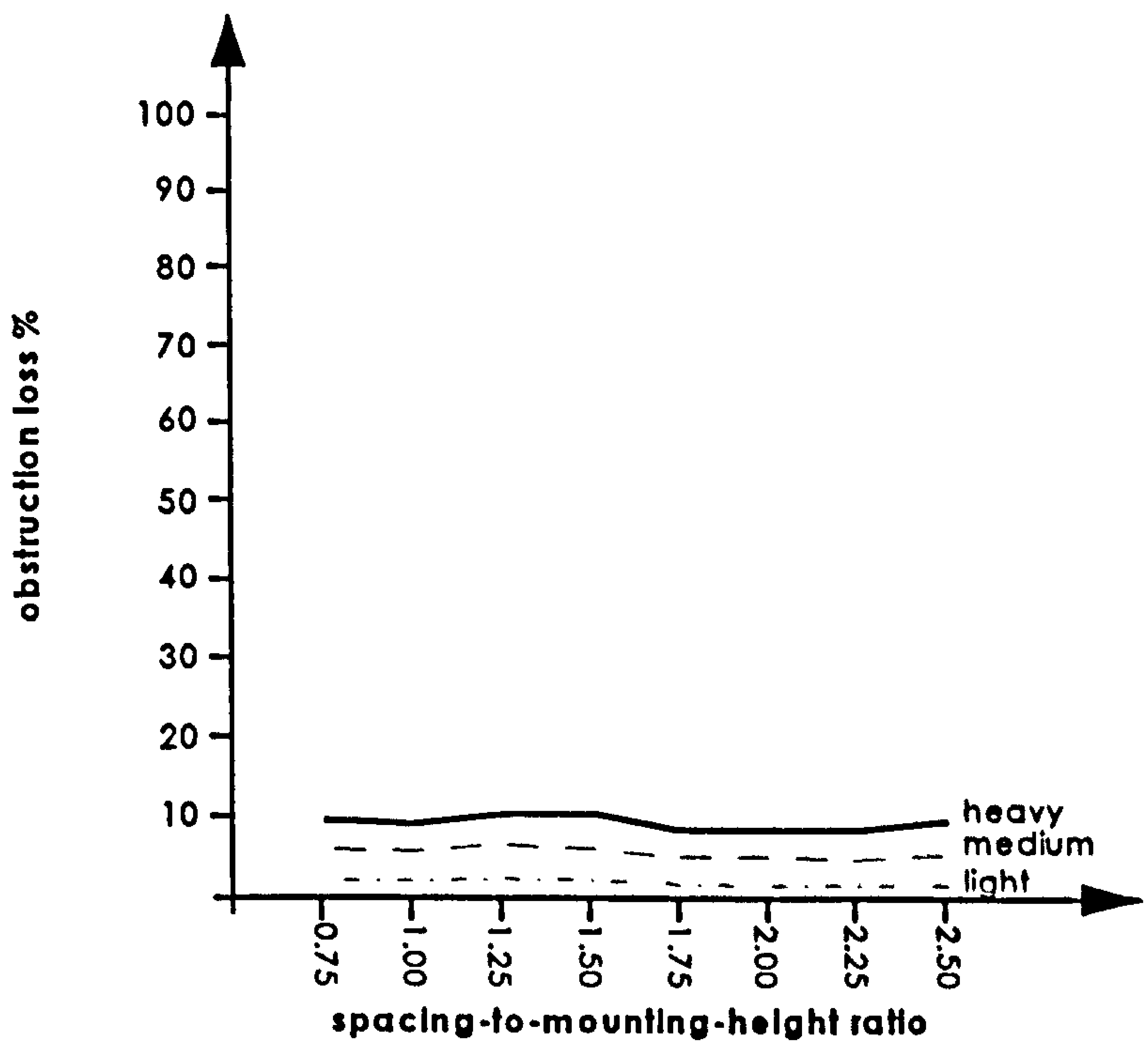


Figure 7.14: Variation of OL over core area with SHR for class 4 luminaire.

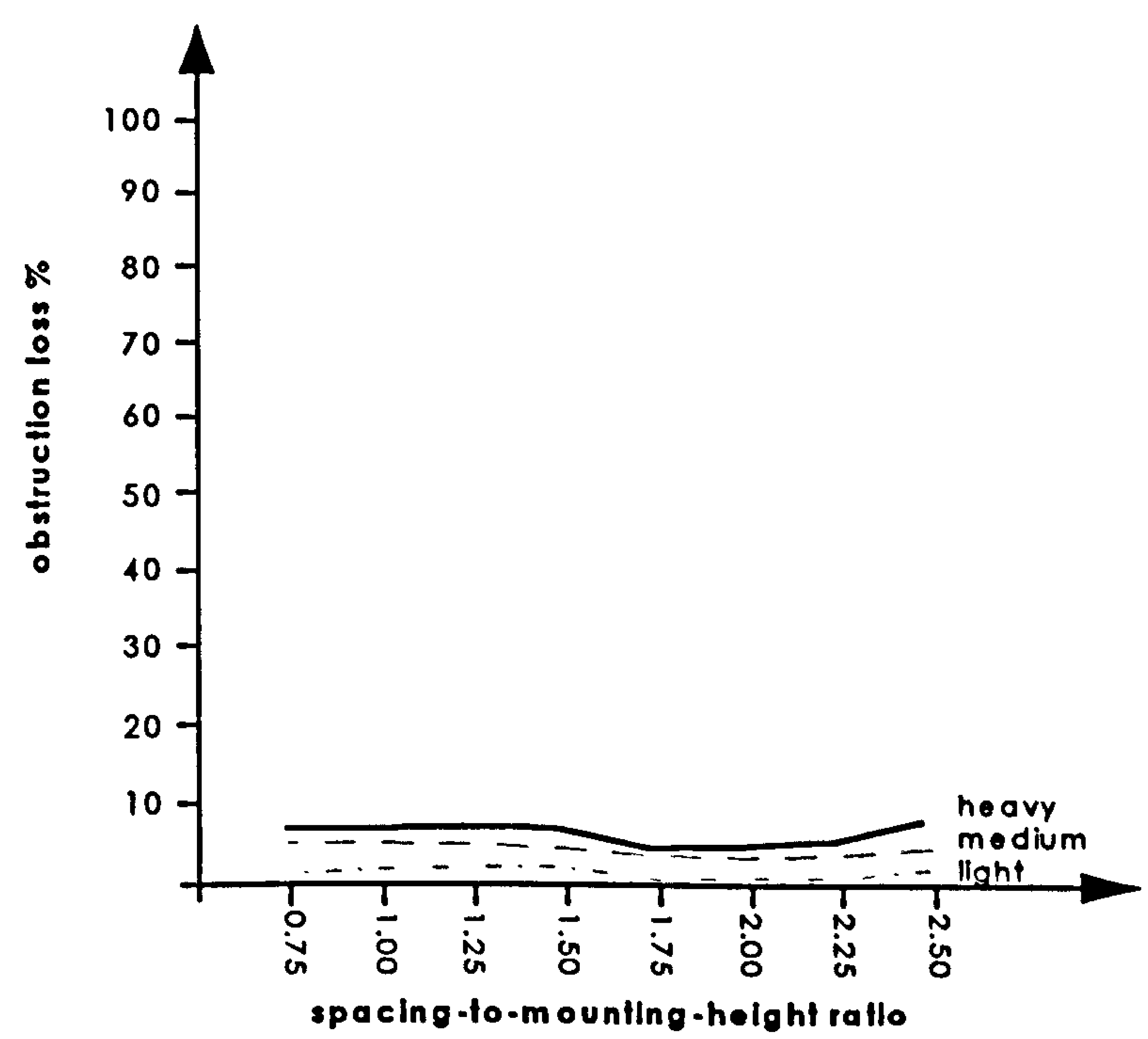


Figure 7.15: Variation of OL over core area with SHR for class 10 luminaire.

7.5.3.2.1 Edge desk

Again VFR and luminaire type were the major influence on the magnitude of obstruction loss, but in the case of the edge desk, a large variation with SHR was evident. Typical examples of the variation for class 1 bare batten luminaires and class 10 VDT luminaires are shown in figures 7.16 and 7.17. From these graphs it can be seen that there is no easily identifiable trend. In all obstruction and luminaire cases the characteristic curves were similar for SHR 0.75 to approximately 1.75, at which point the heavy case then increased, peaked and decreased. The medium case exhibited the same behaviour to a lesser extent, but the light case continued to decrease through all values of SHR to a minimum at 2.50.

For the edge task location, the variations in OL can be linked to some extent with the geometrical relationship between task and luminaire position. The sharp peak, for instance, in the heavy obstruction case at SHR 2.00 (evident for all luminaire types) was due to the fact that, for this situation, the edge task was furthest away from any single luminaire. So the contribution, that was blocked by the partition, was substantial and caused a high reduction in the illuminance.

7.5.3.2.2 Central desk

For the case of the central desk, as for the edge desk, VFR and luminaire type were the primary influences (see figures 7.18 and 7.19), but the variation had a definite trend. For the lower SHR values, the OL was around the middle of its two extreme values, it then decreased for one to two steps of SHR to a minimum value and finally increased for the remaining SHR values to a maximum value. The magnitude of the OL was once again greater for broadspread luminaires and the difference in the influence of the three different furniture densities was greatest for this type of luminaire.

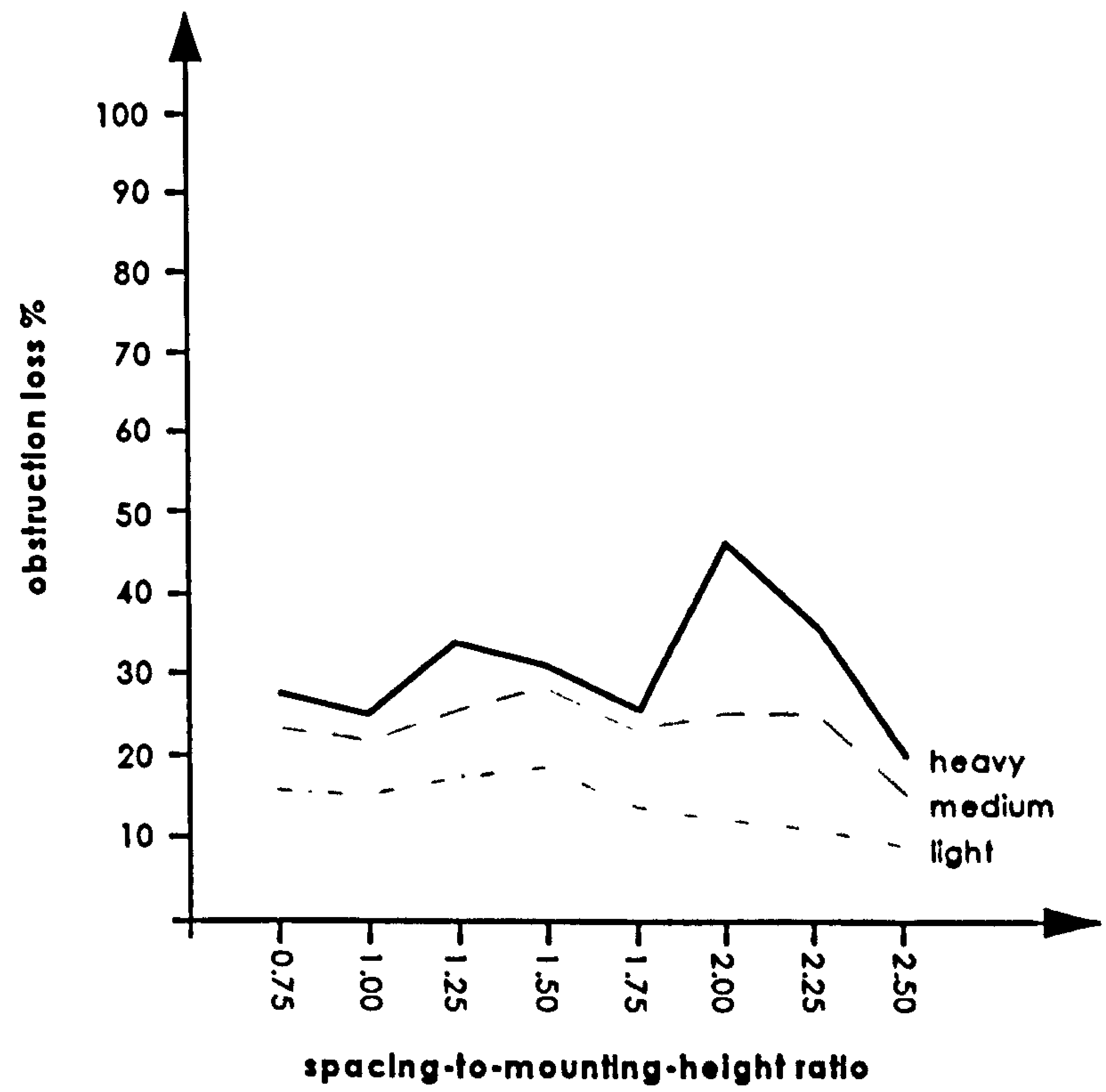


Figure 7.16: Variation of OL over edge desk with SHR for class 1 luminaire.

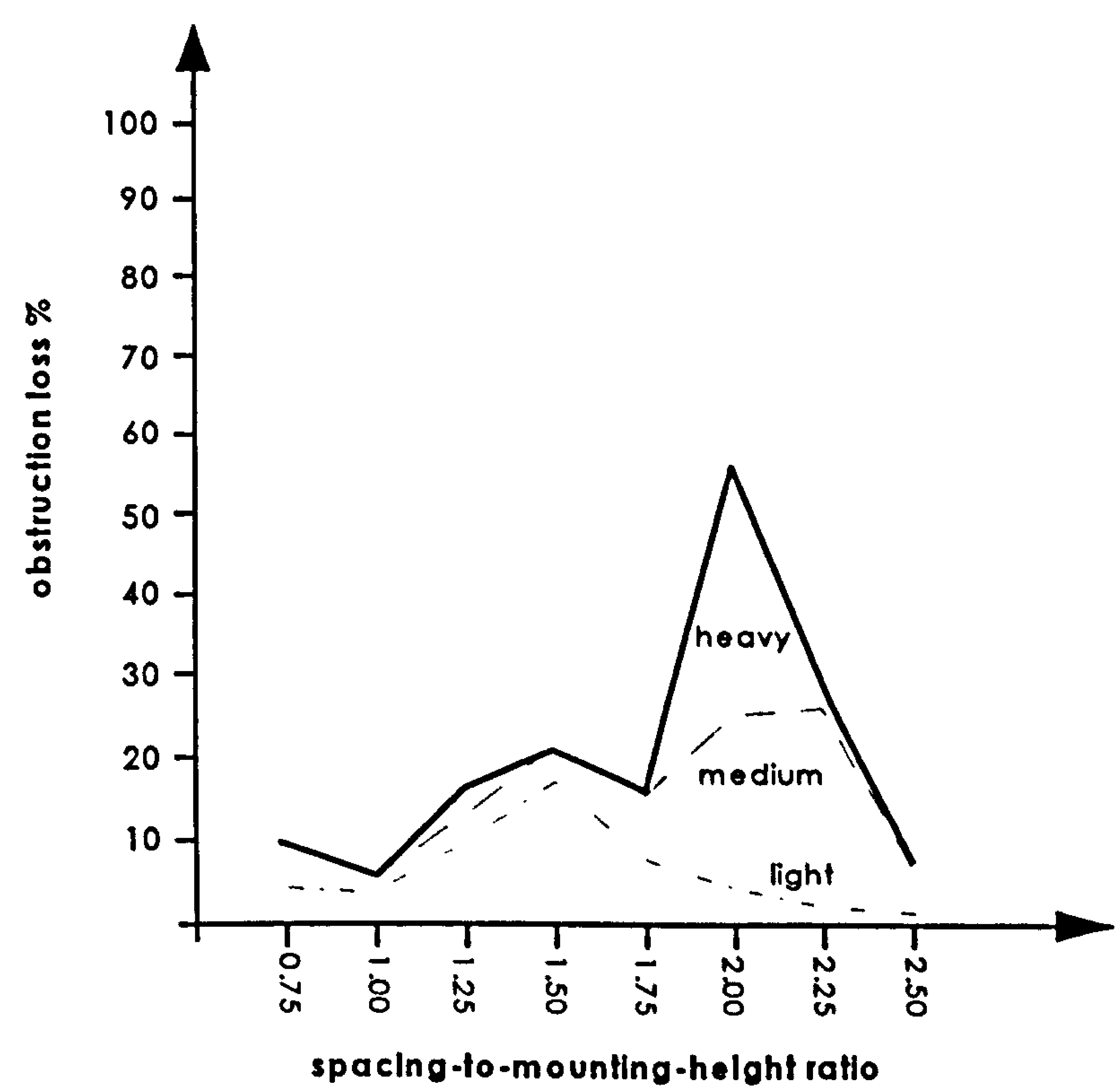


Figure 7.17: Variation of OL over edge desk with SHR for class 10 luminaire.

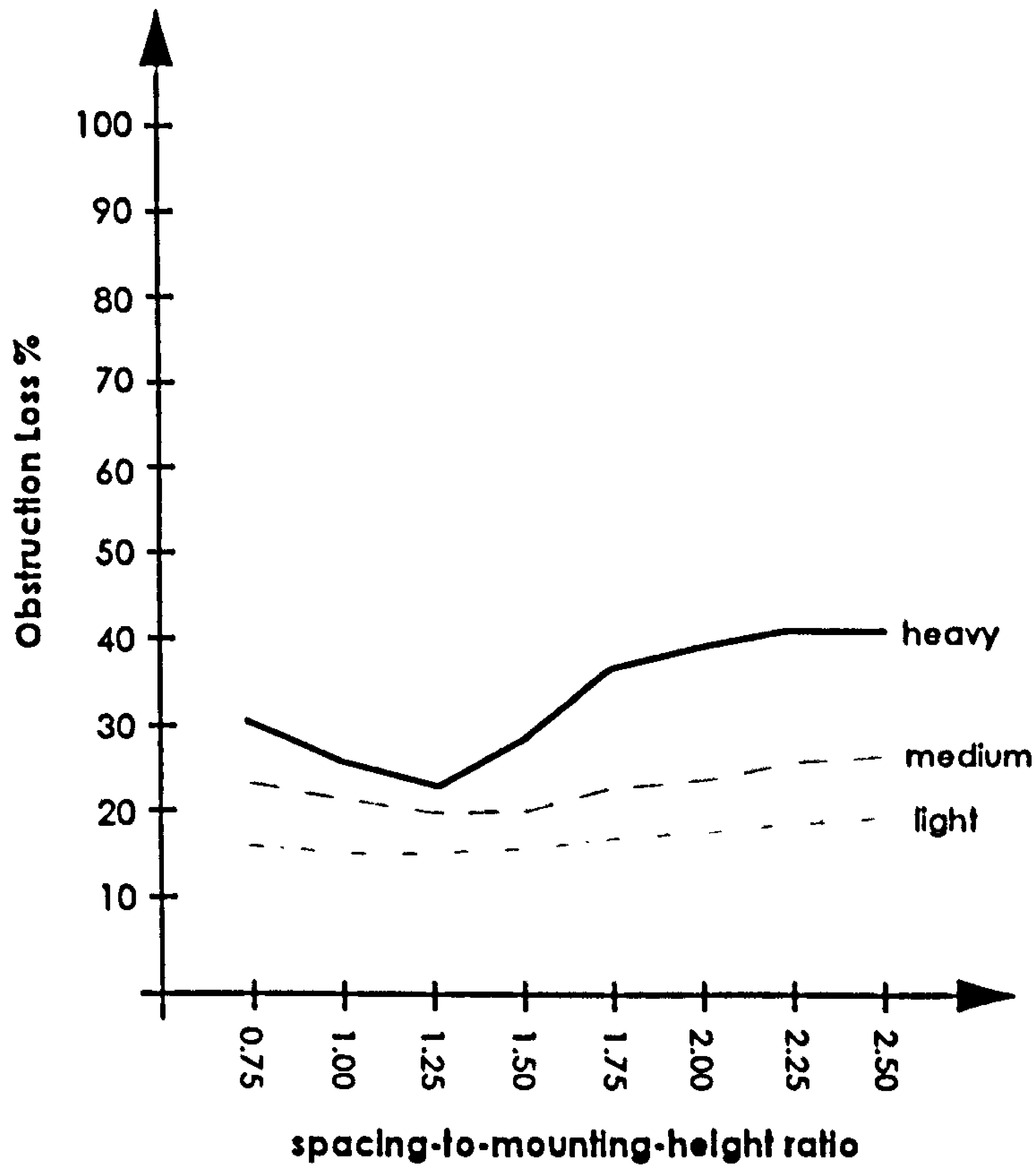


Figure 7.18: Variation of OL over central desk with SHR for class 1 luminaire.

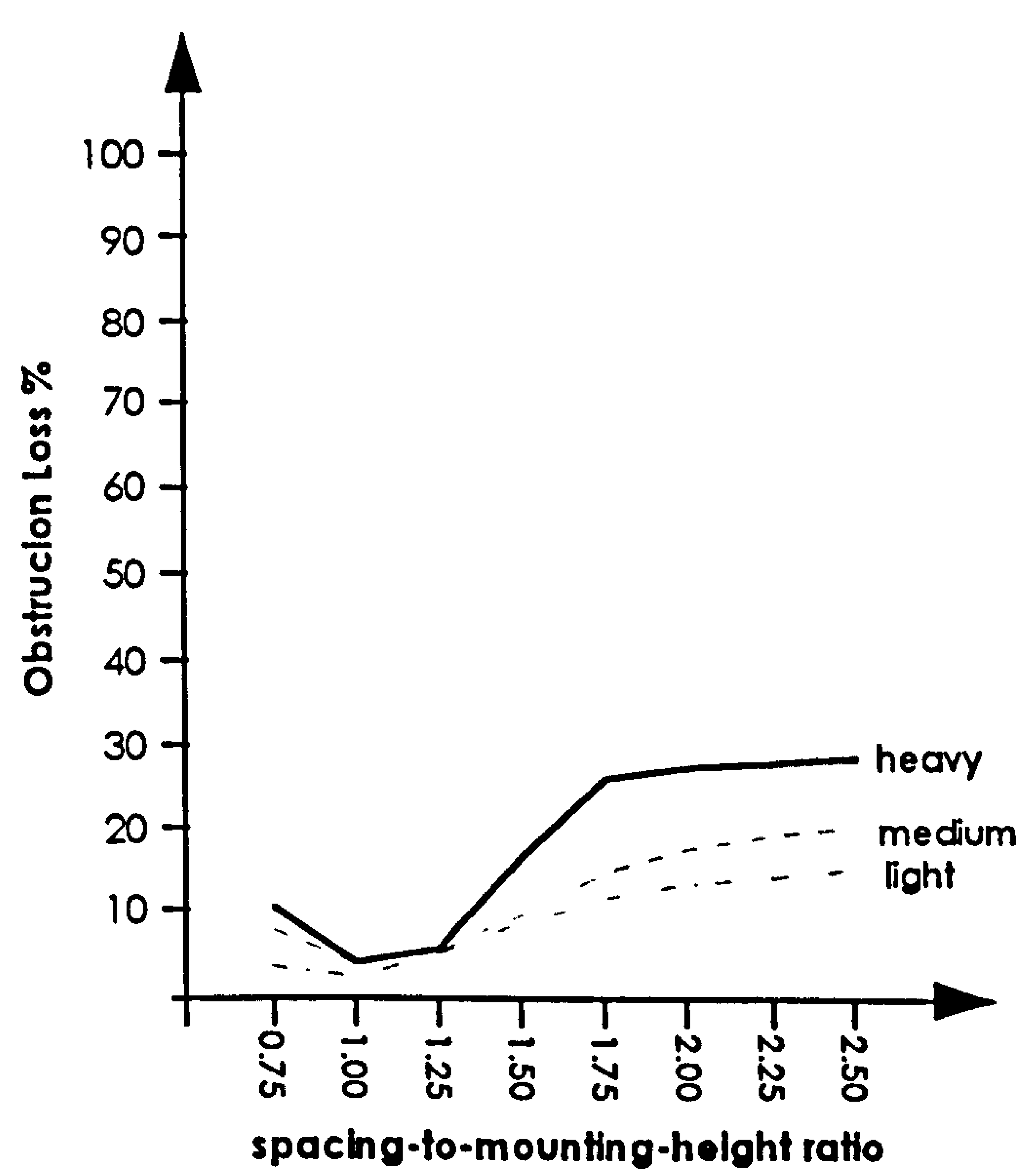


Figure 7.19: Variation of OL over central desk with SHR for class 10 luminaire.

The similarity in the shape of the OL characteristic curves for all the different luminaire types indicates that even for the task areas, SHR had little or no influence on the magnitude of OL. The curves show no distinctive trends around the values of SHR_{nom}, SHR_{max} or SHR_{obs} and therefore, none can be said to perform better than the other.

7.6 Discussion

The inclusion of the uniformity criteria in all the relevant Codes of Practice reinforces its importance as a parameter that must be considered in the design process. The results of this investigation emphasized the inadequacies in the use of the current technique of SHR_{max} as a guide to the relationship between the proposed luminaire spacing and the uniformity that is likely to be achieved in a furnished room.

Although this was only a single study for a limited range of interiors, the results indicated that luminaire spacings close to SHR_{max}, in obstructed interiors, were likely to result in task illuminance uniformity which could be considered inadequate. The concept of SHR_{obs} has been developed explicitly for use in obstructed interiors and *Bougdah*[8] has proposed the use of SHR_{obs}, by designers, in two ways: either to indicate the design SHR at which acceptable task uniformity will be obtained, or to give warning of the need for local lighting. The results of the investigation detailed in this chapter, also add to the evidence that the use of obstructed, rather than conventional, SHR values are likely to achieve consistently better uniformity criteria. Unfortunately, the technique of SHR_{obs} has, to date, proven difficult to implement on a large scale.

All the evidence presented in this chapter indicated the need for a modification to the current legislation detailing SHR_{max} as a technique for determining luminaire spacing. One solution could be the inclusion of the obstructed spacing-to-mounting-height technique in CIBSE Technical Memorandum No. 5, although, some further research is recommended into the importance of the inter-reflected component. If the inclusion of indirect light is shown to be advantageous, then modern programming techniques and computing equipment are adequate for the task of performing the calculation.

From the results of this investigation some general recommendations can be made to assist the designer in the positioning of luminaires using information readily available. For the majority of the luminaires used in this investigation the uniformity ratio had fallen below the threshold, around the nominal value. It has already been established that the uniformity found using direct light only, tends to under-estimate uniformity. Therefore, it seems plausible to deduce that the use of spacings of SHR_{nom} will give adequate uniformity. In cases where extreme variations in illuminance may occur, for instance, when high partitions are used, one step below SHR_{nom} will be necessary to satisfy the required uniformity criteria.

Another important point that can be drawn from the results of this simulation is the association between luminaire position and the reduction in the illuminance over task area, due to the introduction of furniture. This geometrical relationship implies that, in an installation where luminaires are installed at a wide SHR and light is being delivered to the task area at very flat angles, care must be taken in the positioning of large obstructions relative to the luminaires. In this case, it is recommended that luminaires are located directly over the task wherever possible.

The results for obstruction loss (OL) illustrated that the installed spacing-to-mounting-height ratio of the luminaires had little influence on the magnitude of the OL. The important variables were the density of furniture contained in the space and the luminaire type. The magnitude and trends of the results were in good agreement with results detailed in chapters 4 and 5. The difference in magnitude between the OL on the task areas and over the core area can be attributed to the large influence of the geometrical relationship between the small task area and luminaires. One could also argue that the OL over the task is not the most important quantity, as it likely to be above the minimum required standard, as long as the overall effect of light losses have been compensated for using the design method detailed in previous chapter. However, the results are noteworthy, as they indicate that in the worst cases, task lighting may be necessary to compensate for light losses in the order of 40%. The magnitude of the OL would be likely to reduce, if the indirect component were included in the calculation, as an amount of light would be reflected off obstructions onto the task area. This is an area which requires further investigation.

The diversity of illuminance over the core area was below the required limit for most spacings up to SHR_{max} and for most furniture conditions. Problems may arise, however, in installations where a combination of narrow distribution luminaires, spaced near to SHR_{max} and heavy furniture conditions occur.

7.7 Design guidance

The primary relationships and their respective characteristic behaviours that can be derived from this investigation are:

- In an empty room, the luminaire spacing is the primary variable affecting task uniformity.
- The presence of even a low density of furnishing can have a serious detrimental effect on task uniformity.
- The luminaire spacing does not affect the obstruction loss within the limits of this investigation.
- The diversity increases as the luminaire spacing increases.
- Luminaires with a large downward component (e.g. groups 9A and 10) tend to be affected less by the presence of furnishings than broadspread luminaires

From these conclusions and the results of the investigation, the following 'rules-of-thumb' regarding the determination of luminaire spacings for installation in furnished interiors are put forward.

- If SHR_{obs} data is available and furniture conditions are known, then the relevant SHR_{obs} value should be used as the design maximum SHR.
- If SHR_{obs} data is available and furniture conditions are unknown, then the medium case SHR_{obs} value should be used as the design maximum SHR.
- If SHR_{obs} data is not available and furniture conditions are unknown, then the CIBSE Nominal SHR value should be used as the design maximum SHR.
- If SHR_{obs} data is not available and furniture conditions are unknown, but expected to be high (e.g. lots of partitions, high shelving units, etc.), then luminaire spacings one step below the CIBSE Nominal SHR value should be used as the design maximum SHR.
- If a combination of broadspread luminaires and a high density of furnishing is expected, then one step below the CIBSE Maximum SHR value should achieve the required diversity standards.

7.8 References

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2. *Slater A I and Boyce P R*, "Illuminance uniformity on desks: where is the limit?", *Lighting Research and Technology*, 22(4) pp. 165–174 (1990).

3. *CIBSE Code for interior lighting*, "Section 5.3.3.3 Measurement of illuminance variation", *Chartered Institution of Building Services Engineers*, pp. 196 (1994).

4. *CIBSE*, "Technical Memorandum Number 5: The calculation and use of utilisation factors", *Chartered Institution of Building Services Engineers*, (1980).

5. *Illuminating Engineering Society of North America*, "IES Lighting Handbook: Reference and Application", *IES*, New York (1993).

6. *CIBSE Lighting Guide*, "The Industrial Environment", LG1, *CIBSE*(1989).

7. *CIBSE Code for interior lighting*, "Section 4.4.2.1 General Lighting", *Chartered Institution of Building Services Engineers*, pp. 136 (1994).

8. *Bougdah H and Carter D J*, "An improved method of calculating spacing-to-height ratio in obstructed commercial interiors", *Proc. CIBSE National Lighting Conference*, Cambridge, 1, (1), page 337-339; (1990).

9. *Illuminating Engineering Society of North America Lighting Handbook*, "Chapter 9: Lighting calculations", *IES*, New York, pp.414, (1993).

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11. *Steffey G R*, "Architectural Lighting Design", *Van Nostrand Reinhold*, New York, (1990).

12. *Williams H G*, "New directions in commercial flourescant lighting", *IEEE Transcations on Industry Applications*, 27 (6), 1214 (1991).

13. *Leung A S M, Lupton M J and Carter D J*, "Standard obstructions for lighting calculations", *Lighting Research and Technology*, 26, (3), page 161-165; (1994).

14. *CIBSE Code for Interior Lighting*, "Section 3.3.2 Luminaire Characteristics", *Chartered Institution of Building Services Engineers*, pp. 108–124 (1994).

15. *Carter D J and McEwan I*, "The treatment of obstruction in interior lighting design-calculation of spacing to height ratio", *Lighting Research and Technology*, 18, (2), page 79-87; (1986).

16. *McEwan I and Carter D J*, "A survey of lighting in obstructed spaces", *Proceedings Of The 21st Session Of Commission International De l'EClairage*, 1, page 226; (1987).

Chapter 8

Conclusions and recommendations

The work detailed in this thesis brings together a large body of new and existing knowledge pertaining to the artificial lighting of furnished spaces. The current concern for realism in lighting calculations and the acknowledgment of problems related to the presence of obstructions within the interior lighting Codes of Practice (albeit descriptive rather than prescriptive) are just two of the areas that highlight the importance of acknowledging obstruction effects in the lighting design process. Based upon the foundation of research undertaken over the past ten years, this work attempts to bring to a conclusion the development of a technique applicable to the design of artificial lighting installations in furnished spaces.

The review of published literature revealed that three areas of development needed to be addressed. The first of these three areas – the development of appropriate calculation methods – has been covered by the research described in this thesis. The two remaining areas are beyond the scope of a single research project, but it is hoped that this document contains information that can be used as an aid to their investigation. The two unaddressed areas are, the extension of the research to categories of interior other than commercial offices and the inclusion of numerical guidance into Codes and Standards.

Previous work concluded that there was scope for a more detailed investigation of the effect of design parameters on obstruction light loss. The effect of room index was wholly undetermined and the effect of luminaire type was limited to a range of six luminaires. The current research used the most up-to-date classification of luminaire photometric characteristics available to select some 64 examples of luminaires, those being most representative of modern lighting practice in commercial interiors. The effect of room index on light loss was investigated for each of these luminaires and found to be important for a distinct type of luminaire only.

Light loss data, suitable for adaptation into a design method, was generated for each of the aforementioned luminaires over a range of room indices and furniture densities. The ranges of these two variables were selected on the basis of an investigation into the typical scope likely to be encountered in the design of lighting schemes for modern commercial interiors. This investigation included a series of twenty-four photometric surveys of full scale installations. The design data was generated using an improved version of a computer program developed at the University of Liverpool. This program had a proven track record in the simulation of lighting conditions in furnished spaces and was adapted in order to be suitable for the generation of large quantities of results.

This work has achieved the goal of developing a modification to the lumen method of lighting design, capable of compensating for obstruction light loss. The modification enables the designer to predict the likely magnitude of obstruction light loss based on a knowledge of the luminaire maximum spacing-to-mounting-height ratio (SHR), room index (both of which are readily available) and the expected density of furnishings. Examples of the range of furniture density encountered in modern commercial interiors was put forward based upon a number of surveys carried out in working offices. A default value of furniture density was also proposed. The design method was field tested on a limited scale by two major lighting companies – Moorlite Electrical Limited and Thorn Lighting Limited. Both appeared to find the method acceptable and suitable for use as a design tool.

By its nature, the problem of obstruction light loss and the proposed compensatory modification to the lumen method has some associated commercial implications. The method involves the specification of an increased number of luminaires, which usually means higher initial and operating costs. However, this increase in cost also corresponds to an increase in quality compared to an installation designed using the conventional "empty room" assumption, an assumption that may lead to a lower than predicted average working plane illuminance and areas of local shadow. The only solution to the removal of the commercial implications, is the inclusion of the obstruction factor in interior lighting Codes and Standards. Once this information is in the public domain, it is likely to become the *de facto* standard and thus no commercial disadvantage will accrue.

In addition to the relationship between furniture density and light loss, the influence of furniture density and luminaire spacing on uniformity of illuminance was investigated. The effectiveness of the use of the obstructed SHR in achieving a specified level of uniformity in simulated interiors was compared with the use of conventional SHR values. It was demonstrated that the use of maximum SHR may result in measures of uniformity considerably lower than the minimum recommended in current Codes of Practice. Uniformity of illuminance has been linked to user satisfaction and performance and its inclusion in Codes of Practice further emphasizes its importance as a design criterion. The results of this investigation were used to devise a series of "rules-of-thumb", intended to fill the gap in published design standards relating to the spacing of luminaires in obstructed spaces.

The design tools and guidance detailed in this thesis provide a solution to the problem of light loss in commercial interiors attributable to furnishings. It is hoped that the tools and guidance will provide the basis through which current Codes of Practice and Standards can be revised. The need for the effective dissemination and promotion of this work is of the utmost importance if this aim is to be achieved. The guidance offered regarding luminaire spacing and the uniformity of illuminance achieved in obstructed spaces is, at best, rudimentary, but it does highlight the deficiencies in the use of maximum SHR as a guide to determining luminaire layout in furnished spaces. The extension of the research into other categories of interiors, such as industrial, still remains unattempted. This work, however, does provide a procedure which can be adapted for this undertaking.

Appendix One

The interior lighting analysis program

A1.1 Input files

The following text describes all of the input files required to operate the University of Liverpool analysis program.

General information (*general*)

<title>
<desc 1>
<desc 2>
<desc 3>

Key:

title line and three general description lines describing current analysis

Luminaire data (*lumdata*)

<UOL/1>
<lamp output>
<linear or point><luminaire group>
<length><width><identifier 1><identifier 2>
<intensity data for first C angle>
< intensity data >
< intensity data >
<intensity data for last C angle>

Key:

line 1:	UOL/1	data in University of Liverpool format. (see chapter 3 for alternative, TM14, data format)
line 2:	lamp output	total lamp lumen output, e.g. 3 lamps at 2970 lumens lamp output equals 8910
line 3:	luminaire type	1 - point source, 2 - linear source
	luminaire group	luminaire group as specified in CIBSE Code for interior lighting, section 3.3.2
line 4:	luminaire length	luminaire physical length in metres
	luminaire width	luminaire physical width in metres
	identifier 1	for linear luminaires:
	identifier 2	identifier 1 = "1" and identifier 2 = "1" means that the multiplying factor to the factor to the intensities will be

LLO/1000 and there with be 12 'C' planes of 5 degree intervals of γ angles up to 180.

identifier 1 = "2" and identifier 2 = "2" means that the multiplying factor to the factor to the intensities will be LLO/1000 and there with be 4 'C' planes of 5 degree intervals of γ angles up to 180.

for point sources:

identifier 1 = "1" and identifier 2 = "1" means that the multiplying factor to the factor to the intensities will be LLO/1000 and there with be 8 'C' planes of 5 degree intervals of γ angles up to 180.

identifier 1 = "1" and identifier 2 = "1" means that the multiplying factor to the factor to the intensities will be LLO/1000 and there with be 8 'C' planes of 5 degree intervals of γ angles up to 180.

identifier 1 = "2" and identifier 2 = "2" means that the multiplying factor to the factor to the intensities will be LLO/1000 and there with be 1 'C' planes of 5 degree intervals of γ angles up to 180.

identifier 1 = "3" and identifier 2 = "3" means that the multiplying factor to the factor to the intensities will be LLO/1000 and there with be 8 'C' planes of 5 degree intervals of γ angles up to 180.

line 4: intensity data — a column of luminous intensity data for 5 degree intervals of γ angles, measured from the downward vertical in each C-plane up to 180 degrees.
Each subsequent line contains the intensity data for the other relevant C-planes.

Lamp type (*lampdetails*)

<output>
<descrip>

Key:

line 1: <output> lamp lumen output per lamp

line 2: <descrip> description of lamp type

Note: this file is only required for TM14 data format.

Luminaire positioning file (*manposlum*)

<number>

Key:

any number other than 1 indicates that the luminaires are automatically positioned.

Luminaire positions (*manlum1* and *manlum2*)

<x-num><y-num>
<1x1><1y1><1x2><1y2><1x3><1y3>
<2x1><2y1><2x2><2y2><2x3><2y3>

Key:

line 1: number of luminaires in X and Y directions

line 2: coordinates of 1st row of luminaires

line 3: coordinates of 2nd row of luminaires

manlum1 - initial luminaire positions; *manlum2* - luminaire positions after furniture rotated through 90 degrees

Room data (*rminfo*)

<1><2><3><4><5><6><7><8><9><10><11><12><13><14><15><16><17>
<1><2><3><4><5><6><7>
Key:

line 1: 1 working plane height (metres)

2 room length (metres)

3 room width (metres)

4 room height(metres)

5 ceiling reflection factor

	6 to 9	wall reflection factors
	10	floor reflection factor
	11	luminaire utilisation factor
	12	SHRnom (axial)
	13	SHRnom (transverse)
	14	SHRmax (axial)
	15	SHRmax (transverse)
	16	design average illuminance
	17	maintenance factor
line 2:	1	discretisation of ceiling
	2	working plane grid size (metres)
	3	working plane grid start point in X direction
	4	working plane grid start point in y direction
	5	working plane grid end point in X direction
	6	working plane grid end point in Y direction
	7	discretisation of walls

Ceiling data (*ceilinfo*)

<dist><x-dir><y-dir>

Key:

<dist>	distance from ceiling to luminaire (must be greater than 0)
<x-dir><ydir>	number of points in each direction averaged before the illuminance is calculated

Obstruction data file (*obinfo*)

<obnum><obdiv>

<oblen><obwid><obhigh><posind><x-dist><y-dist><obref><obid>

<oblen><obwid><obhigh><posind><x-dist><y-dist><obref><obid>

<oblen><obwid><obhigh><posind><x-dist><y-dist><obref><obid>

<oblen><obwid><obhigh><posind><x-dist><y-dist><obref><obid>

<perimob>

Key:

line 1:	<obnum>	total number of obstructions
	<obdiv>	discretisation of obstruction surfaces

line 2: <oblen> obstruction length (metres)
<obwid> obstruction width (metres)
<obhigh> obstruction height (metres)
<posind> obstruction position indicator to which distance is measured
<x-dist> distance from origin in X-direction
<y-dist> distance from origin in Y-direction
<obref> obstruction reflection factor
<obnum> obstruction identification number
last line: <perimob> number of perimeter obstructions

Additional options (*runoptions*)

<outform>

Key:

<outform> indicates output format - 1 for short format, any other number for long format

A1.2 Example output

The following pages are the results of lighting simulation undertaken using the University of Liverpool lighting analysis program. The output is given is the short format. The program writes the output to a ASCII text file, named "g".

University of Liverpool, Lighting Analysis Program
^^

Analysis title:Test Run of Revised Program
testing
testing
one two three
Date: 14 Nov 95

Working plane height = 0.75 metres
Room length = 5.00 metres, Room width = 12.00 metres, Room height = 3.10 metres
Luminaire mounting height above working plane = 2.35
Installation Floor Area = 60.00

Room reflection factors:
^^^^^^^^^^^^^^^^^^^^^^^^

Ceiling = 0.70
Floor = 0.20
Wall 1 = 0.50
Wall 2 = 0.50

Wall 3 = 0.50
Wall 4 = 0.50
The average reflection factor of the walls = 0.50

Design Illuminance = 500 Lux
Maintenance Factor = 0.80

Room Index = 1.50

The Utilisation Factor used is 0.49
Total lamp output = 5600 lumens (per luminaire)

Total number of luminaires required (calculated by round method) = 14

SHRnom = 1.75
SHRmax = 1.89

Luminaire Positioning Calculations:
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
The luminaire length is 1.22 metres
The luminaire will be split into 3 equal sections
The minimum number of luminaires allowed in the x direction is 2
The minimum number of luminaires allowed in the y direction is 3
The total minimum number of luminaires possible is 6

Luminaires used to acheive design conditions:
^^^
Luminaires in X direction or length = 2
Luminaires in Y direction or width = 7

Installed SHR values:
^^^^^^^^^^^^^^^^^^^^^
In length: 1.06
In width: 0.73

Total number of perimeter and real obstructions:- 18

This is a linear luminaire
with a group 2 OL characteristic

Working plane calculation grid:
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
0.50 metre spacing
Start (X direction) = 0.25
(Y direction) = 0.25

End (X direction) = 4.75
(Y direction) = 11.75

Number of calculation points lengthwise = 9 widthwise = 23

The total average illuminance of the ceiling is = 13.92 Lux

WORKING PLANE ILLUMINANCE GRID FOR THE COMBINED DIRECT AND INDIRECT

COMPONENTS WITH NO OBSTRUCTIONS,

364	388	416	430	430	433	418	390	357
390	425	457	456	462	457	452	420	377
439	491	529	516	522	514	523	485	425
455	490	524	531	541	530	518	481	441
461	505	539	539	545	538	531	498	449
476	518	556	558	557	557	546	512	467
487	547	584	578	581	575	573	540	478
485	535	575	570	575	568	564	530	479
493	540	580	575	580	572	570	535	488
506	562	605	589	599	586	595	558	501
507	547	588	590	591	589	578	544	503
501	546	583	581	587	581	575	543	497
507	548	586	590	591	590	580	545	504
506	561	604	588	600	588	598	560	503
494	539	579	574	582	575	573	538	490
486	534	574	570	576	570	569	533	482
488	546	584	578	583	578	578	545	484
479	520	557	560	559	558	550	517	474
463	507	542	542	548	541	533	504	458
458	492	526	535	545	533	517	489	452
443	496	533	519	526	517	522	488	436
396	432	462	462	465	457	450	422	386
376	401	429	438	433	429	408	383	358

Y DIRECTION
1
1
1
——>X DIRECTION

AVERAGE ILLUMINANCE EQUALS 515 LUX

MINIMUM ILLUMINANCE EQUALS 357 LUX

MAXIMUM ILLUMINANCE EQUALS 605 LUX

MIN TO AVERAGE UNIFORMITY =0.694

MIN TO MAX UNIFORMITY =0.591

WORKING PLANE ILLUMINANCE GRID FOR THE COMBINED DIRECT AND INDIRECT
COMPONENTS WITH THE OBSTRUCTIONS DETAILED ABOVE.

364	379	413	401	373	404	415	381	357
386	410	447	369	271	370	441	404	372
435	460	448	408	0	407	442	453	420
447	454	389	404	400	406	382	444	431
458	500	493	341	346	339	485	493	446
472	507	488	0	0	0	480	500	462
484	543	557	524	511	520	550	536	474
482	527	567	556	556	553	556	521	474
493	524	571	548	538	546	561	520	488
501	553	593	474	321	472	583	548	496
503	536	532	466	0	464	527	531	498
492	533	432	467	446	467	428	529	488
503	535	526	343	342	342	518	532	499
502	547	538	0	0	0	536	544	498
489	534	547	495	501	494	545	533	485
481	527	559	539	540	537	552	525	478
488	535	569	553	555	552	563	532	484
475	516	549	512	442	511	540	513	470
461	474	491	387	0	385	485	470	454
450	457	388	469	458	467	382	452	442

439	479	480	276	275	275	467	470	431
391	413	407	0	0	0	400	403	381
371	393	377	307	275	297	360	373	353

Y DIRECTION
1
1
1
——>X DIRECTION

AVERAGE ILLUMINANCE EQUALS 466 LUX

MINIMUM ILLUMINANCE EQUALS 271 LUX

MAXIMUM ILLUMINANCE EQUALS 593 LUX

MIN TO AVERAGE UNIFORMITY =0.581

MIN TO MAX UNIFORMITY =0.456

Obstruction Loss (%) = 9.60
Total Vertical Surface Area = 0.96
Obstruction Density, VFR =0.0160

Analysis Stage 2
^^^^^^^^^^^^^^^^
Rotating the luminaires through 90 degrees:

This time the SHRnom = 1.75
This time the SHRmax = 2.42

Luminaire Positioning Calculations:
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
The luminaire length is 1.22 metres
The luminaire will be split into 3 equal sections
The minimum number of luminaires allowed in the x direction is 3
The minimum number of luminaires allowed in the y direction is 1
The total minimum number of luminaires possible is 3

Luminaires used to acheive design conditions:
^^
Luminaires in X direction or length = 7
Luminaires in Y direction or width = 2

Working plane calculation grid:
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
0.50 metre spacing

Start (X direction) = 0.25
(Y direction) = 0.25

End (X direction) = 11.75
(Y direction) = 4.75

Number of calculation points lengthwise = 23 widthwise = 9

The total average illuminance of the ceiling is = 13.78 Lux

WORKING PLANE ILLUMINANCE GRID FOR THE COMBINED DIRECT AND INDIRECT
COMPONENTS WITH NO OBSTRUCTIONS,

358	366	394	420	432	419	390	361	349
398	402	433	461	467	460	427	395	385
432	448	482	499	509	497	477	441	420
446	449	483	512	529	511	479	442	435
468	467	502	541	550	541	499	461	460
465	474	511	539	558	538	508	470	461
467	484	523	540	563	542	524	486	470
476	486	526	557	571	556	525	485	478
480	488	528	559	573	558	527	488	484
480	494	535	553	577	553	535	495	484
482	487	528	557	579	557	528	489	486
492	490	529	568	578	568	531	492	496
482	487	526	557	579	557	529	489	486
477	492	532	551	577	554	537	496	485
481	486	525	557	573	559	530	490	485
475	483	522	555	570	558	527	487	480
467	483	522	541	565	543	528	489	473
458	467	505	536	556	536	511	473	465
455	458	495	537	546	538	498	464	466
430	438	474	507	525	508	479	446	442
415	435	470	490	503	492	474	440	426
380	390	421	453	459	452	425	393	391

342	354	382	410	421	407	380	351	346

Y DIRECTION
1
1
1
——>X DIRECTION

AVERAGE ILLUMINANCE EQUALS 487 LUX

MINIMUM ILLUMINANCE EQUALS 342 LUX

MAXIMUM ILLUMINANCE EQUALS 579 LUX

MIN TO AVERAGE UNIFORMITY =0.702

MIN TO MAX UNIFORMITY =0.590

WORKING PLANE ILLUMINANCE GRID FOR THE COMBINED DIRECT AND INDIRECT
COMPONENTS WITH THE OBSTRUCTIONS DETAILED ABOVE.

361	358	393	403	400	402	389	353	349
395	388	427	387	310	386	420	380	381
430	426	403	398	0	396	397	418	416
439	409	336	396	416	399	330	400	425
467	463	430	270	277	268	427	457	457
462	463	428	0	0	0	423	458	457
464	481	502	486	505	484	498	481	466
473	478	518	544	555	543	517	477	473
480	473	520	537	543	537	519	475	484
476	486	523	443	314	443	524	487	480
477	475	451	439	0	440	452	477	481
482	461	362	478	475	478	365	465	487
477	475	462	330	344	330	466	478	482
473	479	462	0	0	0	467	482	481

476	481	496	500	517	502	501	485	481
470	474	510	534	543	535	514	478	475
467	472	509	522	546	524	515	477	473
454	464	497	457	356	459	503	470	462
453	423	442	410	0	411	447	431	463
423	410	325	453	464	452	331	418	435
410	419	408	249	262	250	412	423	422
375	371	338	0	0	0	344	376	387
336	346	333	334	296	332	332	344	341

Y DIRECTION
1
1
1
----->X DIRECTION

AVERAGE ILLUMINANCE EQUALS 437 LUX

MINIMUM ILLUMINANCE EQUALS 249 LUX

MAXIMUM ILLUMINANCE EQUALS 555 LUX

MIN TO AVERAGE UNIFORMITY =0.569

MIN TO MAX UNIFORMITY =0.449

Obstruction Loss (%) = 10.16
Total Vertical Surface Area = 0.96
Obstruction Density, VFR =0.0160

Appendix Two

Results of statistical analysis of OL/VFR data for 16 categories of luminaire

Regression Summary
group 1 OL (room index 1.00) vs. VFR

Count	108
Num. Missing	0
R	.982
R Squared	.965
Adjusted R Squared	.965
RMS Residual	2.177

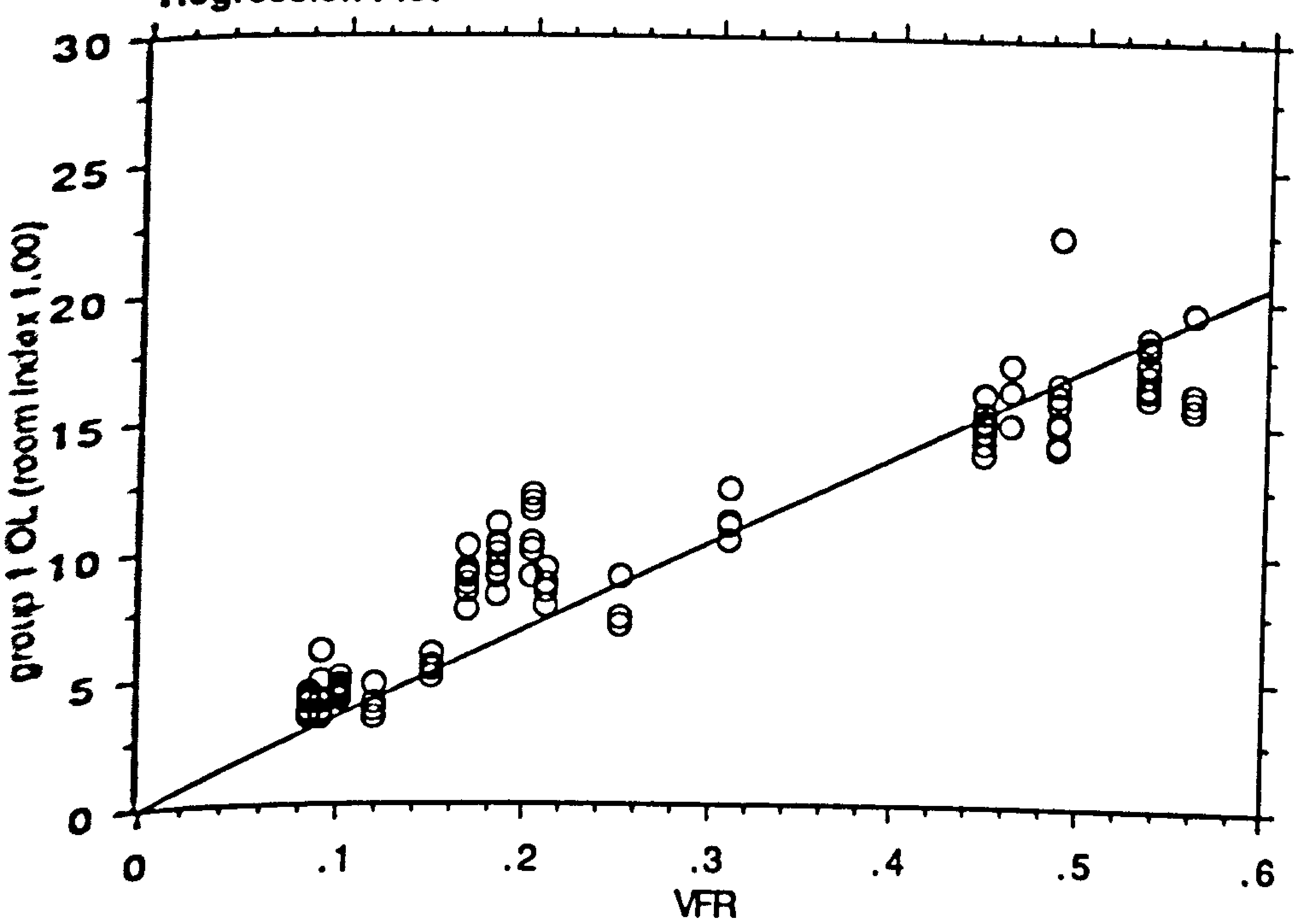
ANOVA Table
group 1 OL (room index 1.00) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	14002.500	14002.500	2953.602	<.0001
Residual	107	507.268	4.741		
Total	108	14509.768			

Regression Coefficients
group 1 OL (room index 1.00) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.368	.632	1.179	54.347	<.0001

Regression Plot



Y = 0 + 34.368 * X; R^2 = .965

Regression Summary
group 1 OL (room index 1.25) vs. VFR

Count	108
Num. Missing	0
R	.988
R Squared	.976
Adjusted R Squared	.976
RMS Residual	1.860

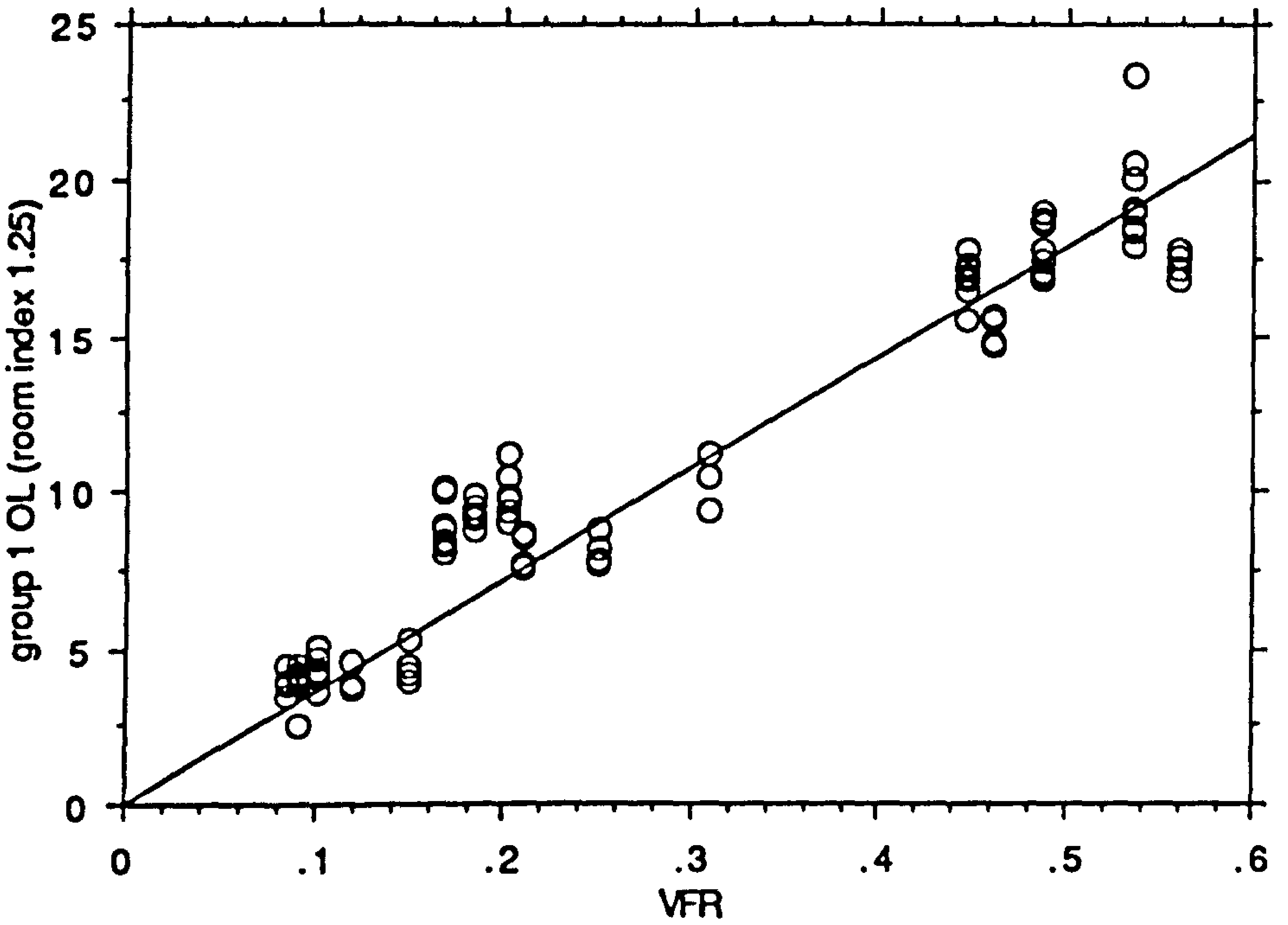
ANOVA Table
group 1 OL (room index 1.25) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	15235.493	15235.493	4405.880	<.0001
Residual	107	370.005	3.458		
Total	108	15605.498			

Regression Coefficients
group 1 OL (room index 1.25) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.850	.540	1.113	66.377	<.0001

Regression Plot



Y = 0 + 35.85 * X; R^2 = .976

Regression Summary
group 1 OL (room index 1.5) vs. VFR

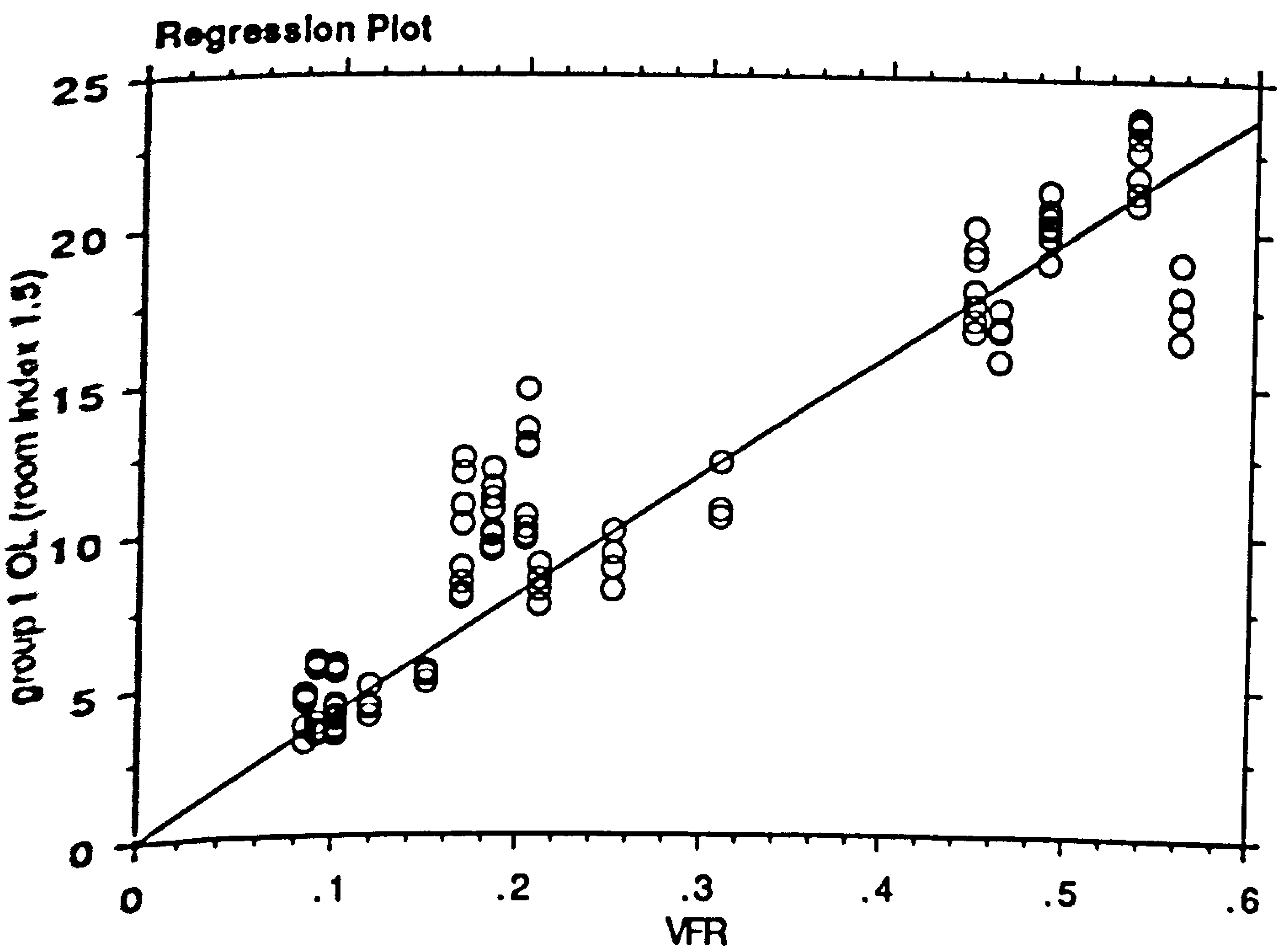
Count	108
Num. Missing	0
R	.983
R Squared	.966
Adjusted R Squared	.966
RMS Residual	2.480

ANOVA Table
group 1 OL (room index 1.5) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	18623.217	18623.217	3028.493	<.0001
Residual	107	657.979	6.149		
Total	108	19281.195			

Regression Coefficients
group 1 OL (room index 1.5) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.636	.720	1.095	55.032	<.0001



$Y = 0 + 39.636 * X; R^2 = .966$

Regression Summary
group 1 OL (room Index 2.0) vs. VFR

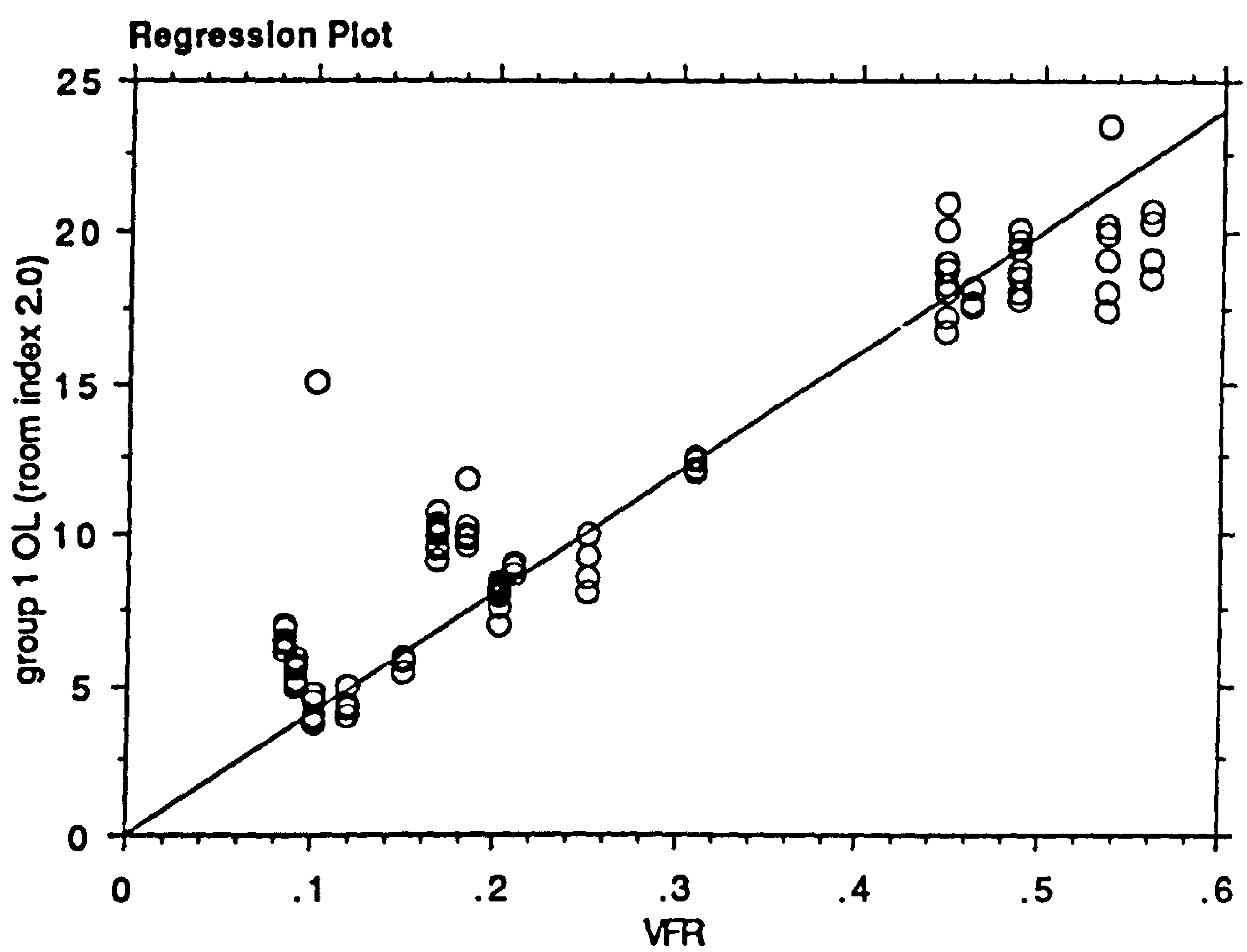
Count	108
Num. Missing	0
R	.987
R Squared	.974
Adjusted R Squared	.973
RMS Residual	2.193

ANOVA Table
group 1 OL (room Index 2.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	18974.356	18974.356	3945.173	<.0001
Residual	107	514.618	4.810		
Total	108	19488.974			

Regression Coefficients
group 1 OL (room Index 2.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	40.007	.637	1.117	62.811	<.0001



Y = 0 + 40.007 * X; R^2 = .974

Regression Summary
group 1 OL (room index 3.0) vs. VFR

Count	72
Num. Missing	0
R	.988
R Squared	.976
Adjusted R Squared	.975
RMS Residual	2.110

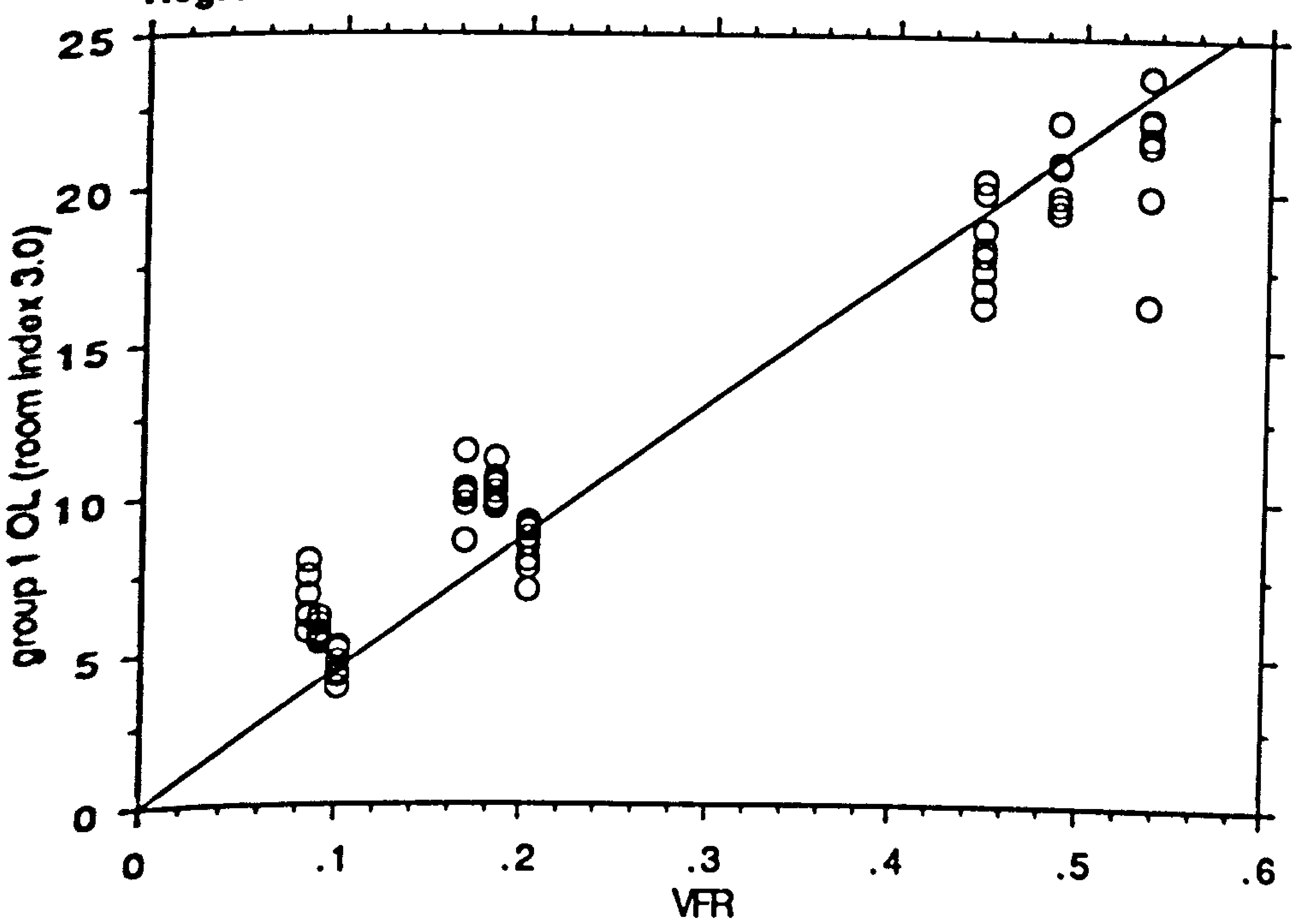
ANOVA Table
group 1 OL (room index 3.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	12682.223	12682.223	2848.535	<.0001
Residual	71	316.106	4.452		
Total	72	12998.329			

Regression Coefficients
group 1 OL (room index 3.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	43.201	.809	1.161	53.372	<.0001

Regression Plot



Y = 0 + 43.201 * X; R^2 = .976

Regression Summary
group 1 OL (room Index 4.0) vs. VFR

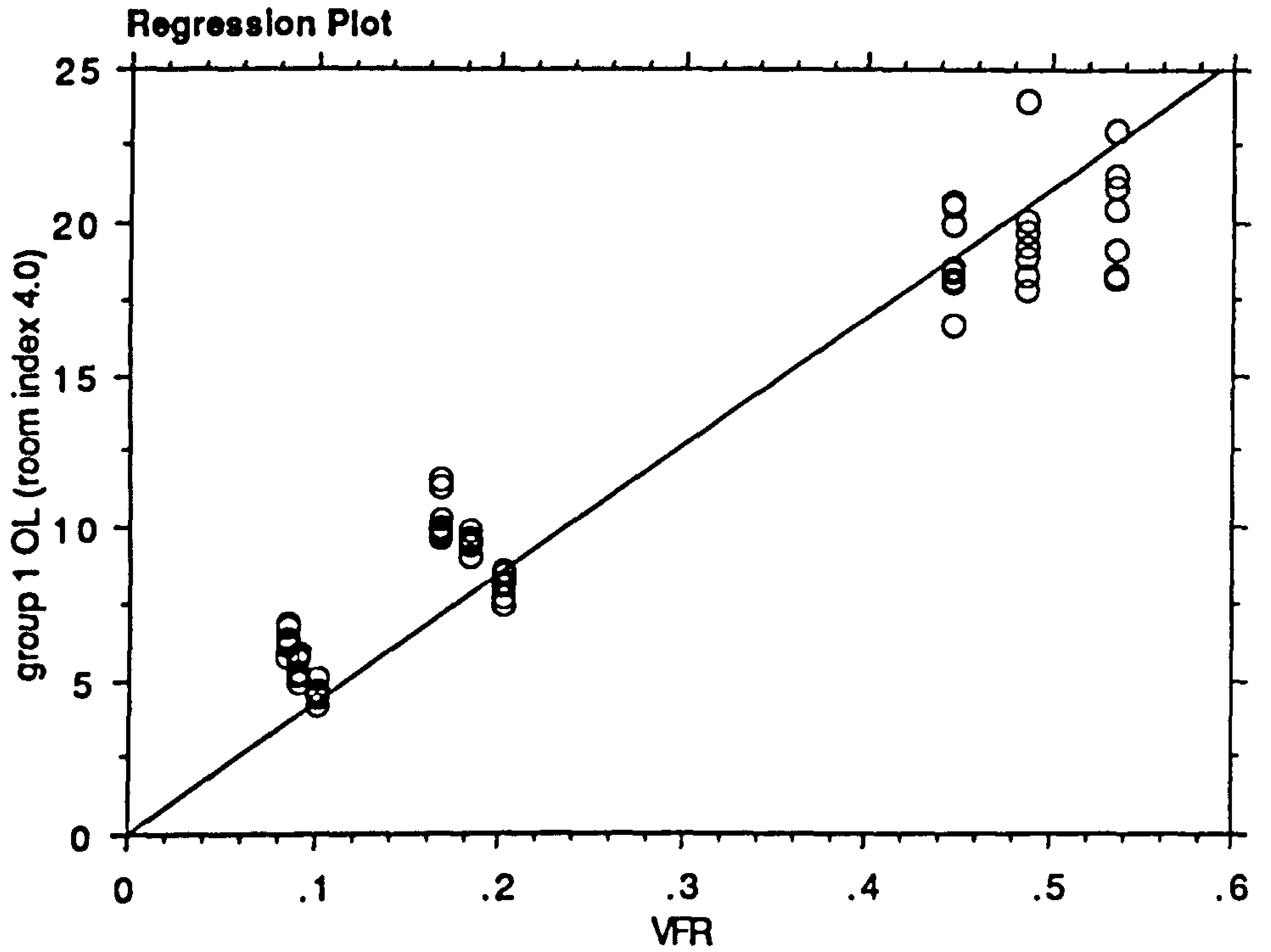
Count	72
Num. Missing	0
R	.988
R Squared	.975
Adjusted R Squared	.975
RMS Residual	2.073

ANOVA Table
group 1 OL (room Index 4.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	12141.374	12141.374	2824.409	<.0001
Residual	71	305.210	4.299		
Total	72	12446.584			

Regression Coefficients
group 1 OL (room Index 4.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	42.270	.795	1.156	53.145	<.0001



Y = 0 + 42.27 * X; R^2 = .975

Regression Summary
group 1 OL (room Index 5.0) vs. VFR

Count	64
Num. Missing	8
R	.989
R Squared	.978
Adjusted R Squared	.978
RMS Residual	1.860

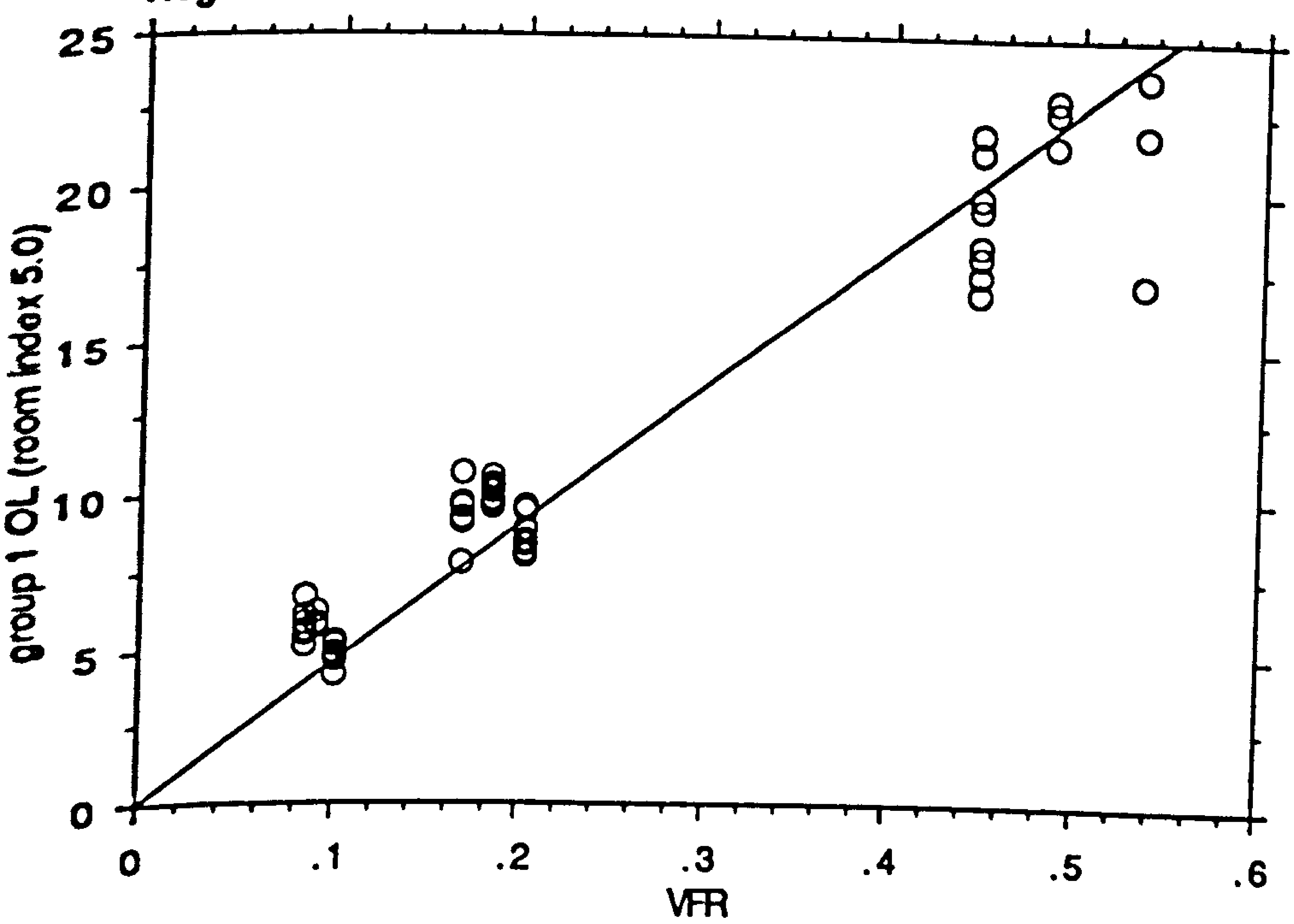
ANOVA Table
group 1 OL (room Index 5.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9638.341	9638.341	2786.090	<.0001
Residual	63	217.945	3.459		
Total	64	9856.286			

Regression Coefficients
group 1 OL (room Index 5.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	45.253	.857	1.132	52.783	<.0001

Regression Plot



Y = 0 + 45.253 * X; R^2 = .978

Regression Summary
Obstruction Loss, Group 2, Room Index 1 vs. VFR

Count	90
Num. Missing	0
R	.981
R Squared	.963
Adjusted R Squared	.962
RMS Residual	2.223

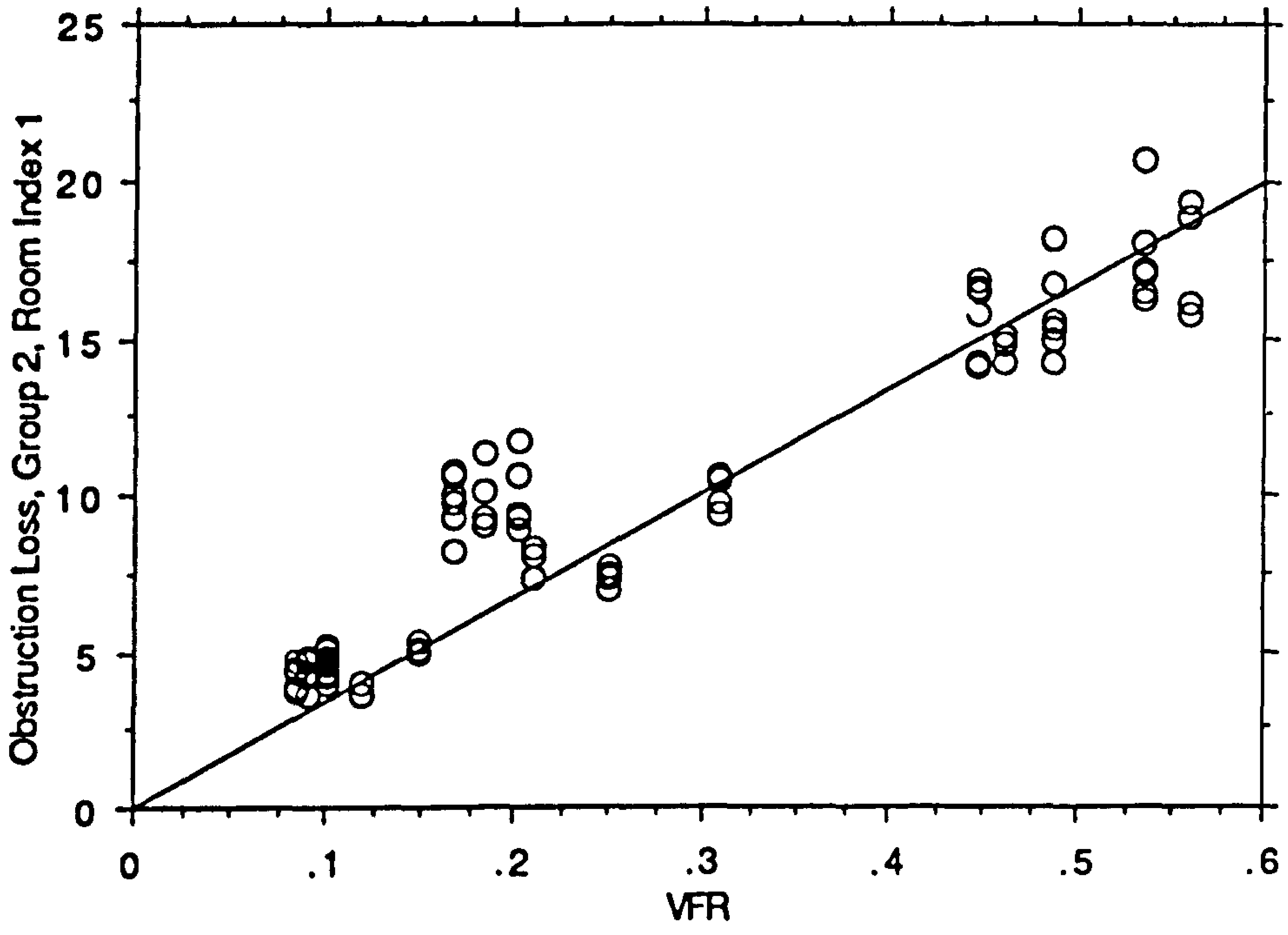
ANOVA Table
Obstruction Loss, Group 2, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	11355.758	11355.758	2298.480	<.0001
Residual	89	439.709	4.941		
Total	90	11795.467			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.440	.697	1.178	47.942	<.0001

Regression Plot



Y = 0 + 33.44 * X; R^2 = .963

Regression Summary
Obstruction Loss, Group 2, Room Index 1.25 vs. VFR

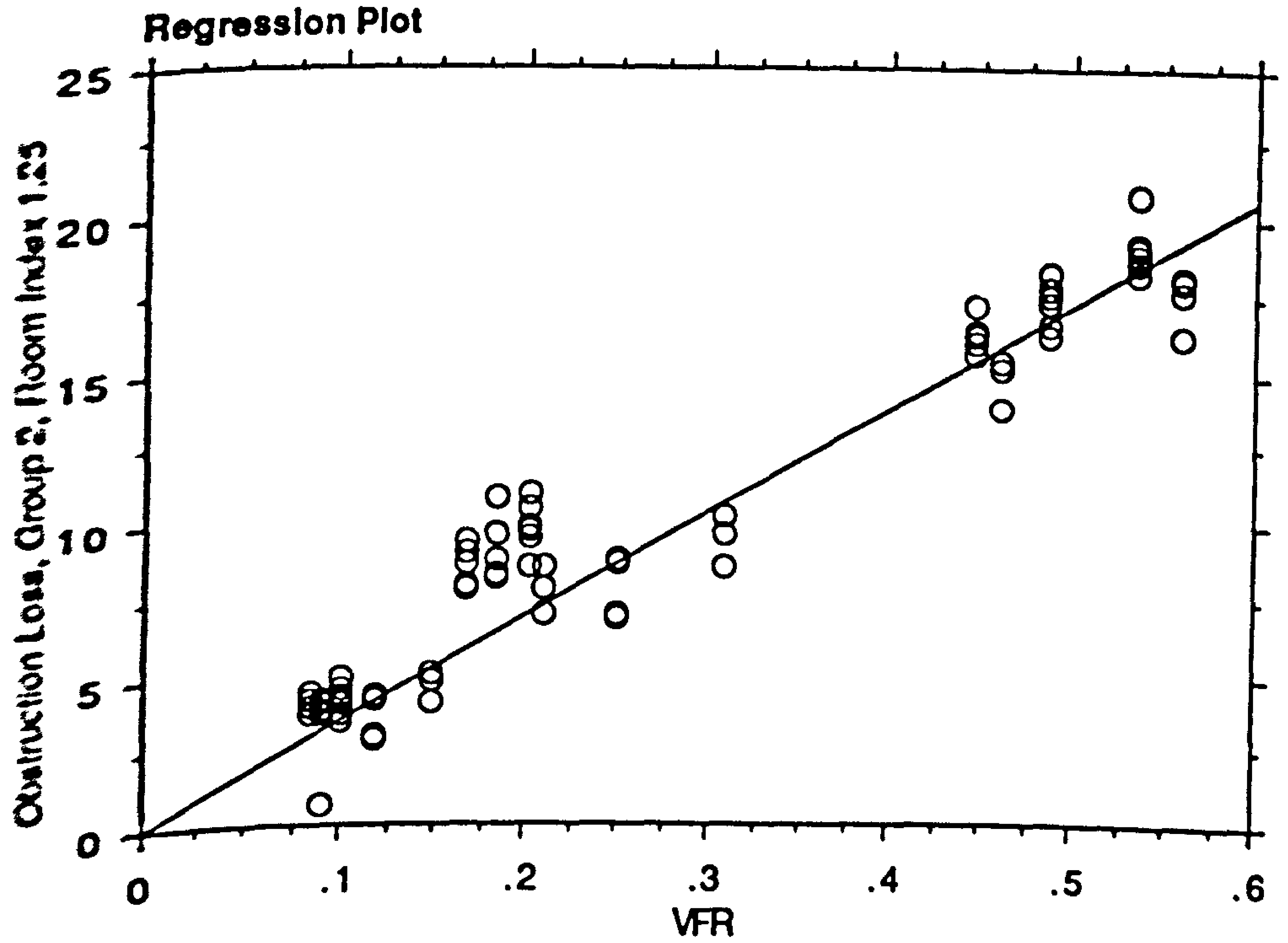
Count	90
Num. Missing	0
R	.987
R Squared	.973
Adjusted R Squared	.973
RMS Residual	1.929

ANOVA Table
Obstruction Loss, Group 2, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	12033.575	12033.575	3234.577	<.0001
Residual	89	331.106	3.720		
Total	90	12364.681			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.423	.605	1.109	56.873	<.0001



$Y = 0 + 34.423 * X; R^2 = .973$

Regression Summary
Obstruction Loss, Group 2, Room Index 1.5 vs. VFR

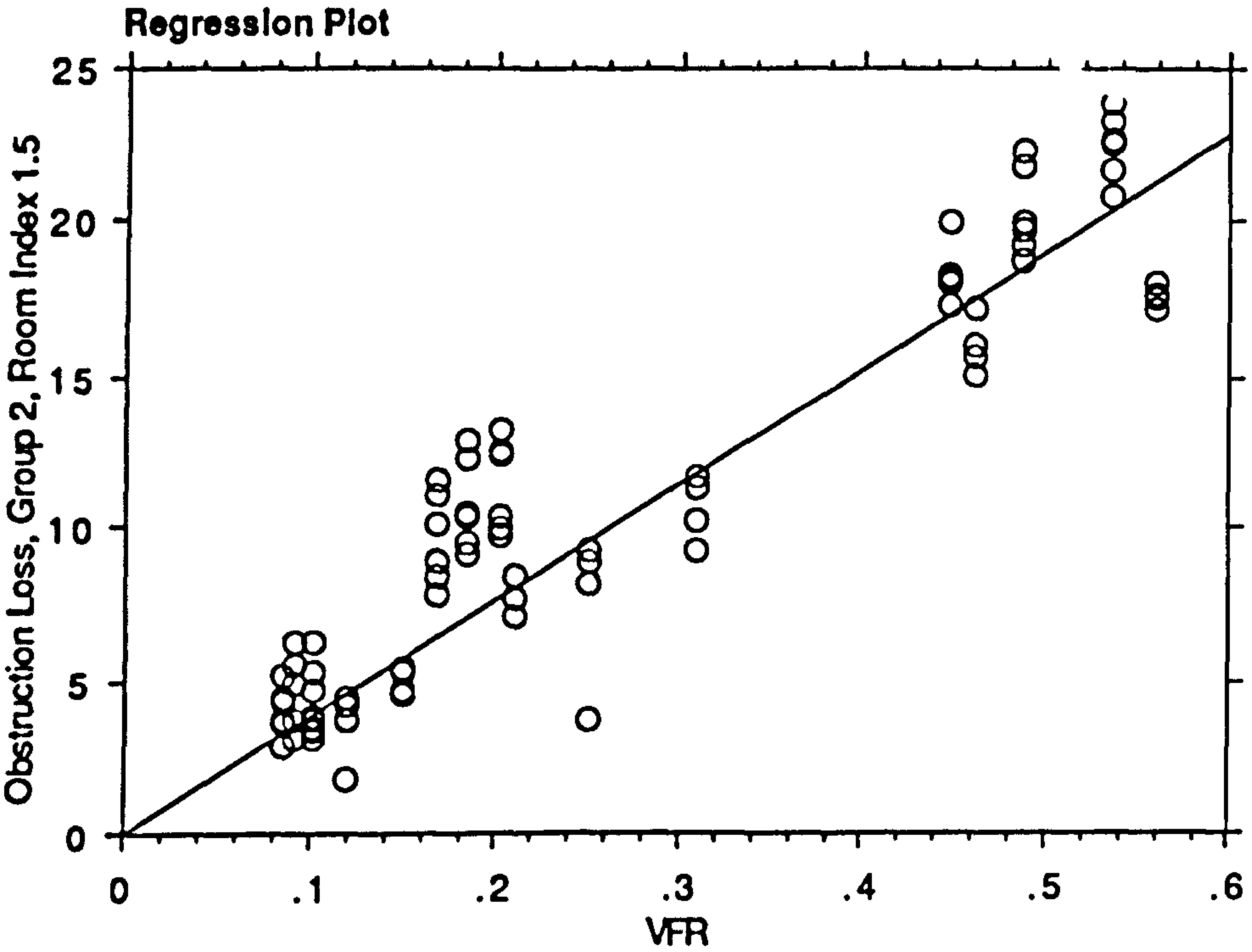
Count	90
Num. Missing	0
R	.980
R Squared	.960
Adjusted R Squared	.959
RMS Residual	2.629

ANOVA Table
Obstruction Loss, Group 2, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	14682.712	14682.712	2124.162	<.0001
Residual	89	615.189	6.912		
Total	90	15297.901			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.024	.825	1.065	46.089	<.0001



Y = 0 + 38.024 * X; R^2 = .96

Regression Summary
Obstruction Loss, Group 2, Room Index 2 vs. VFR

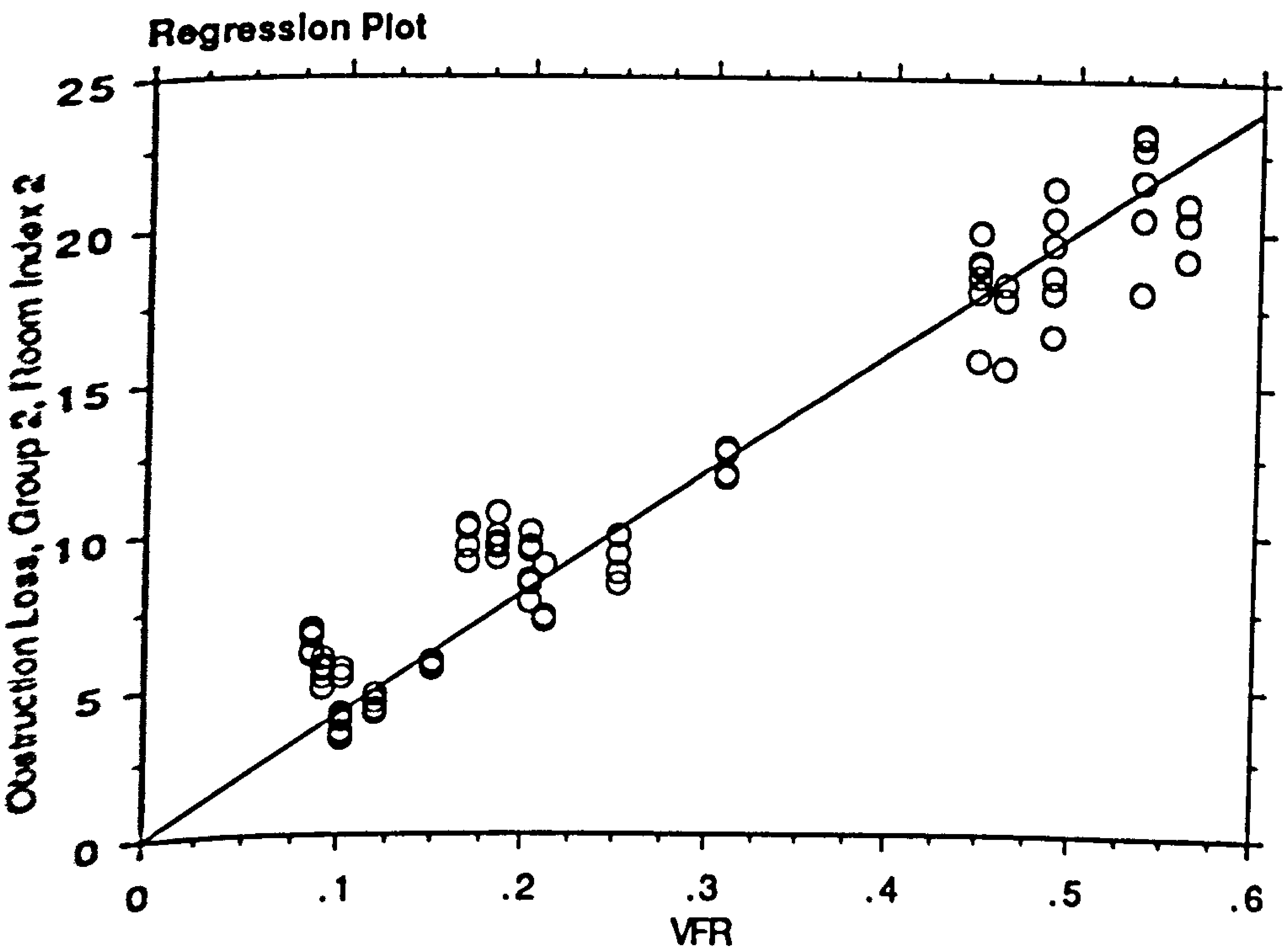
Count	89
Num. Missing	1
R	.991
R Squared	.983
Adjusted R Squared	.983
RMS Residual	1.799

ANOVA Table
Obstruction Loss, Group 2, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	16192.067	16192.067	5002.809	<.0001
Residual	88	284.820	3.237		
Total	89	16476.887			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.987	.565	1.087	70.731	<.0001



Y = 0 + 39.987 * X; R^2 = .983

Regression Summary
Obstruction Loss, Group 2, Room Index 3 vs. VFR

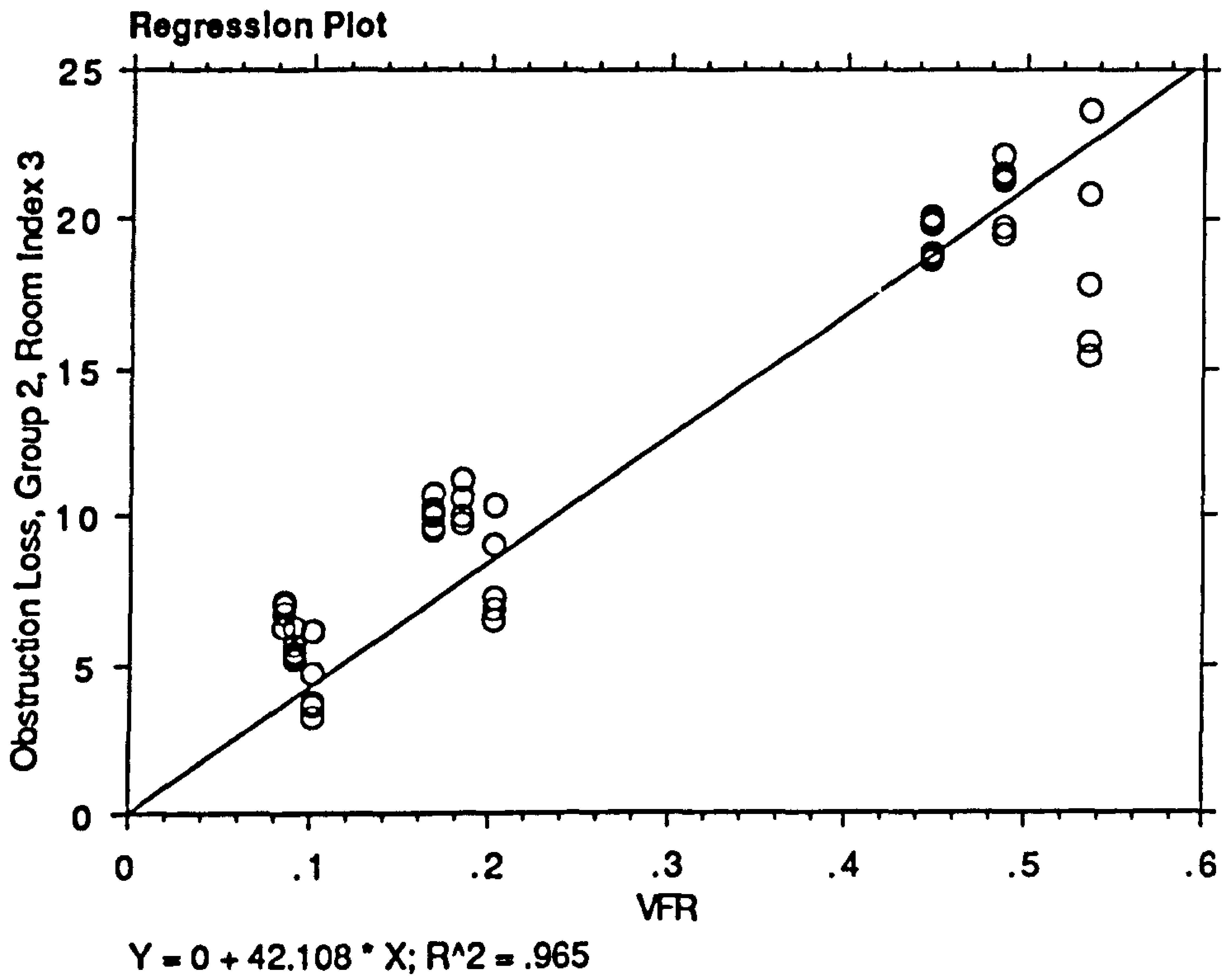
Count	54
Num. Missing	0
R	.982
R Squared	.965
Adjusted R Squared	.965
RMS Residual	2.477

ANOVA Table
Obstruction Loss, Group 2, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9035.537	9035.537	1473.217	<.0001
Residual	53	325.060	6.133		
Total	54	9360.597			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	42.108	1.097	1.147	38.383	<.0001



Regression Summary
Obstruction Loss, Group 2, Room Index 4 vs. VFR

Count	54
Num. Missing	0
R	.986
R Squared	.972
Adjusted R Squared	.972
RMS Residual	2.213

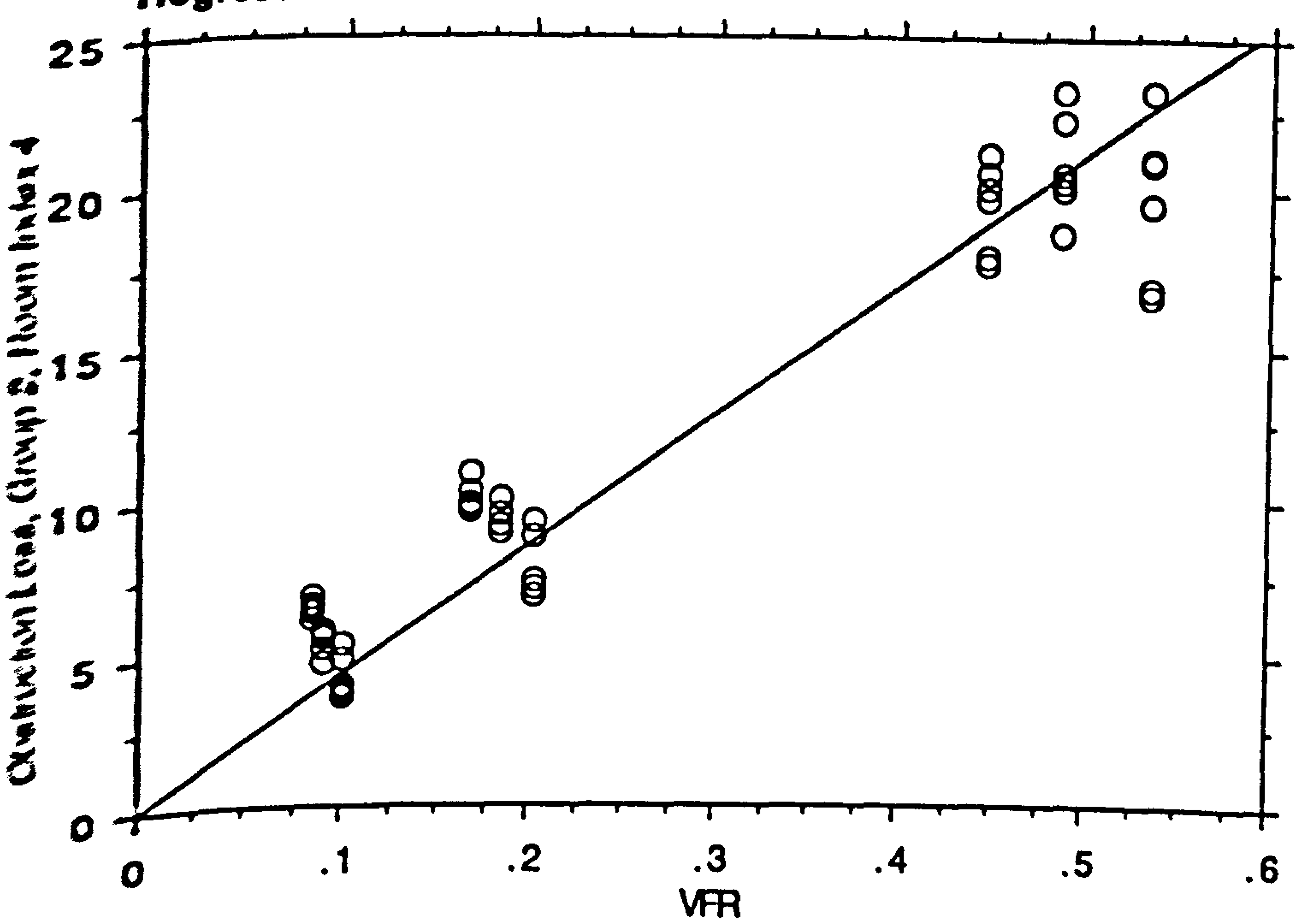
ANOVA Table
Obstruction Loss, Group 2, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9149.750	9149.750	1868.734	<.0001
Residual	53	259.500	4.896		
Total	54	9409.250			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	42.373	.980	1.128	43.229	<.0001

Regression Plot



Y = 0 + 42.373 * X; R^2 = .972

Regression Summary
Obstruction Loss, Group 2, Room Index 5 vs. VFR

Count	48
Num. Missing	6
R	.991
R Squared	.981
Adjusted R Squared	.981
RMS Residual	1.735

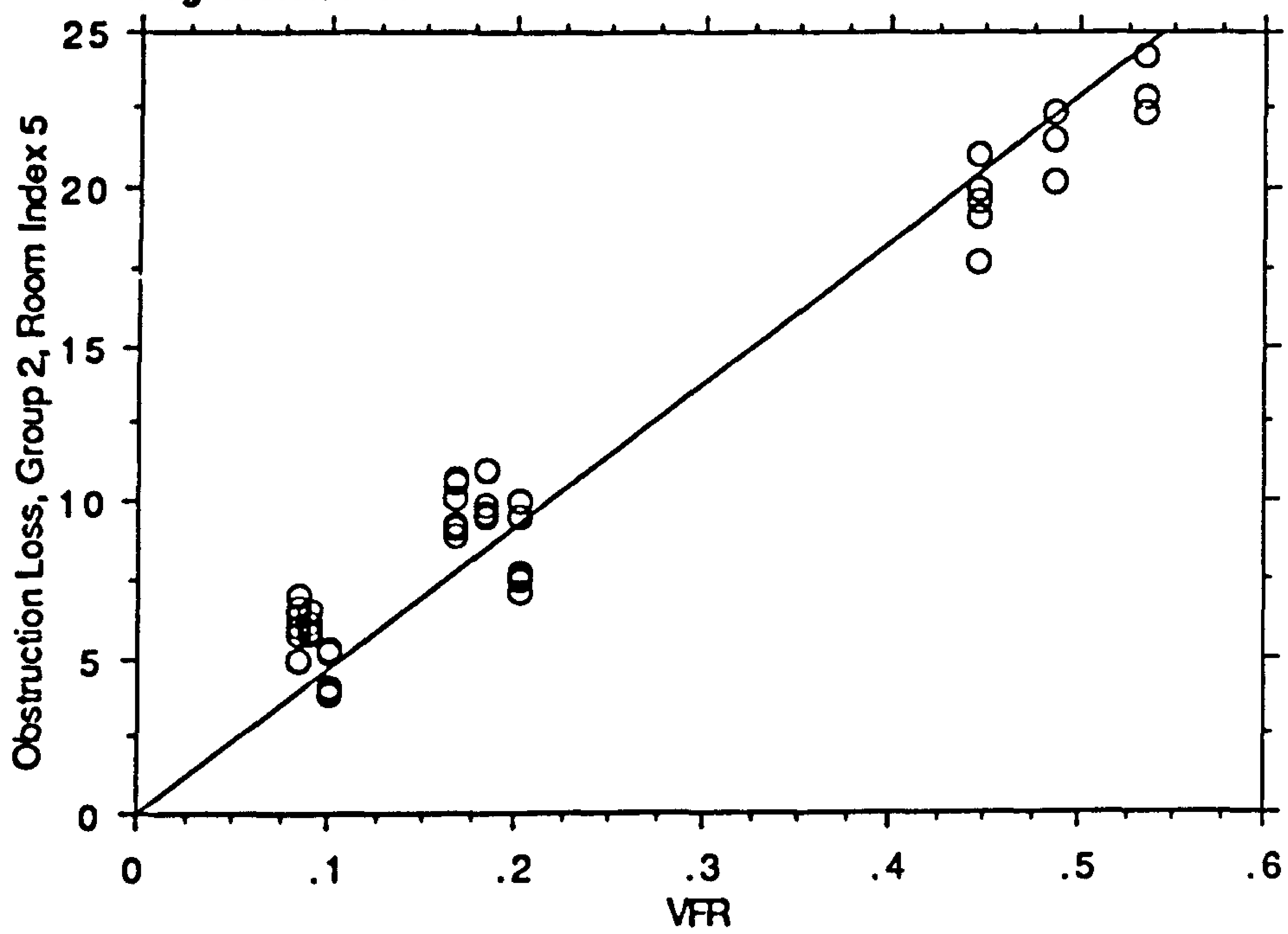
ANOVA Table
Obstruction Loss, Group 2, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7415.803	7415.803	2463.557	<.0001
Residual	47	141.479	3.010		
Total	48	7557.283			

Regression Coefficients
Obstruction Loss, Group 2, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	45.838	.924	1.125	49.634	<.0001

Regression Plot



Y = 0 + 45.838 * X; R^2 = .981

Regression Summary
Obstruction Loss, Group 3, Room Index 1 vs. VFR

Count	63
Num. Missing	0
R	.977
R Squared	.955
Adjusted R Squared	.954
RMS Residual	2.464

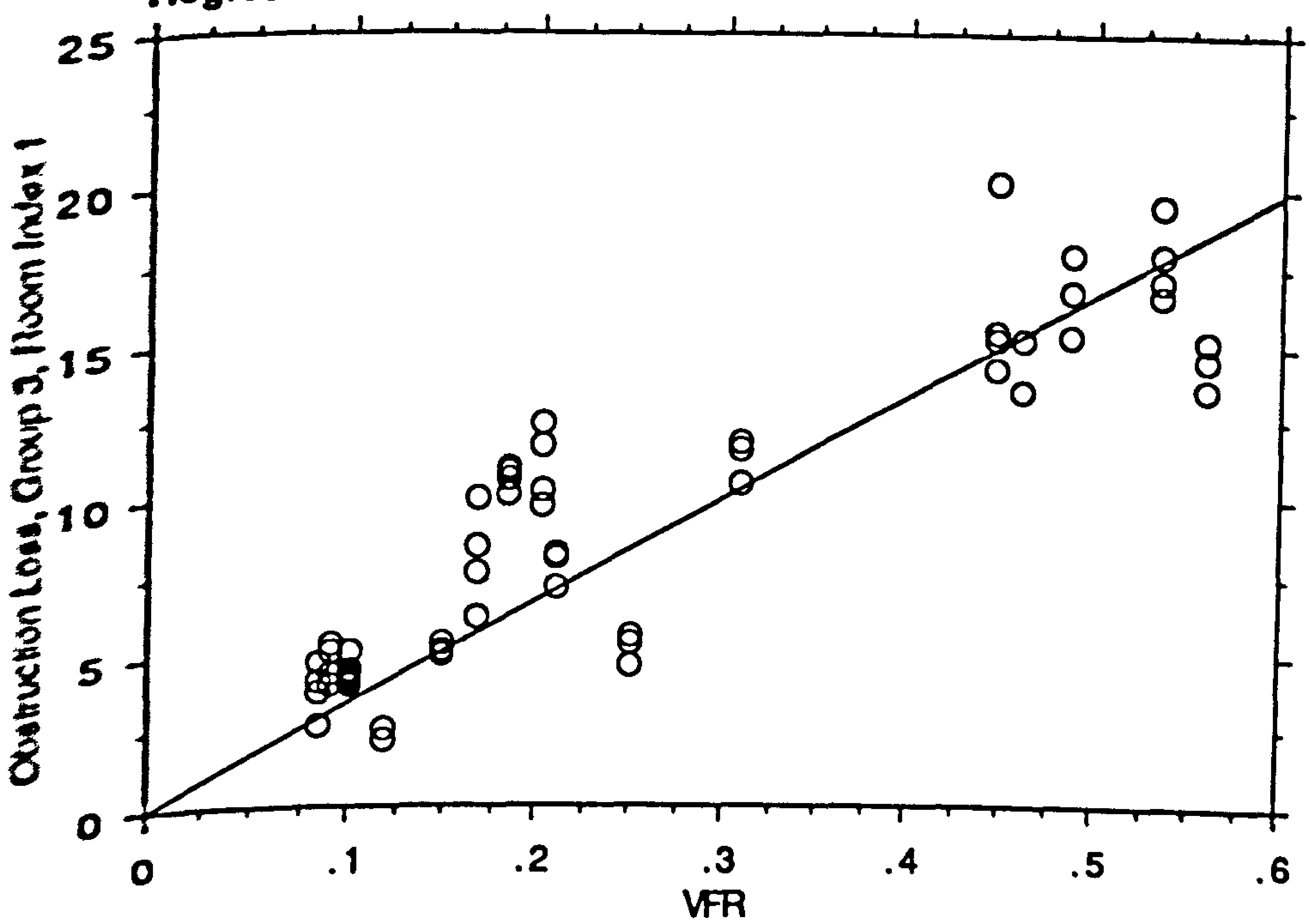
ANOVA Table
Obstruction Loss, Group 3, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7948.745	7948.745	1308.820	<.0001
Residual	62	376.539	6.073		
Total	63	8325.285			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.245	.919	1.105	36.178	<.0001

Regression Plot



Y = 0 + 33.245 * X; R^2 = .955

Regression Summary
Obstruction Loss, Group 3, Room Index 1.25 vs. VFR

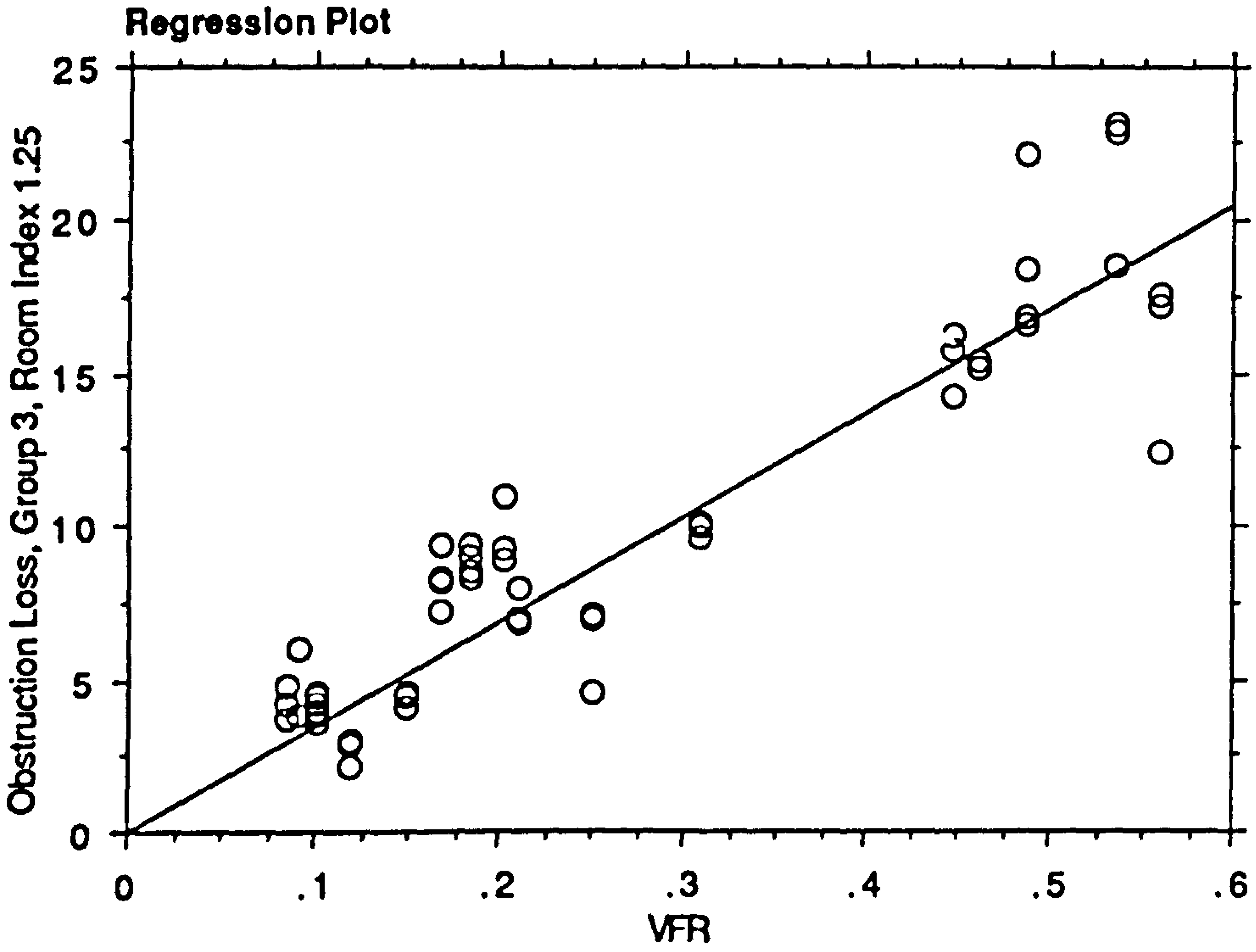
Count	62
Num. Missing	1
R	.981
R Squared	.962
Adjusted R Squared	.962
RMS Residual	2.283

ANOVA Table
Obstruction Loss, Group 3, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8131.241	8131.241	1560.687	<.0001
Residual	61	317.812	5.210		
Total	62	8449.053			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.314	.869	1.052	39.506	<.0001



Y = 0 + 34.314 * X; R^2 = .962

Regression Summary
Obstruction Loss, Group 3, Room Index 1.5 vs. VFR

Count	63
Num. Missing	0
R	.979
R Squared	.958
Adjusted R Squared	.957
RMS Residual	2.559

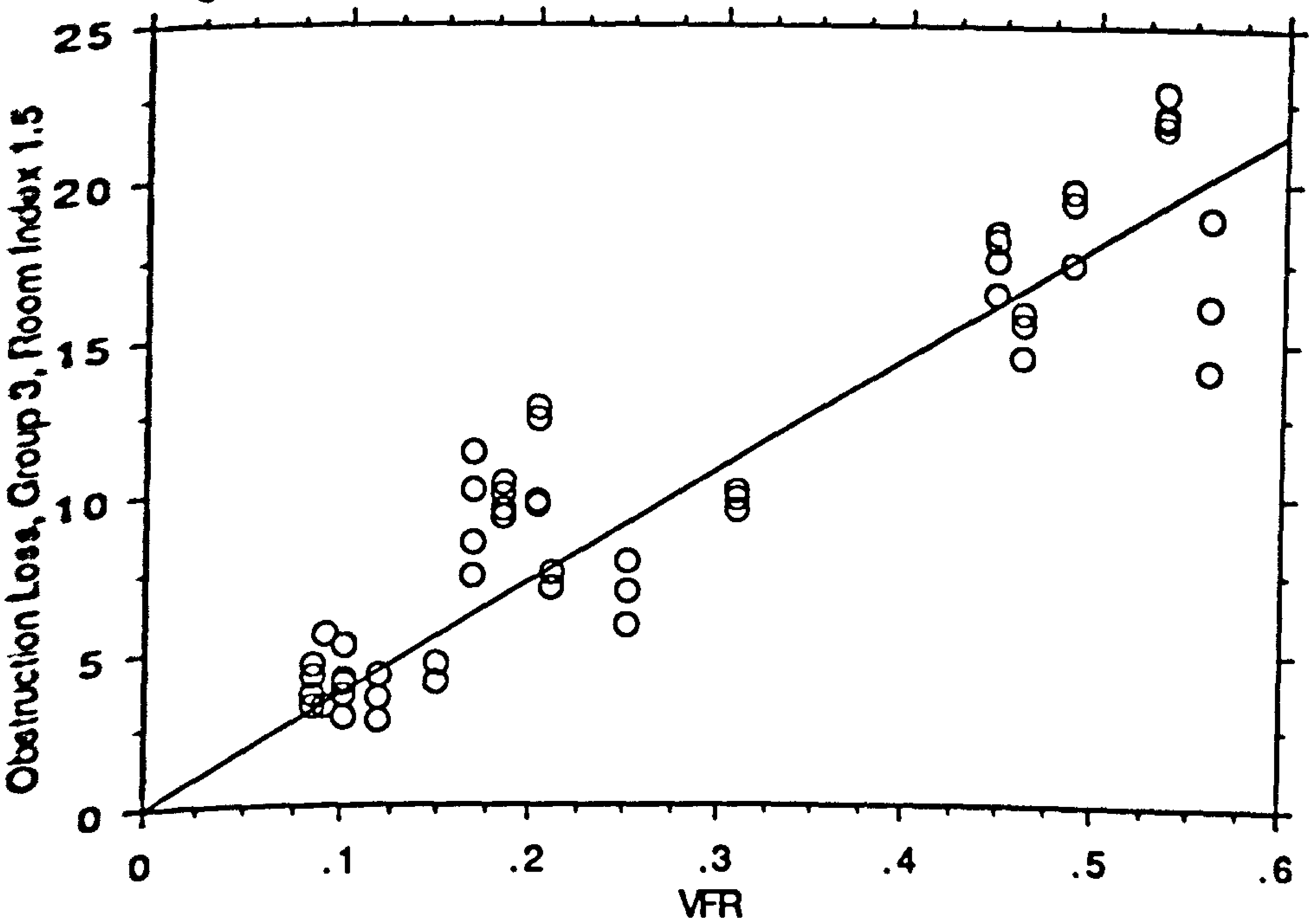
ANOVA Table
Obstruction Loss, Group 3, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9288.212	9288.212	1418.844	<.0001
Residual	62	405.872	6.546		
Total	63	9694.084			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.938	.954	1.054	37.668	<.0001

Regression Plot



Y = 0 + 35.938 * X; R^2 = .958

Regression Summary
Obstruction Loss, Group 3, Room Index 2 vs. VFR

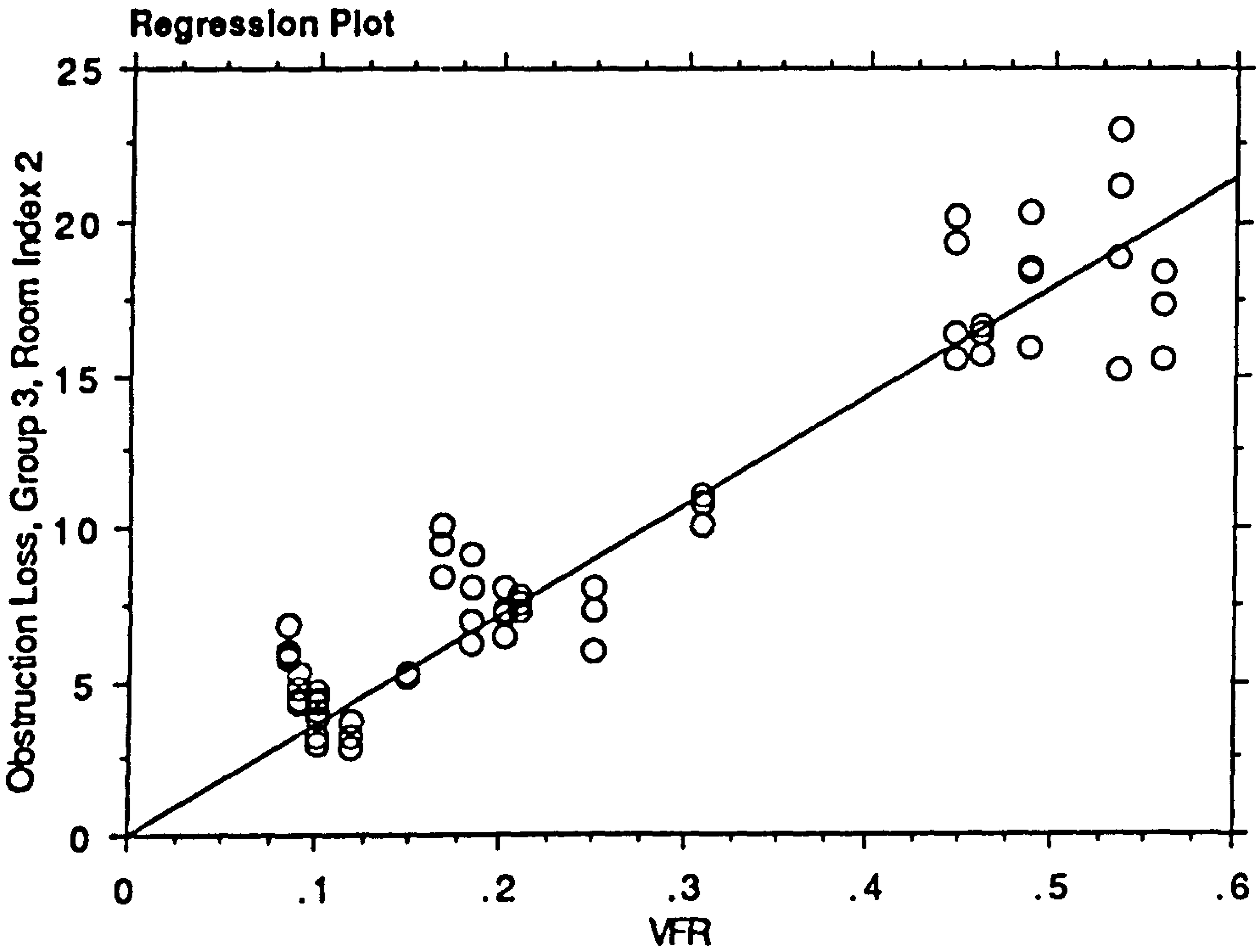
Count	63
Num. Missing	0
R	.987
R Squared	.974
Adjusted R Squared	.973
RMS Residual	1.996

ANOVA Table
Obstruction Loss, Group 3, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9189.735	9189.735	2307.593	<.0001
Residual	62	246.908	3.982		
Total	63	9436.644			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.747	.744	1.064	48.037	<.0001



Y = 0 + 35.747 * X; R^2 = .974

Regression Summary
Obstruction Loss, Group 3, Room Index 3 vs. VFR

Count	36
Num. Missing	0
R	.984
R Squared	.968
Adjusted R Squared	.968
RMS Residual	2.219

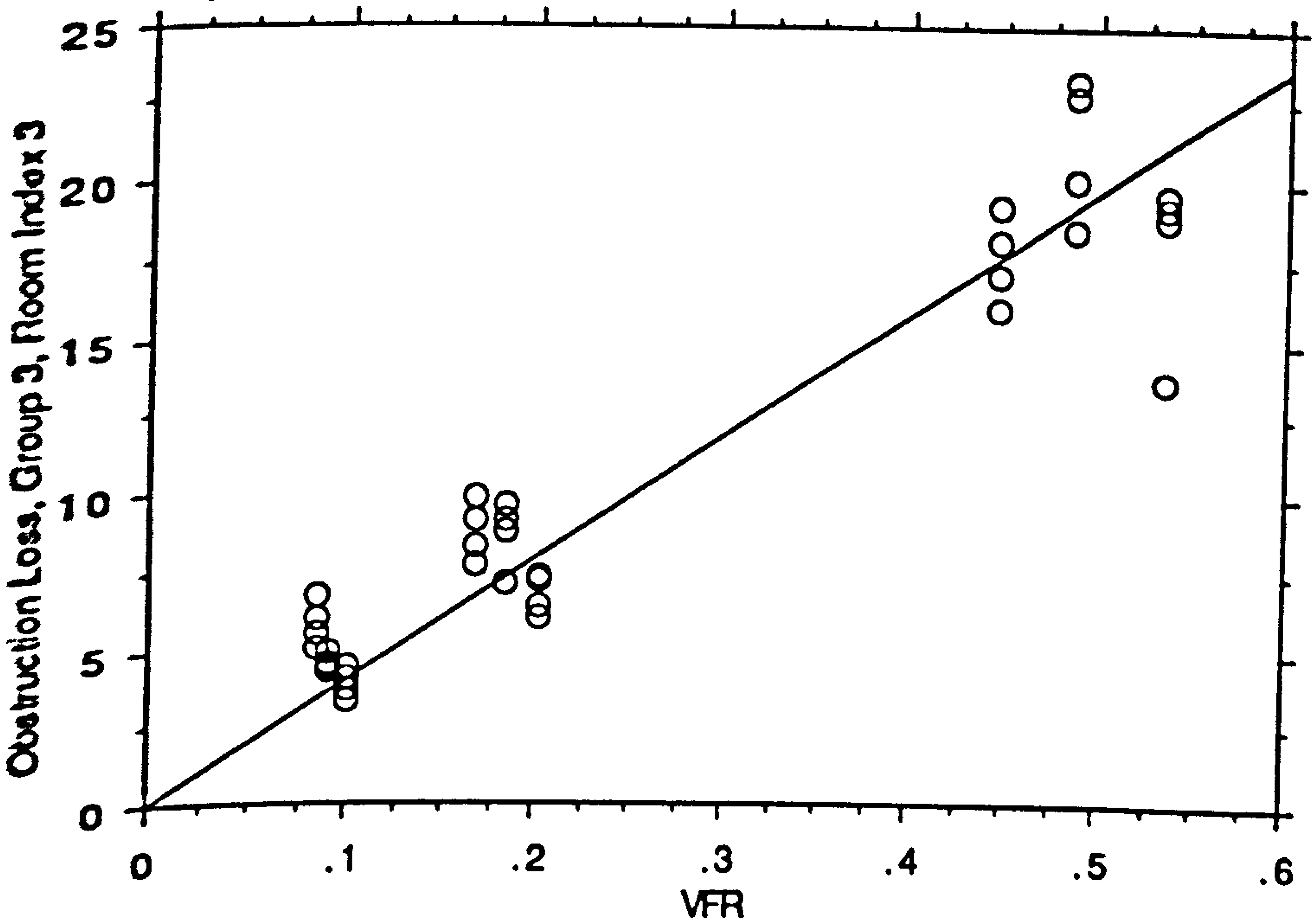
ANOVA Table
Obstruction Loss, Group 3, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5290.188	5290.188	1073.974	<.0001
Residual	35	172.403	4.926		
Total	36	5462.591			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.461	1.204	1.075	32.772	<.0001

Regression Plot



Y = 0 + 39.461 * X; R^2 = .968

Regression Summary
Obstruction Loss, Group 3, Room Index 4 vs. VFR

Count	36
Num. Missing	0
R	.992
R Squared	.983
Adjusted R Squared	.983
RMS Residual	1.613

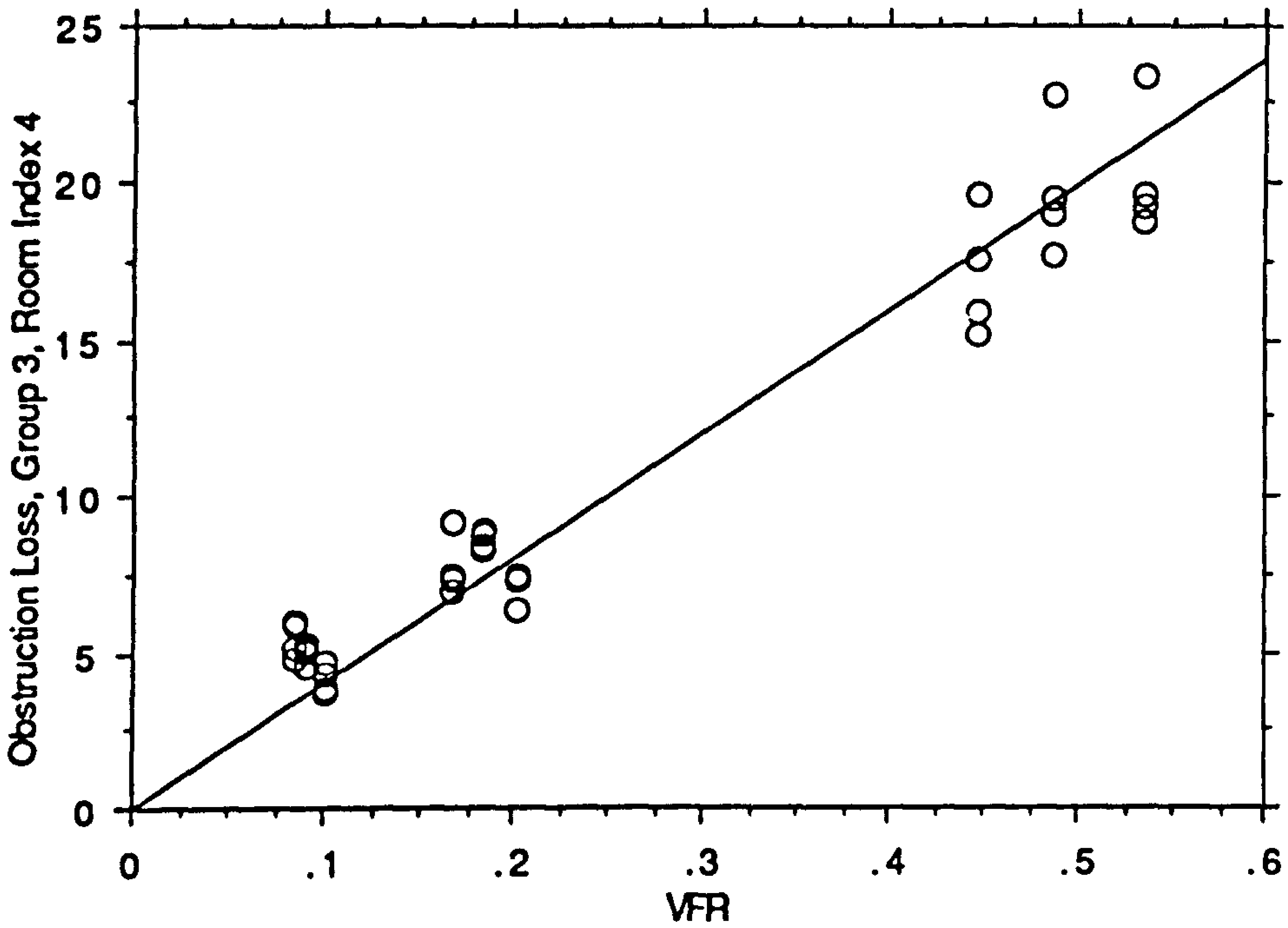
ANOVA Table
Obstruction Loss, Group 3, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5376.208	5376.208	2065.840	<.0001
Residual	35	91.085	2.602		
Total	36	5467.293			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.780	.875	1.083	45.452	<.0001

Regression Plot



Y = 0 + 39.78 * X; R^2 = .983

Regression Summary
Obstruction Loss, Group 3, Room Index 5 vs. VFR

Count	32
Num. Missing	4
R	.990
R Squared	.980
Adjusted R Squared	.980
RMS Residual	1.608

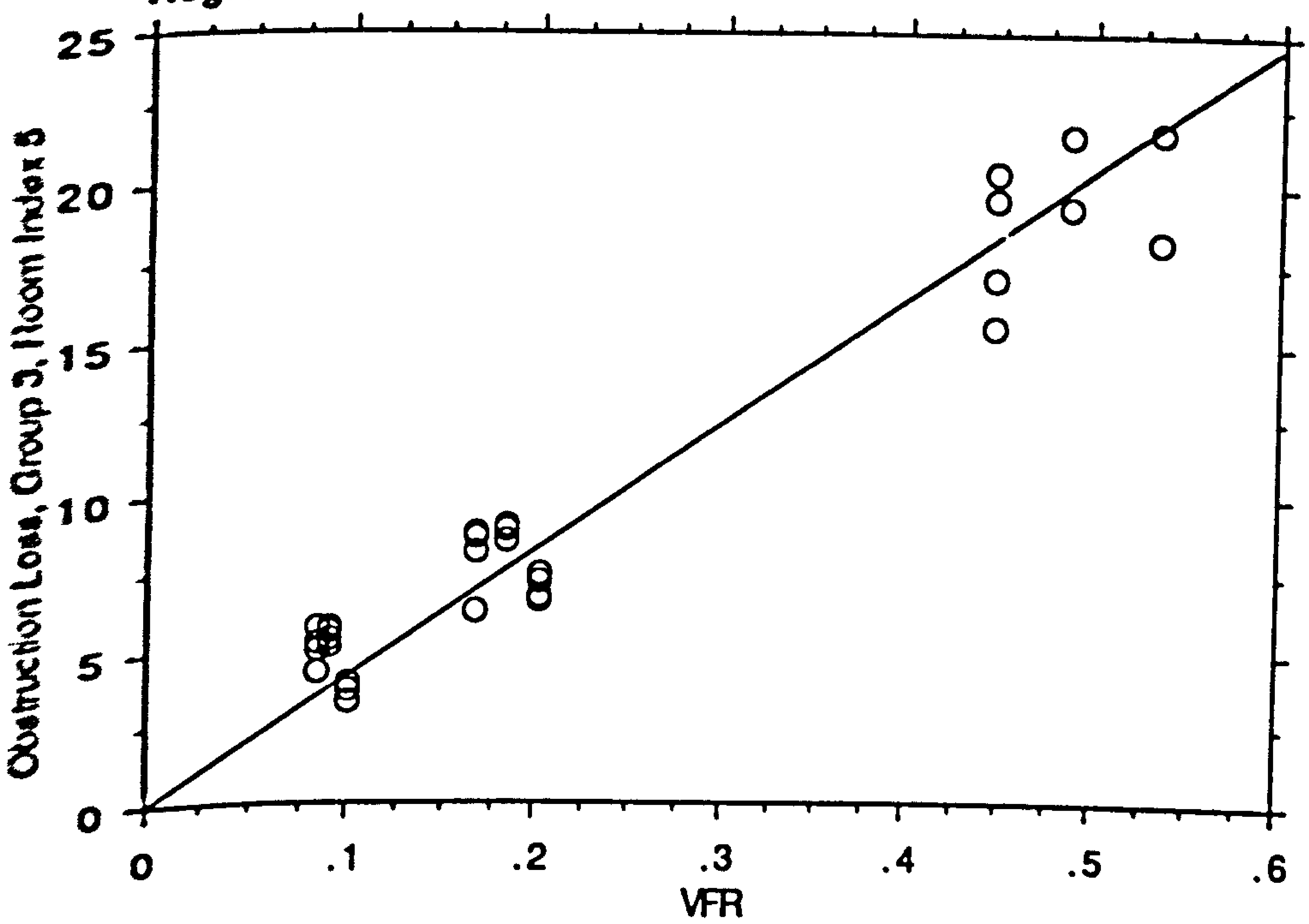
ANOVA Table
Obstruction Loss, Group 3, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3984.623	3984.623	1.54E3	<.0001
Residual	31	80.178	2.586		
Total	32	4064.801			

Regression Coefficients
Obstruction Loss, Group 3, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	41.152	1.048	1.073	3.93E1	<.0001

Regression Plot



Y = 0 + 41.152 * X; R^2 = .98

Regression Summary
Obstruction Loss, Group 4, Room Index 1 vs. VFR

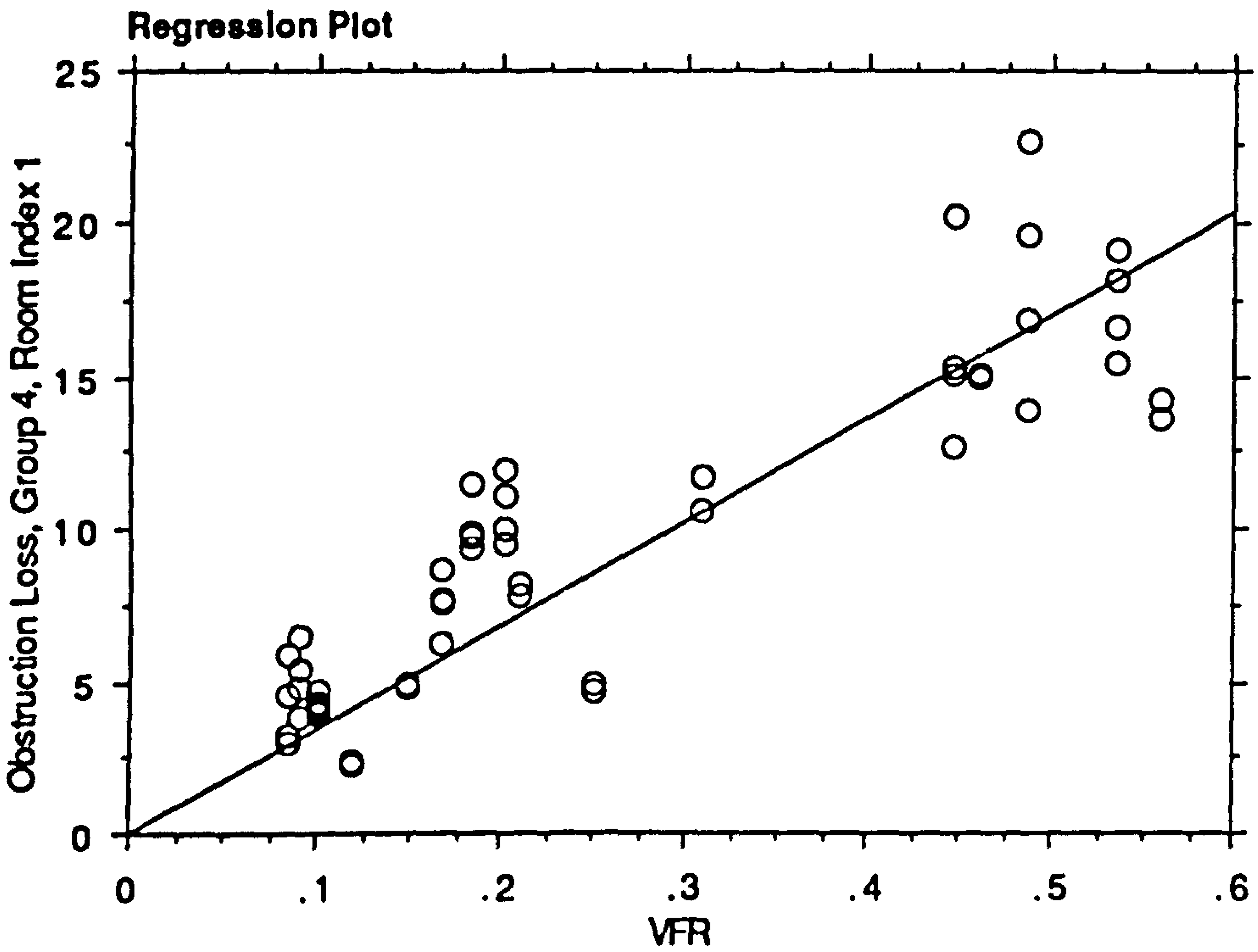
Count	54
Num. Missing	0
R	.972
R Squared	.945
Adjusted R Squared	.944
RMS Residual	2.725

ANOVA Table
Obstruction Loss, Group 4, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6818.350	6818.350	918.434	<.0001
Residual	53	393.466	7.424		
Total	54	7211.816			

Regression Coefficients
Obstruction Loss, Group 4, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.918	1.119	1.100	30.306	<.0001



$Y = 0 + 33.918 * X; R^2 = .945$

Regression Summary
Obstruction Loss, Group 4, Room Index 1.25 vs. VFR

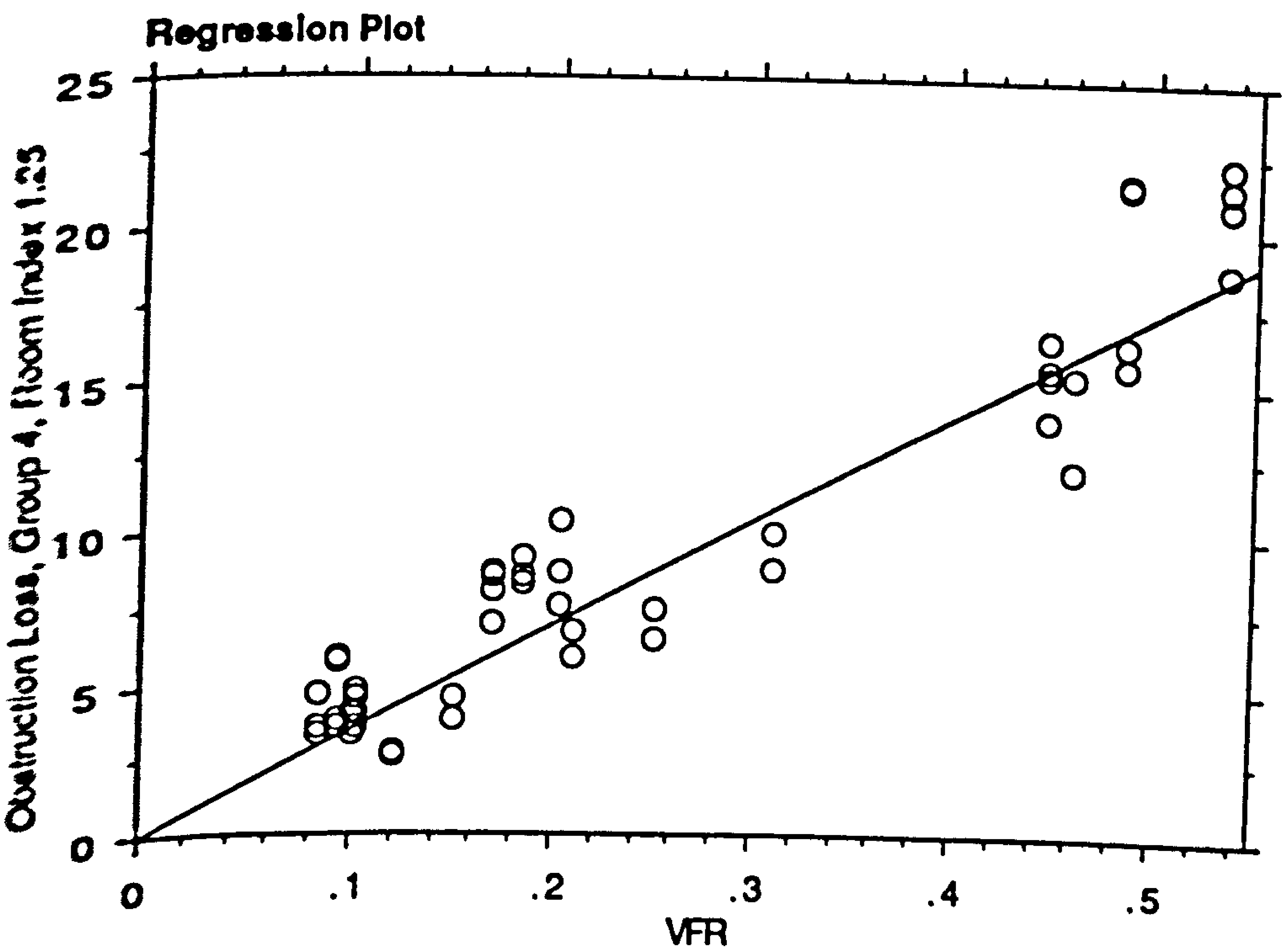
Count	54
Num. Missing	0
R	.981
R Squared	.963
Adjusted R Squared	.963
RMS Residual	2.261

ANOVA Table
Obstruction Loss, Group 4, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7096.830	7096.830	1388.632	<.0001
Residual	53	270.865	5.111		
Total	54	7367.695			

Regression Coefficients
Obstruction Loss, Group 4, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.603	.929	1.046	37.264	<.0001



Y = 0 + 34.603 * X; R^2 = .963

Regression Summary
Obstruction Loss, Group 4, Room Index 1.5 vs. VFR

Count	54
Num. Missing	0
R	.983
R Squared	.966
Adjusted R Squared	.965
RMS Residual	2.291

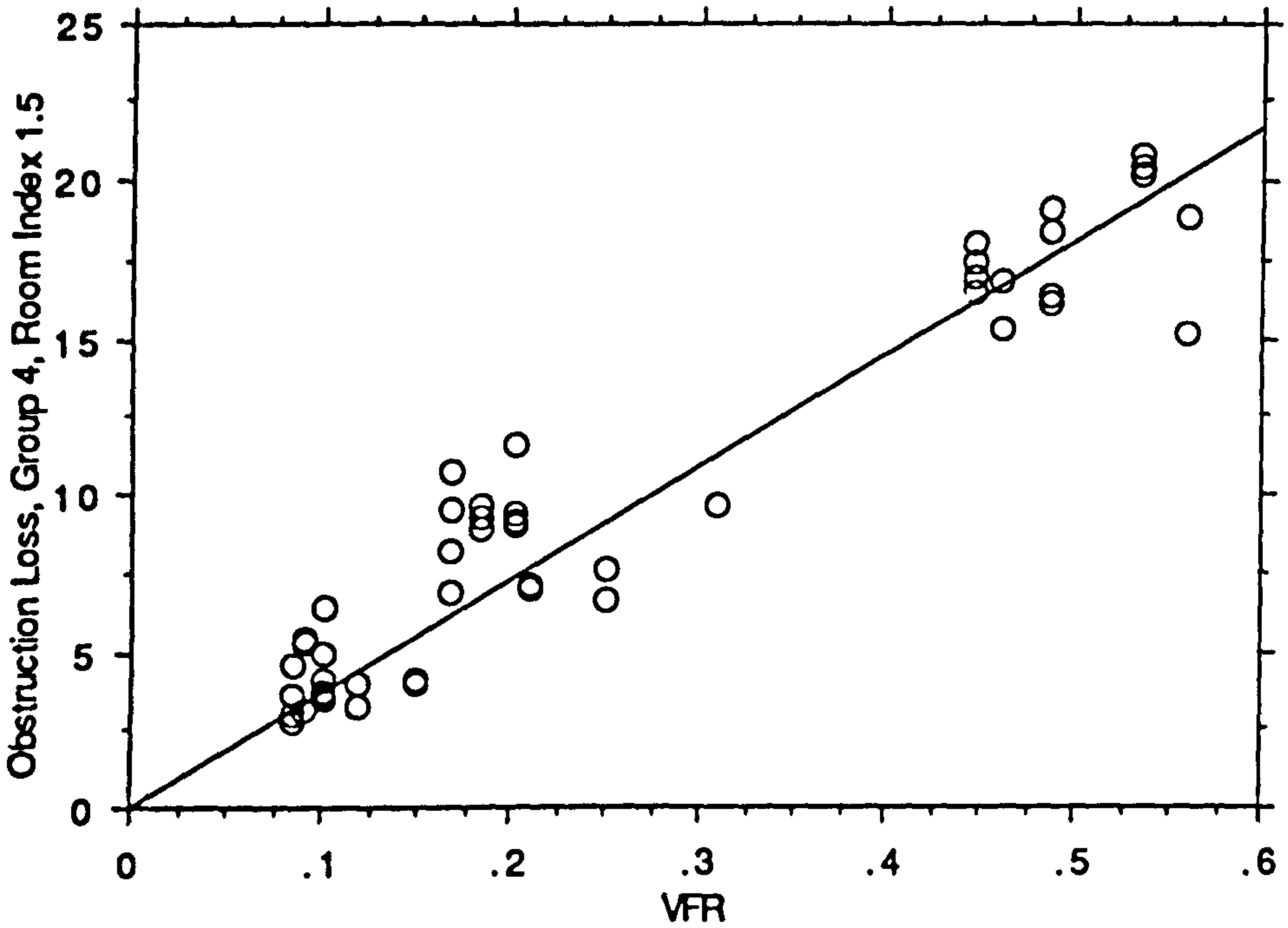
ANOVA Table
Obstruction Loss, Group 4, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7797.865	7797.865	1485.652	<.0001
Residual	53	278.185	5.249		
Total	54	8076.050			

Regression Coefficients
Obstruction Loss, Group 4, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.272	.941	1.056	38.544	<.0001

Regression Plot



Y = 0 + 36.272 * X; R^2 = .966

Regression Summary
Obstruction Loss, Group 4, Room Index 2 vs. VFR

Count	54
Num. Missing	0
R	.992
R Squared	.985
Adjusted R Squared	.984
RMS Residual	1.485

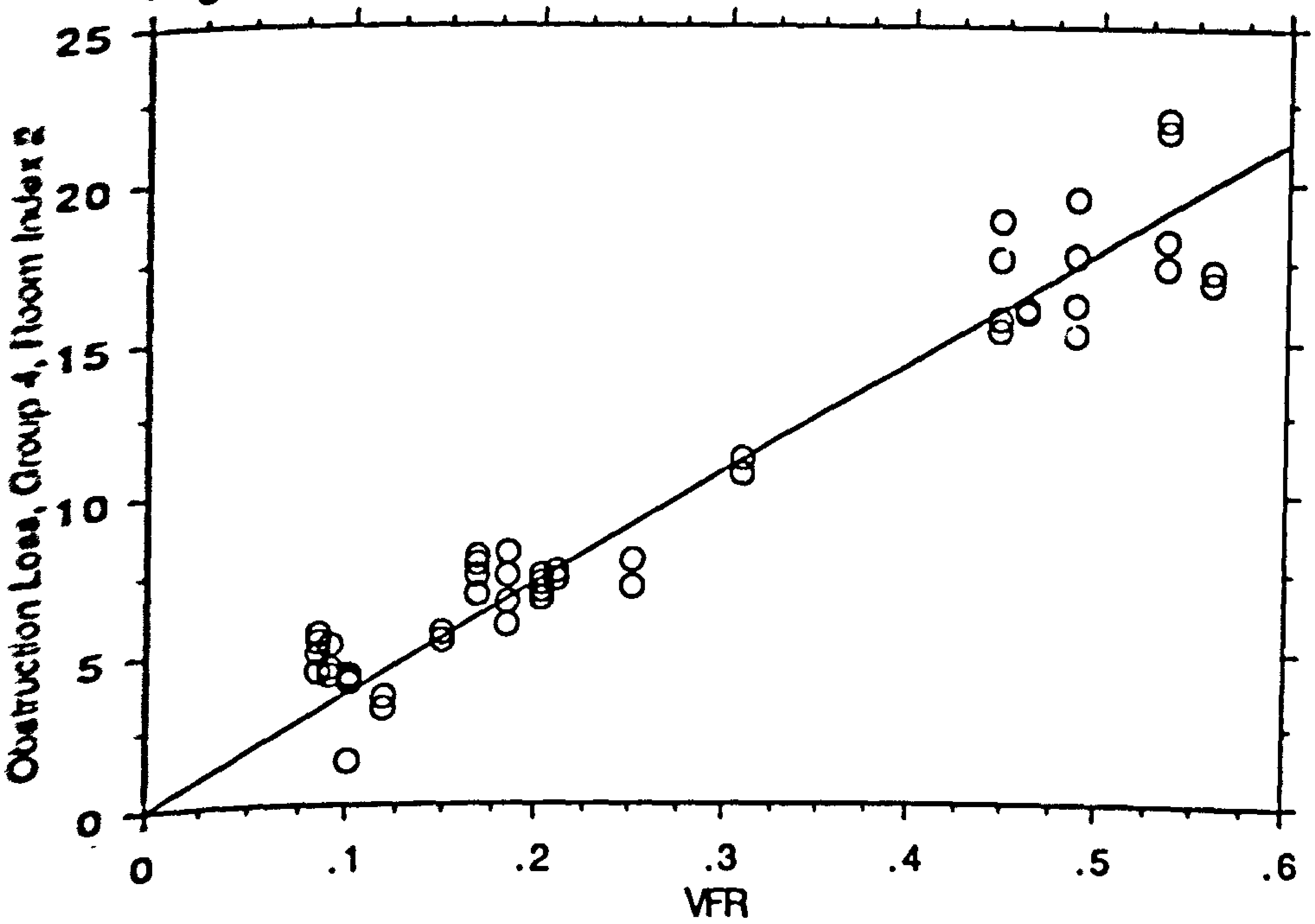
ANOVA Table
Obstruction Loss, Group 4, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7505.144	7505.144	3401.757	<.0001
Residual	53	116.932	2.206		
Total	54	7622.076			

Regression Coefficients
Obstruction Loss, Group 4, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.585	.610	1.038	58.325	<.0001

Regression Plot



Y = 0 + 35.585 * X; R^2 = .985

Regression Summary

Obstruction Loss, Group 4, Room Index 3 vs. VFR

Count	36
Num. Missing	0
R	.994
R Squared	.988
Adjusted R Squared	.988
RMS Residual	1.271

ANOVA Table

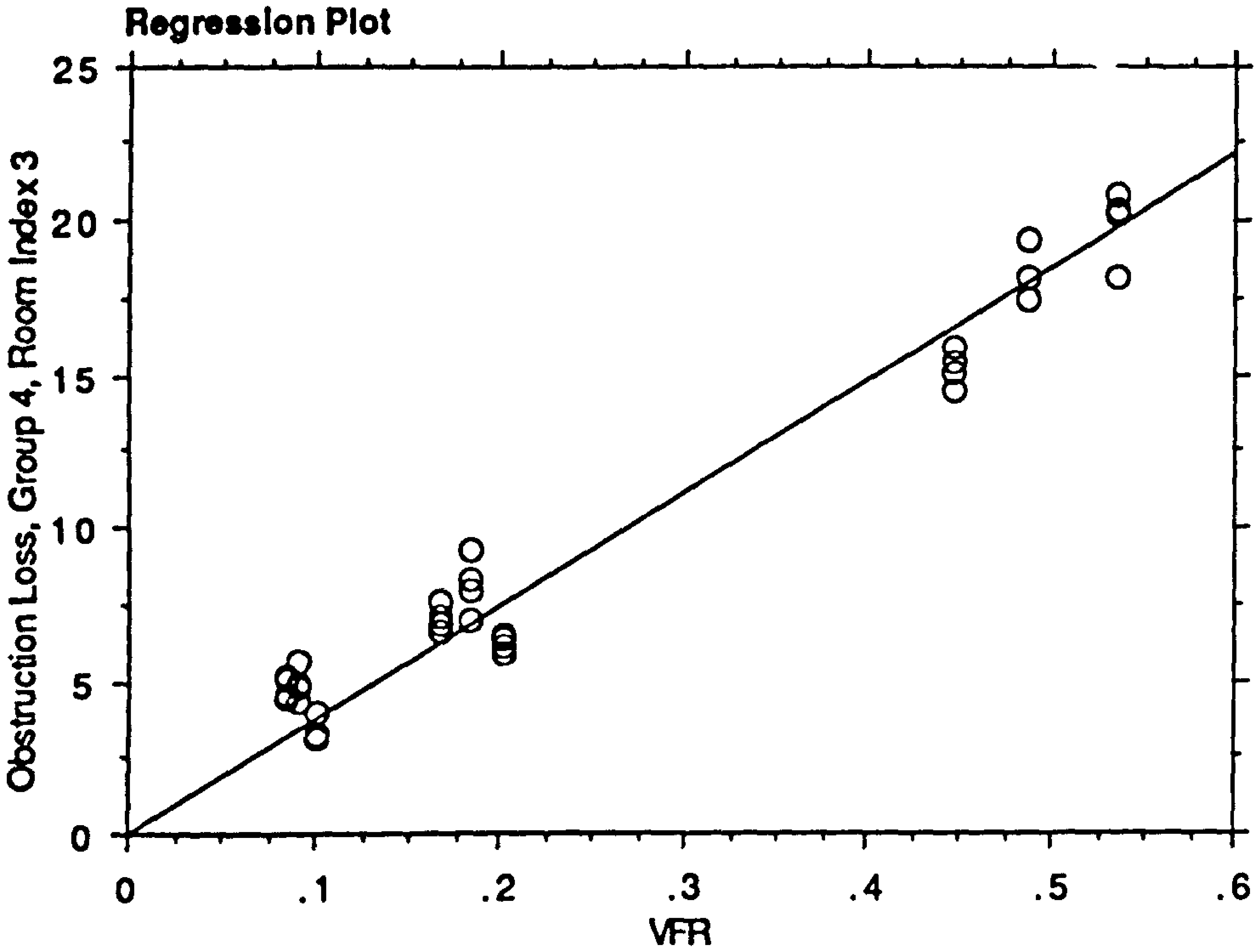
Obstruction Loss, Group 4, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4659.125	4659.125	2882.541	<.0001
Residual	35	56.571	1.616		
Total	36	4715.696			

Regression Coefficients

Obstruction Loss, Group 4, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	37.032	.690	1.063	53.689	<.0001



$Y = 0 + 37.032 * X; R^2 = .988$

Regression Summary
Obstruction Loss, Group 4, Room Index 4 vs. VFR

Count	36
Num. Missing	0
R	.992
R Squared	.983
Adjusted R Squared	.983
RMS Residual	1.491

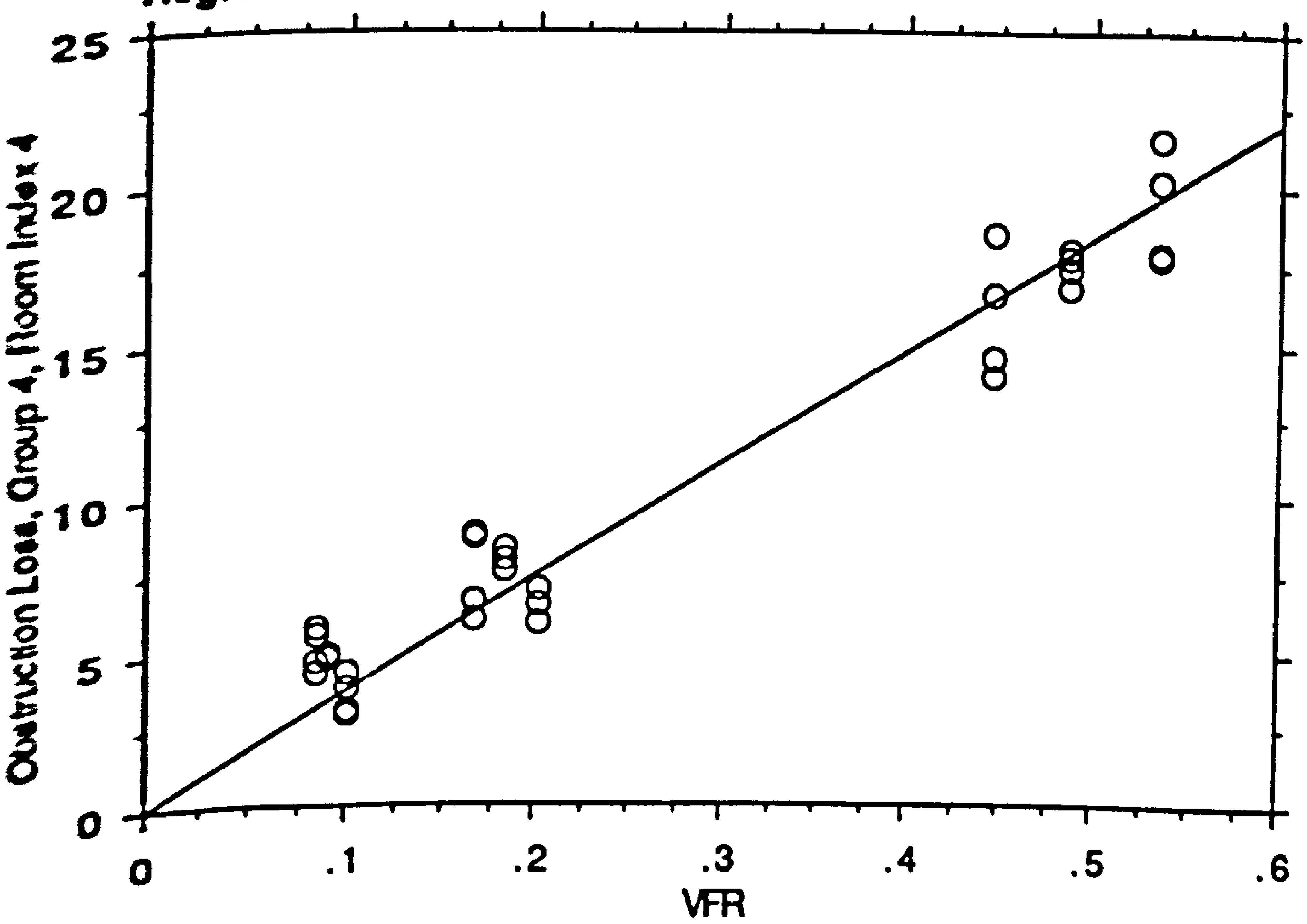
ANOVA Table
Obstruction Loss, Group 4, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4626.512	4626.512	2080.055	<.0001
Residual	35	77.848	2.224		
Total	36	4704.359			

Regression Coefficients
Obstruction Loss, Group 4, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.903	.809	1.084	45.608	<.0001

Regression Plot



Y = 0 + 36.903 * X; R^2 = .983

Regression Summary
Obstruction Loss, Group 4, Room Index 5 vs. VFR

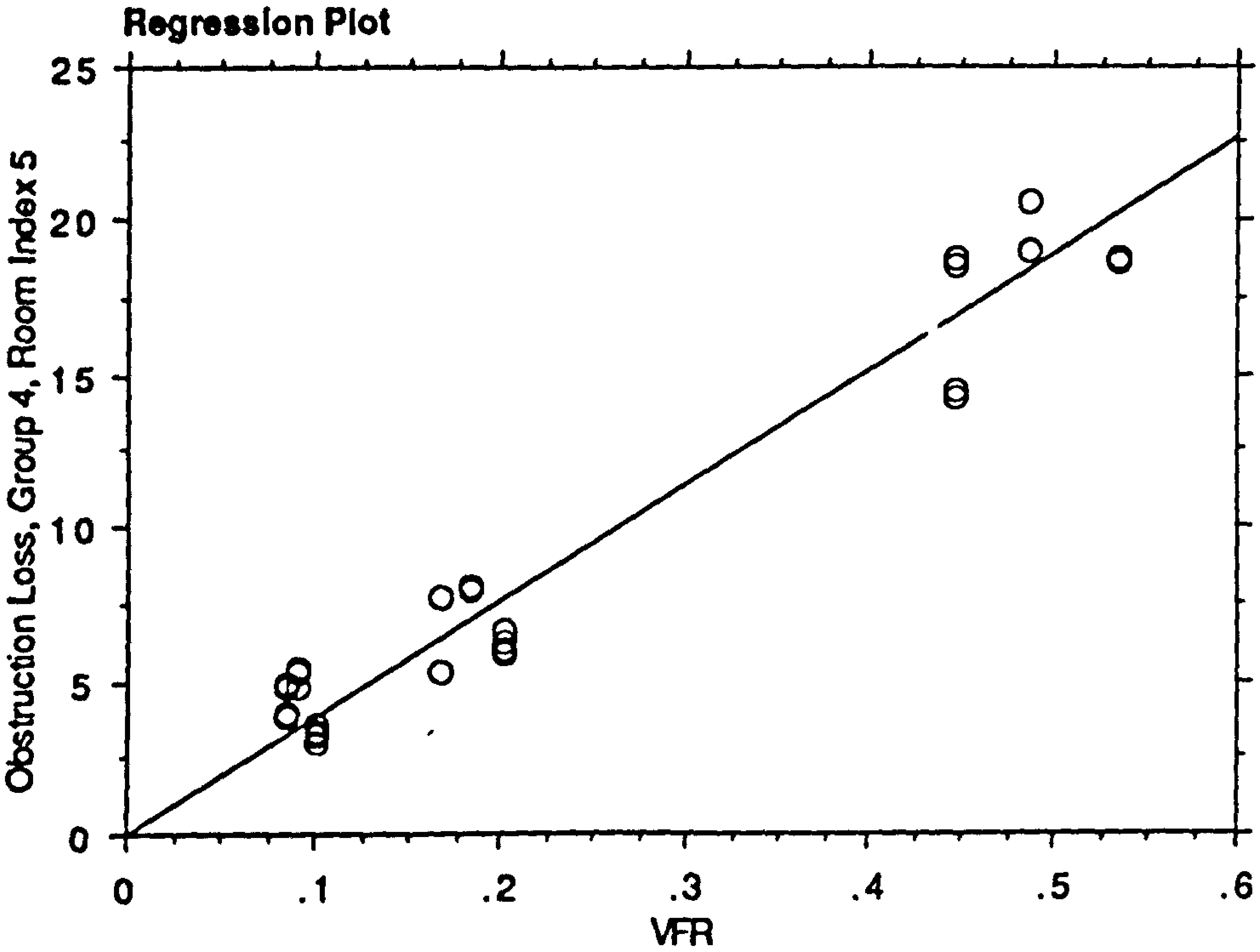
Count	32
Num. Missing	4
R	.990
R Squared	.980
Adjusted R Squared	.980
RMS Residual	1.471

ANOVA Table
Obstruction Loss, Group 4, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3363.556	3363.556	1553.618	<.0001
Residual	31	67.114	2.165		
Total	32	3430.671			

Regression Coefficients
Obstruction Loss, Group 4, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	37.809	.959	1.033	39.416	<.0001



Y = 0 + 37.809 * X; R^2 = .98

Regression Summary
Obstruction Loss, Group 5, Room Index 1 vs. VFR

Count	90
Num. Missing	0
R	.975
R Squared	.950
Adjusted R Squared	.950
RMS Residual	2.602

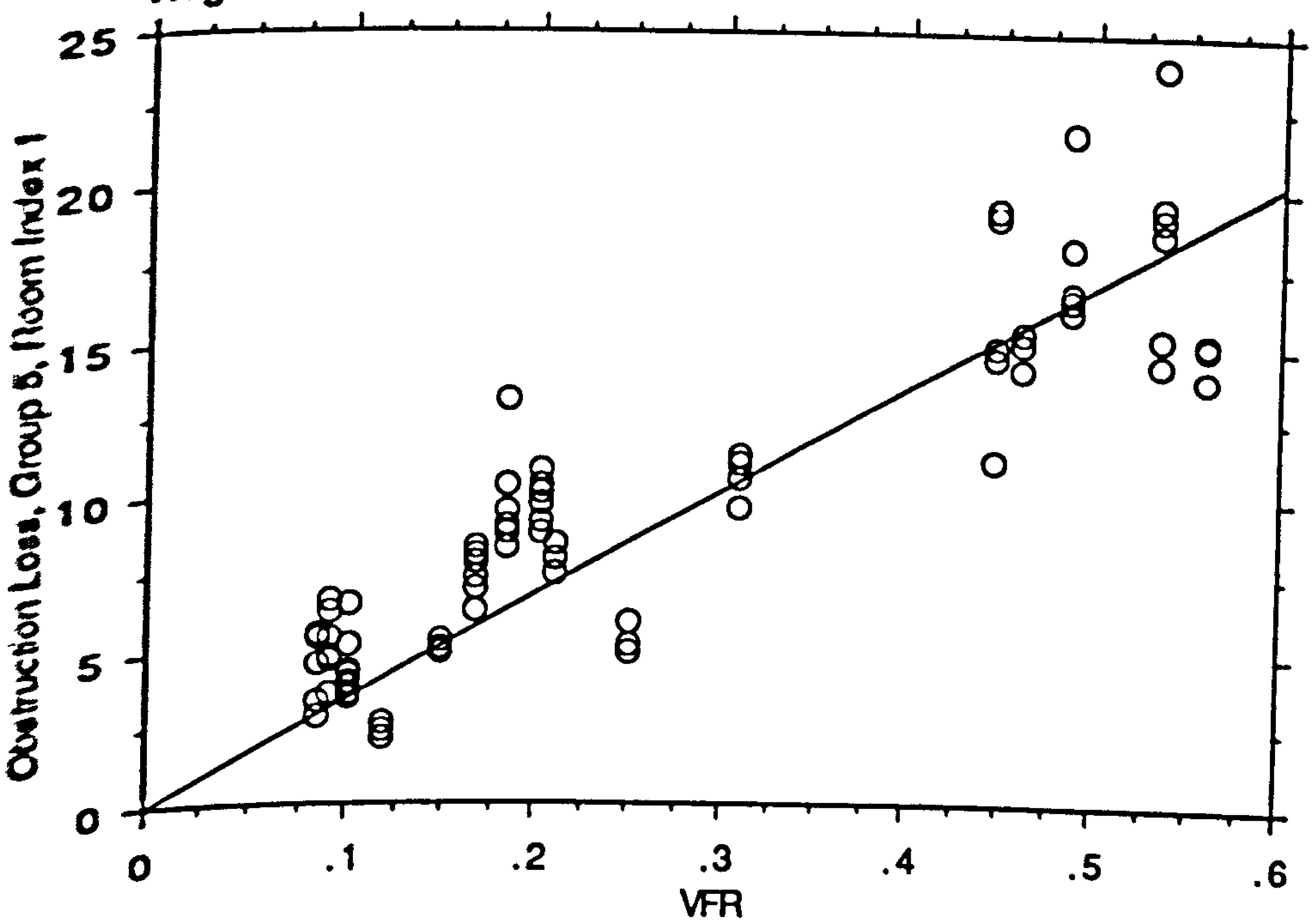
ANOVA Table
Obstruction Loss, Group 5, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	11547.801	11547.801	1705.838	<.0001
Residual	89	602.492	6.770		
Total	90	12150.293			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.721	.816	1.078	41.302	<.0001

Regression Plot



Y = 0 + 33.721 * X; R^2 = .95

Regression Summary
Obstruction Loss, Group 5, Room Index 1.25 vs. VFR

Count	90
Num. Missing	0
R	.982
R Squared	.965
Adjusted R Squared	.965
RMS Residual	2.177

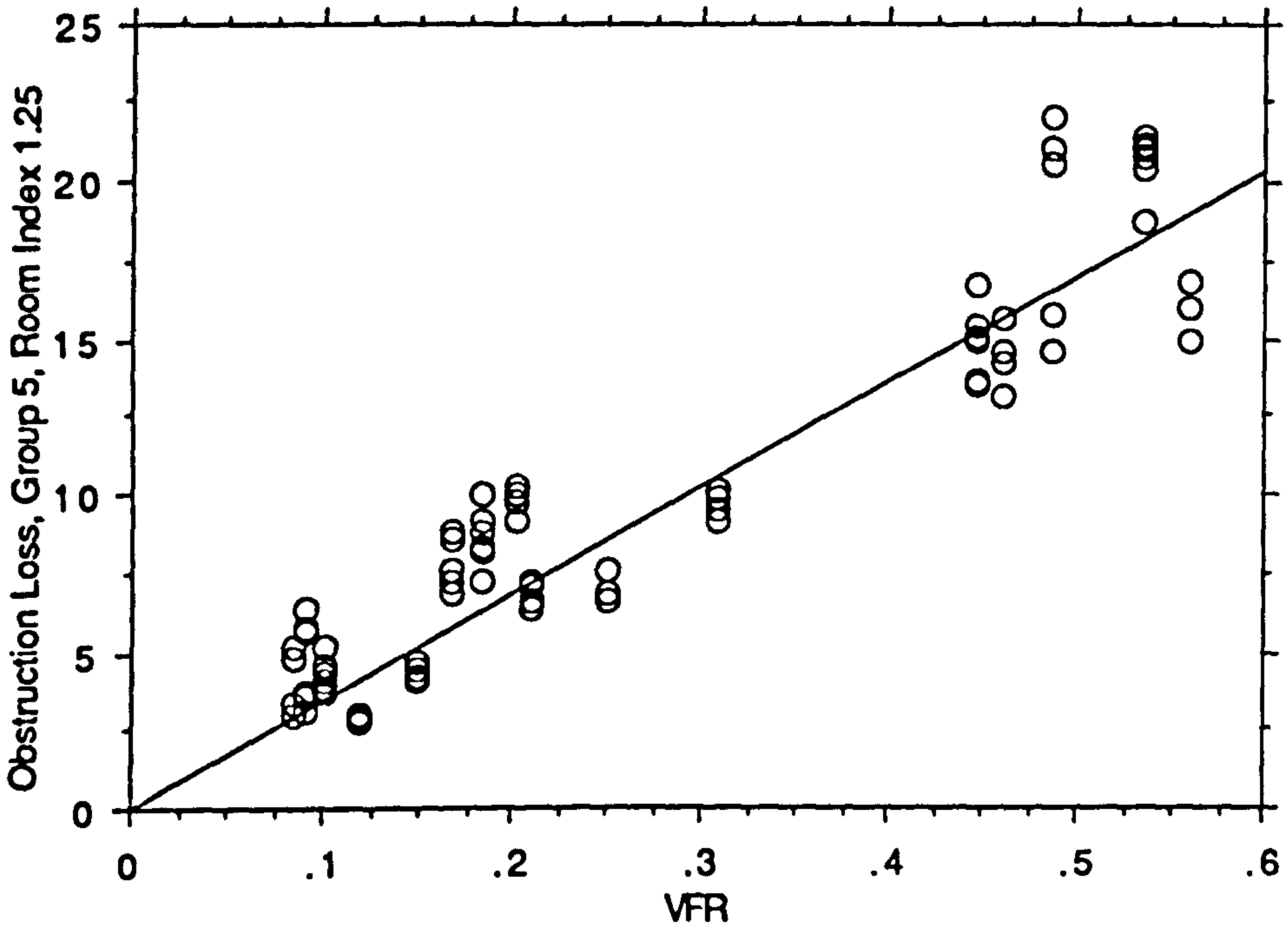
ANOVA Table
Obstruction Loss, Group 5, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	11729.383	11729.383	2475.017	<.0001
Residual	89	421.781	4.739		
Total	90	12151.164			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.985	.683	1.065	49.750	<.0001

Regression Plot



Y = 0 + 33.985 * X; R^2 = .965

Regression Summary
Obstruction Loss, Group 5, Room Index 1.5 vs. VFR

Count	90
Num. Missing	0
R	.987
R Squared	.975
Adjusted R Squared	.974
RMS Residual	1.888

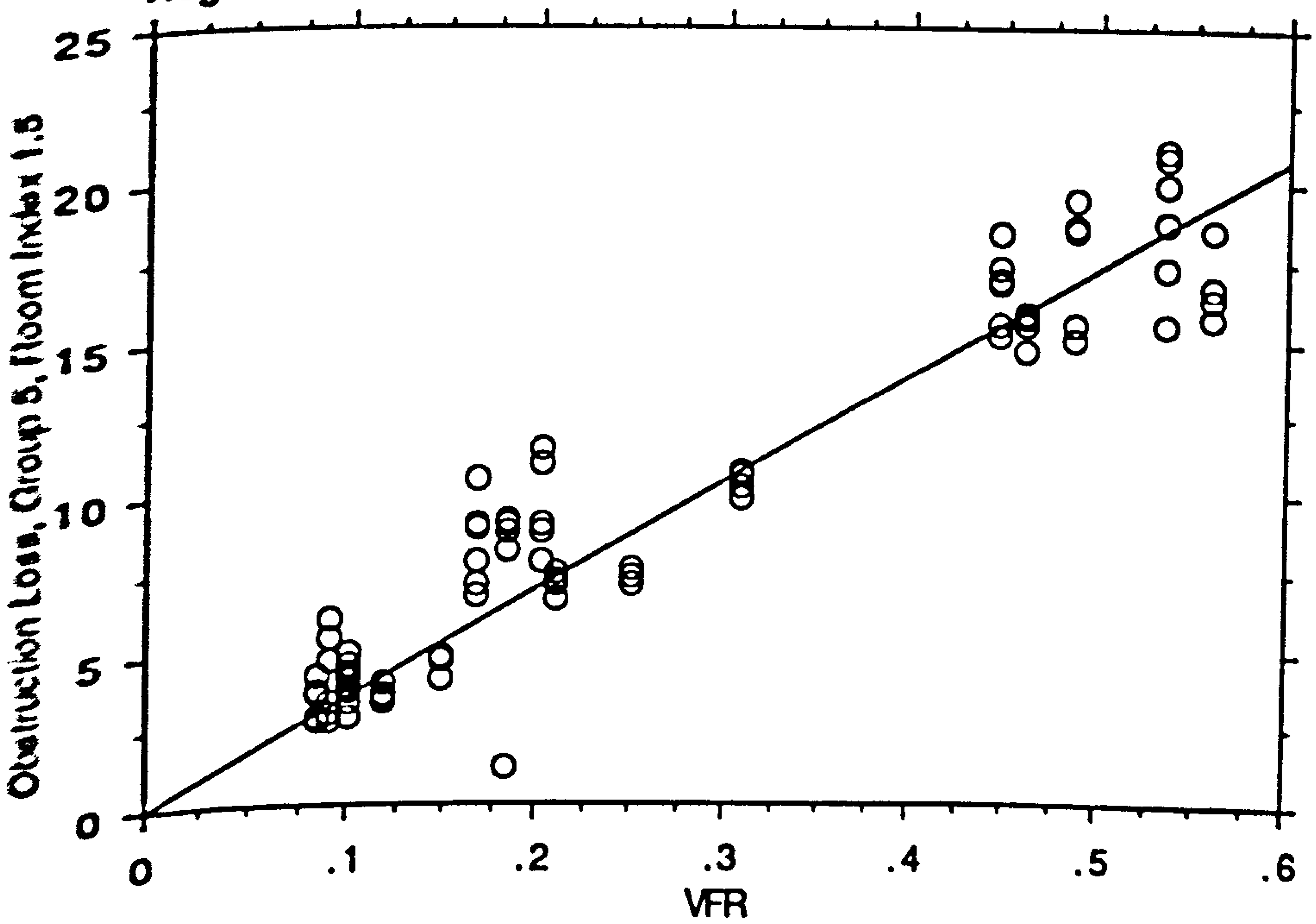
ANOVA Table
Obstruction Loss, Group 5, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	12184.022	12184.022	3416.465	<.0001
Residual	89	317.398	3.566		
Total	90	12501.420			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.638	.593	1.054	58.451	<.0001

Regression Plot



Y = 0 + 34.638 * X; R^2 = .975

Regression Summary
Obstruction Loss, Group 5, Room Index 2 vs. VFR

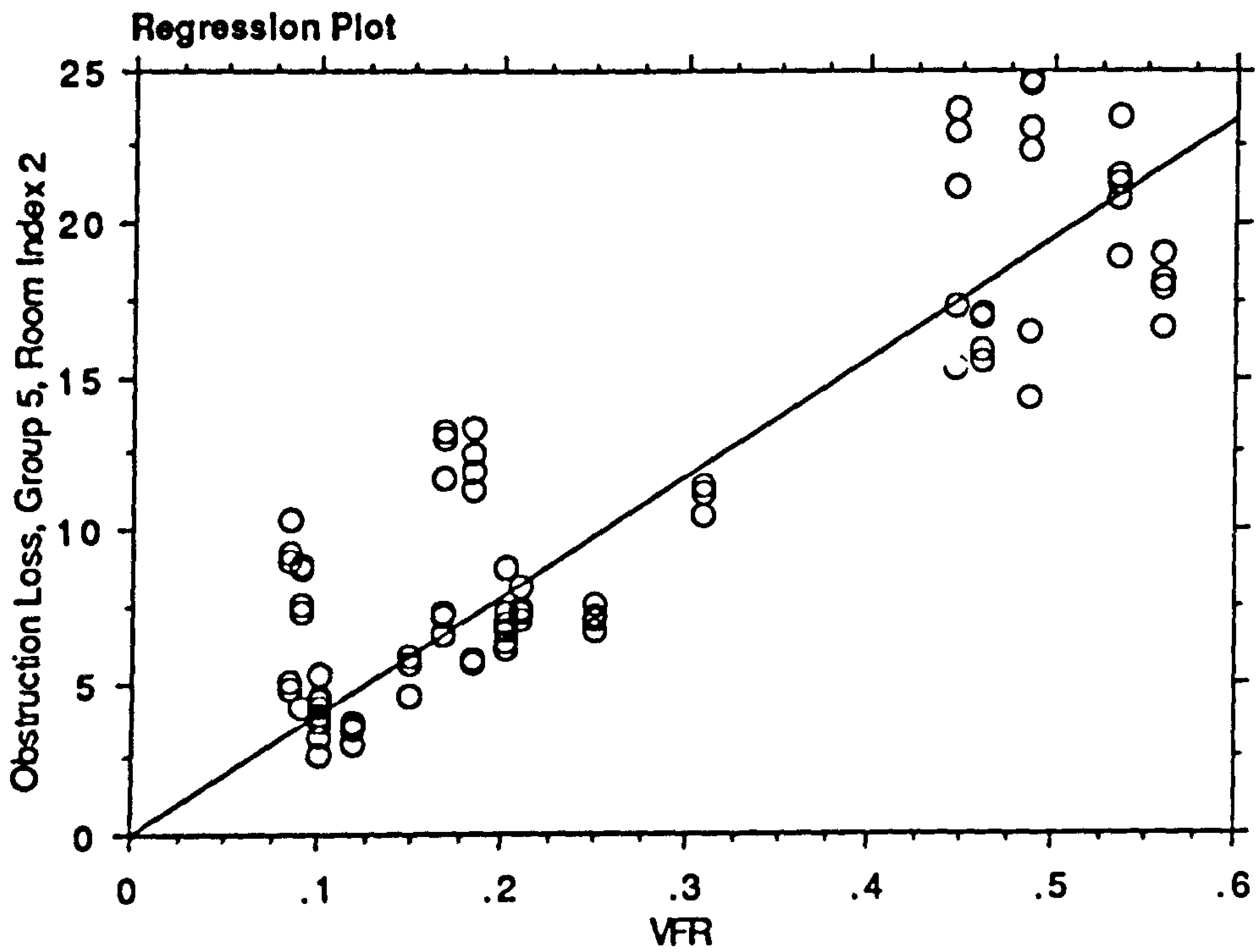
Count	90
Num. Missing	0
R	.972
R Squared	.944
Adjusted R Squared	.944
RMS Residual	3.204

ANOVA Table
Obstruction Loss, Group 5, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	15539.639	15539.639	1513.886	<.0001
Residual	89	913.561	10.265		
Total	90	16453.200			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.118	1.005	1.042	38.909	<.0001



Y = 0 + 39.118 * X; R^2 = .944

Regression Summary
Obstruction Loss, Group 5, Room Index 3 vs. VFR

Count	54
Num. Missing	1
R	.984
R Squared	.968
Adjusted R Squared	.968
RMS Residual	2.059

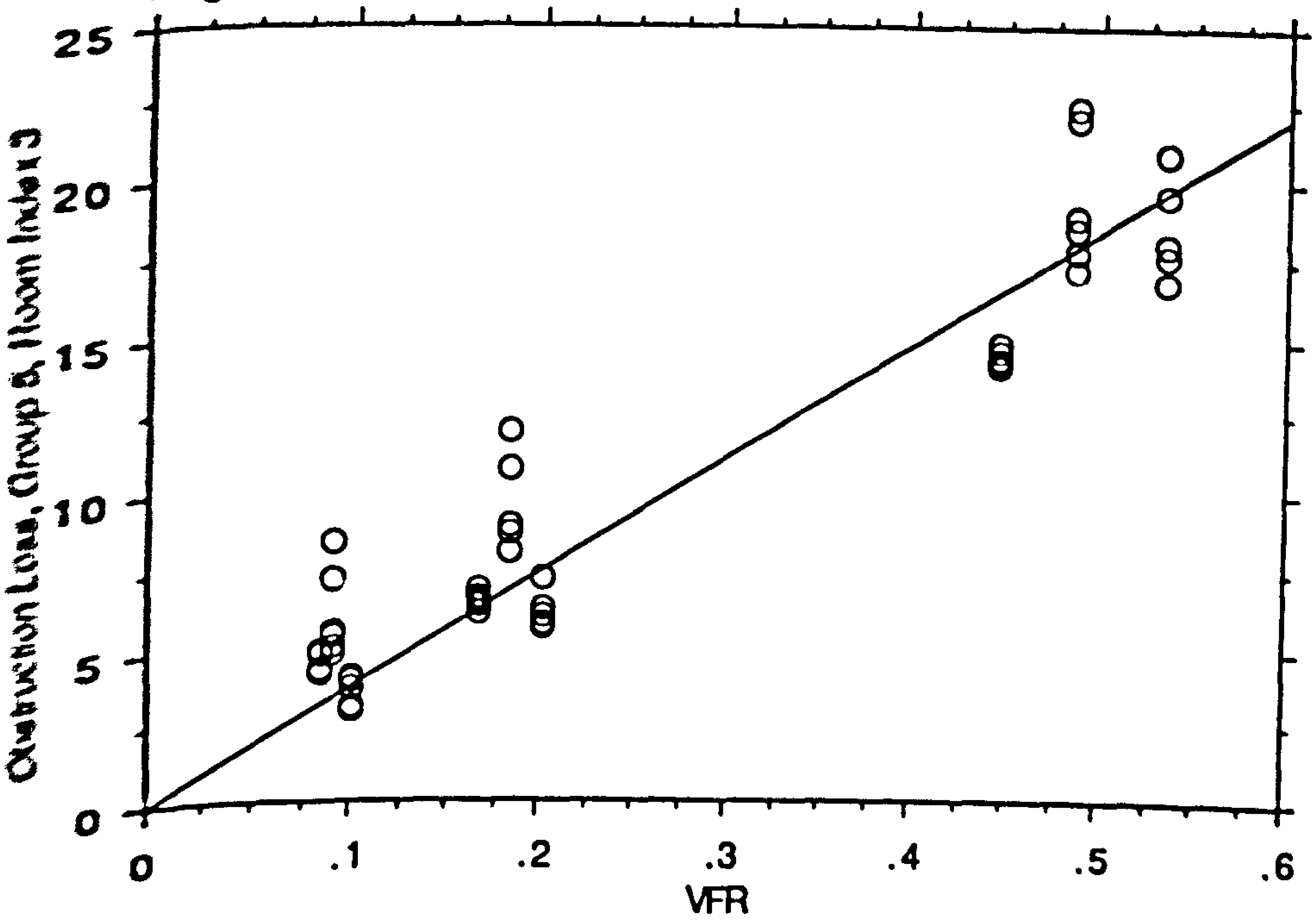
ANOVA Table
Obstruction Loss, Group 5, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6891.564	6891.564	1625.476	<.0001
Residual	53	224.705	4.240		
Total	54	7116.270			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.774	.912	1.083	40.317	<.0001

Regression Plot



Y = 0 + 36.774 * X; R^2 = .968

Regression Summary
Obstruction Loss, Group 5, Room Index 4 vs. VFR

Count	53
Num. Missing	2
R	.989
R Squared	.978
Adjusted R Squared	.978
RMS Residual	1.633

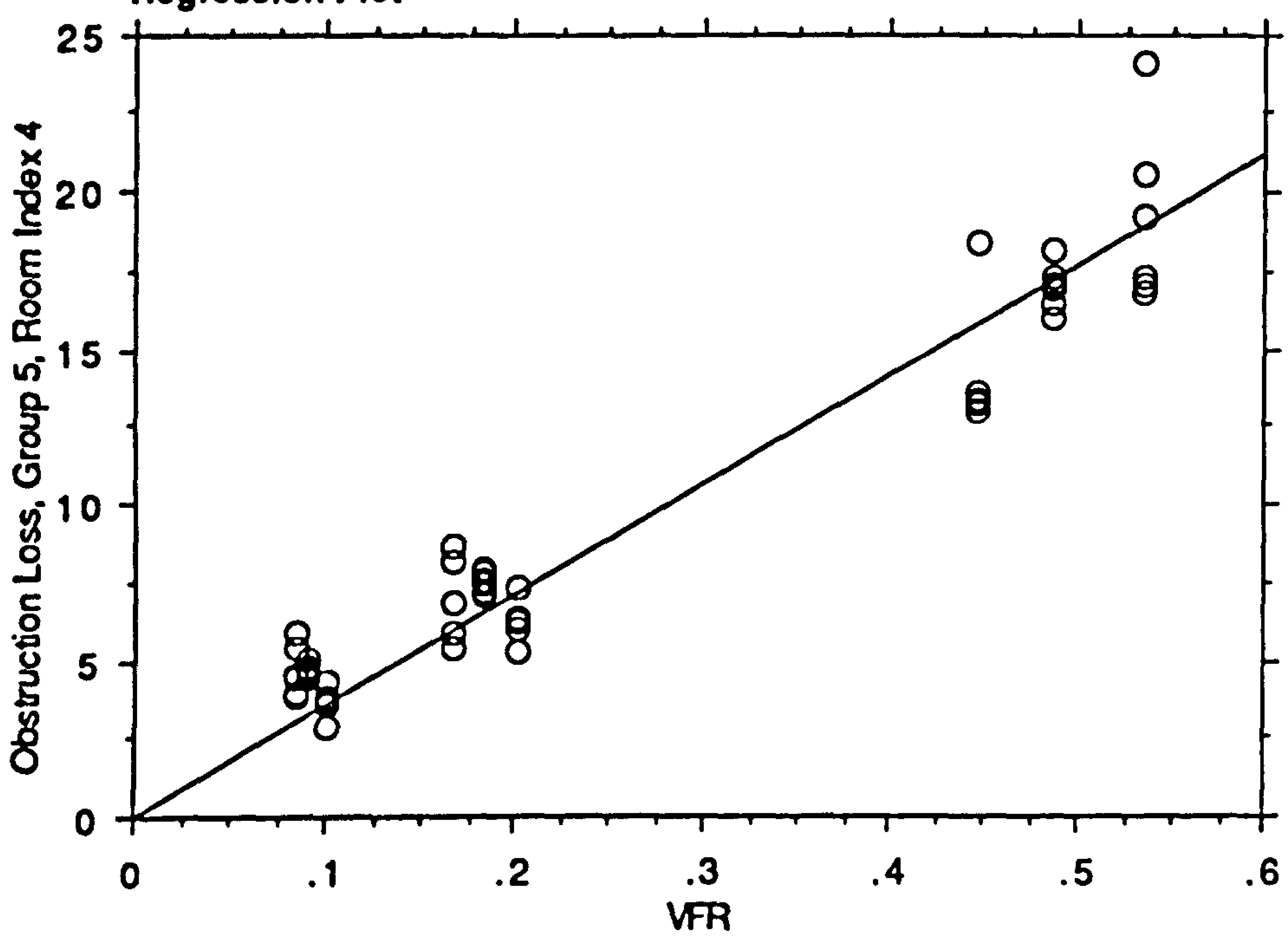
ANOVA Table
Obstruction Loss, Group 5, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6151.956	6151.956	2308.330	<.0001
Residual	52	138.586	2.665		
Total	53	6290.542			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.442	.738	1.064	48.045	<.0001

Regression Plot



Y = 0 + 35.442 * X; R^2 = .978

Regression Summary
Obstruction Loss, Group 5, Room Index 5 vs. VFR

Count	48
Num. Missing	7
R	.991
R Squared	.982
Adjusted R Squared	.981
RMS Residual	1.321

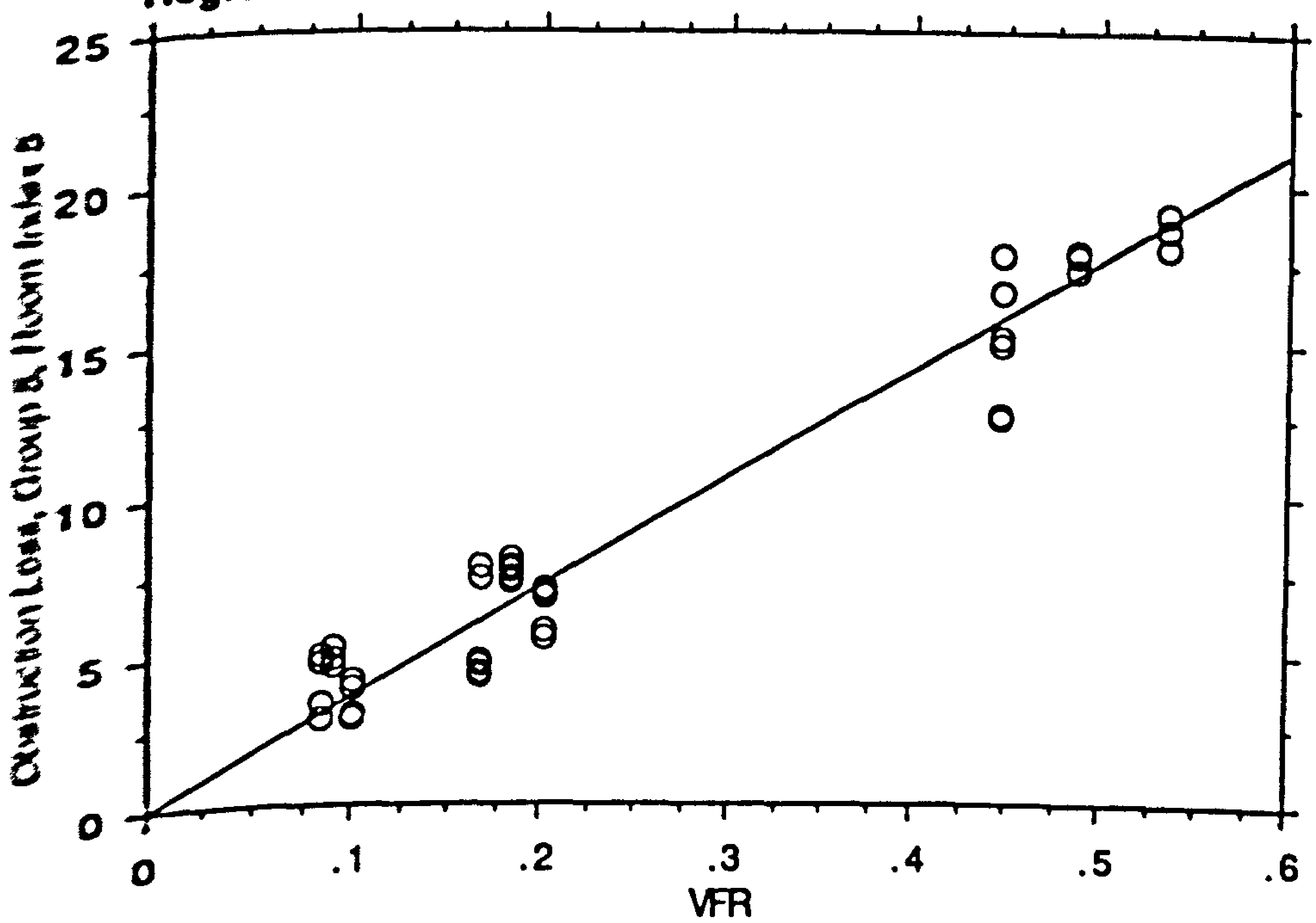
ANOVA Table
Obstruction Loss, Group 5, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4389.193	4389.193	2515.922	<.0001
Residual	47	81.995	1.745		
Total	48	4471.188			

Regression Coefficients
Obstruction Loss, Group 5, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.265	.703	1.043	50.159	<.0001

Regression Plot



Y = 0 + 35.265 * X; R^2 = .982

Regression Summary
Obstruction Loss, Group 6, Room Index 1 vs. VFR

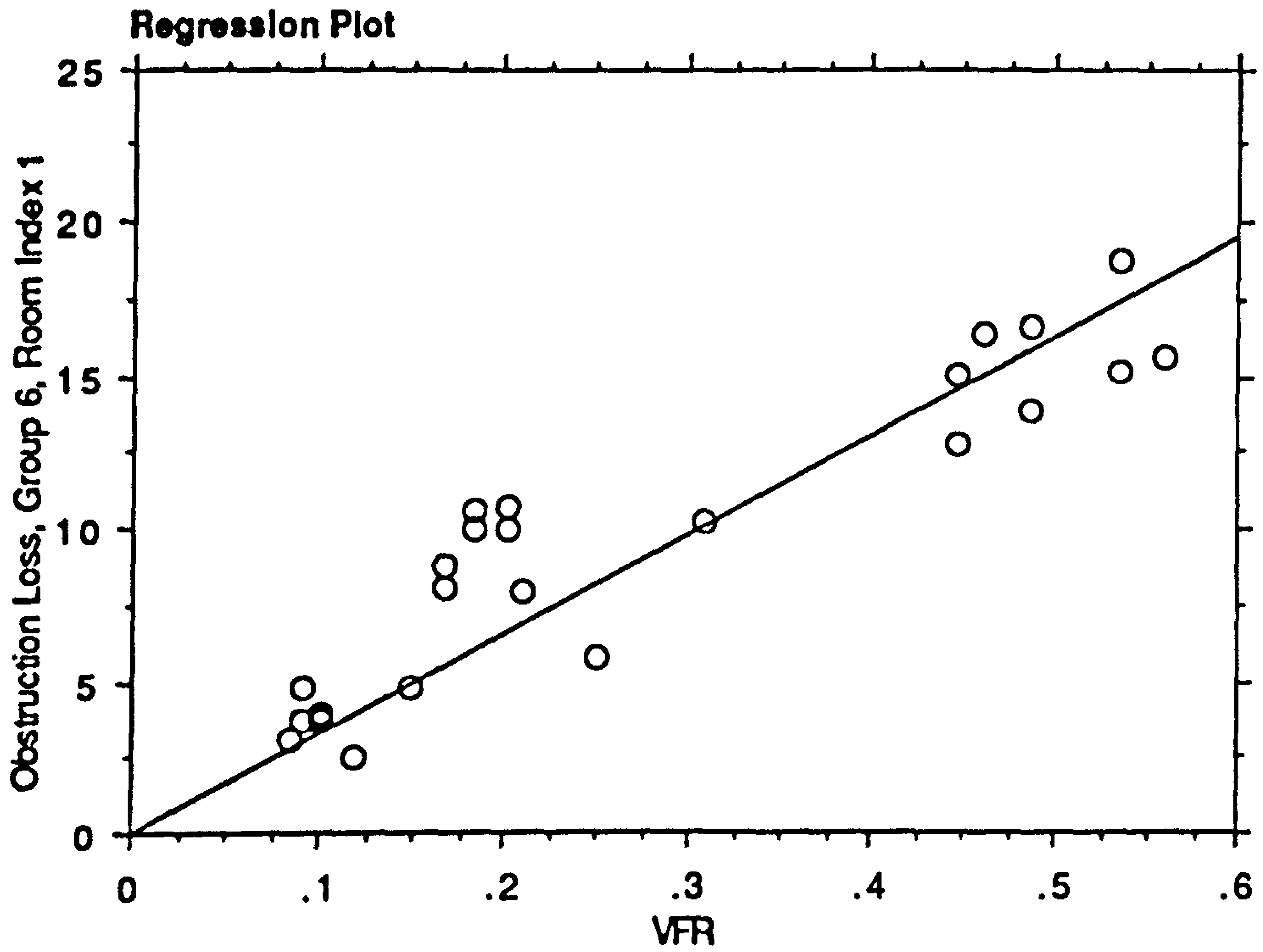
Count	27
Num. Missing	0
R	.980
R Squared	.960
Adjusted R Squared	.959
RMS Residual	2.230

ANOVA Table
Obstruction Loss, Group 6, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3142.415	3142.415	632.159	<.0001
Residual	26	129.244	4.971		
Total	27	3271.659			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	32.564	1.295	1.128	25.143	<.0001



Y = 0 + 32.564 * X; R^2 = .96

Regression Summary
Obstruction Loss, Group 6, Room Index 1.25 vs. VFR

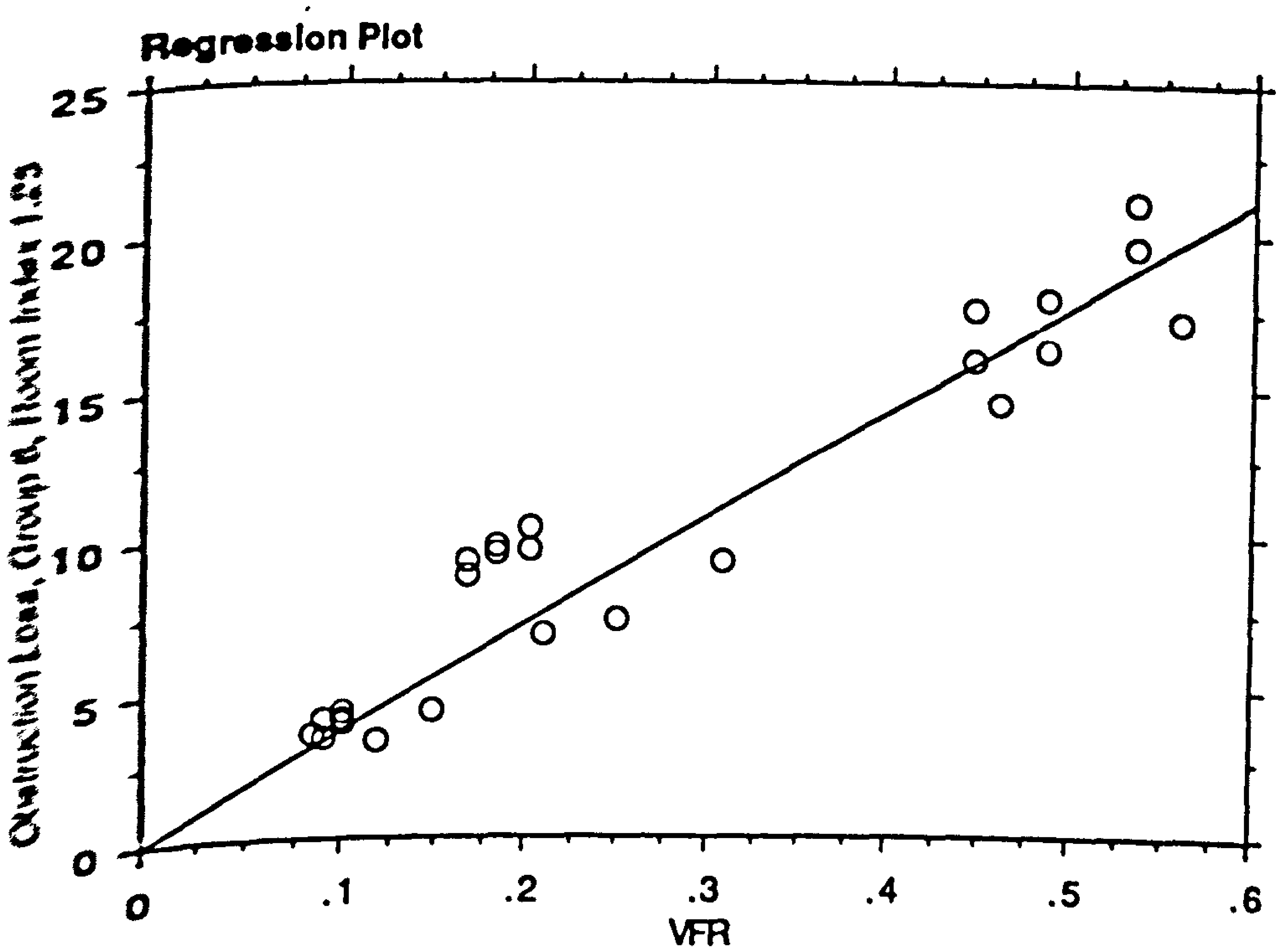
Count	27
Num. Missing	0
R	.986
R Squared	.973
Adjusted R Squared	.972
RMS Residual	1.977

ANOVA Table
Obstruction Loss, Group 6, Room Index 1.25 vs. VFR

	DF	Sum of Squa...	Mean Squ...	F-Value	P-Value
Regression	1	3658.247	3658.247	935.672	<.0001
Residual	26	101.654	3.910		
Total	27	3759.901			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.135	1.149	1.075	30.589	<.0001



$Y = 0 + 35.135 * X; R^2 = .973$

Regression Summary
Obstruction Loss, Group 6, Room Index 1.5 vs. VFR

Count	27
Num. Missing	0
R	.987
R Squared	.975
Adjusted R Squared	.974
RMS Residual	2.083

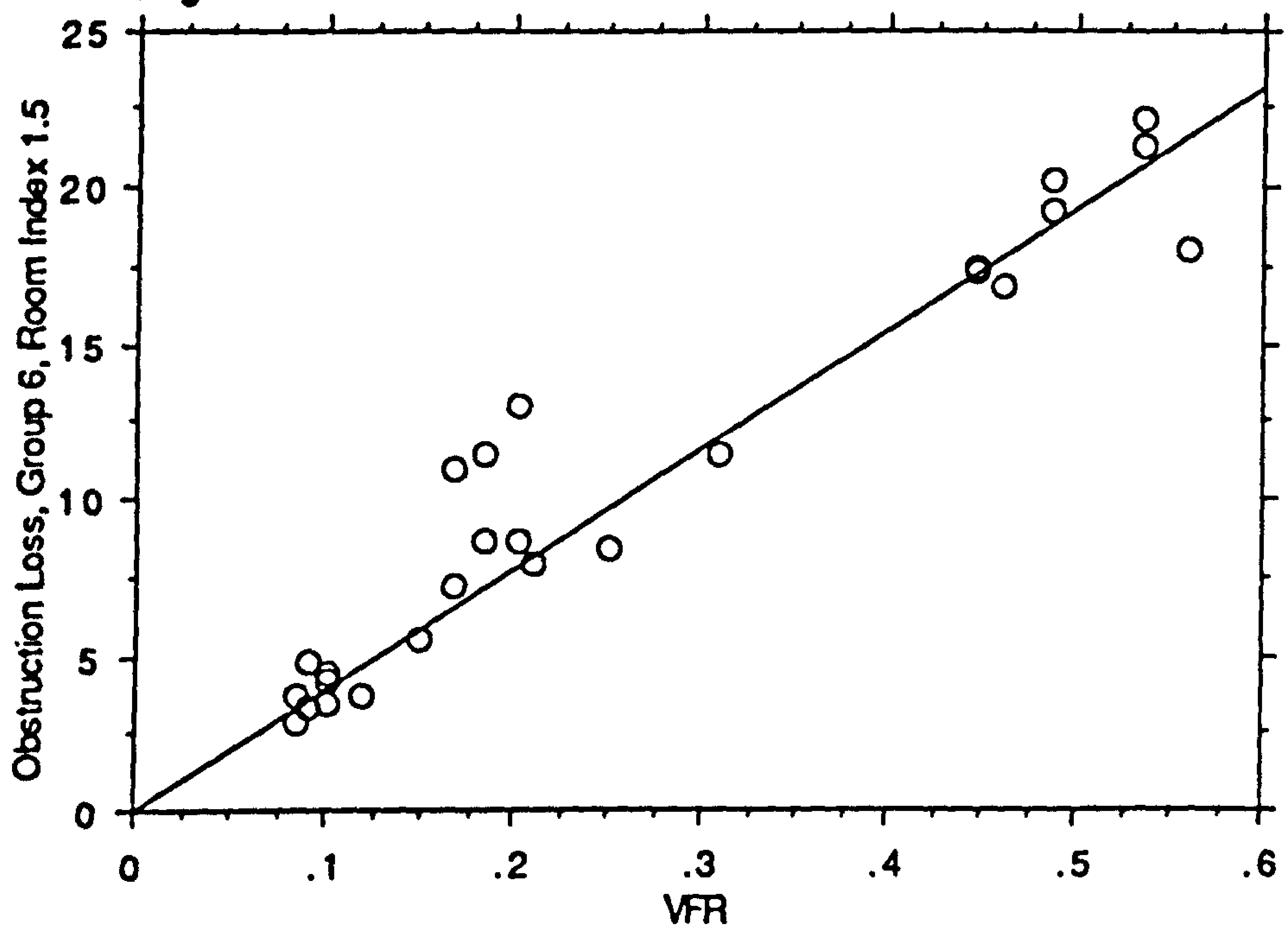
ANOVA Table
Obstruction Loss, Group 6, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4414.009	4414.009	1.018E3	<.0001
Residual	26	112.774	4.337		
Total	27	4526.783			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.594	1.210	1.069	31.901	<.0001

Regression Plot



Y = 0 + 38.594 * X; R^2 = .975

Regression Summary
Obstruction Loss, Group 6, Room Index 2 vs. VFR

Count	27
Num. Missing	0
R	.996
R Squared	.992
Adjusted R Squared	.991
RMS Residual	1.182

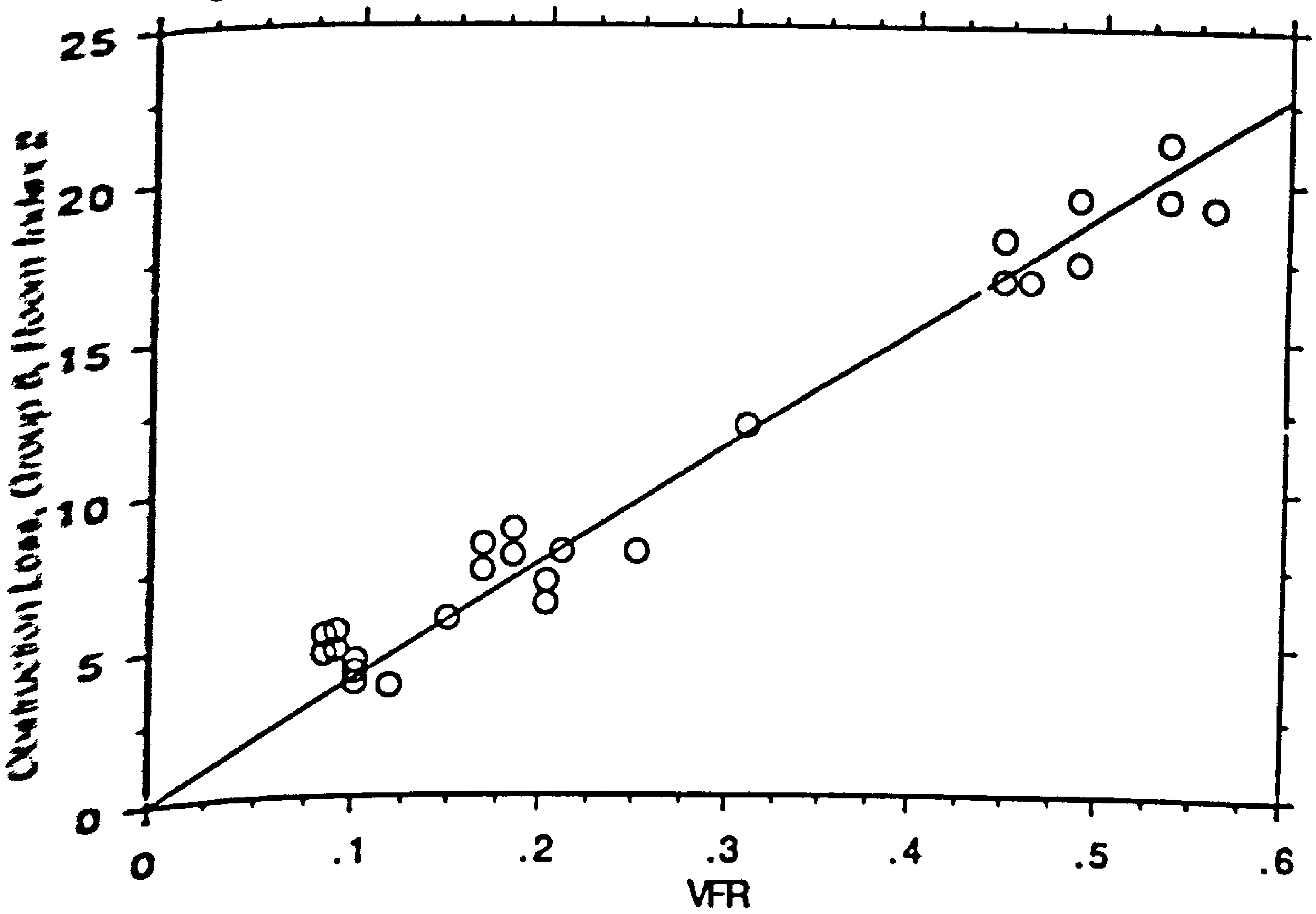
ANOVA Table
Obstruction Loss, Group 6, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4309.857	4309.857	3087.245	<.0001
Residual	26	36.297	1.396		
Total	27	4346.154			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.136	.686	1.050	55.563	<.0001

Regression Plot



Y = 0 + 38.136 * X; R^2 = .992

Regression Summary
Obstruction Loss, Group 6, Room Index 3 vs. VFR

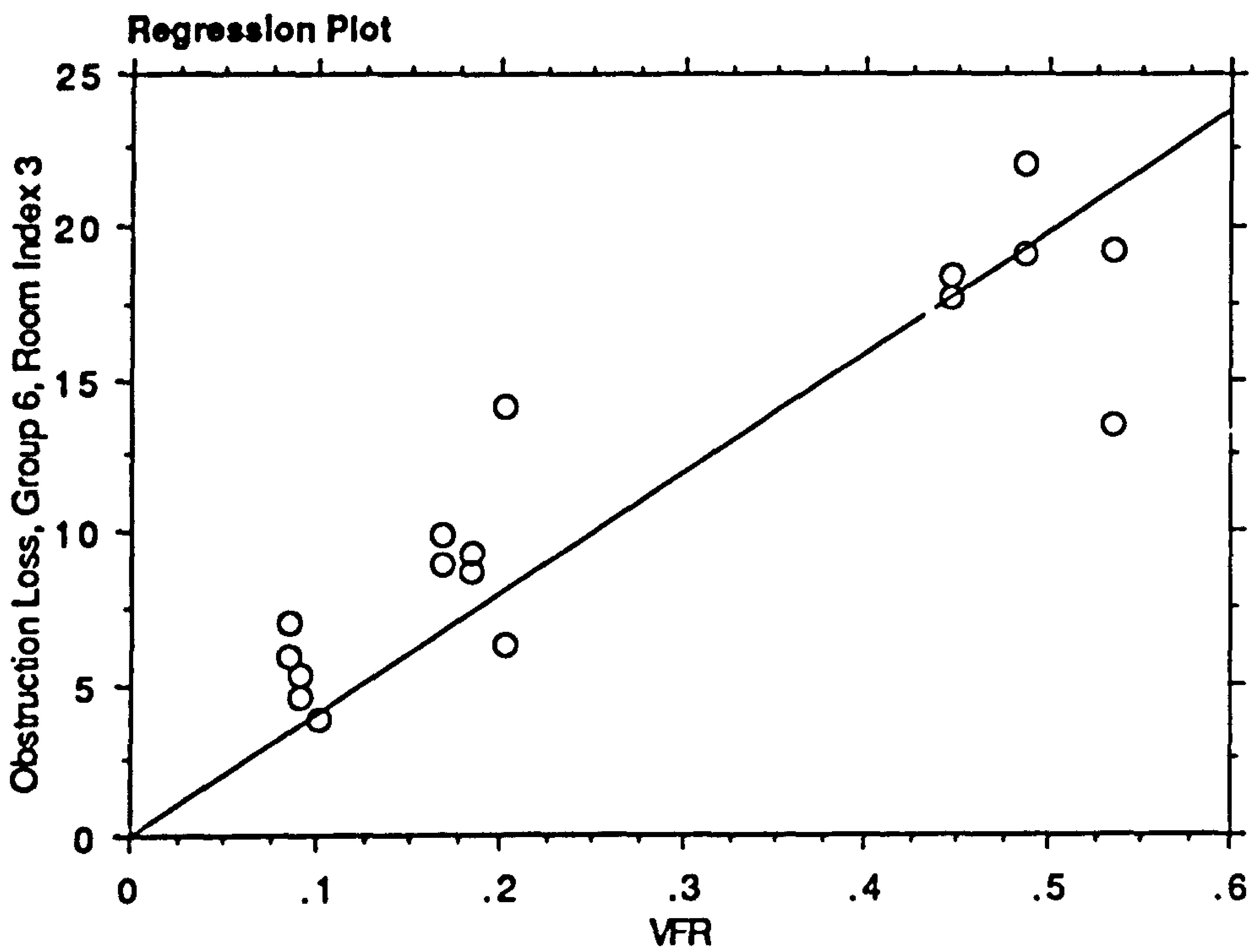
Count	18
Num. Missing	1
R	.972
R Squared	.944
Adjusted R Squared	.941
RMS Residual	3.036

ANOVA Table
Obstruction Loss, Group 6, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2659.698	2659.698	288.524	<.0001
Residual	17	156.711	9.218		
Total	18	2816.409			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.570	2.330	1.142	16.986	<.0001



Y = 0 + 39.57 * X; R^2 = .944

Regression Summary
Obstruction Loss, Group 6, Room Index 4 vs. VFR

Count	18
Num. Missing	1
R	.990
R Squared	.980
Adjusted R Squared	.979
RMS Residual	1.701

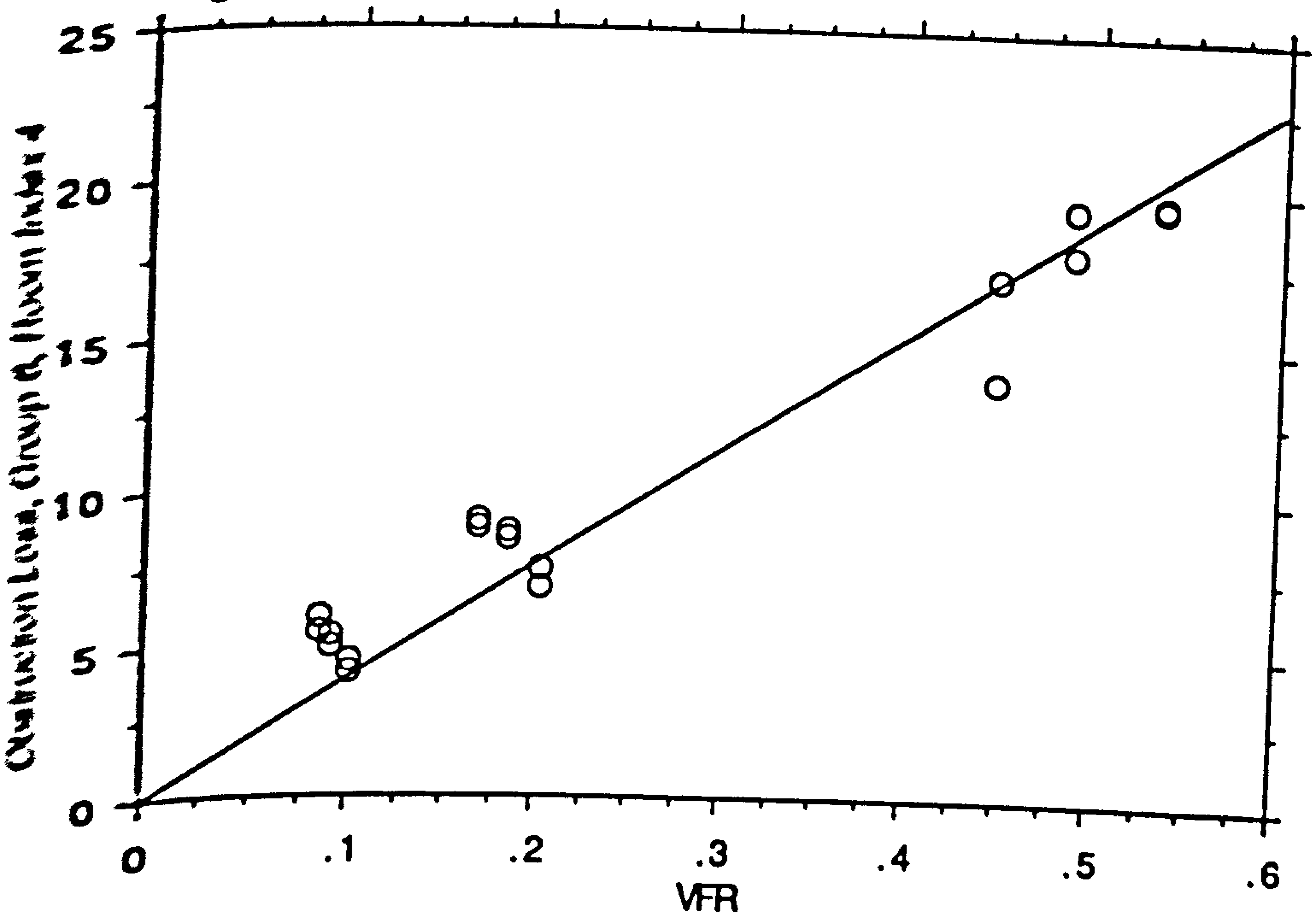
ANOVA Table
Obstruction Loss, Group 6, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2470.189	2470.189	853.370	<.0001
Residual	17	49.209	2.895		
Total	18	2519.398			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.134	1.305	1.154	29.212	<.0001

Regression Plot



Y = 0 + 38.134 * X; R^2 = .98

Regression Summary
Obstruction Loss, Group 6, Room Index 5 vs. VFR

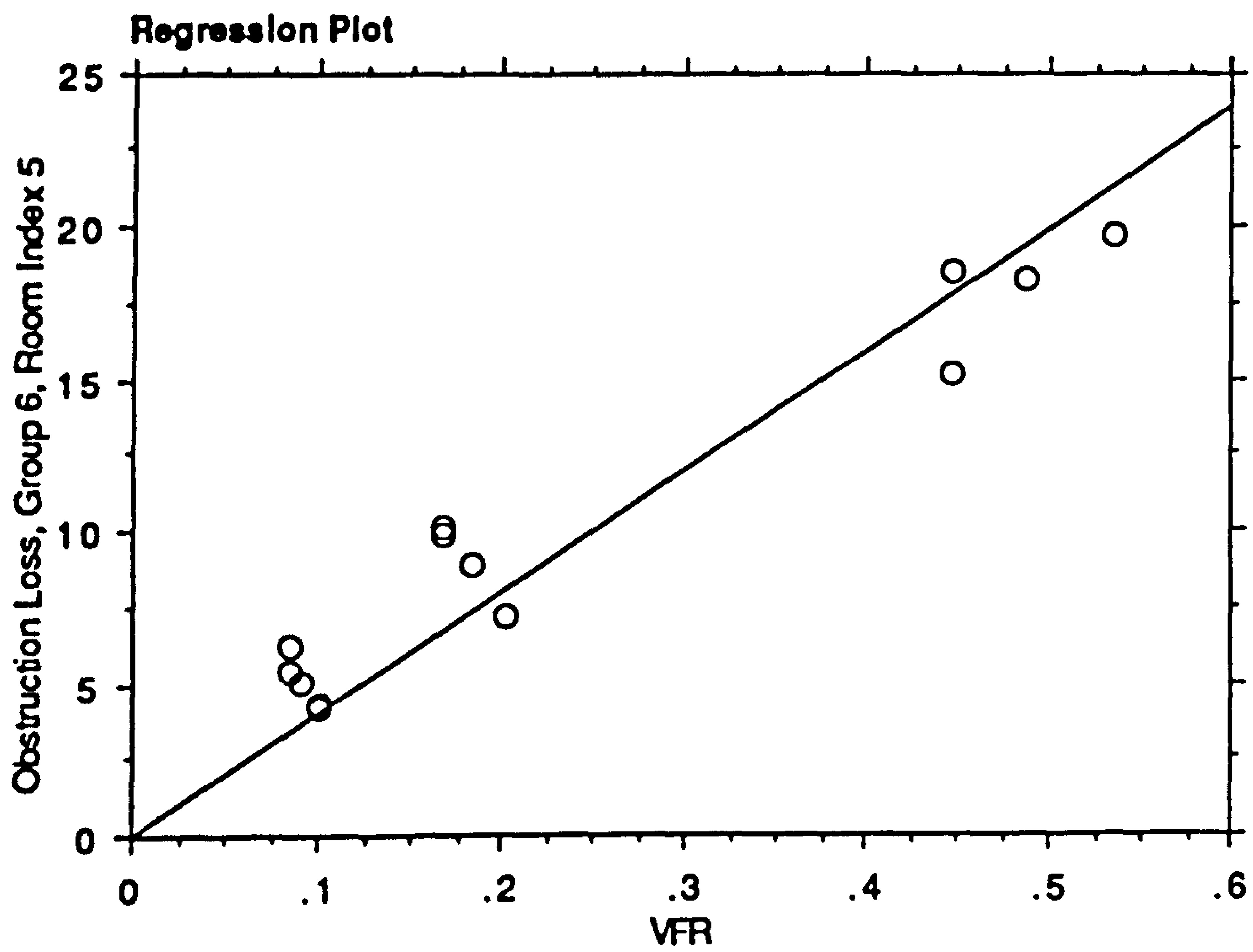
Count	16
Num. Missing	3
R	.985
R Squared	.971
Adjusted R Squared	.969
RMS Residual	1.941

ANOVA Table
Obstruction Loss, Group 6, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1874.173	1874.173	497.584	<.0001
Residual	15	56.498	3.767		
Total	16	1930.672			

Regression Coefficients
Obstruction Loss, Group 6, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.913	1.789	1.182	22.307	<.0001



Y = 0 + 39.913 * X; R^2 = .971

Regression Summary
Obstruction Loss, Group 7, Room Index 1 vs. VFR

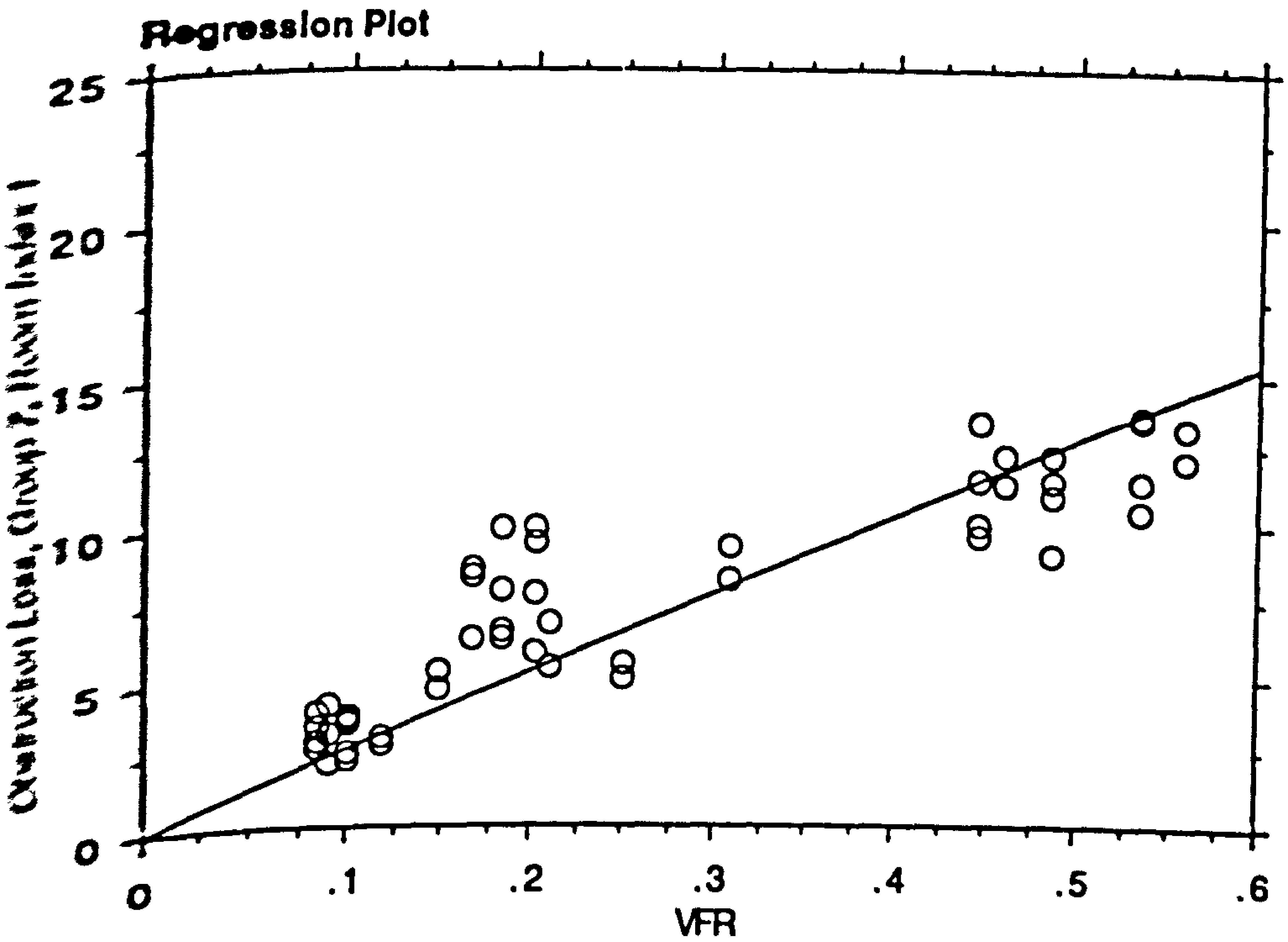
Count	54
Num. Missing	0
R	.973
R Squared	.948
Adjusted R Squared	.947
RMS Residual	2.014

ANOVA Table
Obstruction Loss, Group 7, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3888.868	3888.868	959.106	<.0001
Residual	53	214.898	4.055		
Total	54	4103.766			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	25.615	.827	1.160	30.969	<.0001



Y = 0 + 25.615 * X; R^2 = .948

Regression Summary
Obstruction Loss, Group 7, Room Index 1.25 vs. VFR

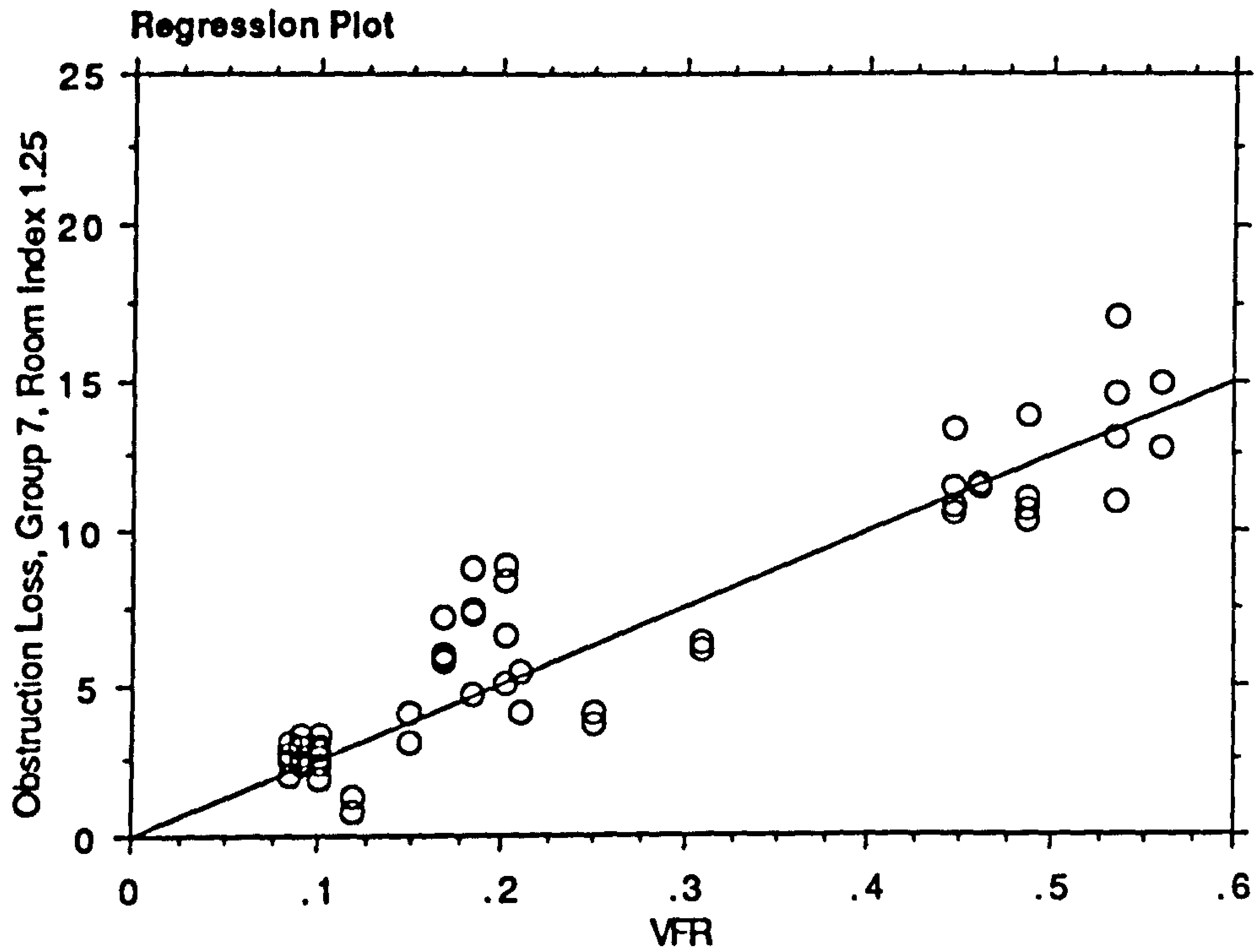
Count	54
Num. Missing	0
R	.979
R Squared	.958
Adjusted R Squared	.957
RMS Residual	1.750

ANOVA Table
Obstruction Loss, Group 7, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3702.785	3702.785	1208.559	<.0001
Residual	53	162.381	3.064		
Total	54	3865.166			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	24.995	.719	1.031	34.764	<.0001



Y = 0 + 24.995 * X; R^2 = .958

Regression Summary
Obstruction Loss, Group 7, Room Index 1.5 vs. VFR

Count	54
Num. Missing	0
R	.969
R Squared	.939
Adjusted R Squared	.938
RMS Residual	2.247

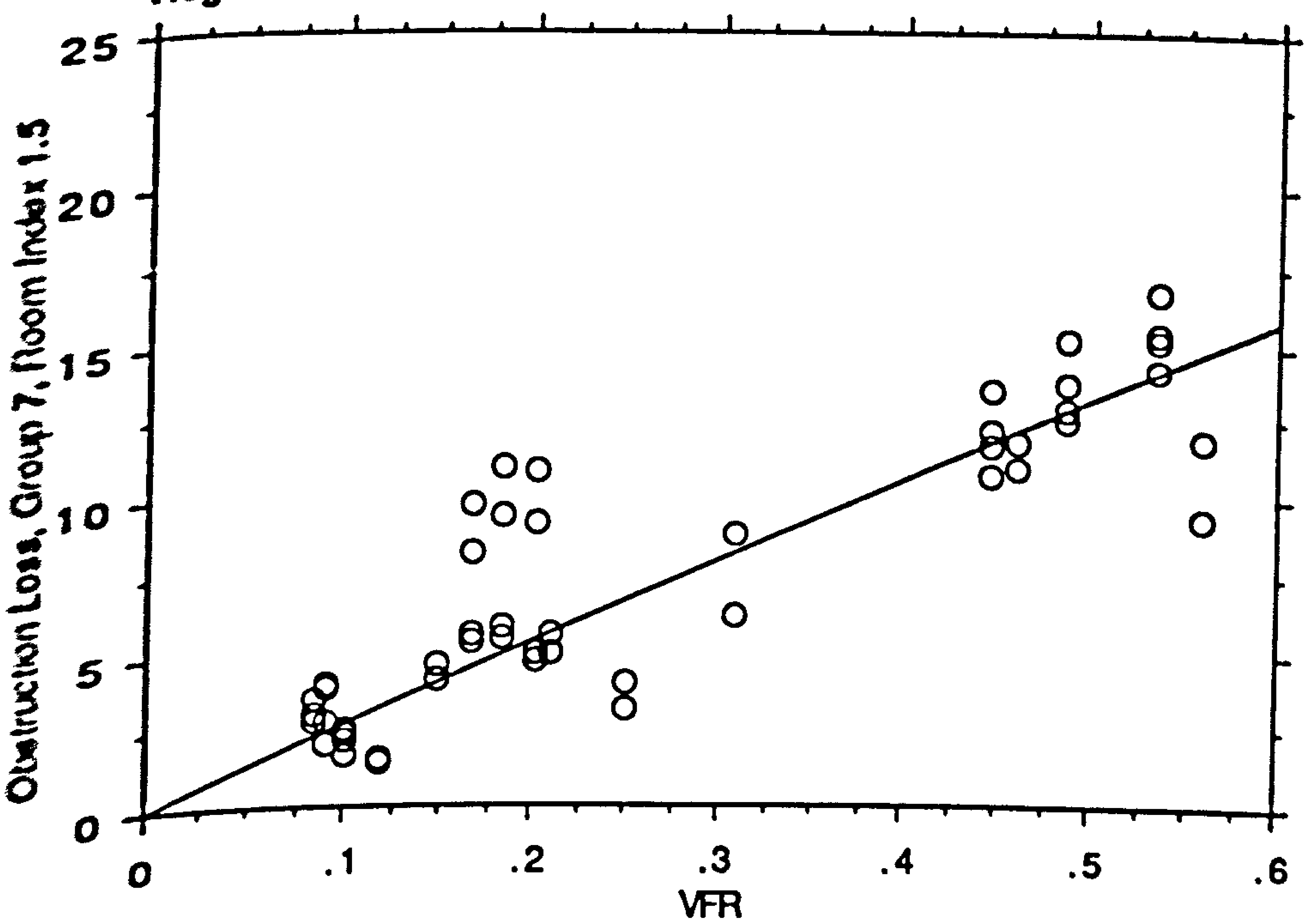
ANOVA Table
Obstruction Loss, Group 7, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4096.833	4096.833	811.422	<.0001
Residual	53	267.595	5.049		
Total	54	4364.428			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.291	.923	1.020	28.485	<.0001

Regression Plot



Y = 0 + 26.291 * X; R^2 = .939

Regression Summary
Obstruction Loss, Group 7, Room Index 2 vs. VFR

Count	54
Num. Missing	0
R	.951
R Squared	.905
Adjusted R Squared	.903
RMS Residual	2.378

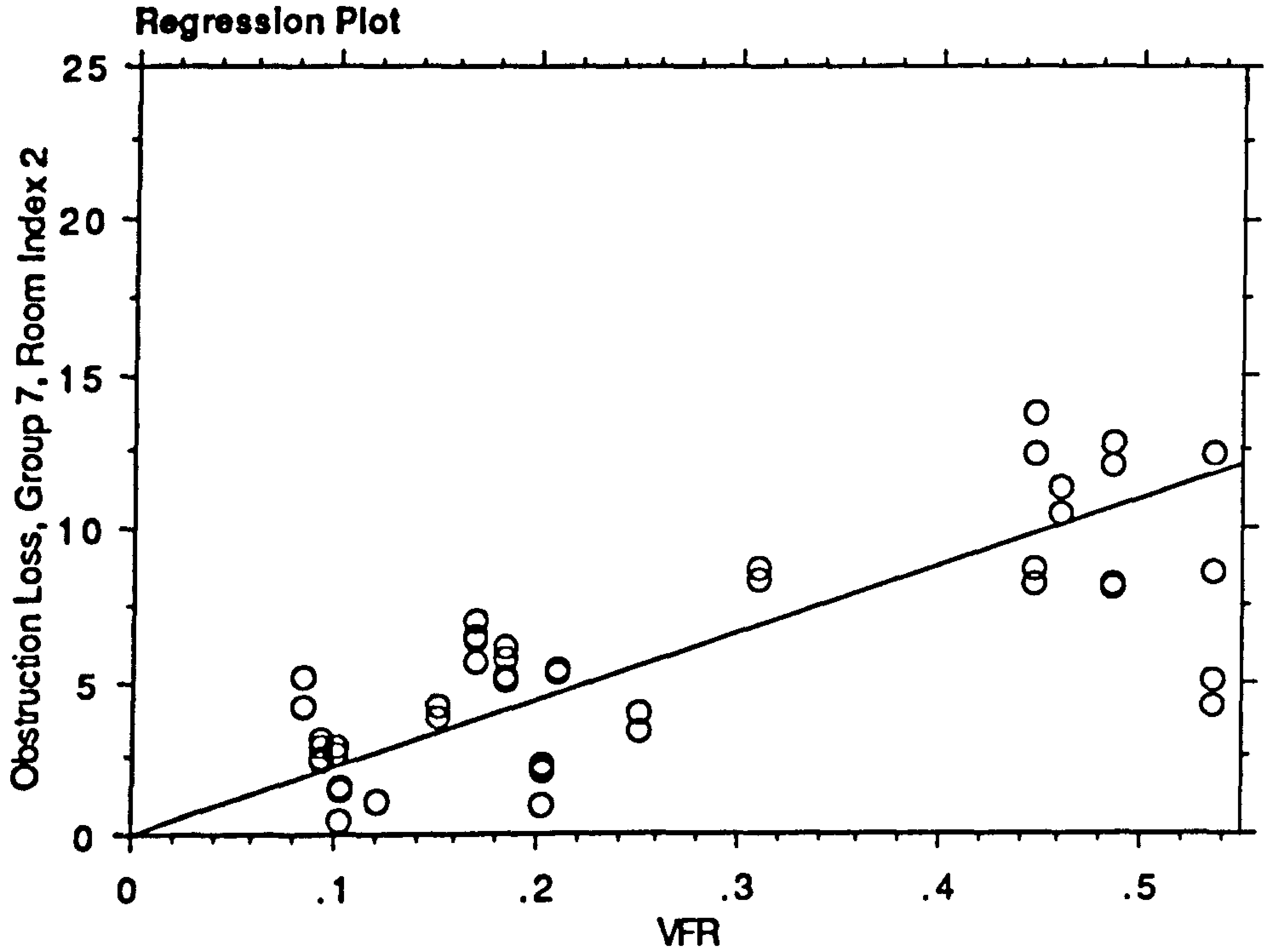
ANOVA Table
Obstruction Loss, Group 7, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2846.055	2846.055	503.135	<.0001
Residual	53	299.802	5.657		
Total	54	3145.857			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	21.913	.977	.924	22.431	<.0001

Regression Plot



Y = 0 + 21.913 * X; R^2 = .905

Regression Summary
Obstruction Loss, Group 7, Room Index 3 vs. VFR

Count	36
Num. Missing	0
R	.949
R Squared	.901
Adjusted R Squared	.898
RMS Residual	2.337

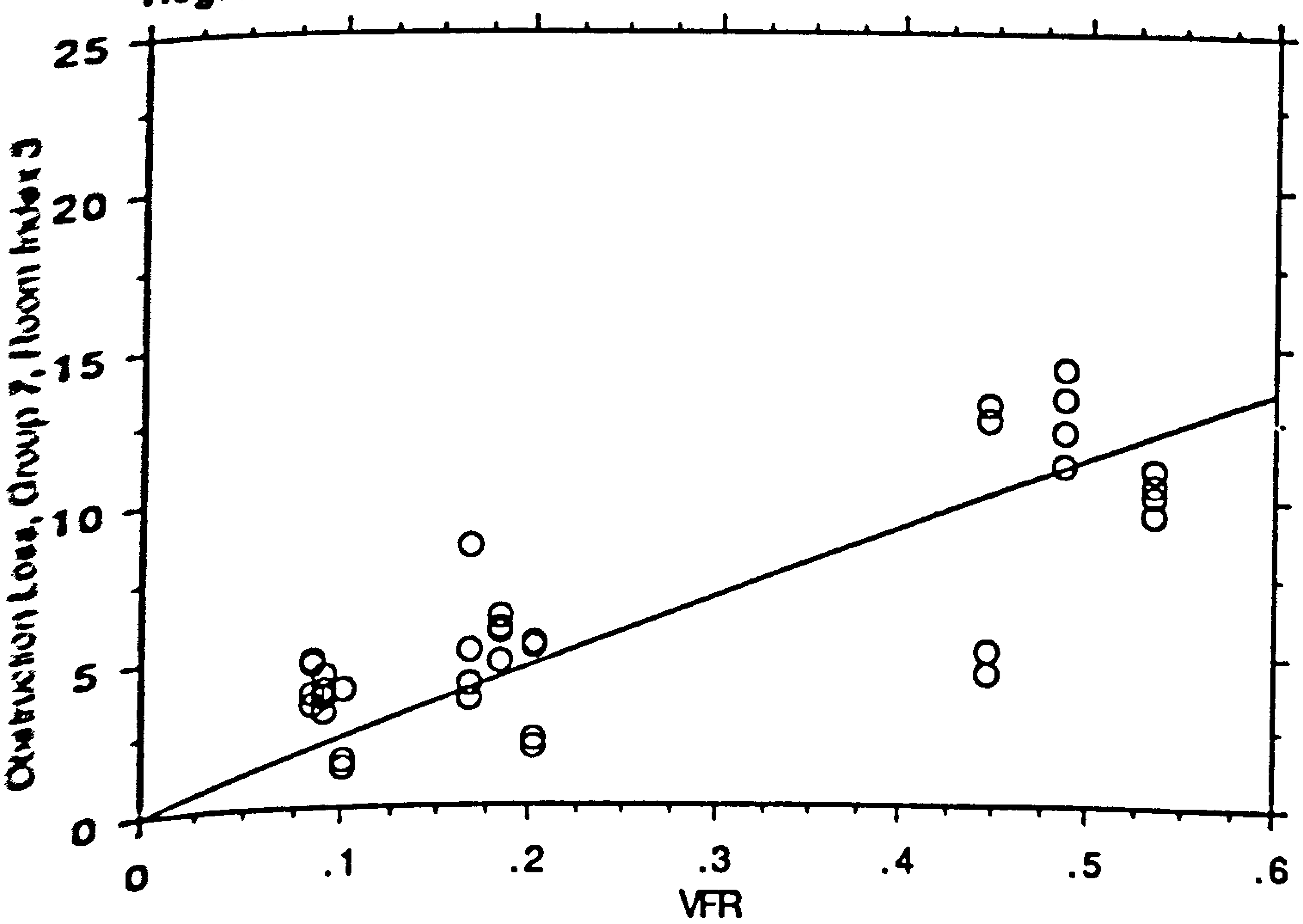
ANOVA Table
Obstruction Loss, Group 7, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1740.371	1740.371	318.773	<.0001
Residual	35	191.086	5.460		
Total	36	1931.456			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	22.633	1.268	1.044	17.854	<.0001

Regression Plot



Y = 0 + 22.633 * X; R^2 = .901

Regression Summary
Obstruction Loss, Group 7, Room Index 4 vs. VFR

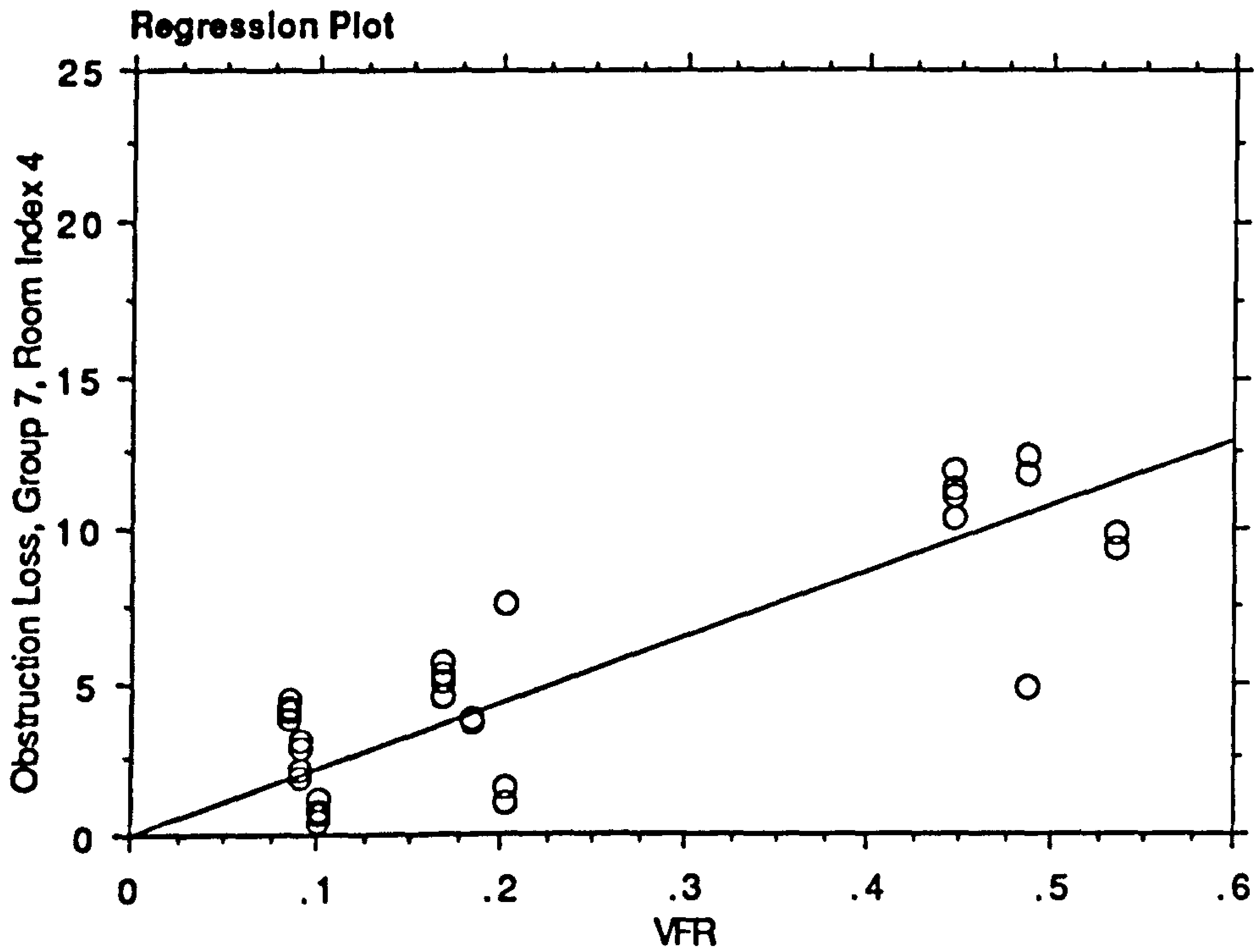
Count	33
Num. Missing	3
R	.948
R Squared	.898
Adjusted R Squared	.895
RMS Residual	2.058

ANOVA Table
Obstruction Loss, Group 7, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1199.057	1199.057	283.236	<.0001
Residual	32	135.470	4.233		
Total	33	1334.527			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	21.520	1.279	.921	16.830	<.0001



Y = 0 + 21.52 * X; R^2 = .898

Regression Summary
Obstruction Loss, Group 7, Room Index 5 vs. VFR

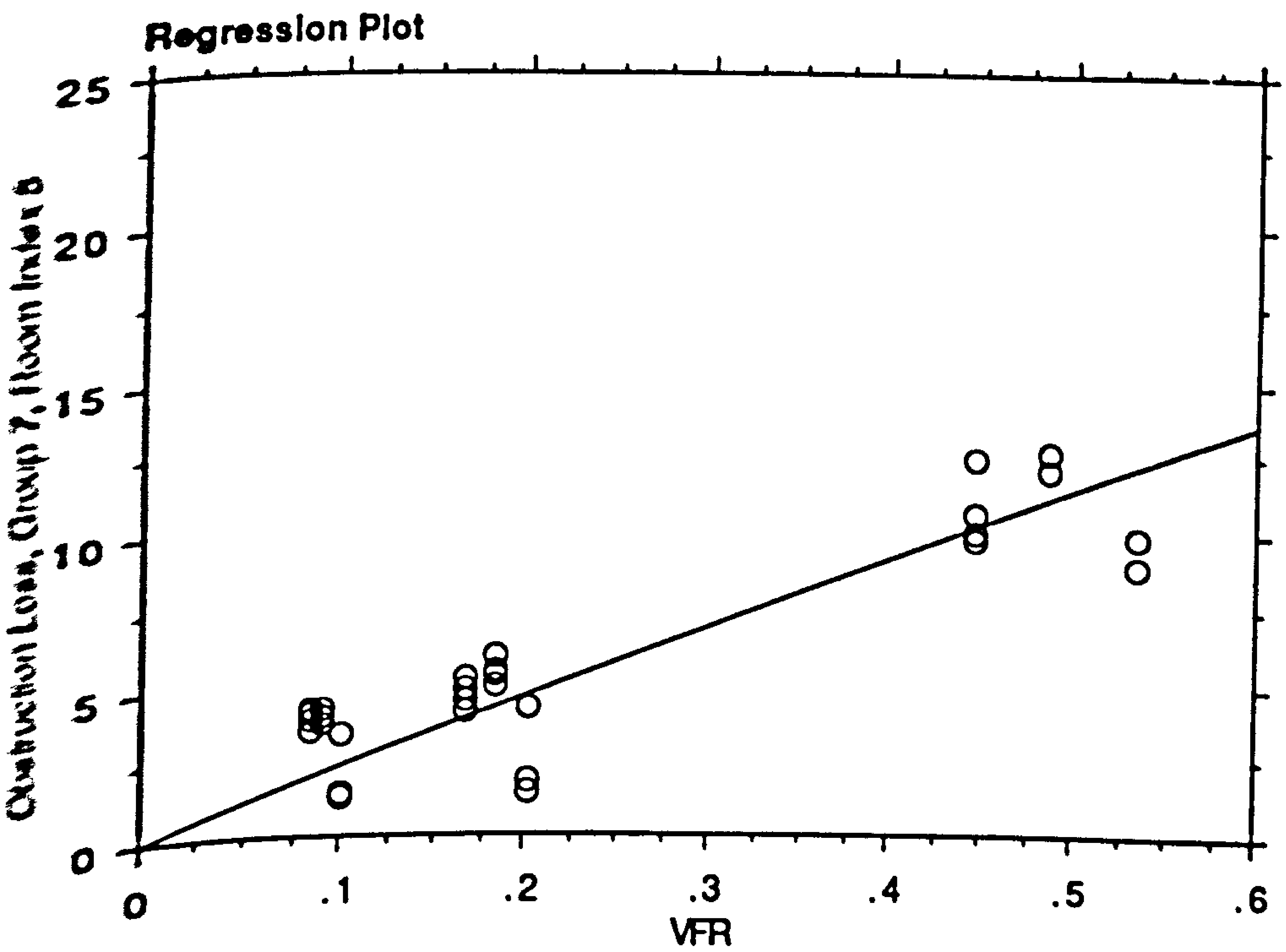
Count	32
Num. Missing	4
R	.964
R Squared	.929
Adjusted R Squared	.927
RMS Residual	1.737

ANOVA Table
Obstruction Loss, Group 7, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1226.842	1226.842	406.406	<.0001
Residual	31	93.582	3.019		
Total	32	1320.423			

Regression Coefficients
Obstruction Loss, Group 7, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	22.834	1.133	1.040	20.160	<.0001



Y = 0 + 22.834 * X; R^2 = .929

Regression Summary
group 8 OL (room index 1.00) vs. VFR

Count	108
Num. Missing	0
R	.981
R Squared	.963
Adjusted R Squared	.962
RMS Residual	2.106

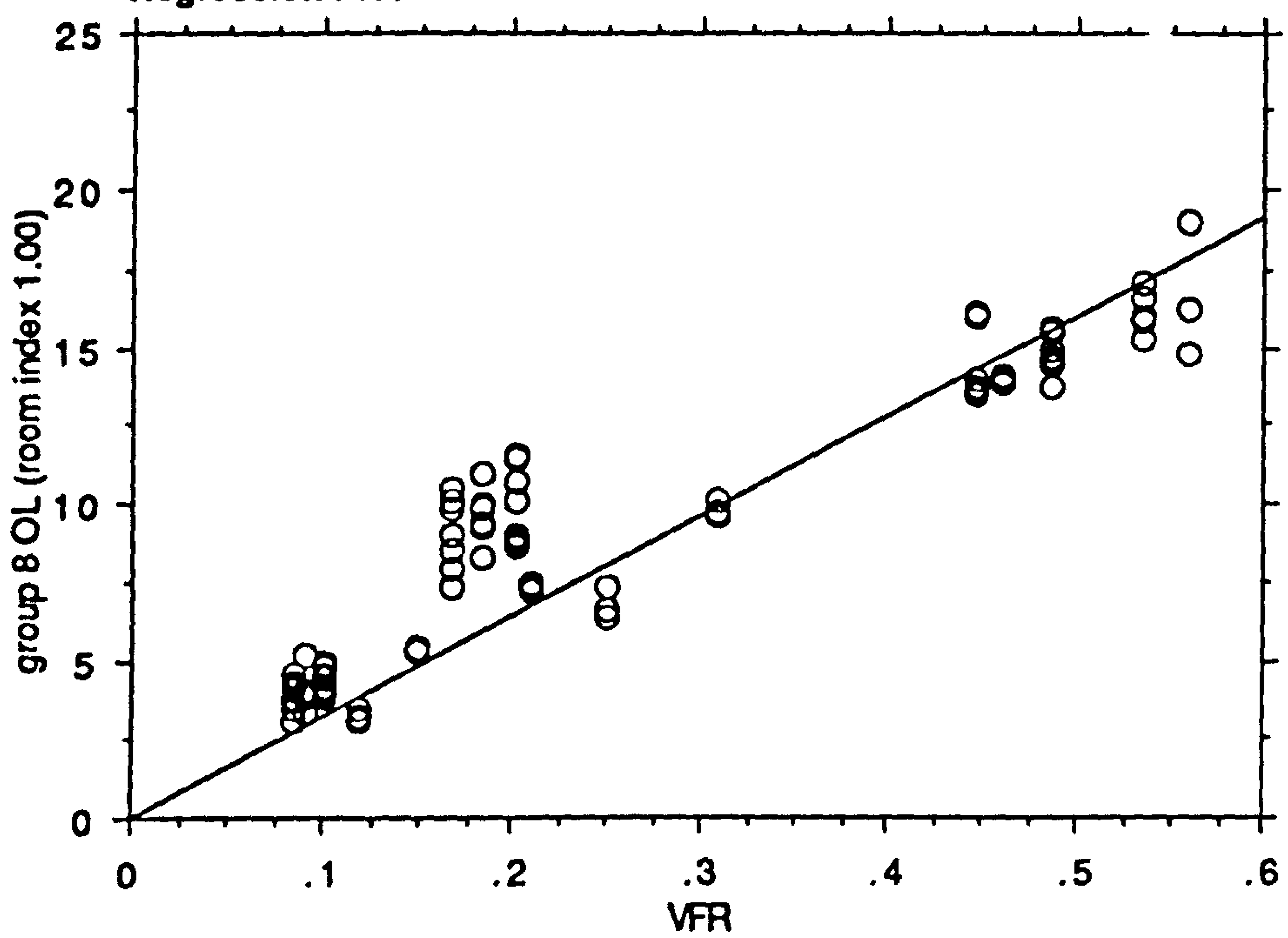
ANOVA Table
group 8 OL (room index 1.00) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	12215.861	12215.861	2754.419	<.0001
Residual	107	474.545	4.435		
Total	108	12690.406	.		

Regression Coefficients
group 8 OL (room index 1.00) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	32.101	.612	1.190	52.483	<.0001

Regression Plot



$Y = 0 + 32.101 * X; R^2 = .963$

Regression Summary
group 8 OL (room Index 1.25) vs. VFR

Count	108
Num. Missing	0
R	.986
R Squared	.973
Adjusted R Squared	.973
RMS Residual	1.836

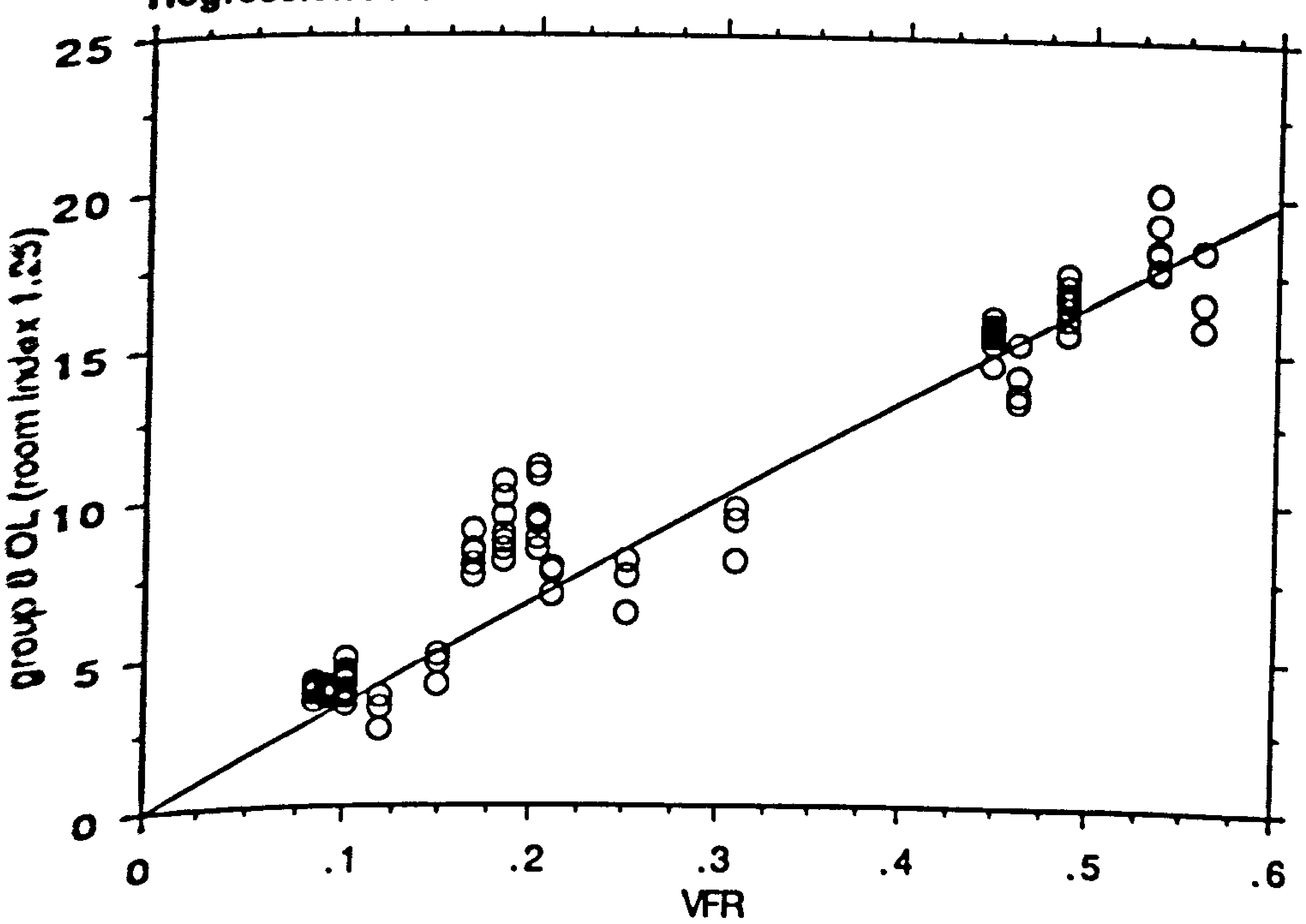
ANOVA Table
group 8 OL (room Index 1.25) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	12963.552	12963.552	3844.118	<.0001
Residual	#	360.837	3.372		
Total	#	13324.389			

Regression Coefficients
group 8 OL (room Index 1.25) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.069	.533	1.105	62.001	<.0001

Regression Plot



Y = 0 + 33.069 * X; R^2 = .973

Regression Summary
group 8 OL (room index 1.5) vs. VFR

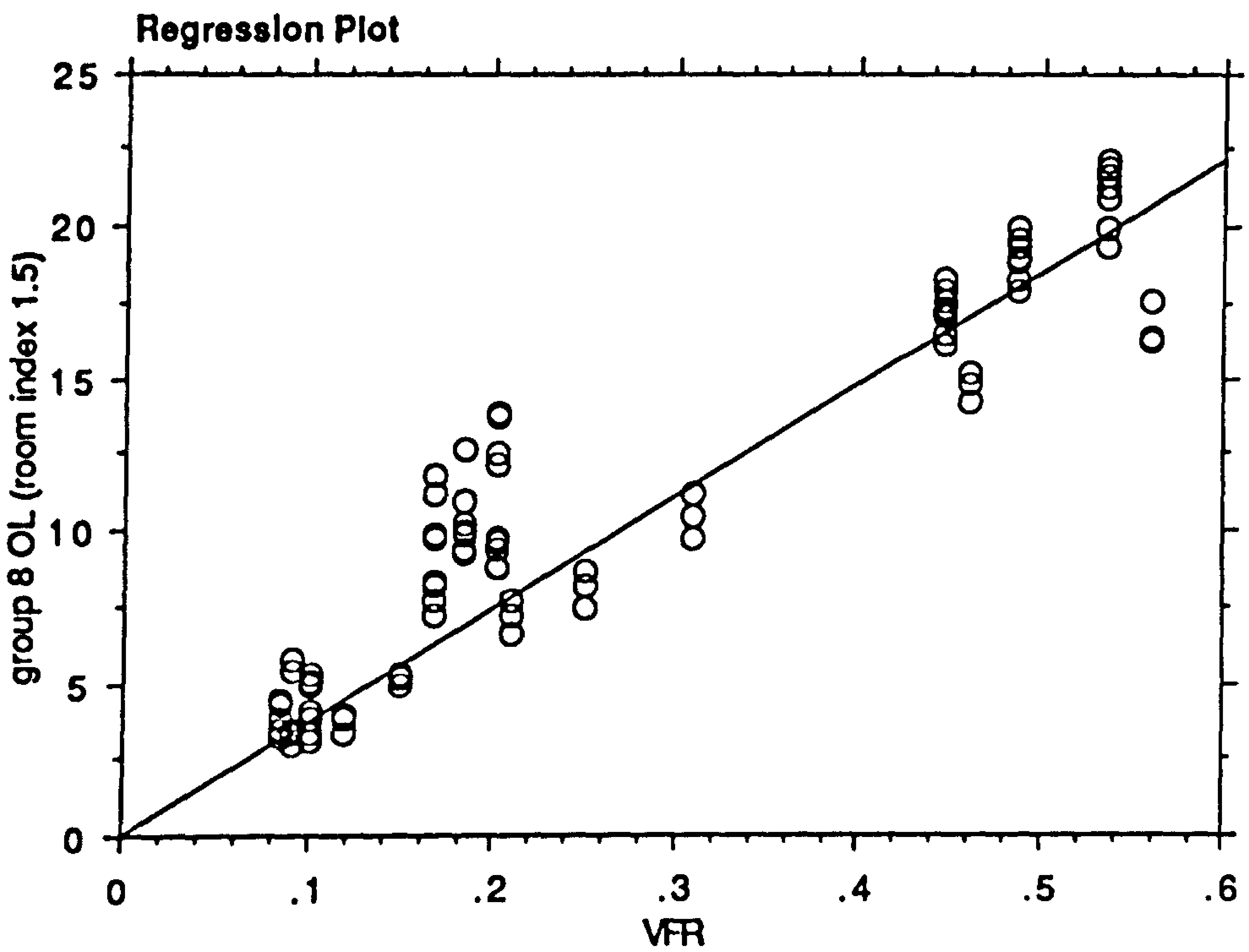
Count	108
Num. Missing	0
R	.981
R Squared	.963
Adjusted R Squared	.963
RMS Residual	2.414

ANOVA Table
group 8 OL (room index 1.5) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	16272.888	16272.888	2791.568	<.0001
Residual	#	623.735	5.829		
Total	#	16896.623			

Regression Coefficients
group 8 OL (room index 1.5) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	37.050	.701	1.090	52.835	<.0001



Y = 0 + 37.05 * X; R^2 = .963

Regression Summary
group 8 OL (room Index 2.0) vs. VFR

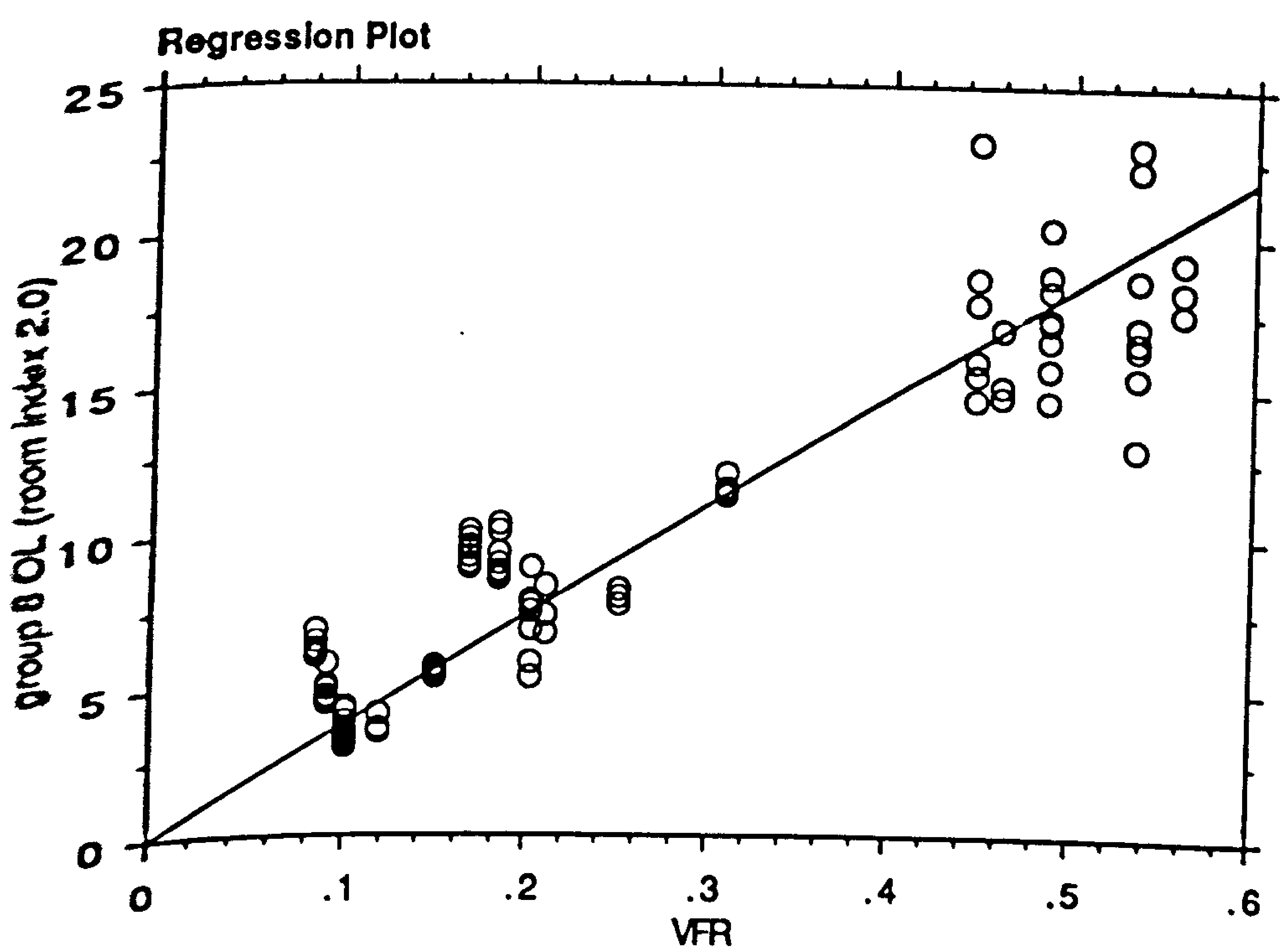
Count	108
Num. Missing	0
R	.984
R Squared	.968
Adjusted R Squared	.968
RMS Residual	2.197

ANOVA Table
group 8 OL (room Index 2.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	15877.088	15877.088	3288.453	<.0001
Residual	107	516.610	4.828		
Total	108	16393.698			

Regression Coefficients
group 8 OL (room Index 2.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.597	.638	1.079	57.345	<.0001



Y = 0 + 36.597 * X; R^2 = .968

Regression Summary
group 8 OL (room index 3.0) vs. VFR

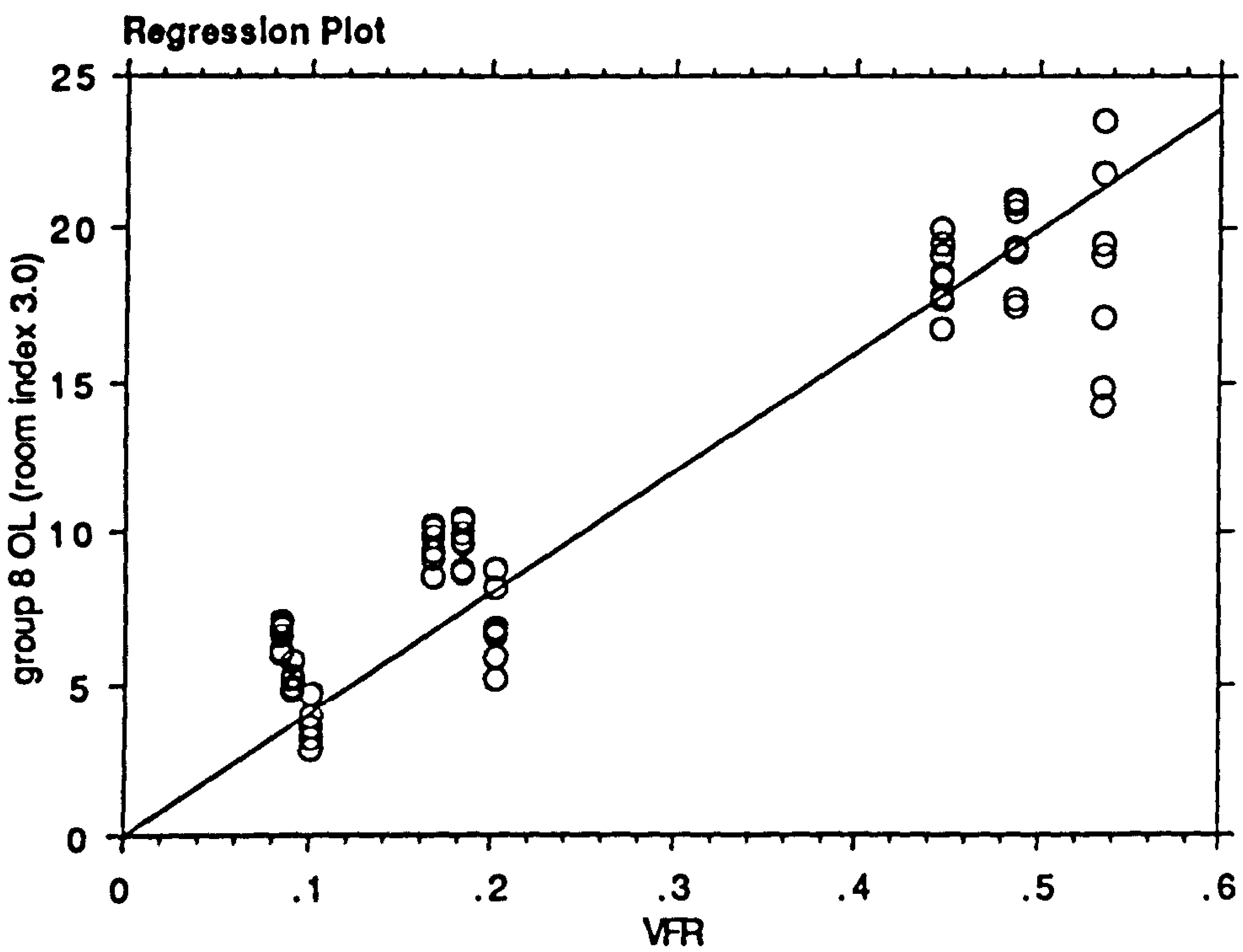
Count	71
Num. Missing	1
R	.983
R Squared	.965
Adjusted R Squared	.965
RMS Residual	2.355

ANOVA Table
group 8 OL (room index 3.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10820.313	10820.313	1950.556	<.0001
Residual	70	388.311	5.547		
Total	71	11208.624			

Regression Coefficients
group 8 OL (room index 3.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.924	.904	1.126	44.165	<.0001



Y = 0 + 39.924 * X; R^2 = .965

Regression Summary
group 8 OL (room index 4.0) vs. VFR

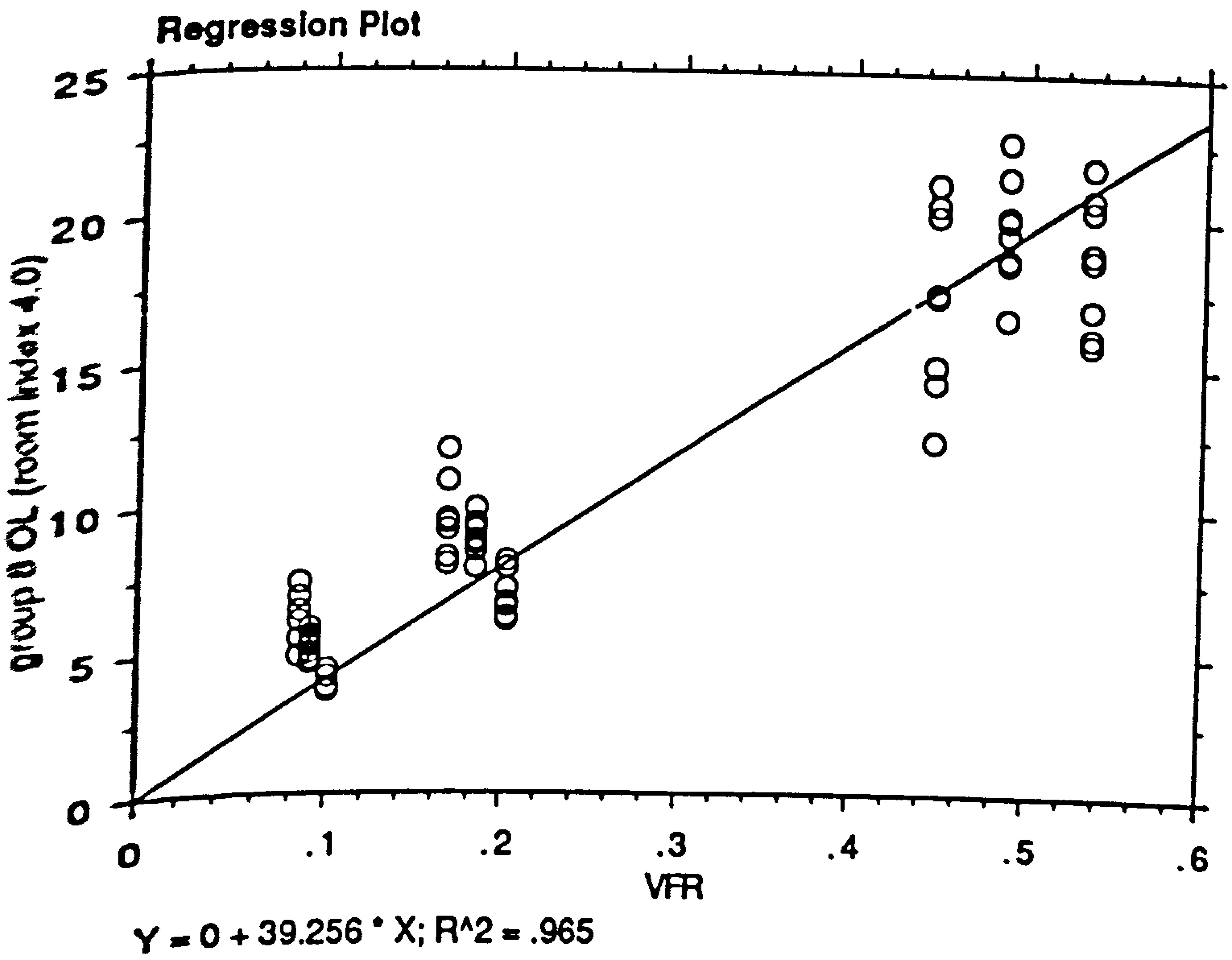
Count	71
Num. Missing	1
R	.982
R Squared	.965
Adjusted R Squared	.965
RMS Residual	2.325

ANOVA Table
group 8 OL (room index 4.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10461.125	10461.125	1935.620	<.0001
Residual	70	378.317	5.405		
Total	71	10839.443			

Regression Coefficients
group 8 OL (room index 4.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.256	.892	1.112	43.996	<.0001



Regression Summary
group 8 OL (room Index 5.0) vs. VFR

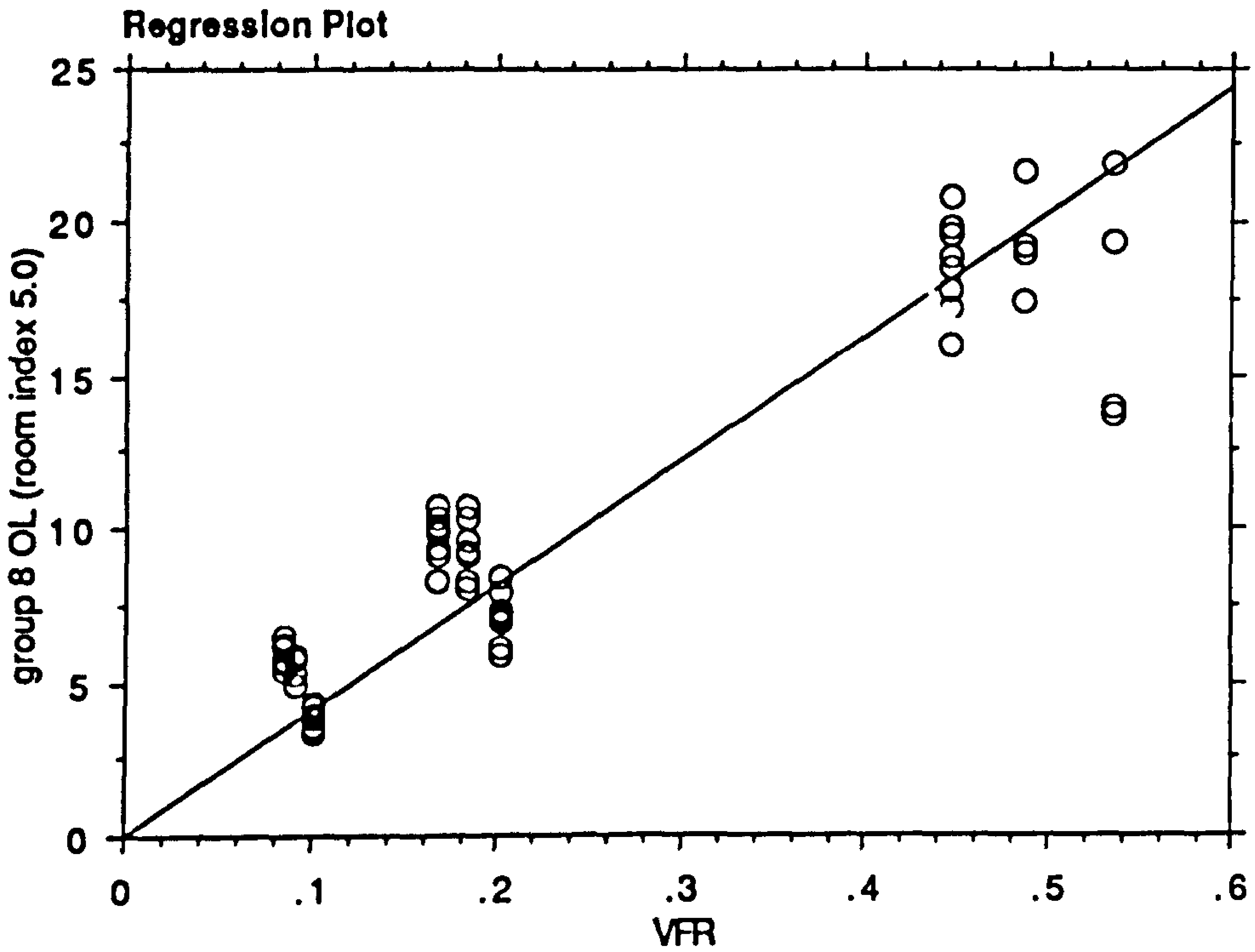
Count	64
Num. Missing	8
R	.978
R Squared	.956
Adjusted R Squared	.955
RMS Residual	2.389

ANOVA Table
group 8 OL (room Index 5.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7749.259	7749.259	1357.954	<.0001
Residual	63	359.514	5.707		
Total	64	8108.773			

Regression Coefficients
group 8 OL (room Index 5.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	40.577	1.101	1.138	36.850	<.0001



Y = 0 + 40.577 * X; R^2 = .956

Regression Summary
group 9a OL (room Index 1.00) vs. VFR

Count	99
Num. Missing	0
R	.960
R Squared	.921
Adjusted R Squared	.920
RMS Residual	2.783

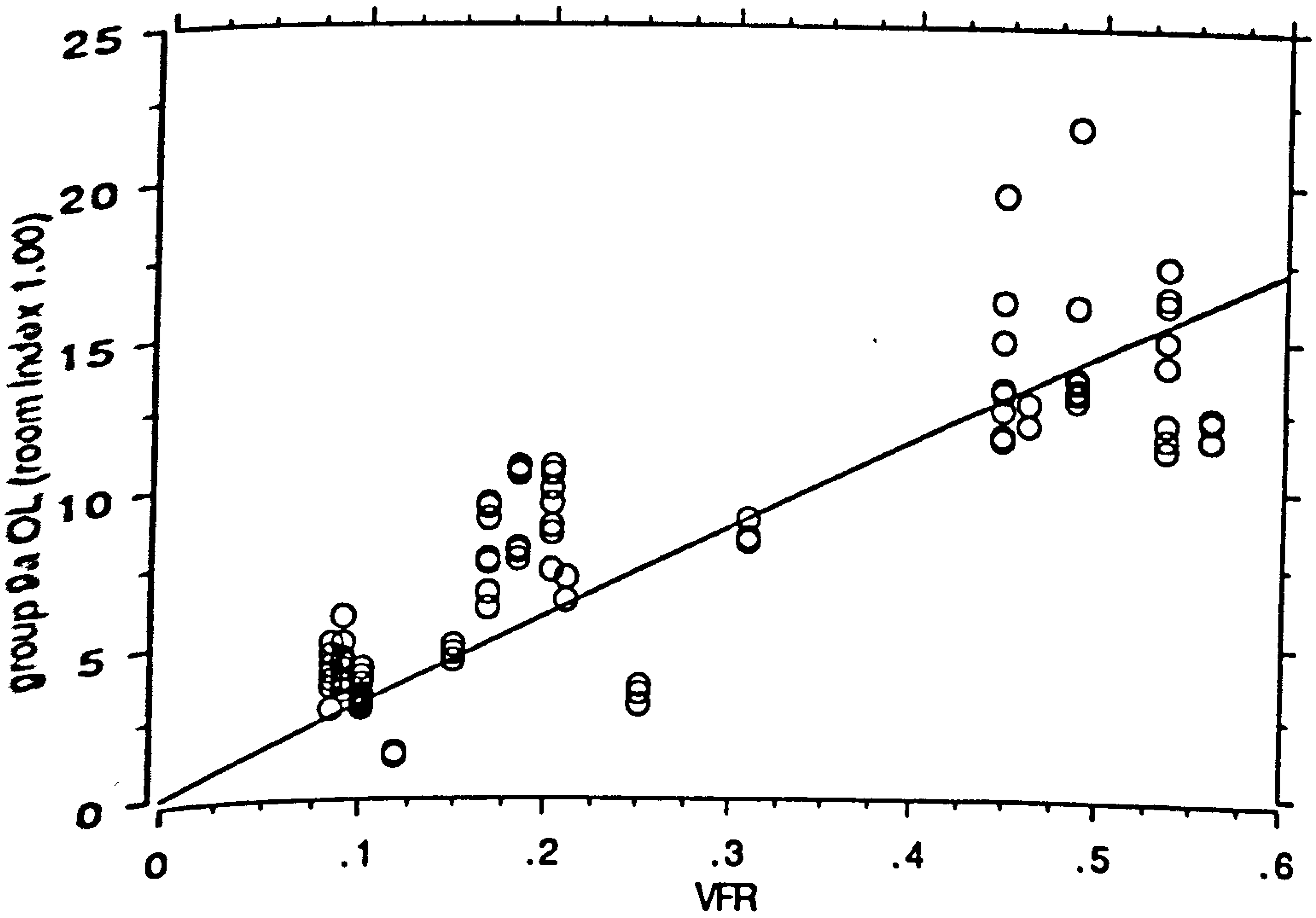
ANOVA Table
group 9a OL (room Index 1.00) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8813.782	8813.782	1137.627	<.0001
Residual	98	759.256	7.748		
Total	99	9573.038			

Regression Coefficients
group 9a OL (room Index 1.00) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.849	.855	1.069	33.729	<.0001

Regression Plot



Y = 0 + 28.849 * X; R^2 = .921

Regression Summary
group 9a OL (room index 1.25) vs. VFR

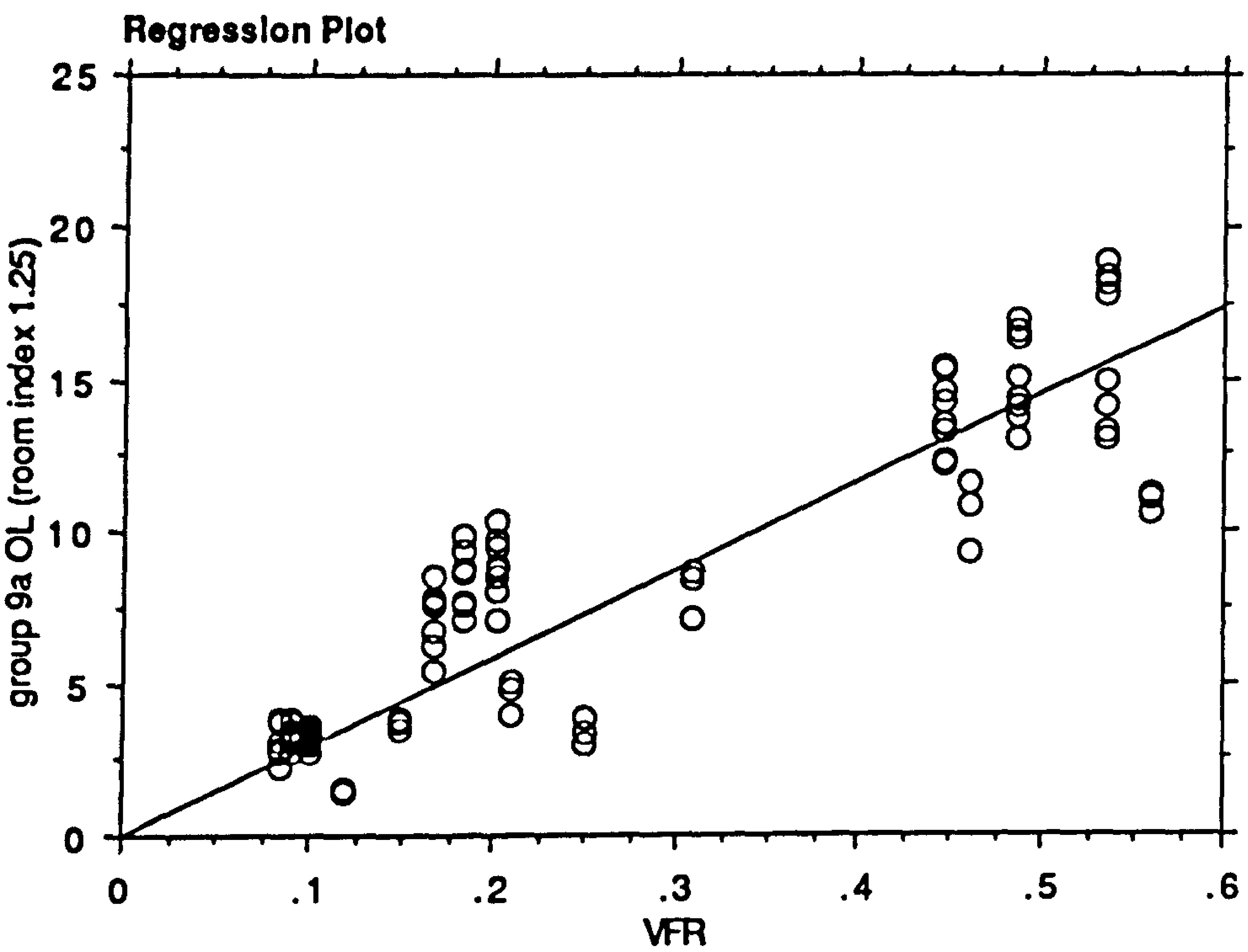
Count	99
Num. Missing	0
R	.972
R Squared	.945
Adjusted R Squared	.944
RMS Residual	2.299

ANOVA Table
group 9a OL (room index 1.25) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8860.161	8860.161	1676.111	<.0001
Residual	98	518.042	5.286		
Total	99	9378.203			

Regression Coefficients
group 9a OL (room index 1.25) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.925	.707	1.044	40.940	<.0001



Y = 0 + 28.925 * X; R^2 = .945

Regression Summary
group 9a OL (room index 1.50) vs. VFR

Count	99
Num. Missing	0
R	.969
R Squared	.940
Adjusted R Squared	.939
RMS Residual	2.537

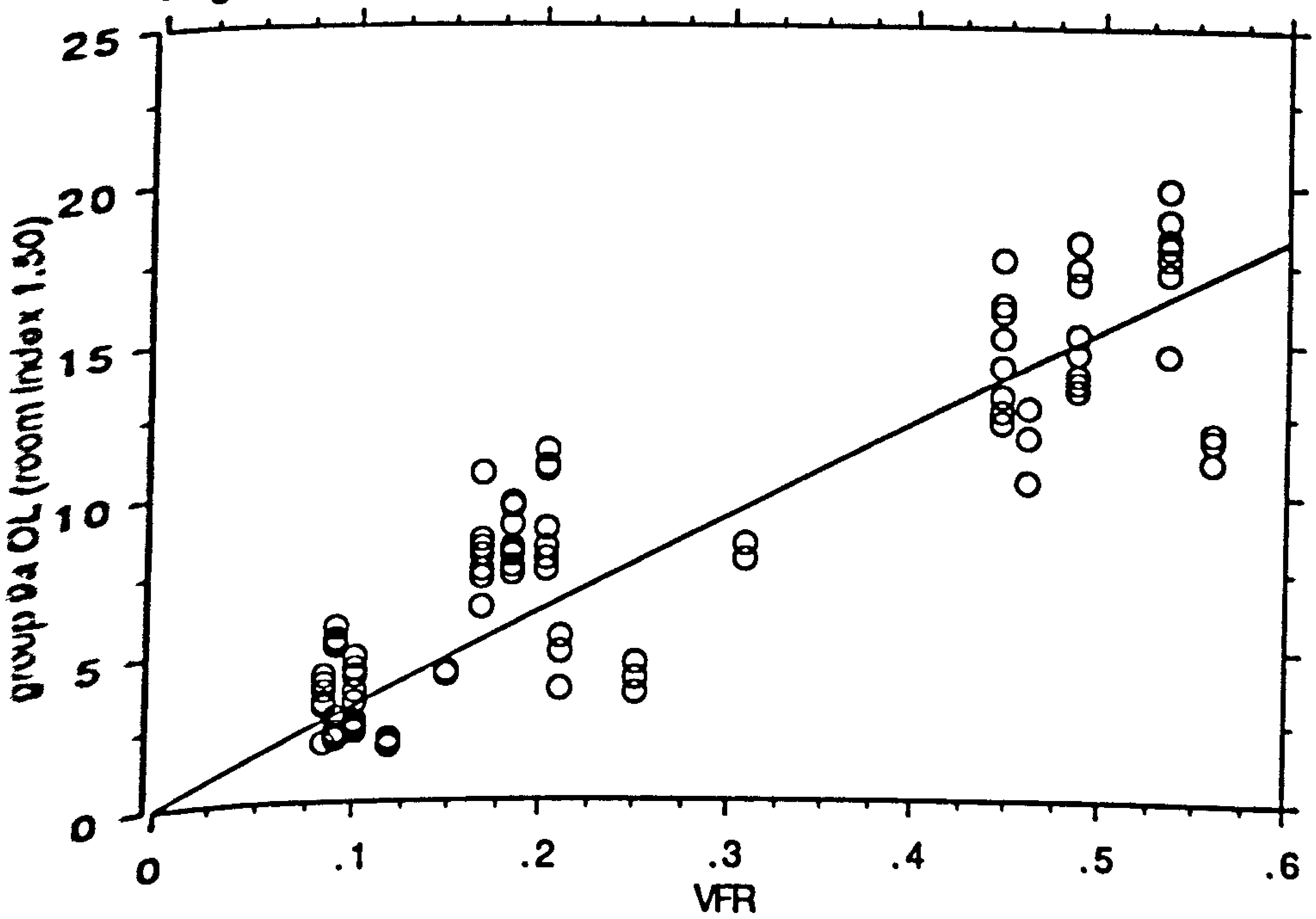
ANOVA Table
group 9a OL (room index 1.50) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9856.629	9856.629	1531.374	<.0001
Residual	98	630.773	6.436		
Total	99	10487.402			

Regression Coefficients
group 9a OL (room index 1.50) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	30.509	.780	1.044	39.133	<.0001

Regression Plot



Y = 0 + 30.509 * X; R^2 = .94

Regression Summary
group 9a OL (room index 2) vs. VFR

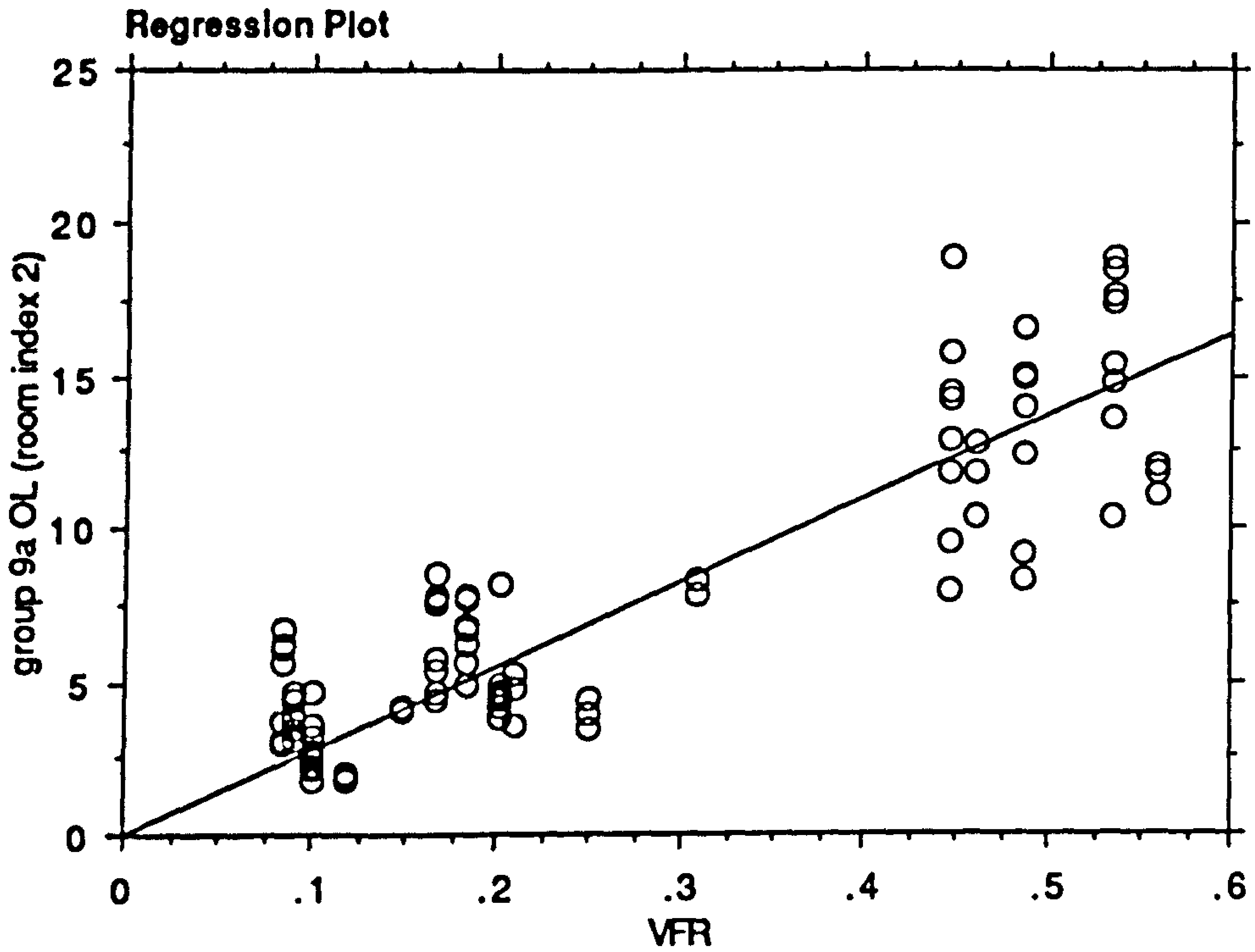
Count	99
Num. Missing	0
R	.969
R Squared	.940
Adjusted R Squared	.939
RMS Residual	2.275

ANOVA Table
group 9a OL (room index 2) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7894.387	7894.387	1525.859	<.0001
Residual	98	507.026	5.174		
Total	99	8401.412			

Regression Coefficients
group 9a OL (room index 2) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	27.303	.699	1.008	39.062	<.0001



Y = 0 + 27.303 * X; R^2 = .94

Regression Summary
group 9a OL (room index 3) vs. VFR

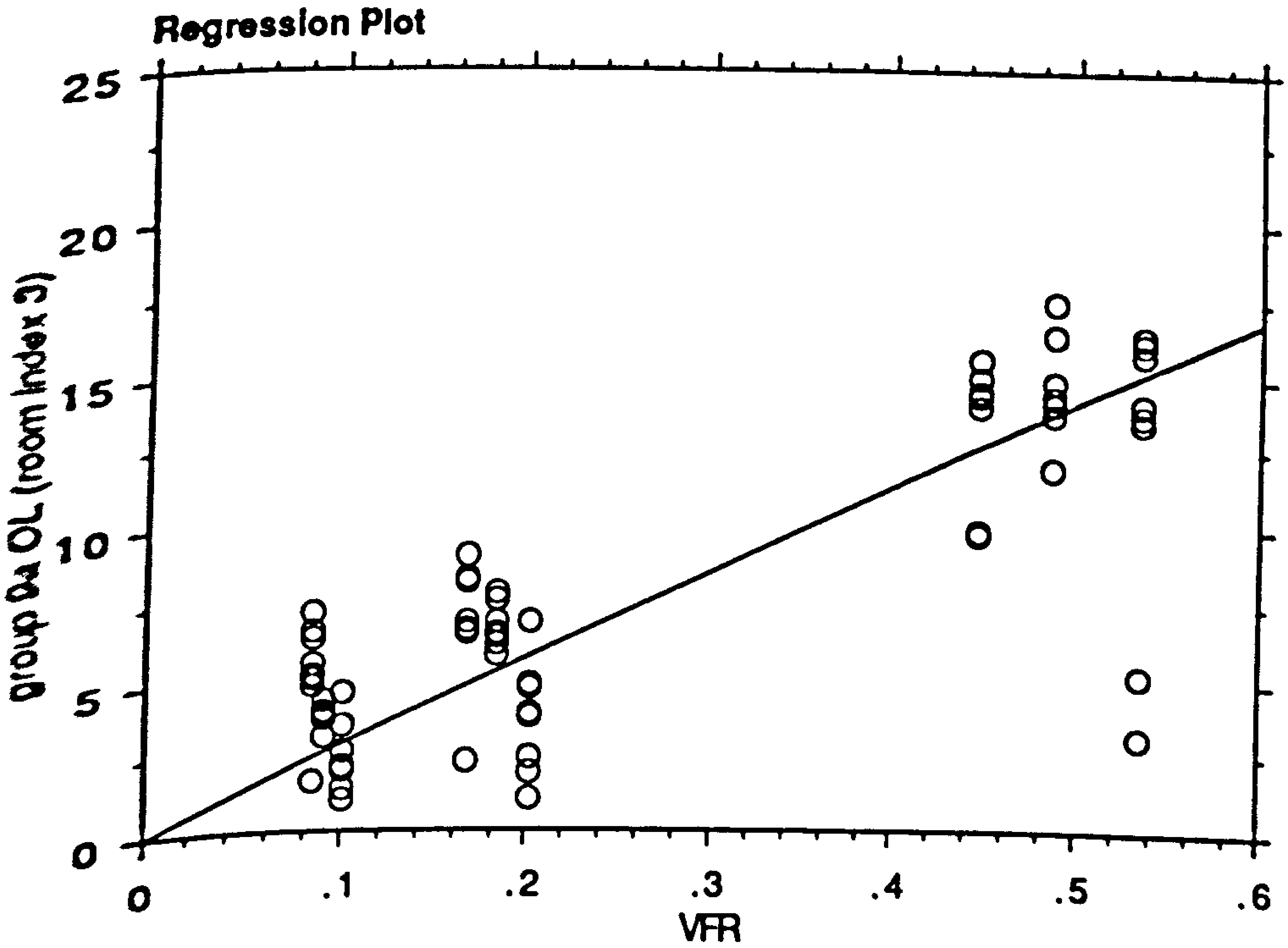
Count	72
Num. Missing	0
R	.950
R Squared	.903
Adjusted R Squared	.902
RMS Residual	2.855

ANOVA Table
group 9a OL (room index 3) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5384.235	5384.235	660.650	<.0001
Residual	71	578.643	8.150		
Total	72	5962.878			

Regression Coefficients
group 9a OL (room index 3) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.149	1.095	.992	25.703	<.0001



Y = 0 + 28.149 * X; R^2 = .903

Regression Summary
group 9a OL (room index 4) vs. VFR

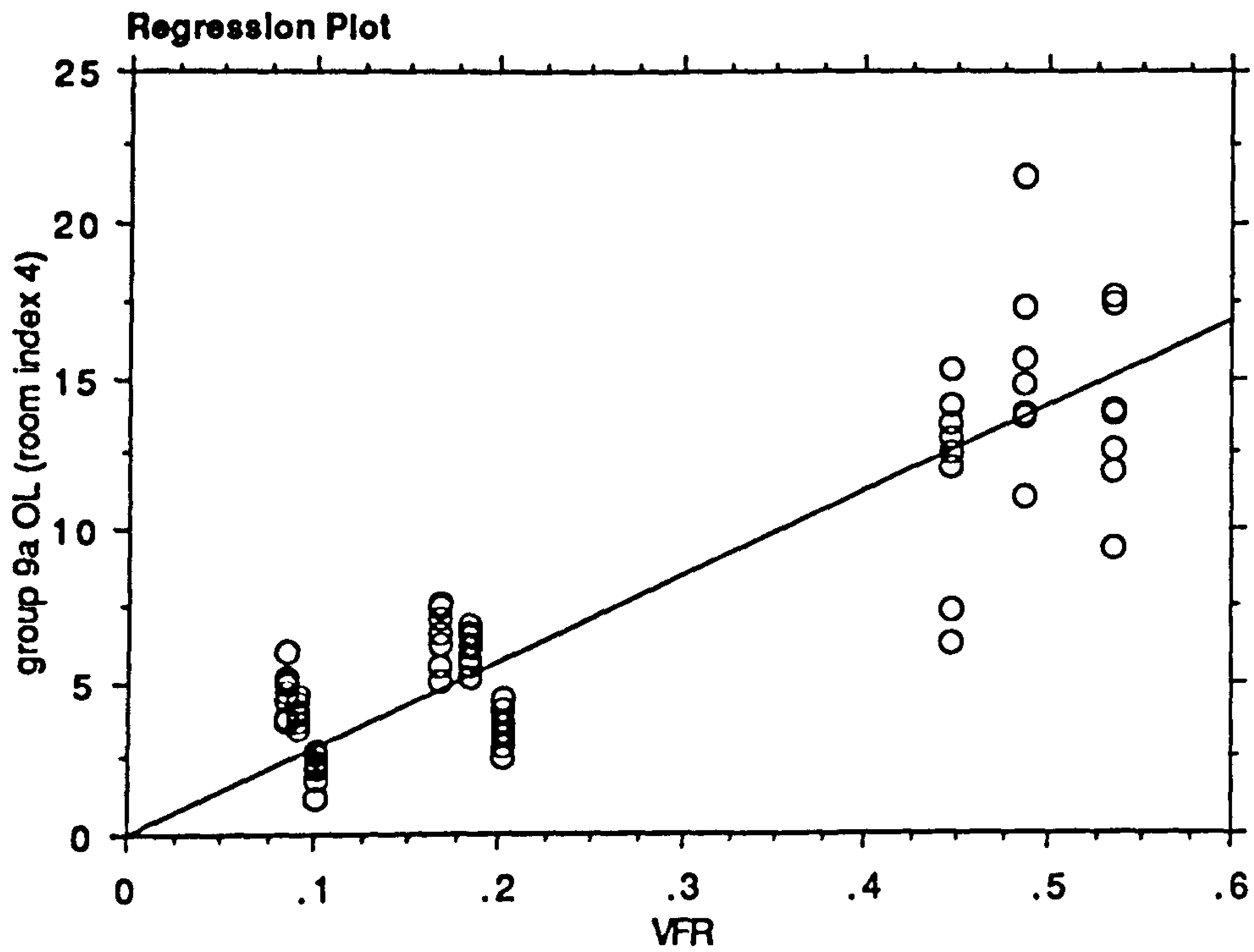
Count	72
Num. Missing	0
R	.967
R Squared	.934
Adjusted R Squared	.933
RMS Residual	2.317

ANOVA Table
group 9a OL (room index 4) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5424.594	5424.594	1.011E3	<.0001
Residual	71	381.133	5.368		
Total	72	5805.727			

Regression Coefficients
group 9a OL (room index 4) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.254	.889	.991	31.789	<.0001



Y = 0 + 28.254 * X; R^2 = .934

Regression Summary
group 9a OL (room Index 5) vs. VFR

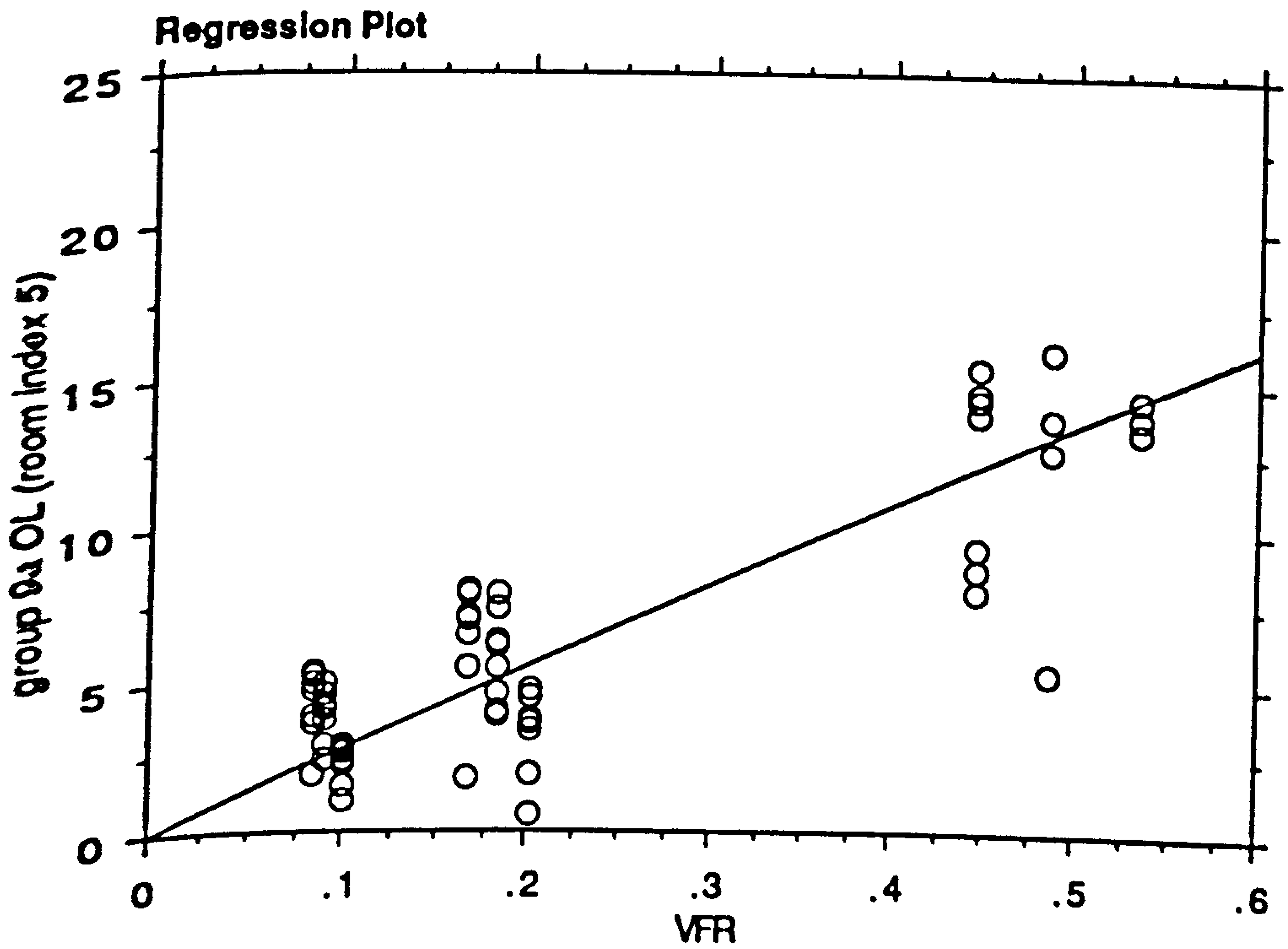
Count	63
Num. Missing	9
R	.954
R Squared	.909
Adjusted R Squared	.908
RMS Residual	2.277

ANOVA Table
group 9a OL (room Index 5) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3223.638	3223.638	621.621	<.0001
Residual	62	321.523	5.186		
Total	63	3545.161			

Regression Coefficients
group 9a OL (room Index 5) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	27.004	1.083	.979	24.932	<.0001



Y = 0 + 27.004 * X; R^2 = .909

Regression Summary
Obstruction Loss, Group 9B, Room Index 1 vs. VFR

Count	90
Num. Missing	0
R	.977
R Squared	.955
Adjusted R Squared	.954
RMS Residual	2.122

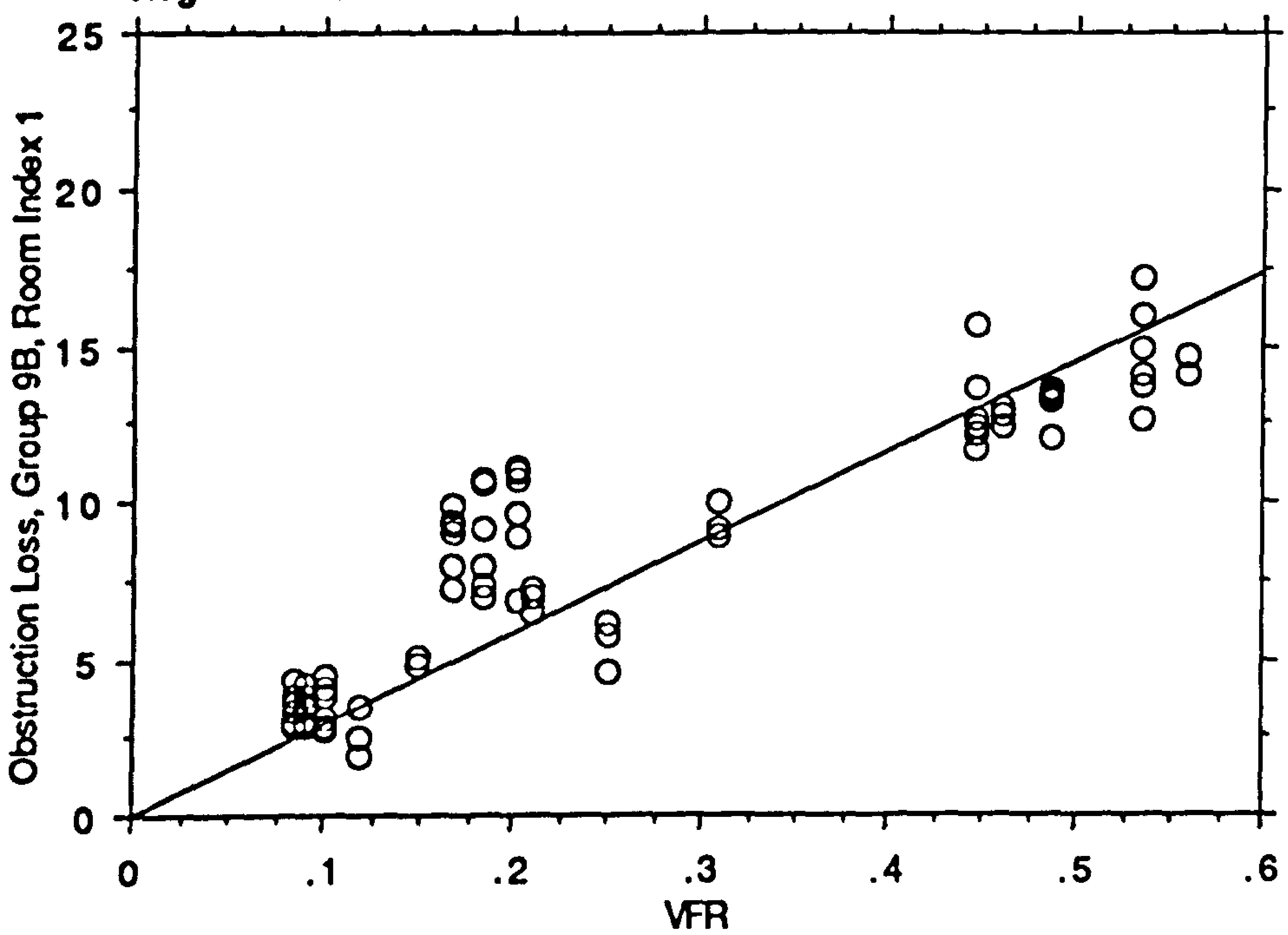
ANOVA Table
Obstruction Loss, Group 9B, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8502.155	8502.155	1888.810	<.0001
Residual	89	400.618	4.501		
Total	90	8902.773			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.935	.666	1.141	43.460	<.0001

Regression Plot



Y = 0 + 28.935 * X; R^2 = .955

Regression Summary
Obstruction Loss, Group 9B, Room Index 1.25 vs. VFR

Count	90
Num. Missing	0
R	.975
R Squared	.950
Adjusted R Squared	.950
RMS Residual	2.303

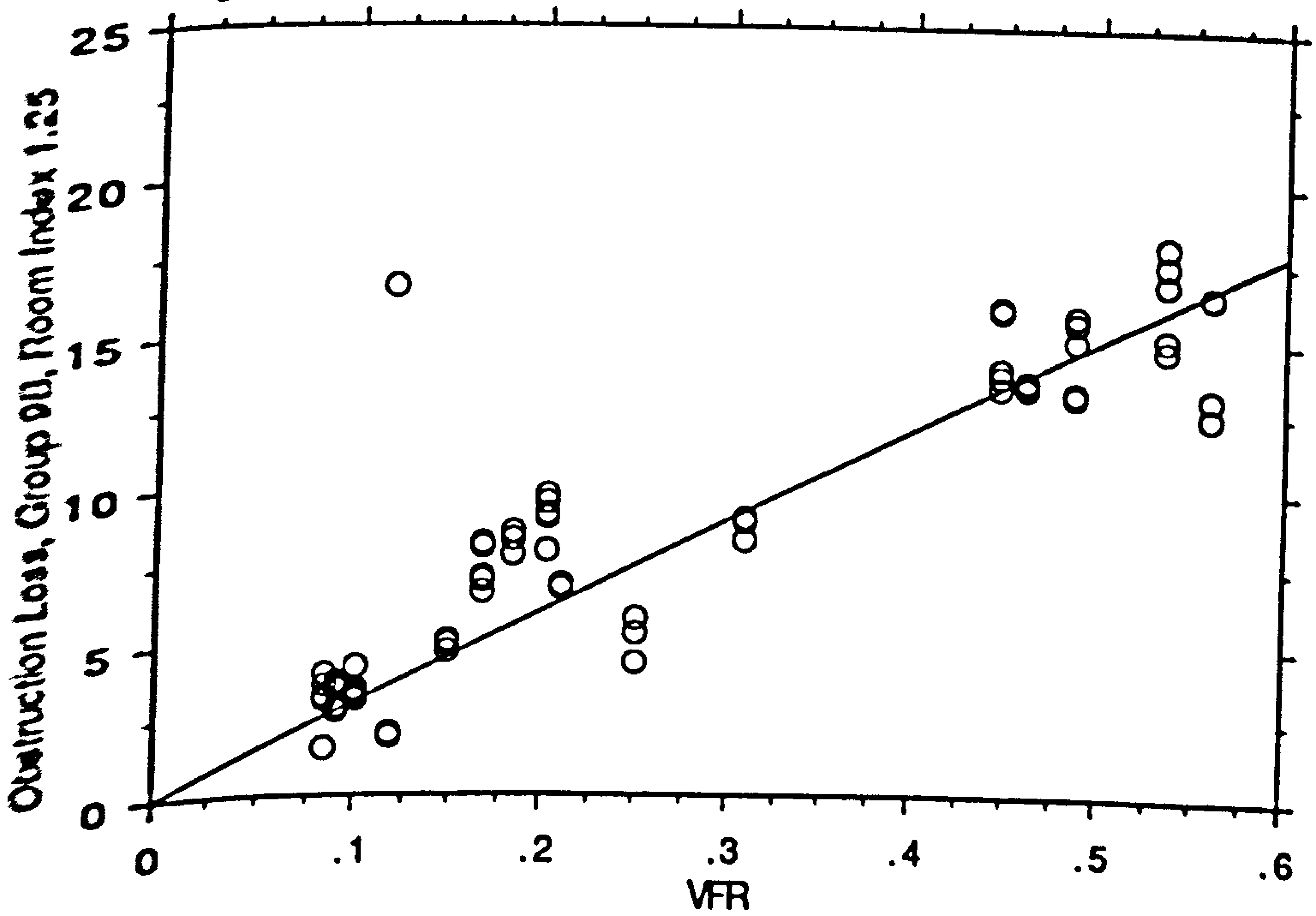
ANOVA Table
Obstruction Loss, Group 9B, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9020.932	9020.932	1700.571	<.0001
Residual	89	472.114	5.305		
Total	90	9493.046			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	29.804	.723	1.084	41.238	<.0001

Regression Plot



Y = 0 + 29.804 * X; R^2 = .95

Regression Summary
Obstruction Loss, Group 9B, Room Index 1.5 vs. VFR

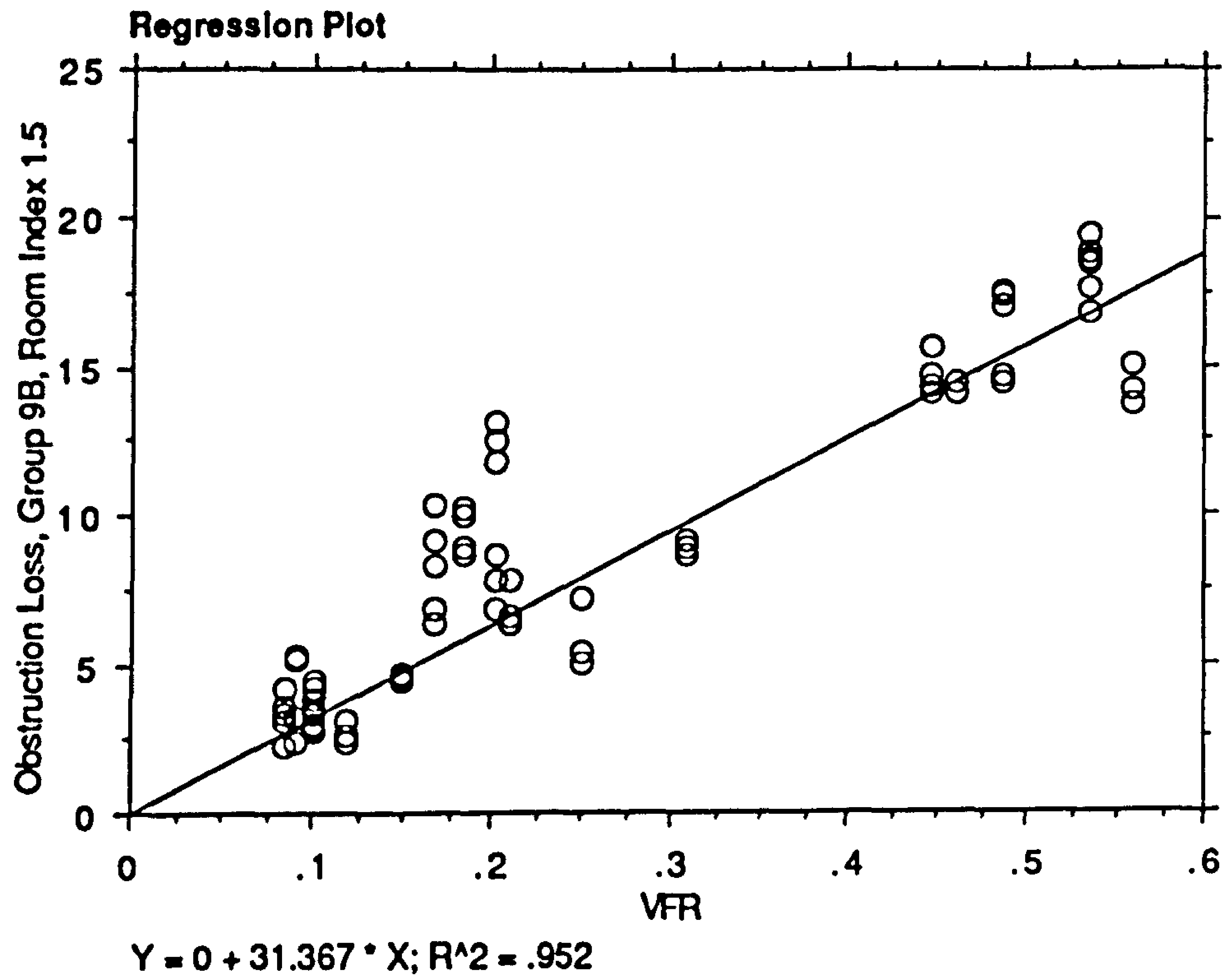
Count	90
Num. Missing	0
R	.976
R Squared	.952
Adjusted R Squared	.951
RMS Residual	2.386

ANOVA Table
Obstruction Loss, Group 9B, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9991.737	9991.737	1755.236	<.0001
Residual	89	506.635	5.693		
Total	90	10498.373			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	31.367	.749	1.074	41.896	<.0001



Y = 0 + 31.367 * X; R^2 = .952

Regression Summary
Obstruction Loss, Group 9B, Room Index 2 vs. VFR

Count	90
Num. Missing	0
R	.979
R Squared	.959
Adjusted R Squared	.959
RMS Residual	2.206

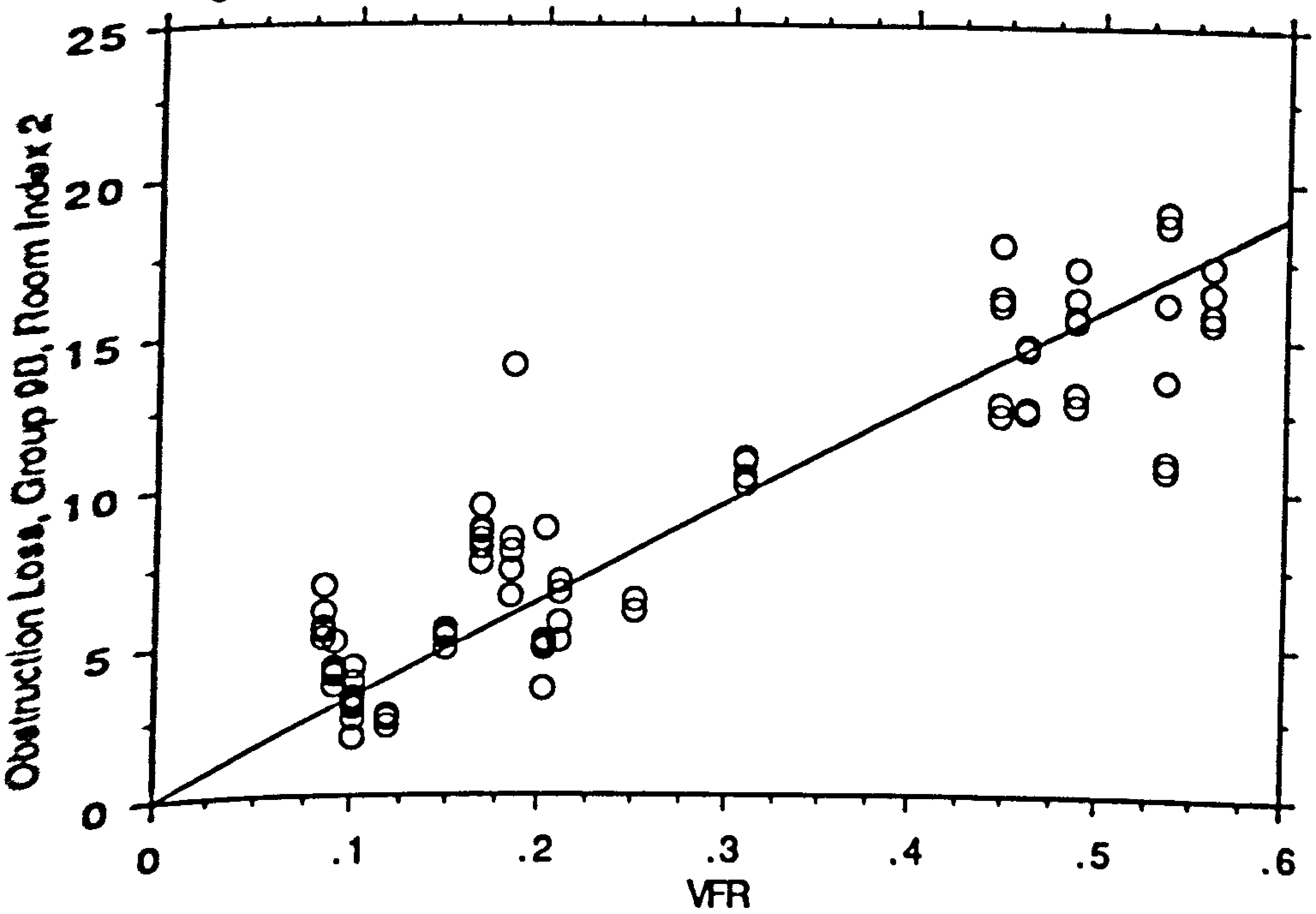
ANOVA Table
Obstruction Loss, Group 9B, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10191.553	10191.553	2094.297	<.0001
Residual	89	433.104	4.866		
Total	90	10624.657			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	31.679	.692	1.028	45.763	<.0001

Regression Plot



Y = 0 + 31.679 * X; R^2 = .959

Regression Summary
Obstruction Loss, Group 9B, Room Index 3 vs. VFR

Count	54
Num. Missing	0
R	.972
R Squared	.945
Adjusted R Squared	.944
RMS Residual	2.339

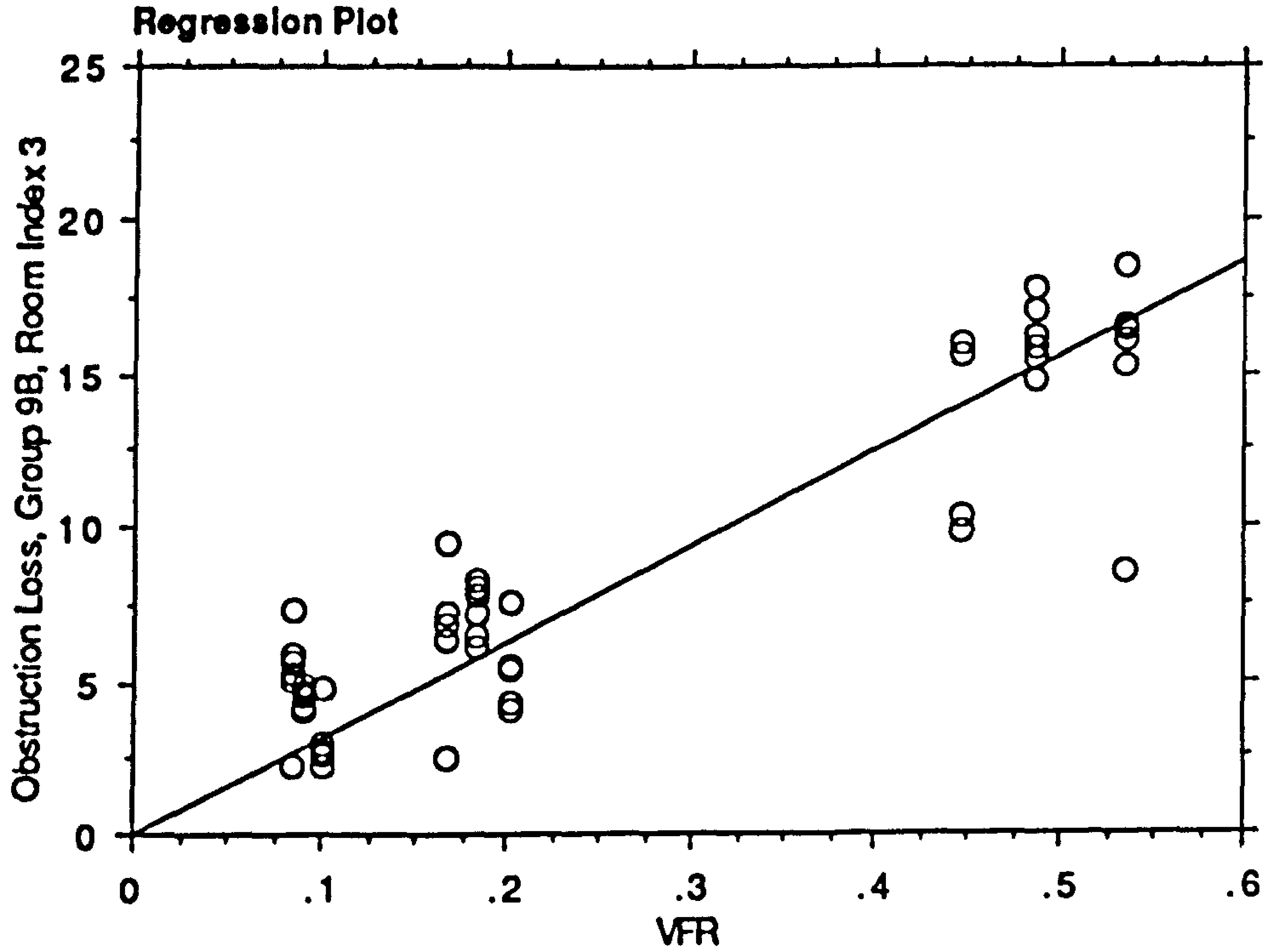
ANOVA Table
Obstruction Loss, Group 9B, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4987.498	4987.498	911.324	<.0001
Residual	53	290.059	5.473		
Total	54	5277.557			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	31.284	1.036	1.064	30.188	<.0001

Regression Plot



Y = 0 + 31.284 * X; R^2 = .945

Regression Summary
Obstruction Loss, Group 9B, Room Index 4 vs. VFR

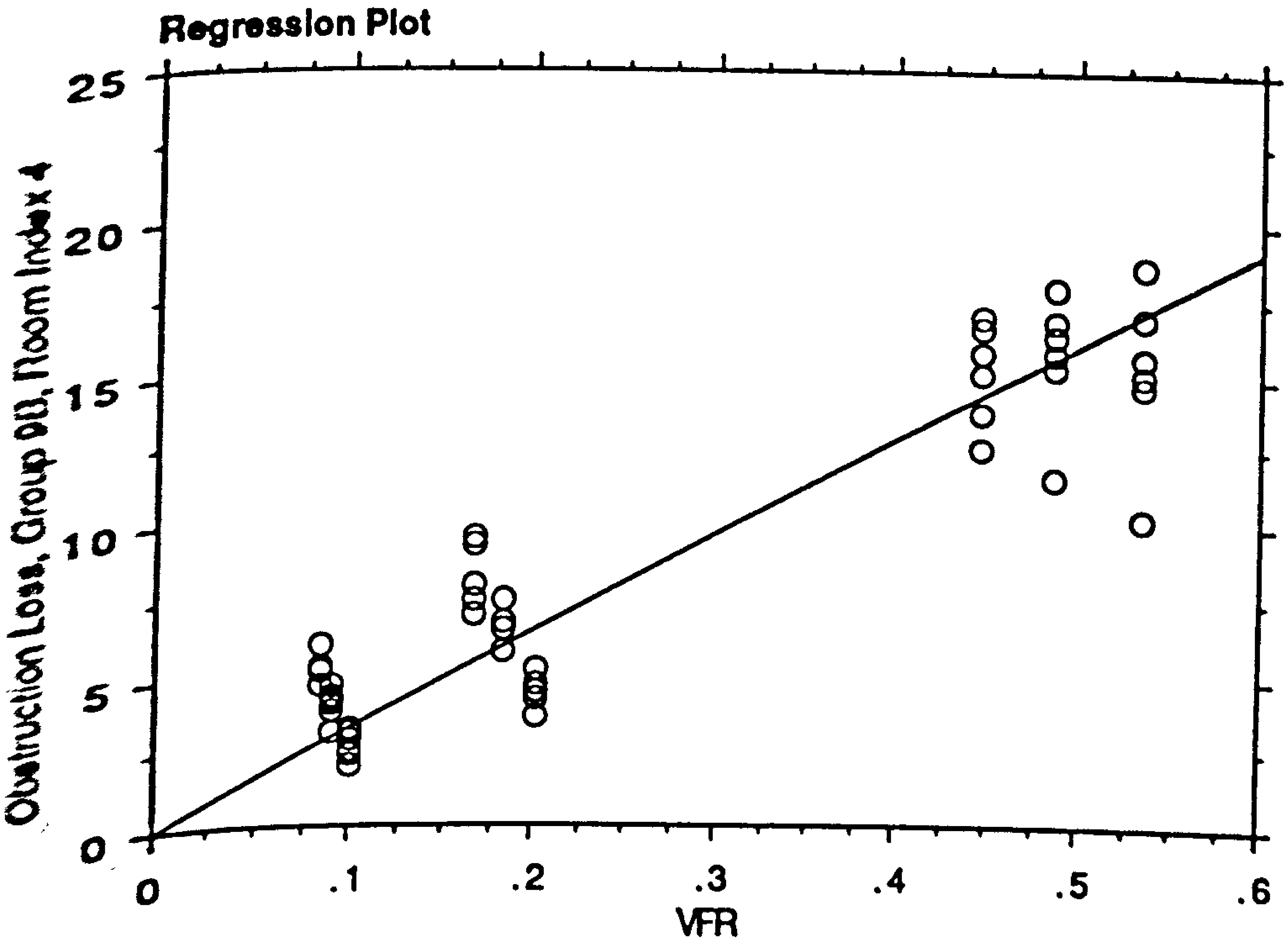
Count	54
Num. Missing	0
R	.978
R Squared	.957
Adjusted R Squared	.956
RMS Residual	2.110

ANOVA Table
Obstruction Loss, Group 9B, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5202.854	5202.854	1168.146	<.0001
Residual	53	236.059	4.454		
Total	54	5438.913			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	31.953	.935	1.058	34.178	<.0001



Y = 0 + 31.953 * X; R^2 = .957

Regression Summary
Obstruction Loss, Group 9B, Room Index 5 vs. VFR

Count	48
Num. Missing	6
R	.984
R Squared	.968
Adjusted R Squared	.967
RMS Residual	1.650

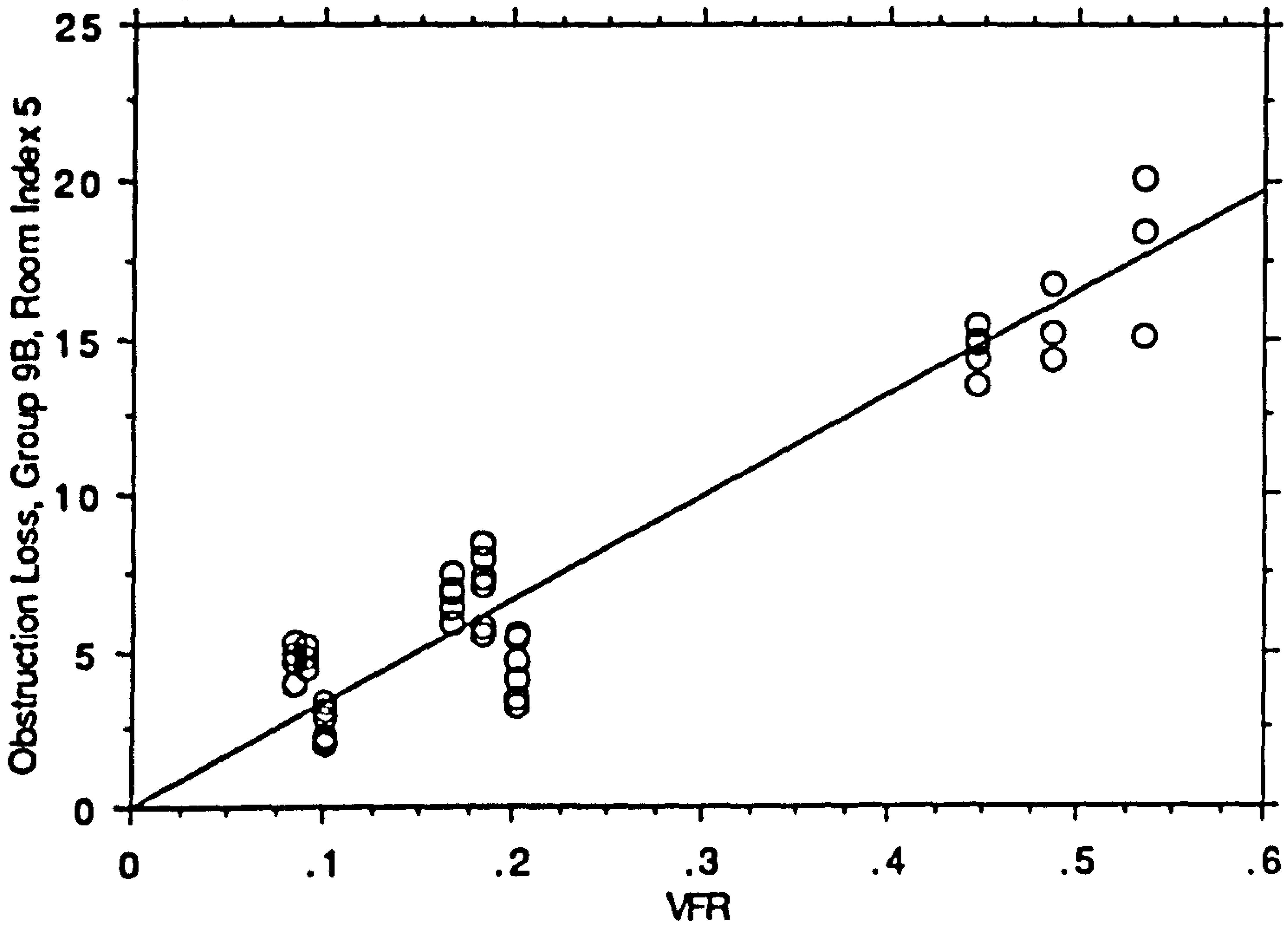
ANOVA Table
Obstruction Loss, Group 9B, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3846.669	3846.669	1413.476	<.0001
Residual	47	127.907	2.721		
Total	48	3974.576			

Regression Coefficients
Obstruction Loss, Group 9B, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.013	.878	1.046	37.596	<.0001

Regression Plot



Y = 0 + 33.013 * X; R^2 = .968

Regression Summary
Obstruction Loss, Group 9C, Room Index 1 vs. VFR

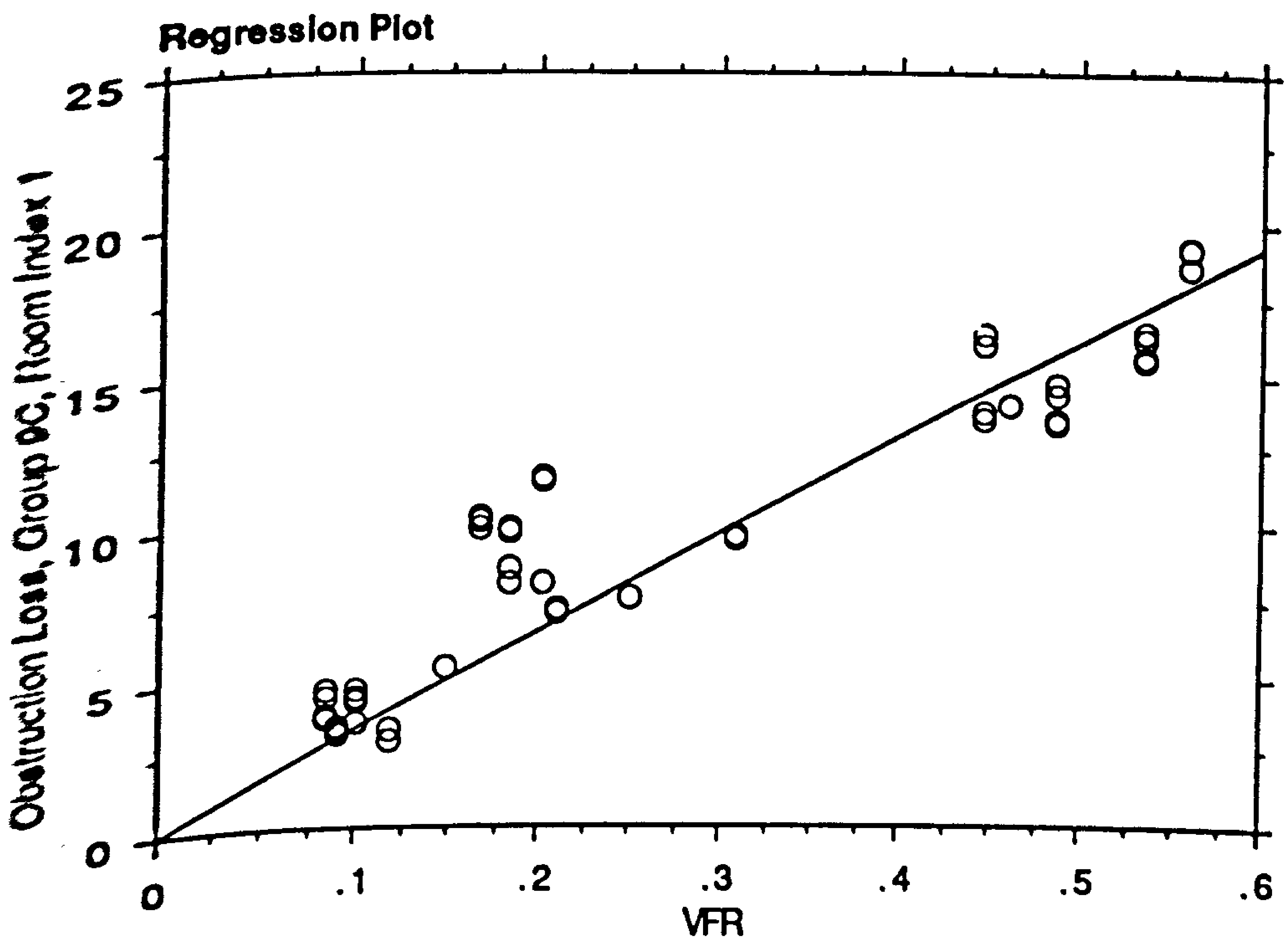
Count	54
Num. Missing	0
R	.980
R Squared	.961
Adjusted R Squared	.960
RMS Residual	2.172

ANOVA Table
Obstruction Loss, Group 9C, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6168.081	6168.081	1307.725	<.0001
Residual	53	249.983	4.717		
Total	54	6418.064			

Regression Coefficients
Obstruction Loss, Group 9C, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	32.260	.892	1.159	36.162	<.0001



Y = 0 + 32.26 * X; R^2 = .961

Regression Summary

Obstruction Loss, Group 9C, Room Index 1.25 vs. VFR

Count	54
Num. Missing	0
R	.990
R Squared	.980
Adjusted R Squared	.980
RMS Residual	1.612

ANOVA Table

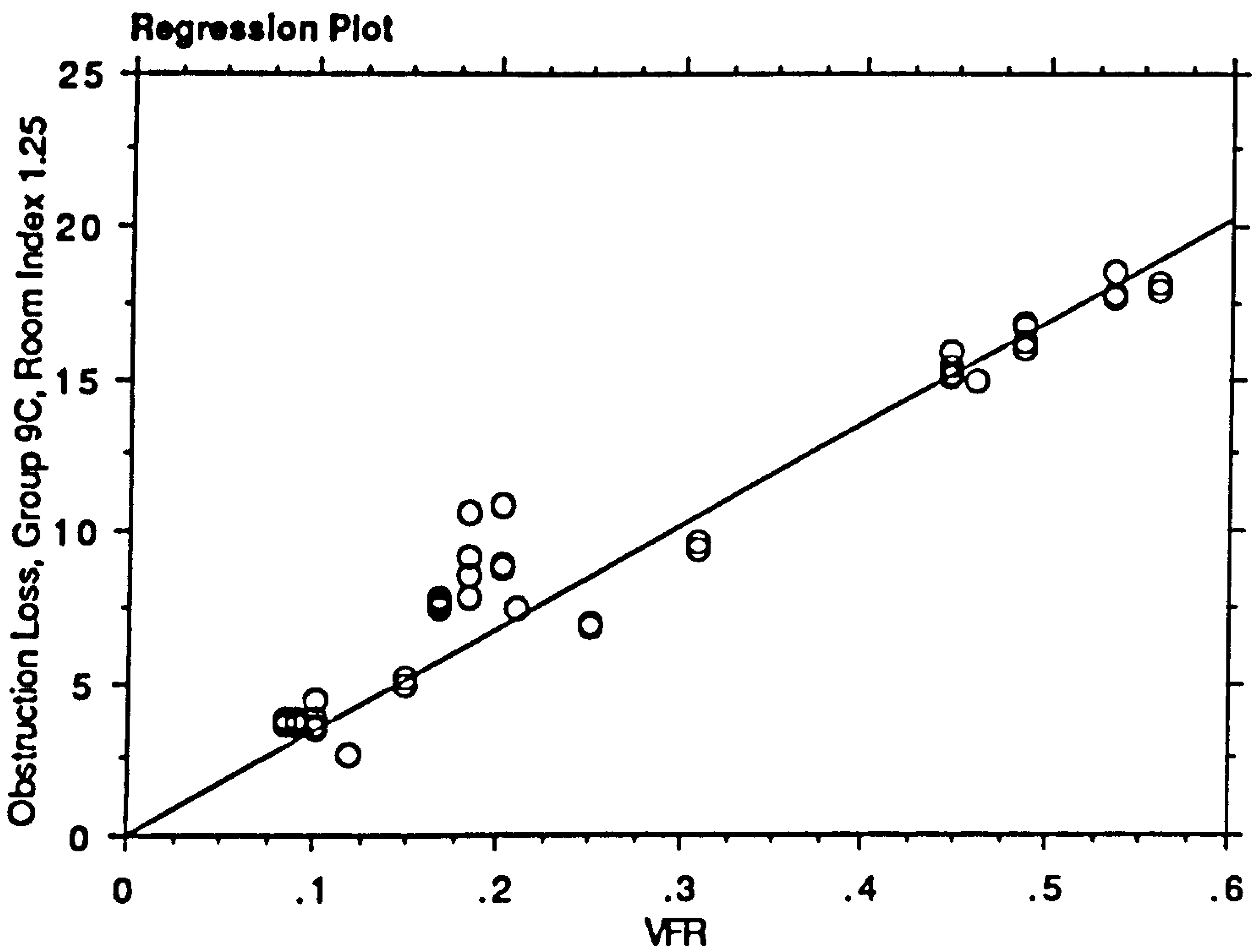
Obstruction Loss, Group 9C, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6805.941	6805.941	2620.045	<.0001
Residual	53	137.675	2.598		
Total	54	6943.616			

Regression Coefficients

Obstruction Loss, Group 9C, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.887	.662	1.102	51.186	<.0001



Y = 0 + 33.887 * X; R^2 = .98

Regression Summary
Obstruction Loss, Group 9C, Room Index 1.5 vs. VFR

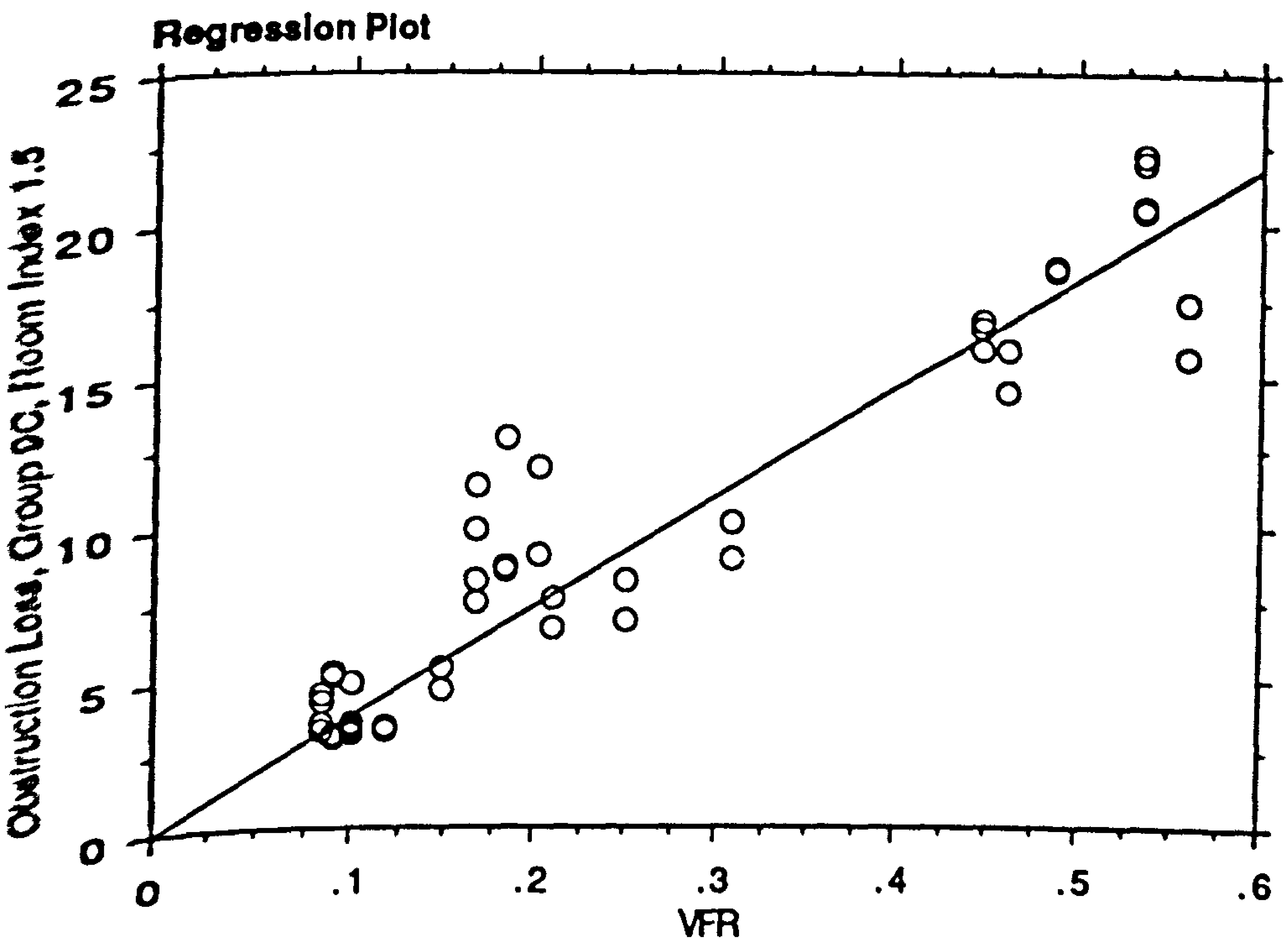
Count	53
Num. Missing	1
R	.980
R Squared	.960
Adjusted R Squared	.959
RMS Residual	2.460

ANOVA Table
Obstruction Loss, Group 9C, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7574.770	7574.770	1251.900	<.0001
Residual	52	314.632	6.051		
Total	53	7889.402			

Regression Coefficients
Obstruction Loss, Group 9C, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.364	1.028	1.073	35.382	<.0001



Y = 0 + 36.364 * X; R^2 = .96

Regression Summary
Obstruction Loss, Group 9C, Room Index 2 vs. VFR

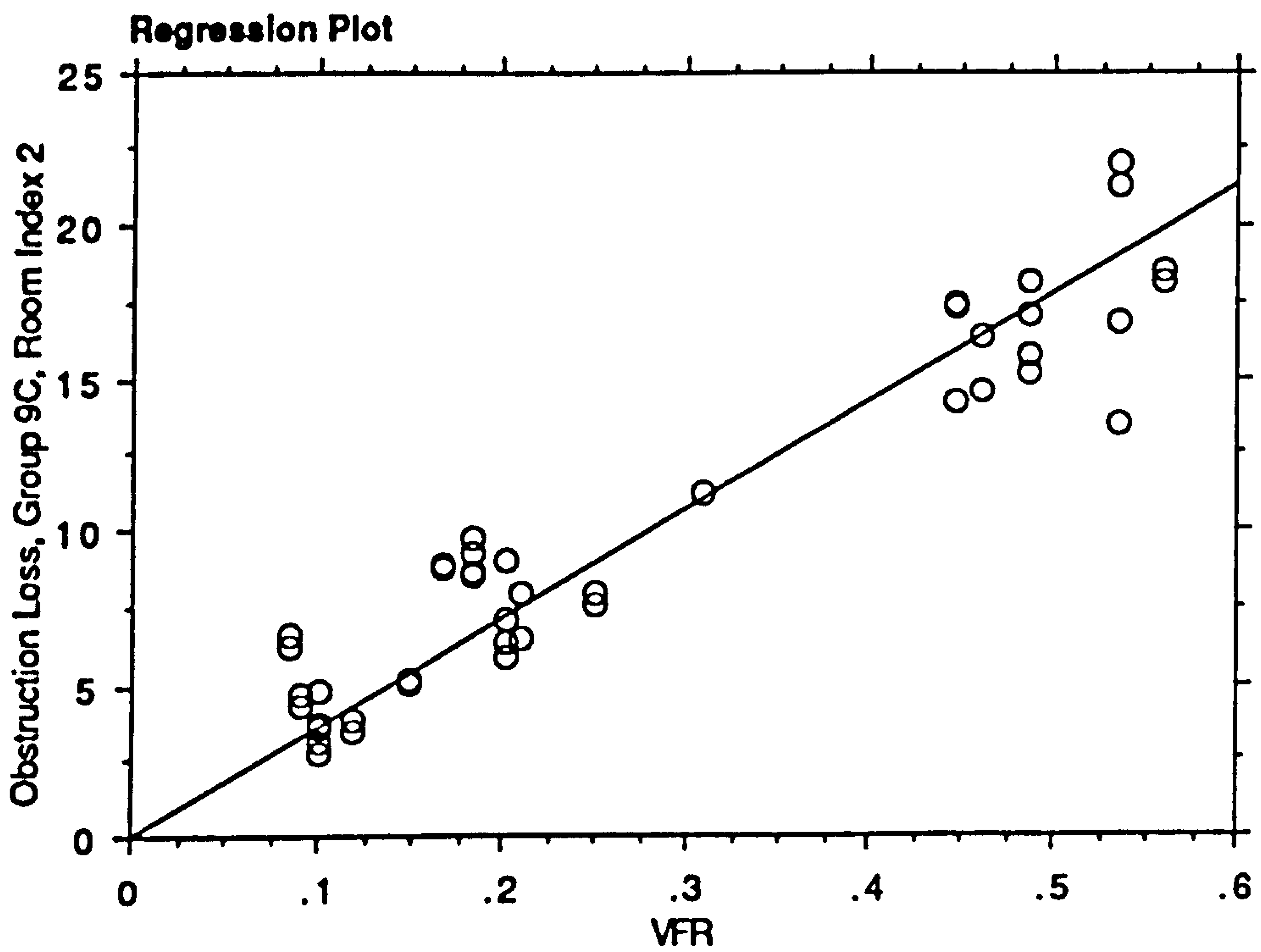
Count	54
Num. Missing	0
R	.987
R Squared	.974
Adjusted R Squared	.973
RMS Residual	1.961

ANOVA Table
Obstruction Loss, Group 9C, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7489.842	7489.842	1947.792	<.0001
Residual	53	203.801	3.845		
Total	54	7693.642			

Regression Coefficients
Obstruction Loss, Group 9C, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.548	.805	1.090	44.134	<.0001



Y = 0 + 35.548 * X; R^2 = .974

Regression Summary
Obstruction Loss, Group 9C, Room Index 3 vs. VFR

Count	36
Num. Missing	0
R	.982
R Squared	.964
Adjusted R Squared	.963
RMS Residual	2.285

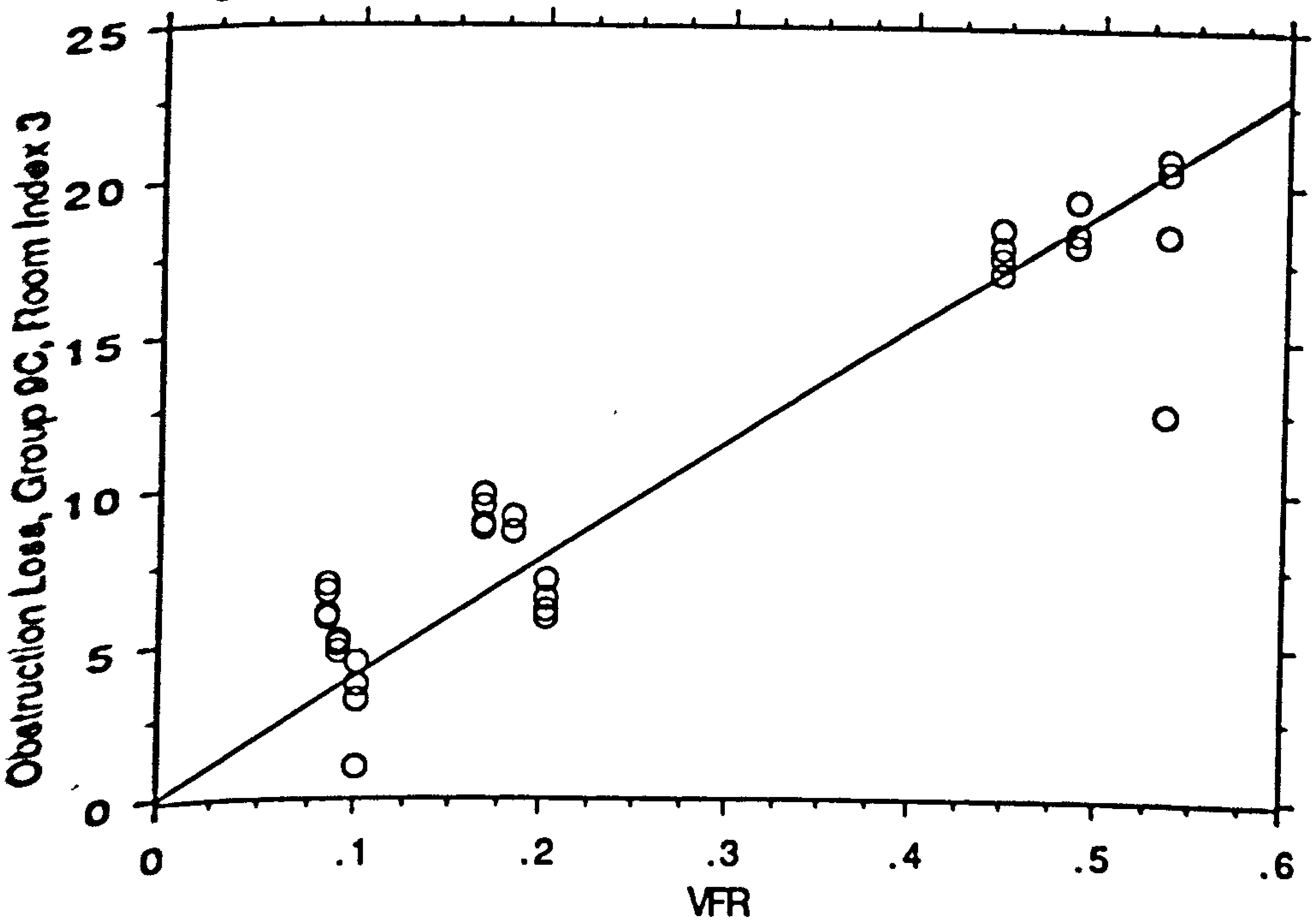
ANOVA Table
Obstruction Loss, Group 9C, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4943.506	4943.506	946.888	<.0001
Residual	35	182.728	5.221		
Total	36	5126.233			

Regression Coefficients
Obstruction Loss, Group 9C, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.146	1.240	1.098	30.772	<.0001

Regression Plot



Y = 0 + 38.146 * X; R^2 = .964

Regression Summary
Obstruction Loss, Group 9C, Room Index 4 vs. VFR

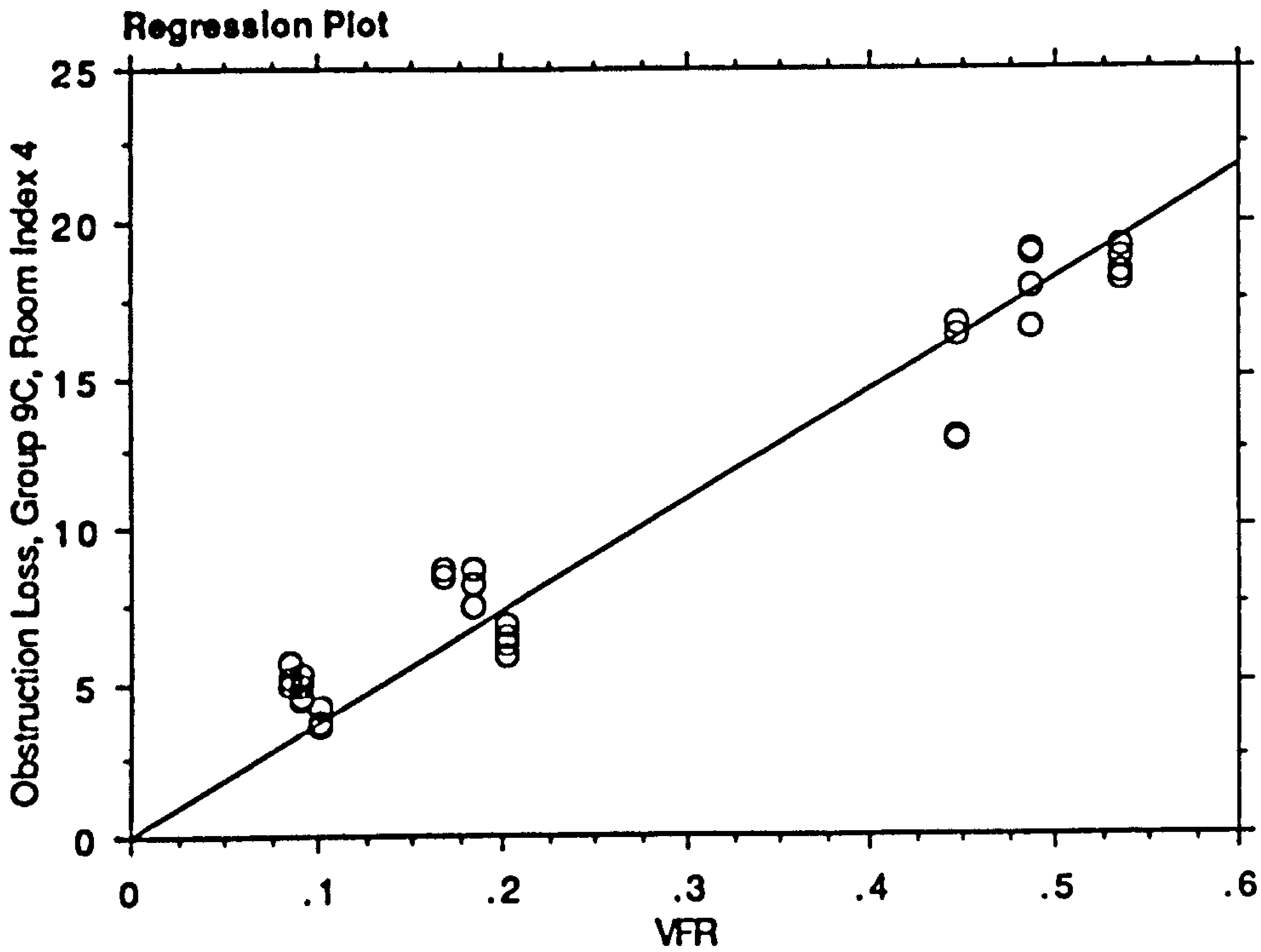
Count	36
Num. Missing	0
R	.989
R Squared	.979
Adjusted R Squared	.978
RMS Residual	1.681

ANOVA Table
Obstruction Loss, Group 9C, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4523.659	4523.659	1601.177	<.0001
Residual	35	98.882	2.825		
Total	36	4622.542			

Regression Coefficients
Obstruction Loss, Group 9C, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.490	.912	1.125	40.015	<.0001



Y = 0 + 36.49 * X; R^2 = .979

Regression Summary
Obstruction Loss, Group 9C, Room Index 5 vs. VFR

Count	32
Num. Missing	4
R	.983
R Squared	.967
Adjusted R Squared	.966
RMS Residual	1.960

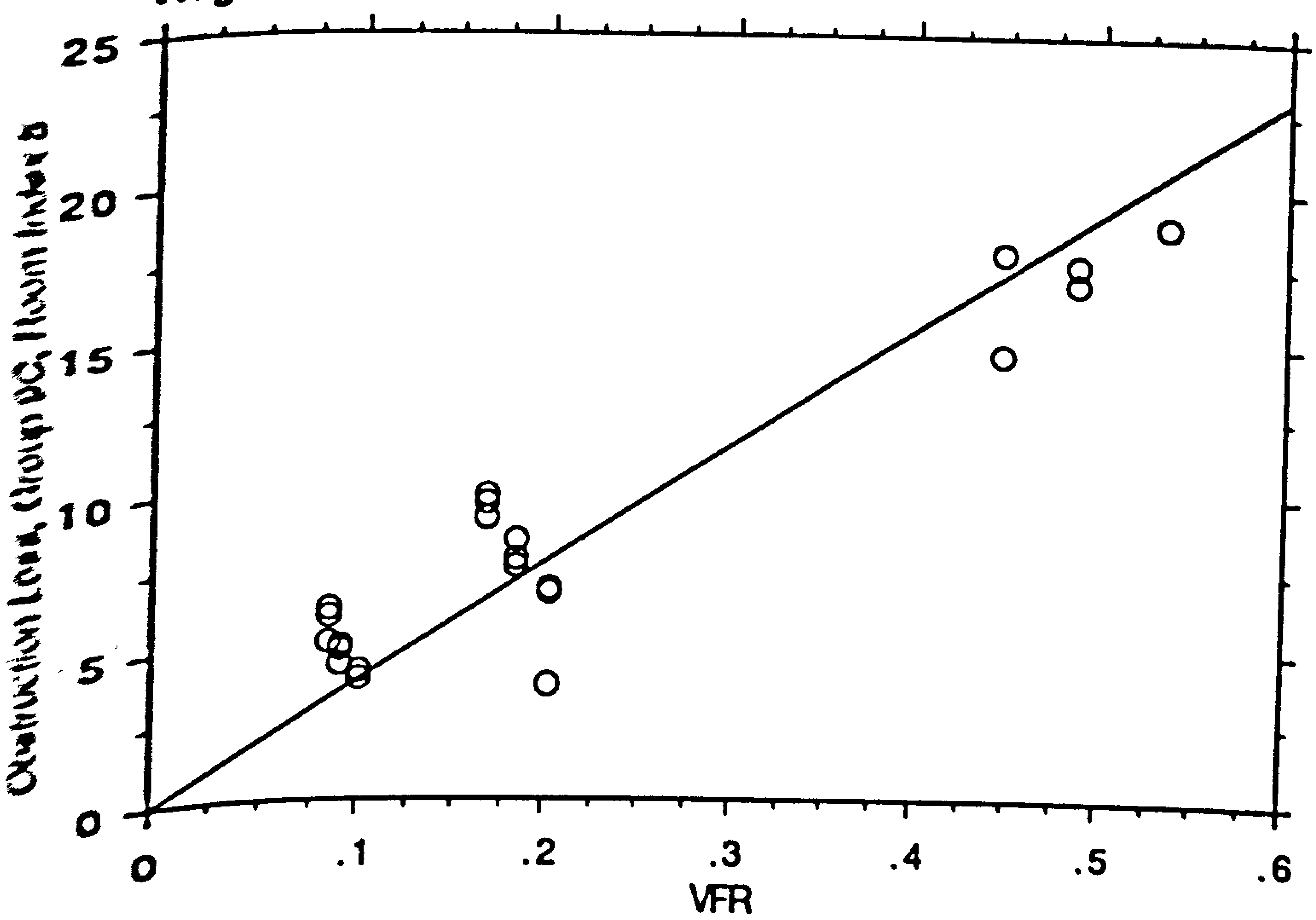
ANOVA Table
Obstruction Loss, Group 9C, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3474.155	3474.155	904.483	<.0001
Residual	31	119.072	3.841		
Total	32	3593.227			

Regression Coefficients
Obstruction Loss, Group 9C, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.425	1.278	1.136	30.075	<.0001

Regression Plot



Y = 0 + 38.425 * X; R^2 = .967

Regression Summary
group 10 OL (room index 1.00) vs. VFR

Count	108
Num. Missing	0
R	.968
R Squared	.938
Adjusted R Squared	.937
RMS Residual	2.478

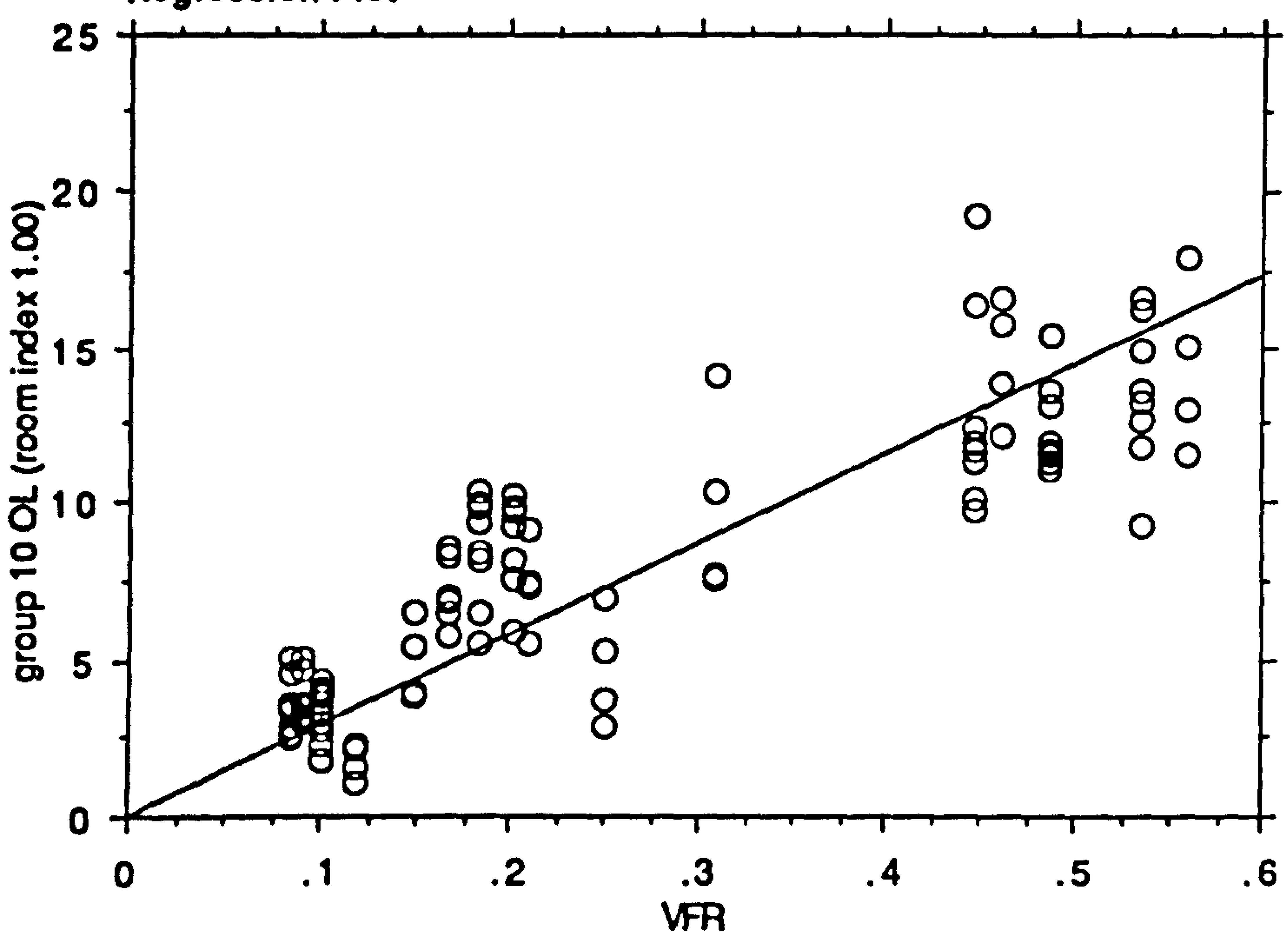
ANOVA Table
group 10 OL (room index 1.00) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9908.584	9908.584	1613.742	<.0001
Residual	107	656.994	6.140		
Total	108	10565.578			

Regression Coefficients
group 10 OL (room index 1.00) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.911	.720	1.050	40.171	<.0001

Regression Plot



Y = 0 + 28.911 * X; R^2 = .938

Regression Summary
group 10 OL (room Index 1.25) vs. VFR

Count	108
Num. Missing	0
R	.968
R Squared	.938
Adjusted R Squared	.937
RMS Residual	2.287

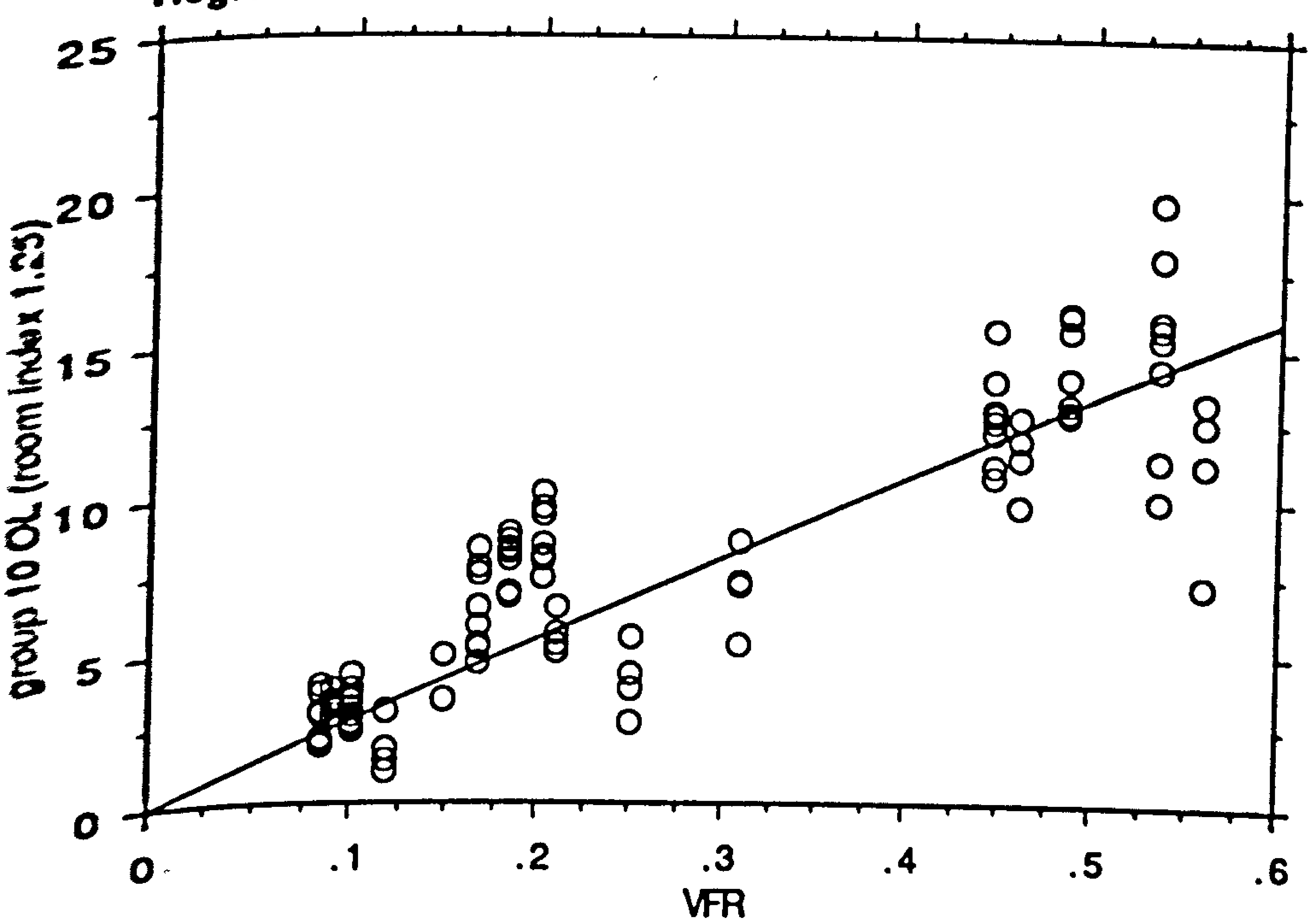
ANOVA Table
group 10 OL (room Index 1.25) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8395.431	8395.431	1605.468	<.0001
Residual	107	559.532	5.229		
Total	108	8954.963			

Regression Coefficients
group 10 OL (room Index 1.25) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.612	.664	1.037	40.068	<.0001

Regression Plot



Y = 0 + 26.612 * X; R^2 = .938

Regression Summary
group 10 OL (room index 1.5) vs. VFR

Count	108
Num. Missing	0
R	.972
R Squared	.945
Adjusted R Squared	.944
RMS Residual	2.236

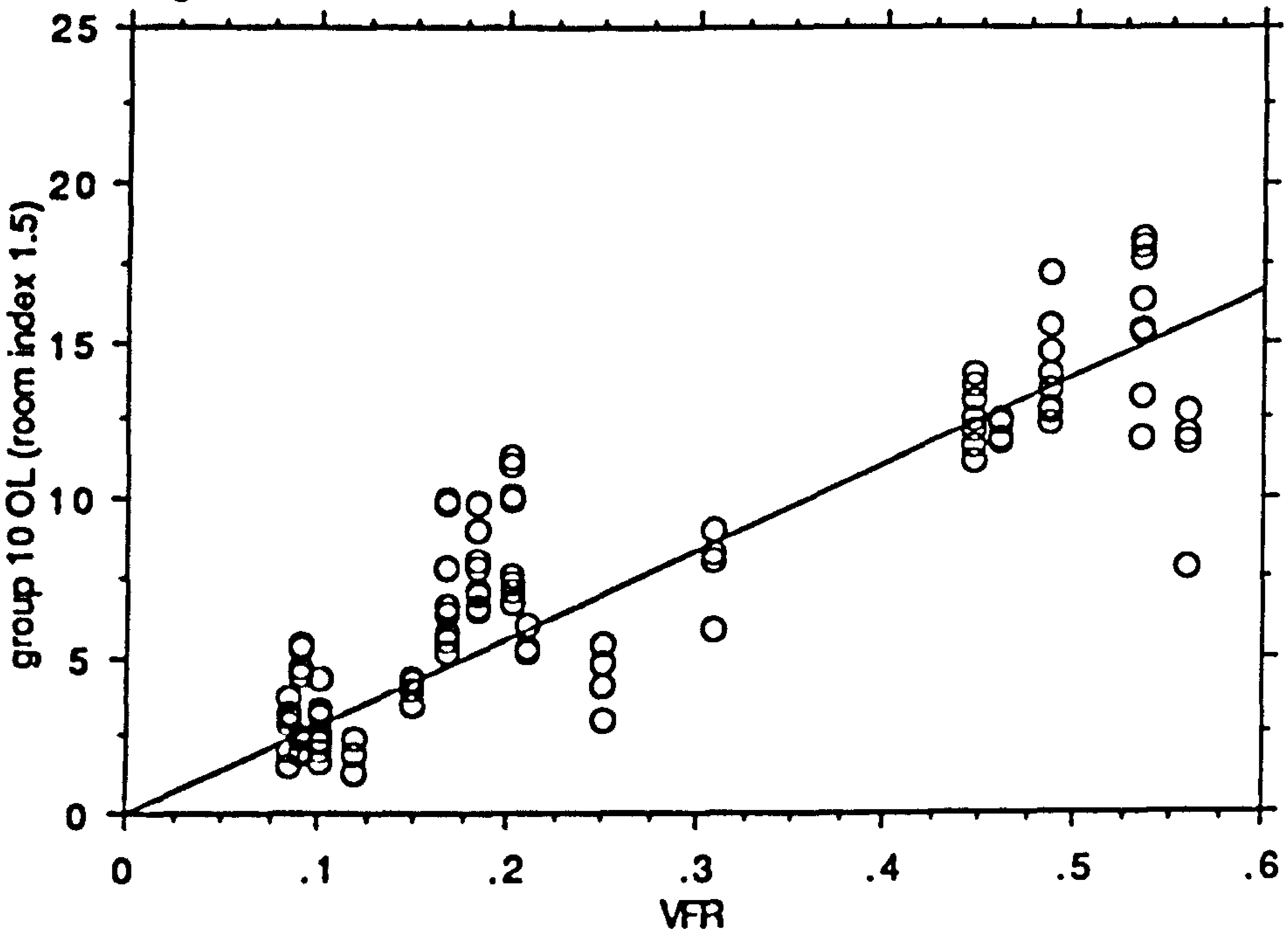
ANOVA Table
group 10 OL (room index 1.5) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9161.729	9161.729	1832.053	<.0001
Residual	107	535.086	5.001		
Total	108	9696.815			

Regression Coefficients
group 10 OL (room index 1.5) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	27.800	.649	1.043	42.802	<.0001

Regression Plot



Y = 0 + 27.8 * X; R^2 = .945

Regression Summary
group 10 OL (room Index 2.0) vs. VFR

Count	108
Num. Missing	0
R	.965
R Squared	.931
Adjusted R Squared	.931
RMS Residual	2.417

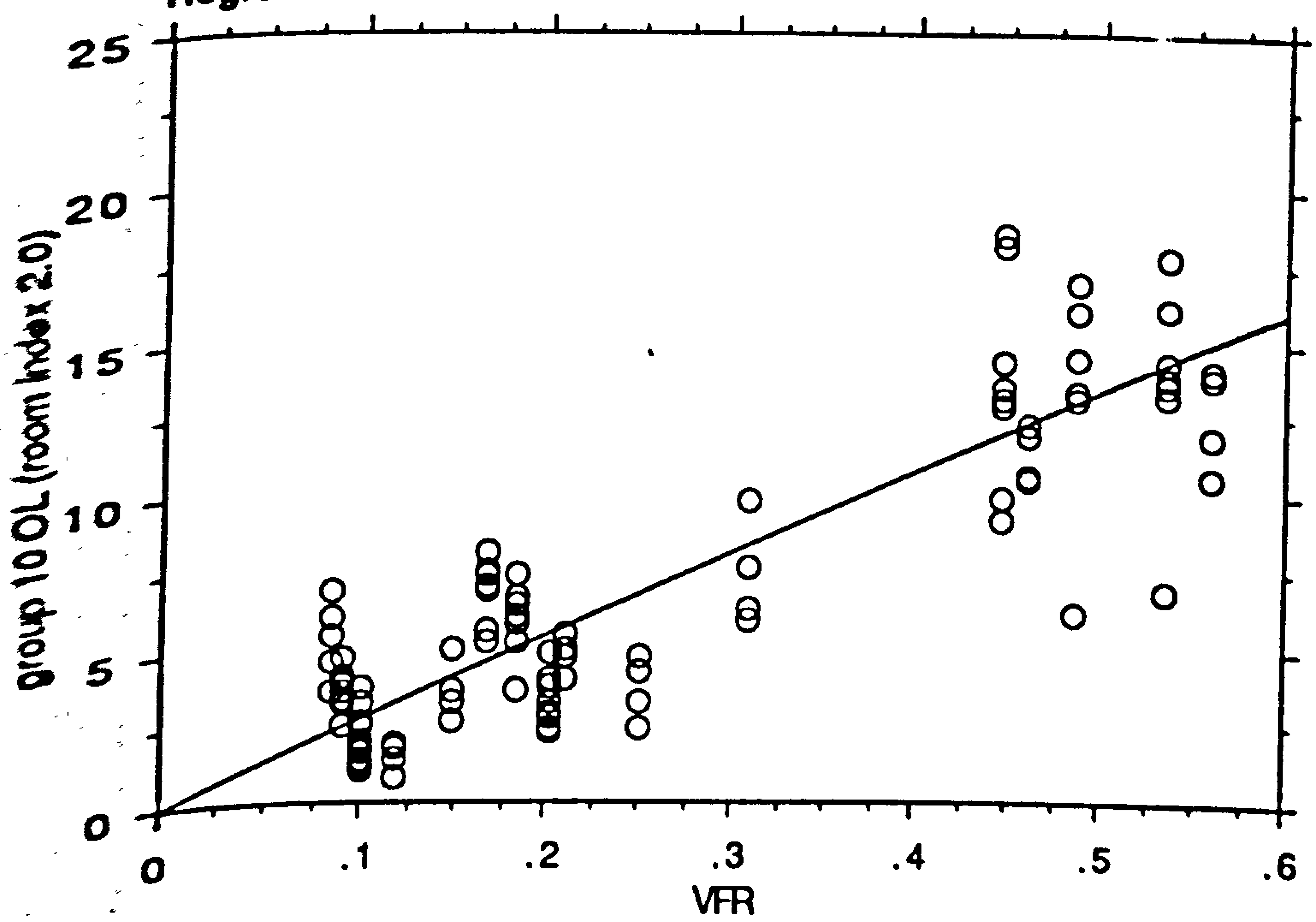
ANOVA Table
group 10 OL (room Index 2.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8474.918	8474.918	1450.333	<.0001
Residual	107	625.247	5.843		
Total	108	9100.165			

Regression Coefficients
group 10 OL (room Index 2.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.738	.702	.937	38.083	<.0001

Regression Plot



Y = 0 + 26.738 * X; R^2 = .931

Regression Summary
group 10 OL (room index 3.0) vs. VFR

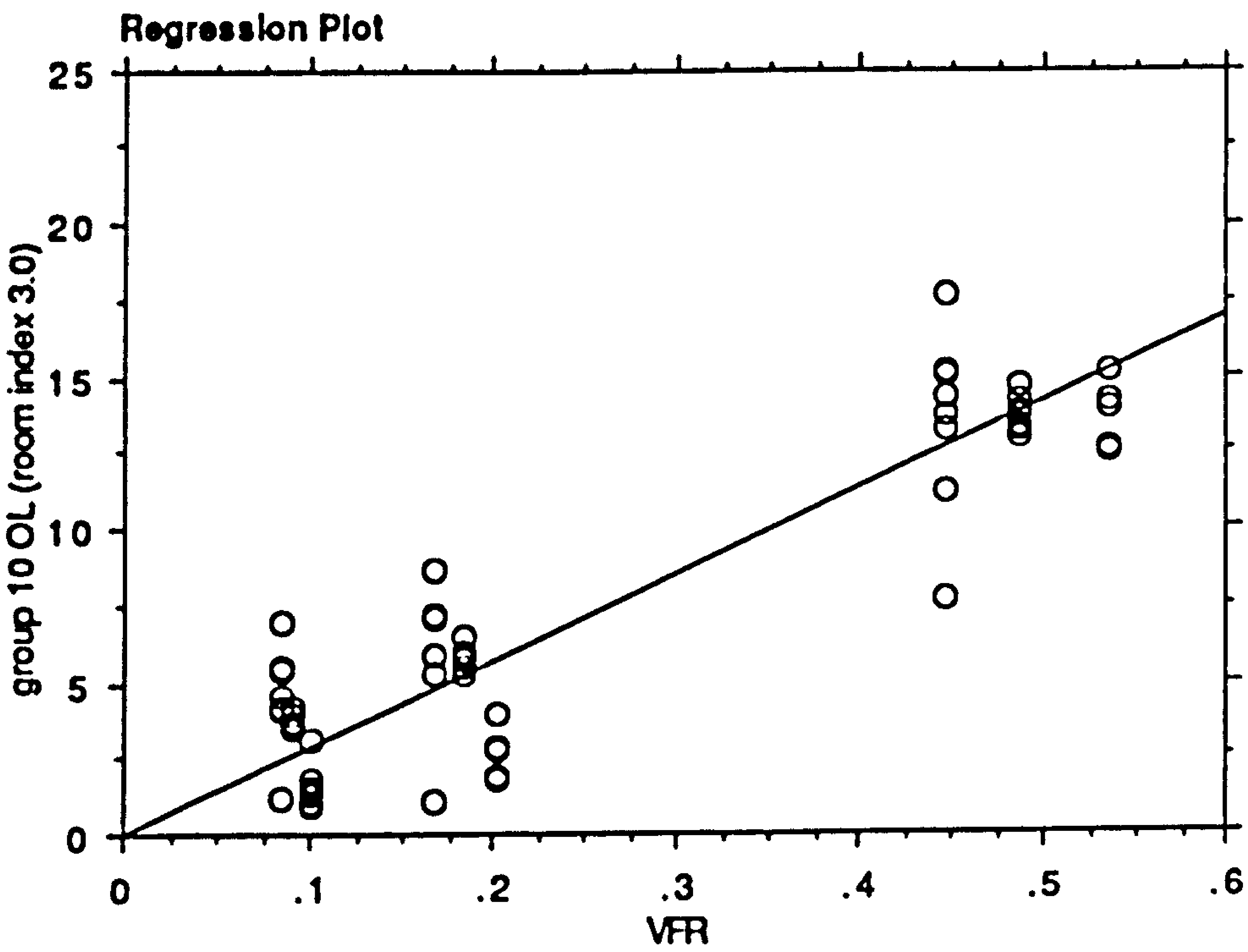
Count	66
Num. Missing	6
R	.971
R Squared	.944
Adjusted R Squared	.943
RMS Residual	2.080

ANOVA Table
group 10 OL (room index 3.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4708.960	4708.960	1088.249	<.0001
Residual	65	281.261	4.327		
Total	66	4990.221			

Regression Coefficients
group 10 OL (room index 3.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.456	.863	.986	32.989	<.0001



Y = 0 + 28.456 * X; R^2 = .944

Regression Summary
group 10 OL (room index 4.0) vs. VFR

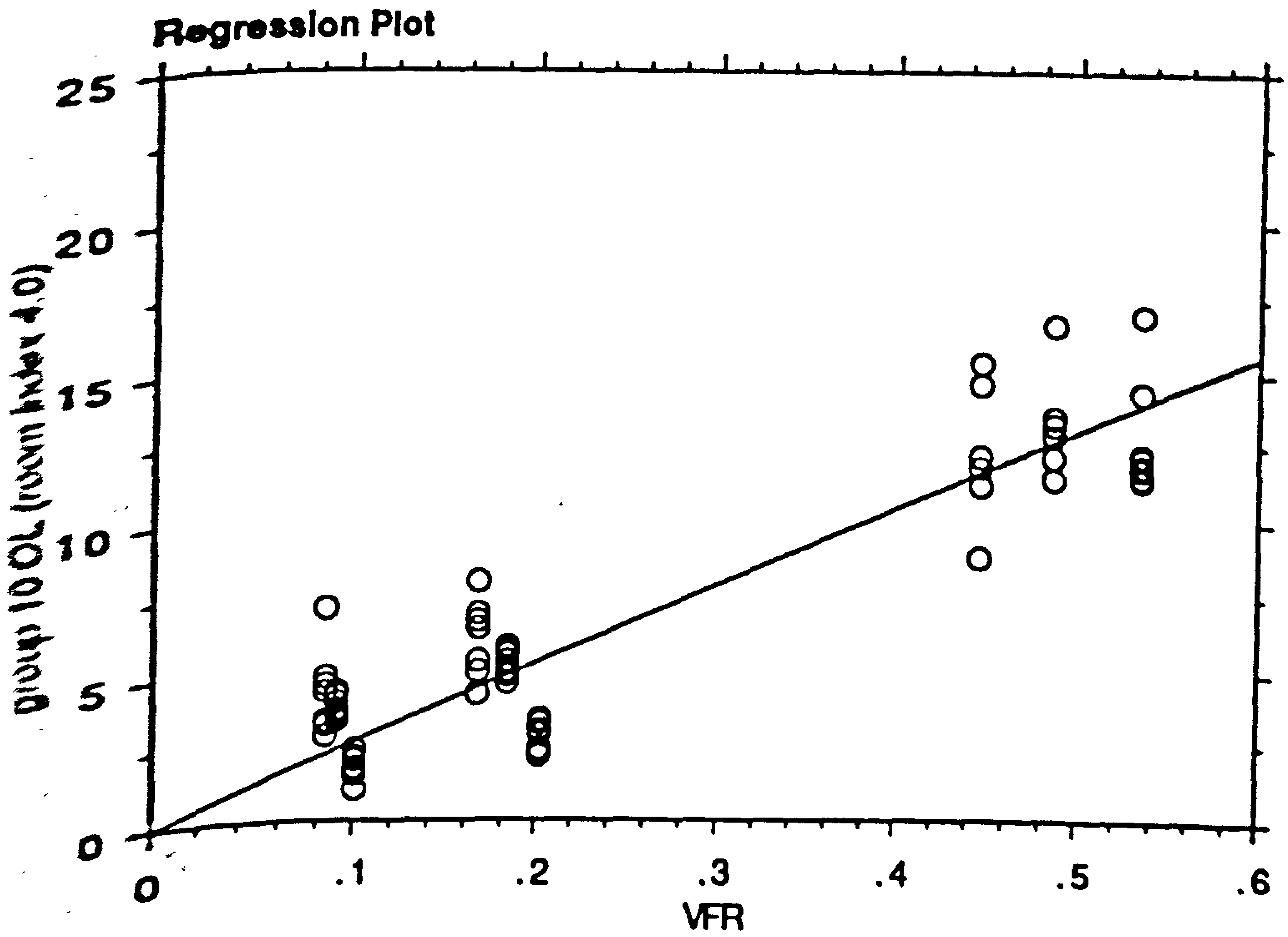
Count	70
Num. Missing	2
R	.973
R Squared	.946
Adjusted R Squared	.945
RMS Residual	1.895

ANOVA Table
group 10 OL (room index 4.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4319.753	4319.753	1203.48	<.0001
Residual	69	247.668	3.589		
Total	70	4567.421			

Regression Coefficients
group 10 OL (room index 4.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	25.984	.749	.996	34.691	<.0001



Y = 0 + 25.984 * X; R^2 = .946

Regression Summary
group 10 OL (room Index 5.0) vs. VFR

Count	56
Num. Missing	16
R	.955
R Squared	.912
Adjusted R Squared	.911
RMS Residual	2.008

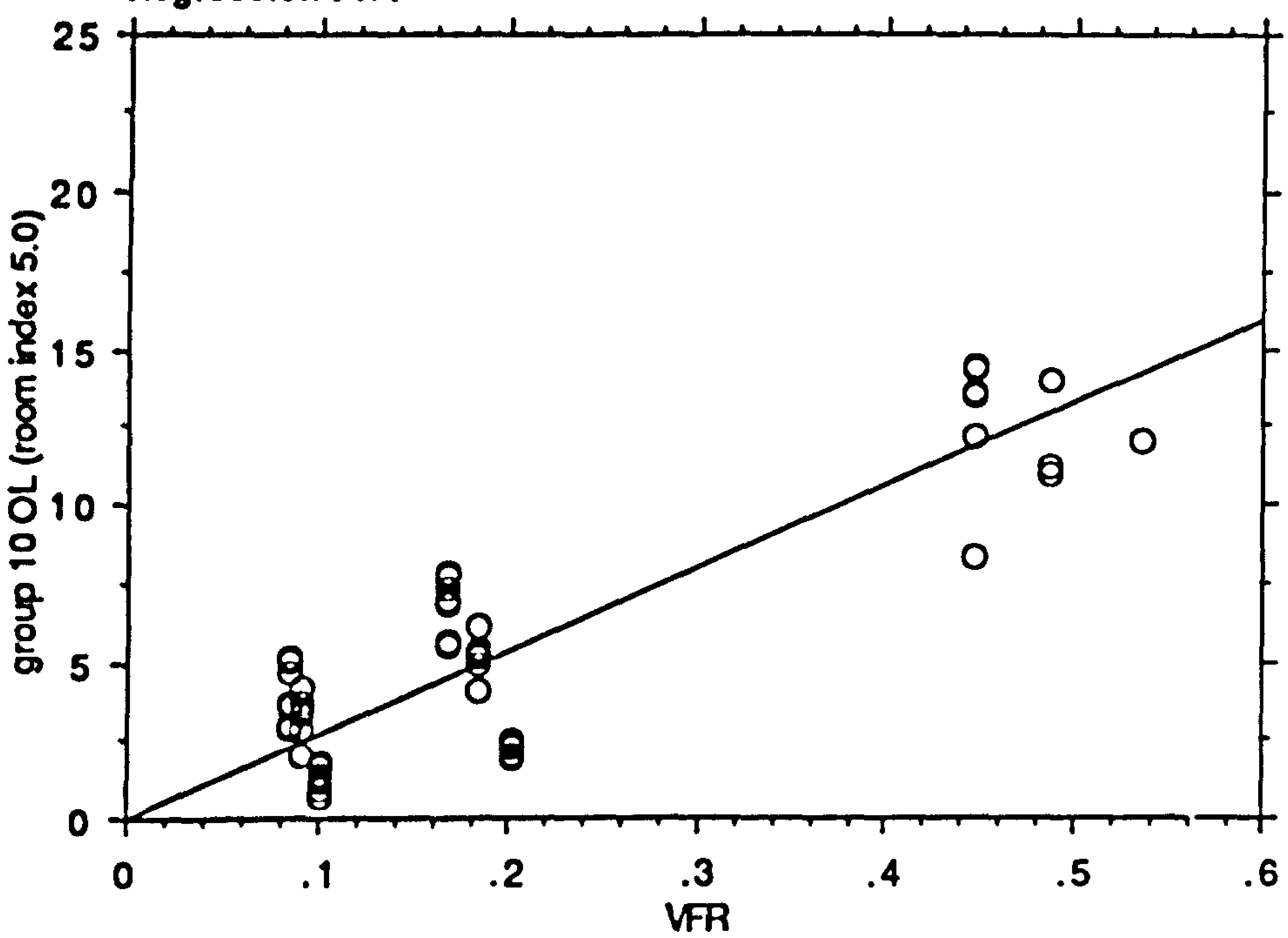
ANOVA Table
group 10 OL (room Index 5.0) vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2309.768	2309.768	573.101	<.0001
Residual	55	221.667	4.030		
Total	56	2531.435			

Regression Coefficients
group 10 OL (room Index 5.0) vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.490	1.107	.963	23.940	<.0001

Regression Plot



Y = 0 + 26.49 * X; R^2 = .912

Regression Summary
Obstruction Loss, Group 11, Room Index 1 vs. VFR

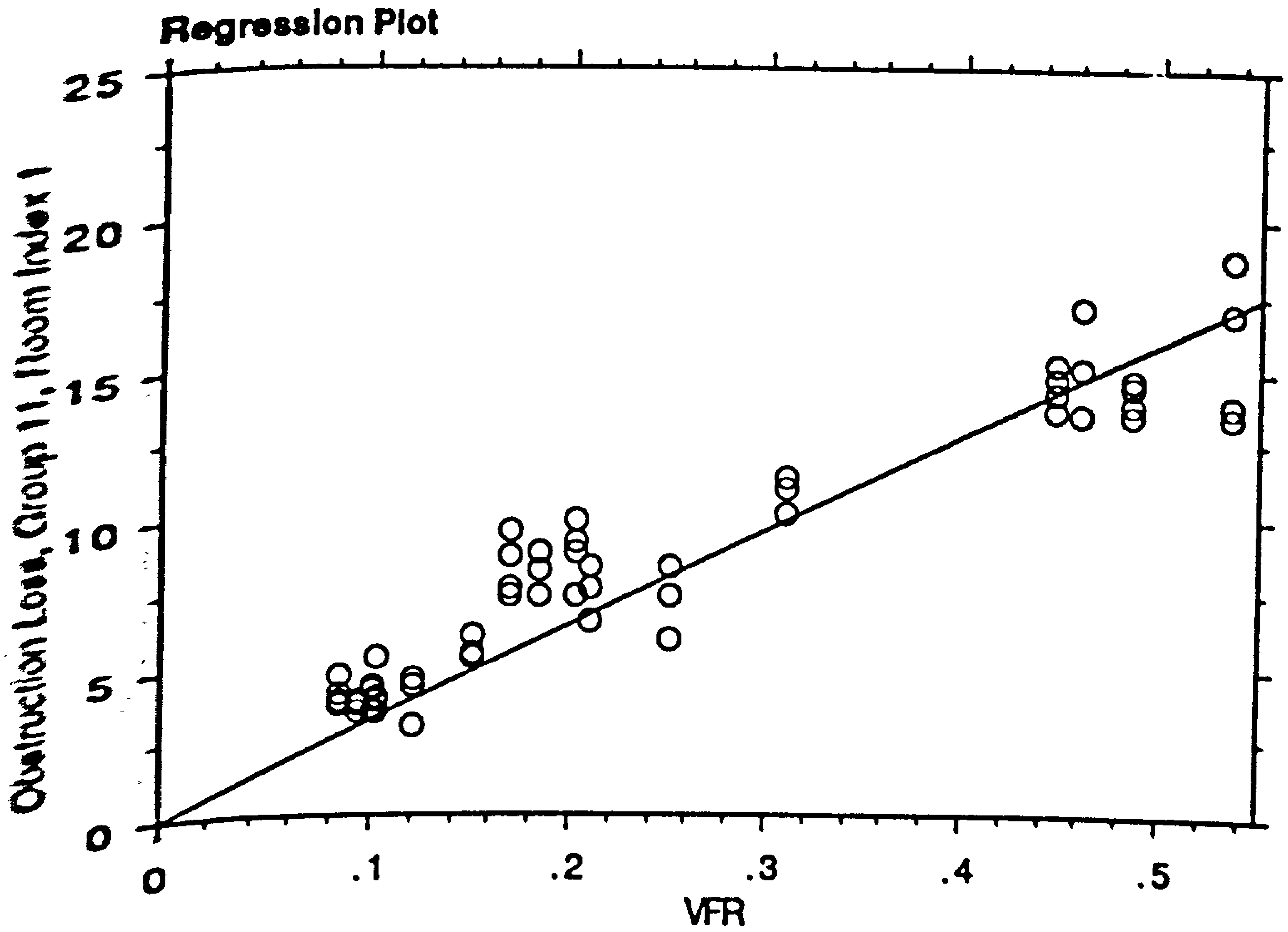
Count	63
Num. Missing	0
R	.986
R Squared	.973
Adjusted R Squared	.972
RMS Residual	1.803

ANOVA Table
Obstruction Loss, Group 11, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7245.939	7245.939	2228.225	<.0001
Residual	62	201.617	3.252		
Total	63	7447.556			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	31.742	.672	1.141	47.204	<.0001



$Y = 0 + 31.742 * X; R^2 = .973$

Regression Summary
Obstruction Loss, Group 11, Room Index 1.25 vs. VFR

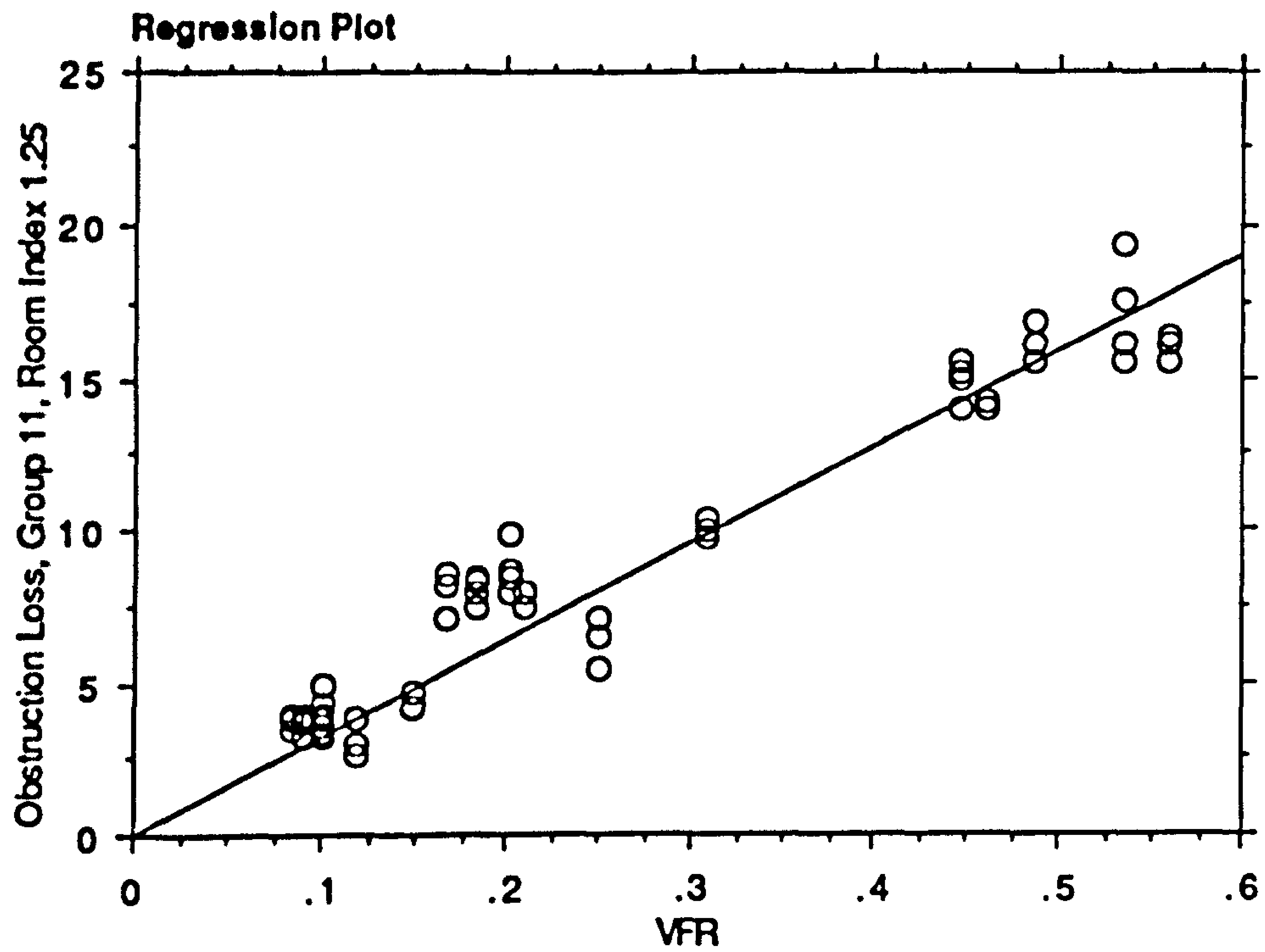
Count	63
Num. Missing	0
R	.990
R Squared	.980
Adjusted R Squared	.979
RMS Residual	1.555

ANOVA Table
Obstruction Loss, Group 11, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7244.999	7244.999	2996.488	<.0001
Residual	62	149.905	2.418		
Total	63	7394.904			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	31.740	.580	1.107	54.740	<.0001



Y = 0 + 31.74 * X; R^2 = .98

Regression Summary
Obstruction Loss, Group 11, Room Index 1.5 vs. VFR

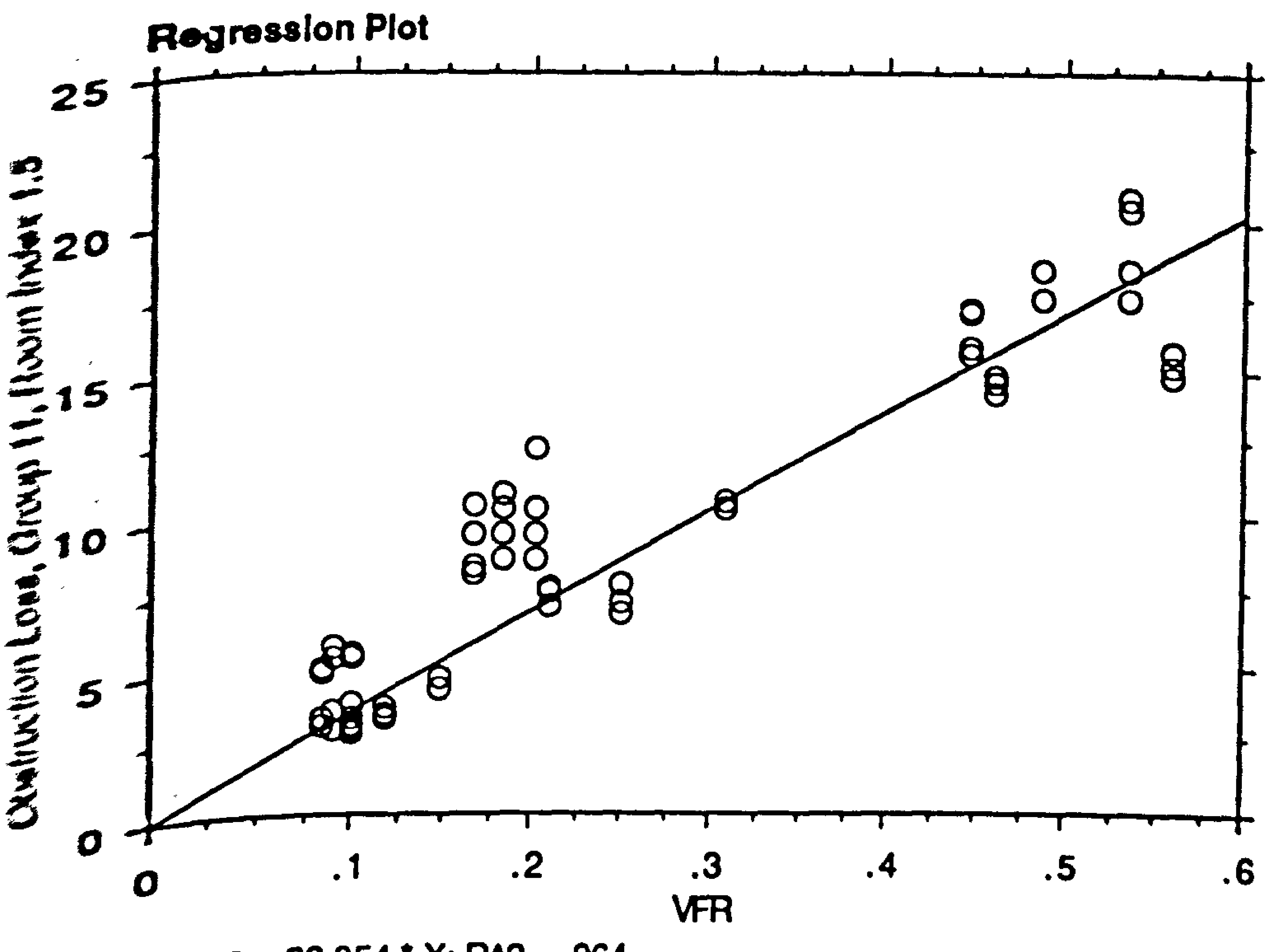
Count	63
Num. Missing	0
R	.982
R Squared	.964
Adjusted R Squared	.963
RMS Residual	2.233

ANOVA Table
Obstruction Loss, Group 11, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8242.555	8242.555	1653.639	<.0001
Residual	62	309.039	4.984		
Total	63	8551.593			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.854	.833	1.098	40.665	<.0001



Y = 0 + 33.854 * X; R^2 = .964

Regression Summary
Obstruction Loss, Group 11, Room Index 2.0 vs. VFR

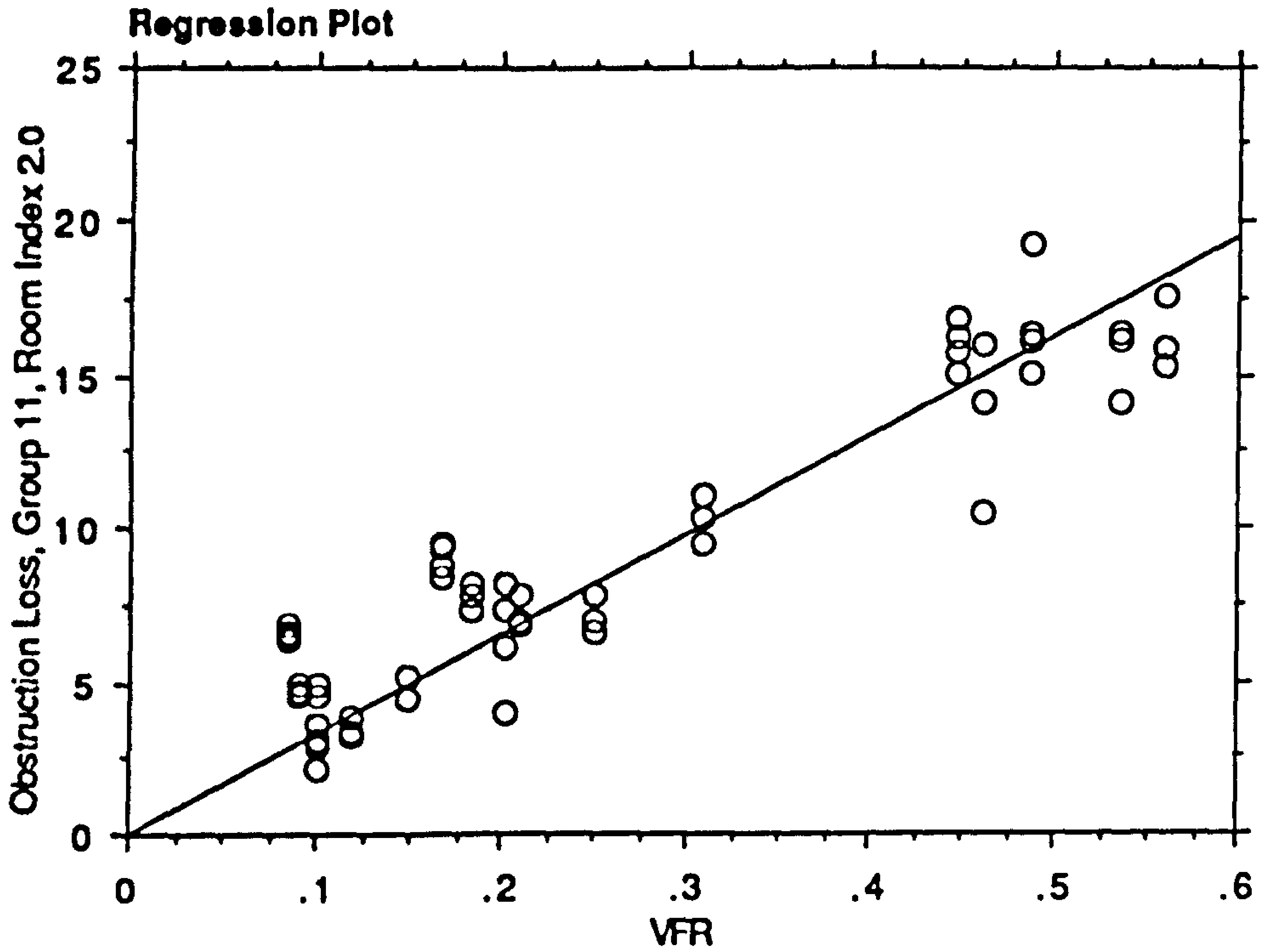
Count	63
Num. Missing	0
R	.984
R Squared	.969
Adjusted R Squared	.969
RMS Residual	1.989

ANOVA Table
Obstruction Loss, Group 11, Room Index 2.0 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7687.850	7687.850	1943.510	<.0001
Residual	62	245.250	3.956		
Total	63	7933.100			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 2.0 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	32.695	.742	1.091	44.085	<.0001



Y = 0 + 32.695 * X; R^2 = .969

Regression Summary
Obstruction Loss, Group 11, Room Index 3.0 vs. VFR

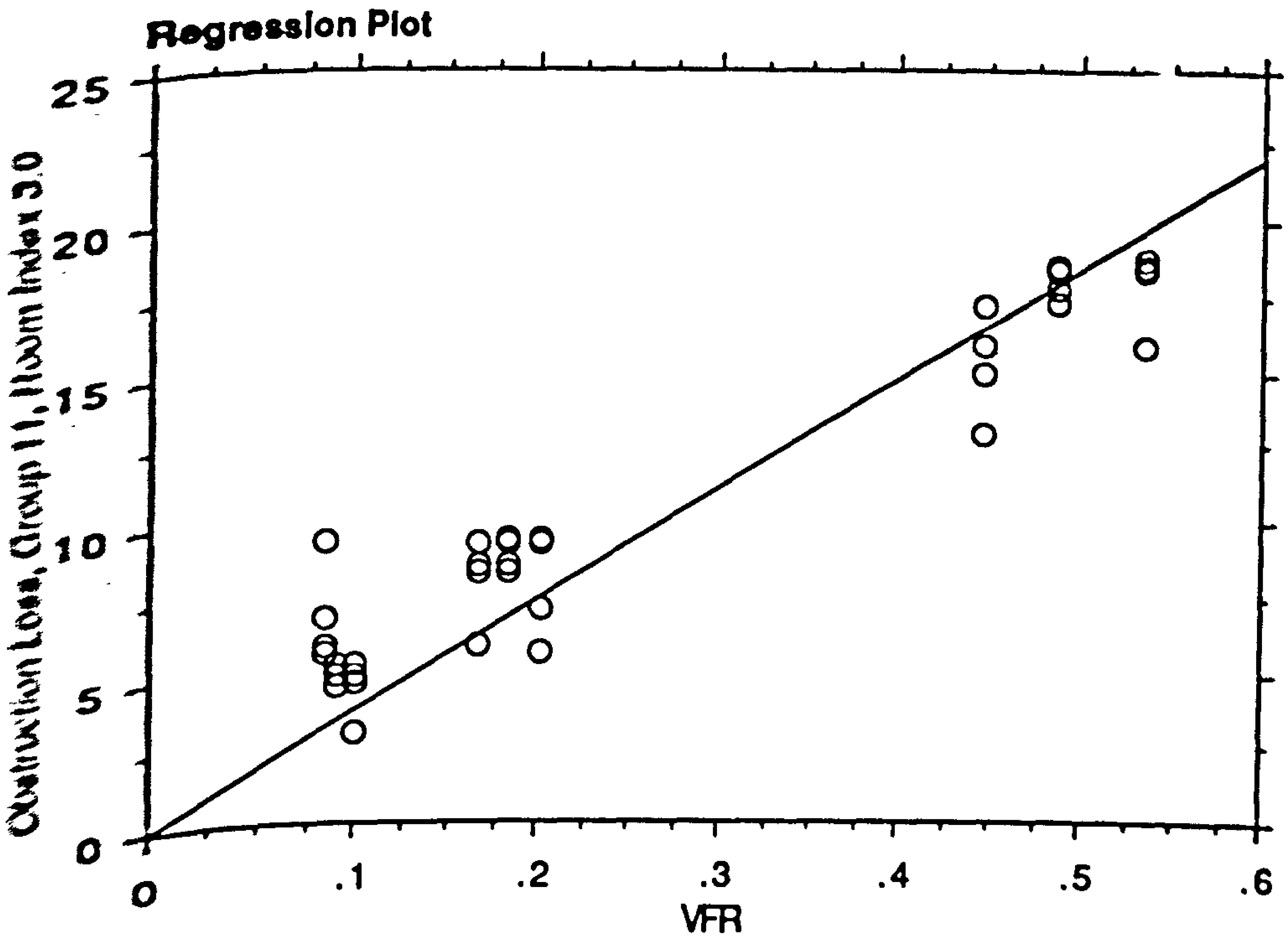
Count	36
Num. Missing	0
R	.982
R Squared	.965
Adjusted R Squared	.964
RMS Residual	2.197

ANOVA Table
Obstruction Loss, Group 11, Room Index 3.0 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4602.729	4602.729	953.559	<.0001
Residual	35	168.941	4.827		
Total	36	4771.671			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 3.0 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.808	1.192	1.217	30.880	<.0001



Y = 0 + 36.808 * X; R^2 = .965

Regression Summary
Obstruction Loss, Group 11, Room Index 4.0 vs. VFR

Count	29
Num. Missing	7
R	.973
R Squared	.948
Adjusted R Squared	.946
RMS Residual	2.321

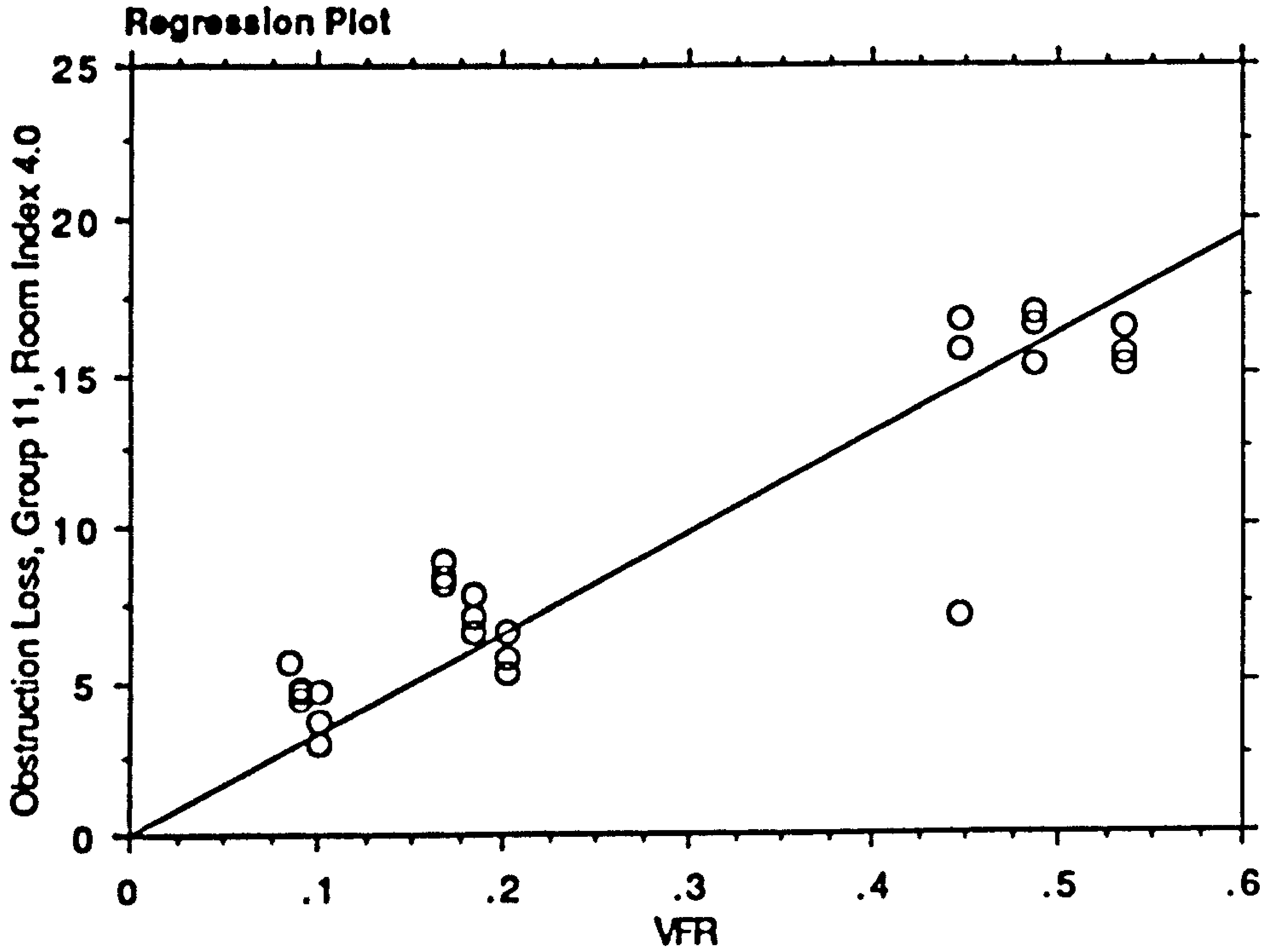
ANOVA Table
Obstruction Loss, Group 11, Room Index 4.0 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2725.518	2725.518	506.086	<.0001
Residual	28	150.793	5.385		
Total	29	2876.311			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 4.0 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	32.586	1.449	1.159	22.496	<.0001

Regression Plot



Y = 0 + 32.586 * X; R^2 = .948

Regression Summary
Obstruction Loss, Group 11, Room Index 5.0 vs. VFR

Count	23
Num. Missing	13
R	.988
R Squared	.976
Adjusted R Squared	.975
RMS Residual	1.720

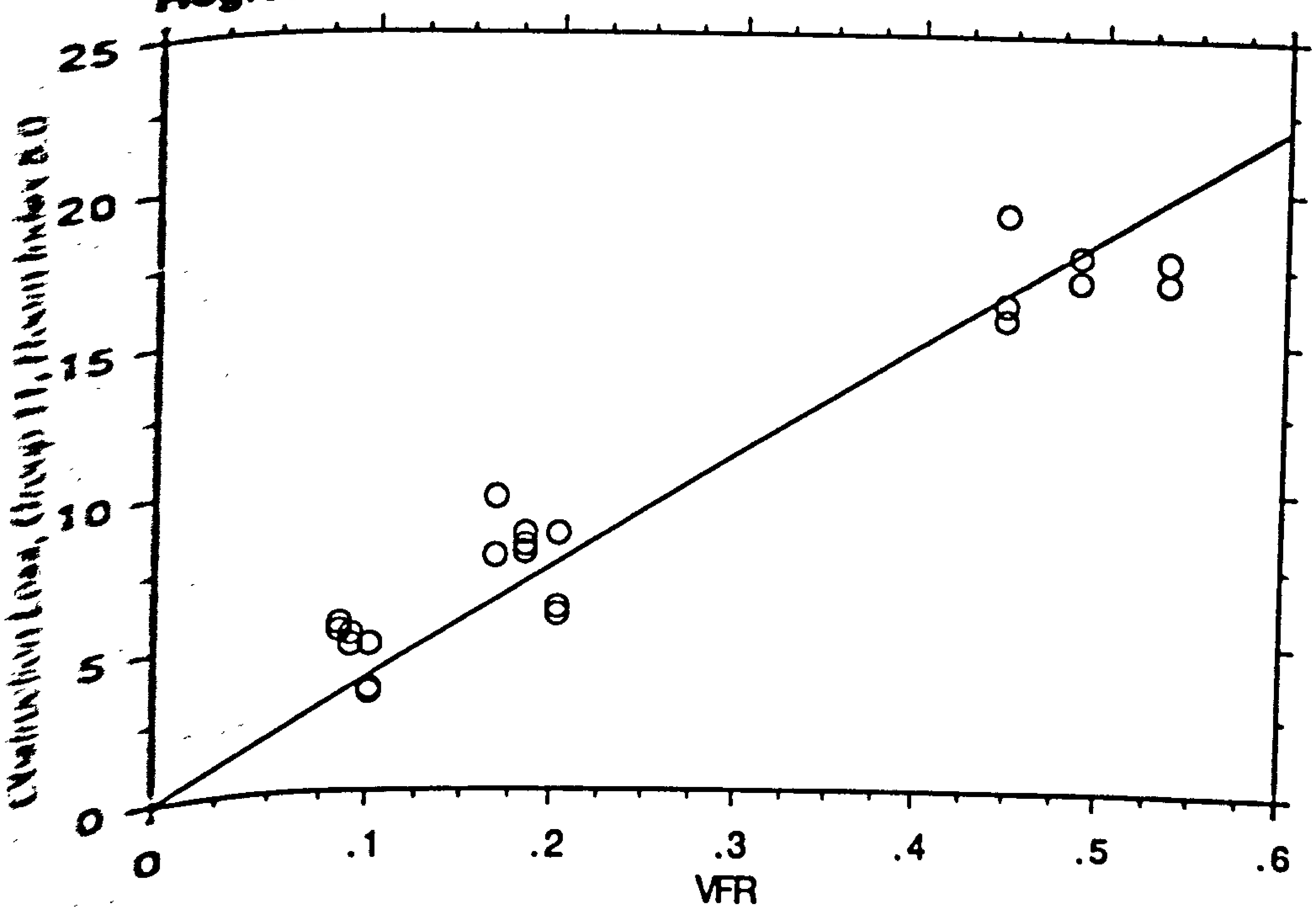
ANOVA Table
Obstruction Loss, Group 11, Room Index 5.0 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	2693.582	2693.582	910.701	<.0001
Residual	22	65.069	2.958		
Total	23	2758.651			

Regression Coefficients
Obstruction Loss, Group 11, Room Index 5.0 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	36.785	1.219	1.128	30.178	<.0001

Regression Plot



Y = 0 + 36.785 * X; R^2 = .976

Regression Summary
Obstruction Loss, Group 12, Room Index 1 vs. VFR

Count	81
Num. Missing	0
R	.978
R Squared	.957
Adjusted R Squared	.957
RMS Residual	2.365

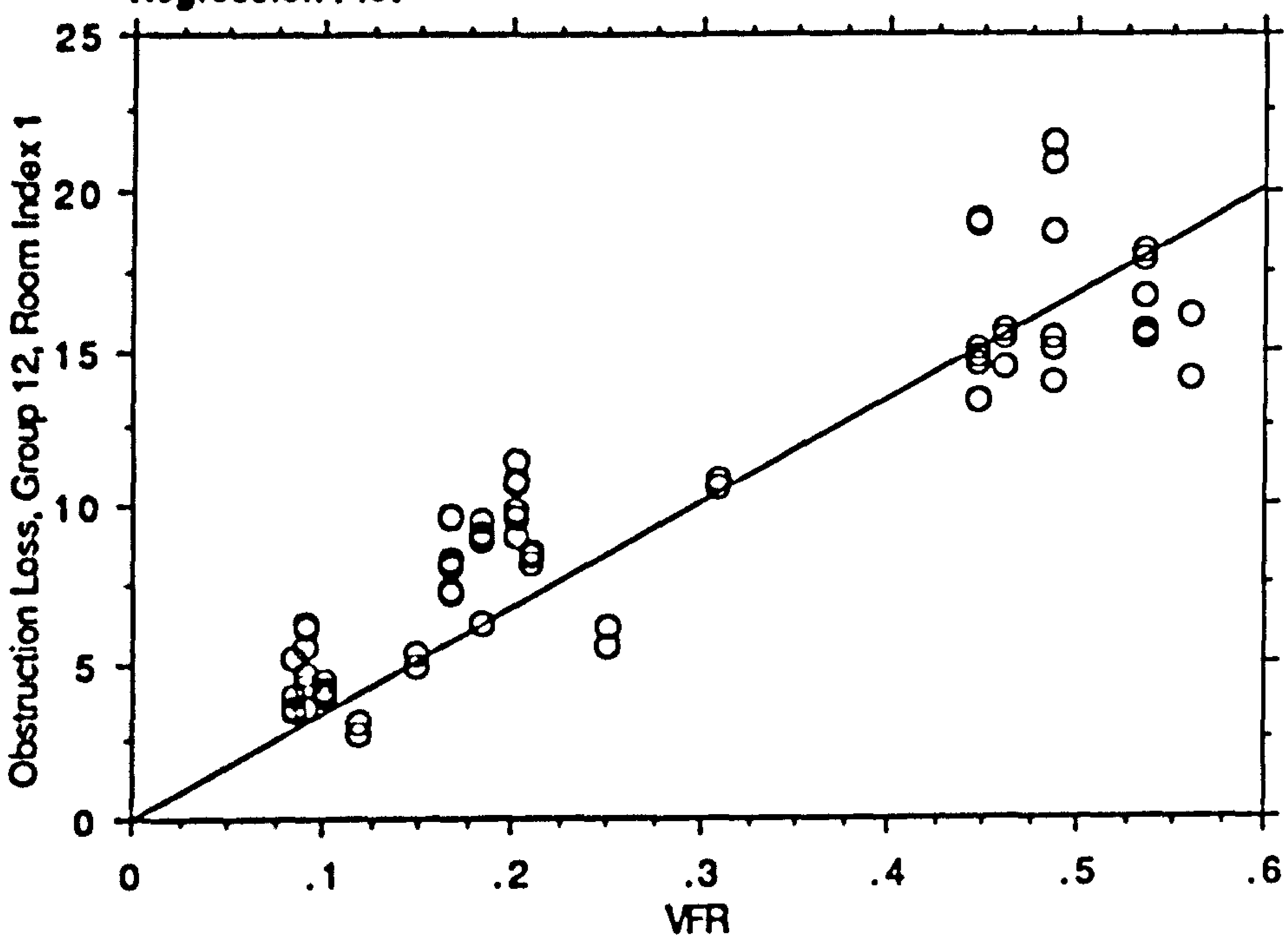
ANOVA Table
Obstruction Loss, Group 12, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9989.771	9989.771	1786.007	<.0001
Residual	80	447.468	5.593		
Total	81	10437.240			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.521	.793	1.132	42.261	<.0001

Regression Plot



Y = 0 + 33.521 * X; R^2 = .957

Regression Summary
Obstruction Loss, Group 12, Room Index 1.25 vs. VFR

Count	81
Num. Missing	0
R	.980
R Squared	.961
Adjusted R Squared	.961
RMS Residual	2.321

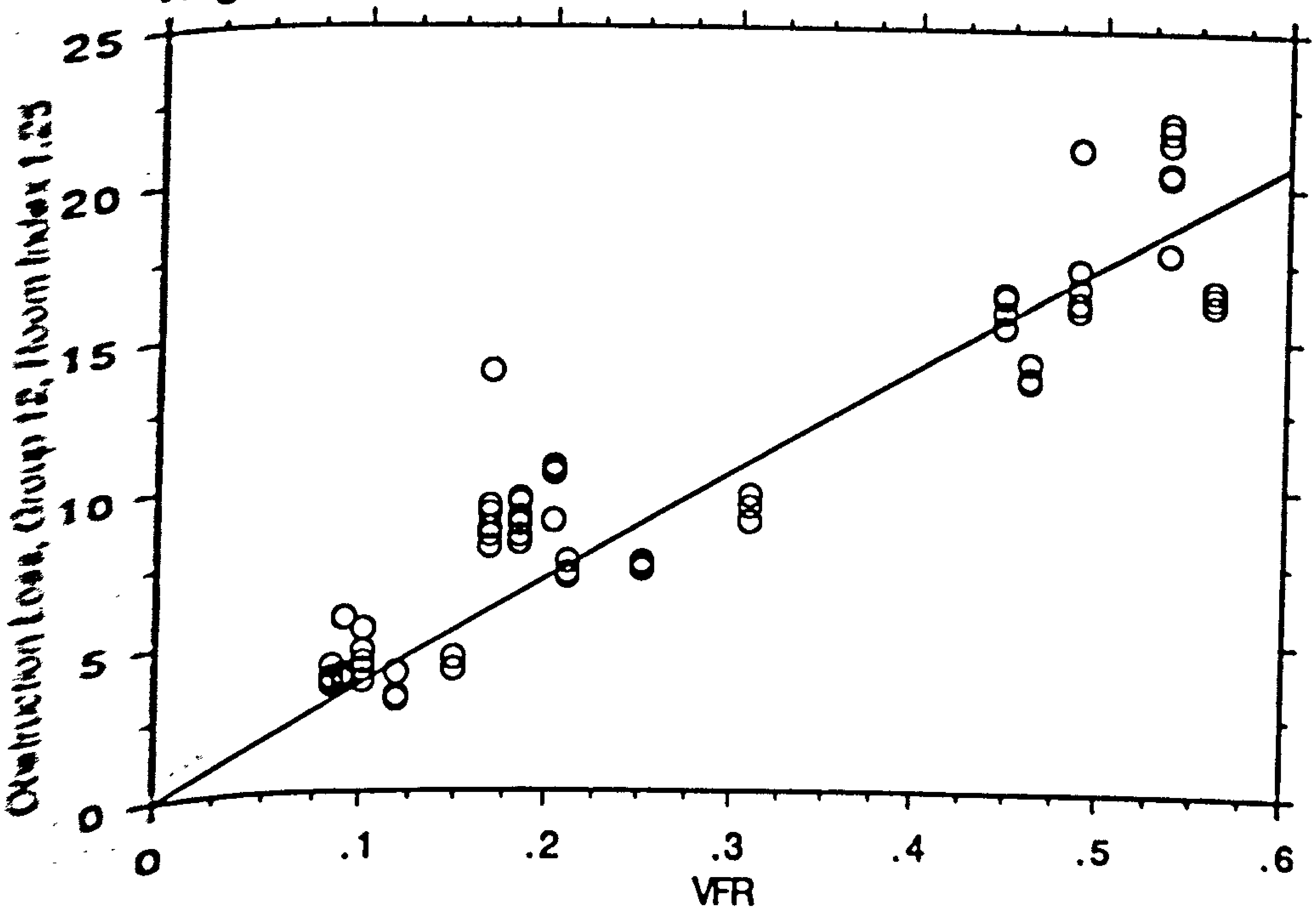
ANOVA Table
Obstruction Loss, Group 12, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10714.033	10714.033	1988.805	<.0001
Residual	80	430.974	5.387		
Total	81	11145.007			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	34.715	.778	1.090	44.596	<.0001

Regression Plot



Y = 0 + 34.715 * X; R^2 = .961

Regression Summary
Obstruction Loss, Group 12, Room Index 1.5 vs. VFR

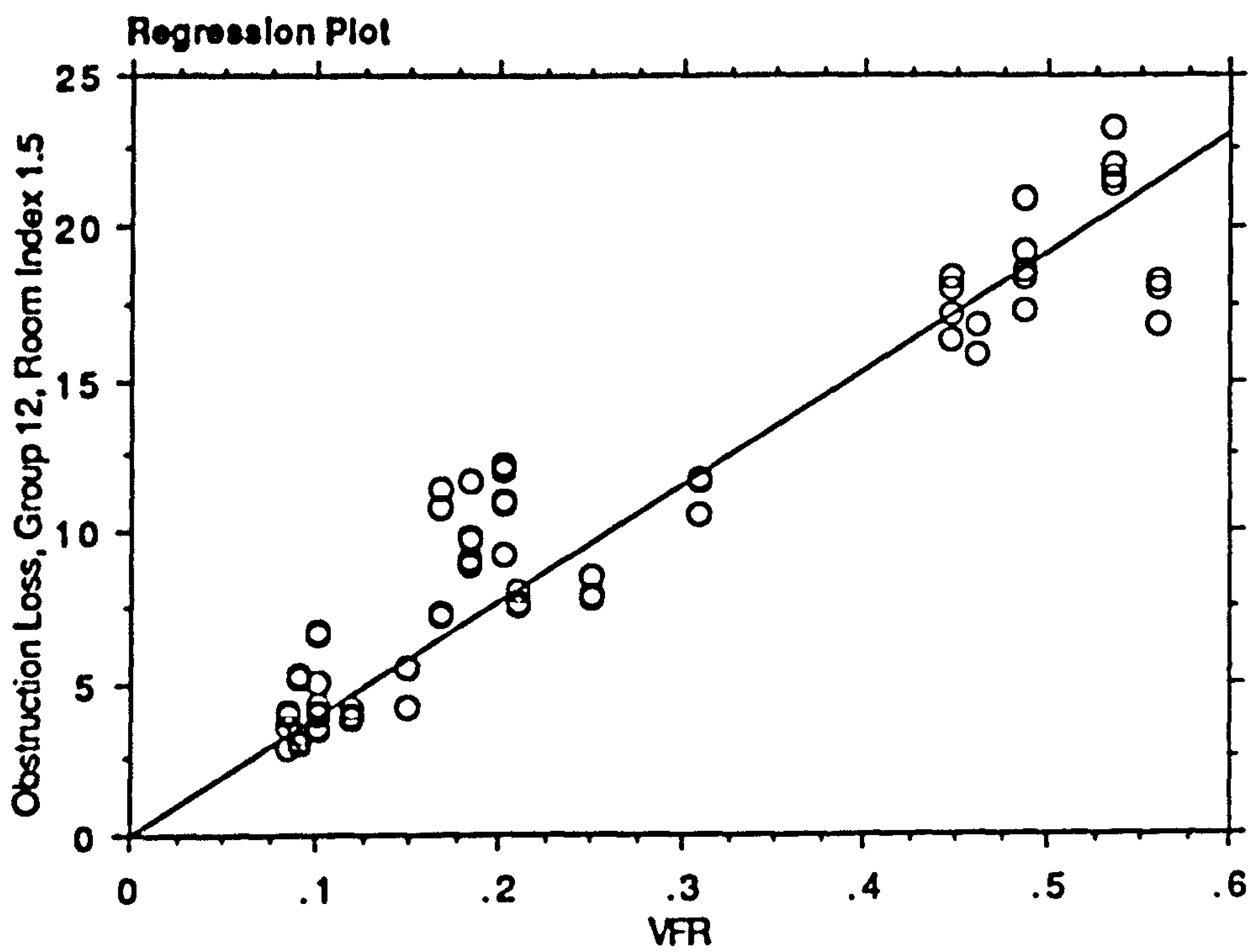
Count	80
Num. Missing	1
R	.986
R Squared	.972
Adjusted R Squared	.972
RMS Residual	2.184

ANOVA Table
Obstruction Loss, Group 12, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	13110.731	13110.731	2748.601	<.0001
Residual	79	376.827	4.770		
Total	80	13487.559			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.417	.733	1.085	52.427	<.0001



Y = 0 + 38.417 * X; R^2 = .972

Regression Summary
Obstruction Loss, Group 12, Room Index 2 vs. VFR

Count	81
Num. Missing	0
R	.975
R Squared	.951
Adjusted R Squared	.951
RMS Residual	3.018

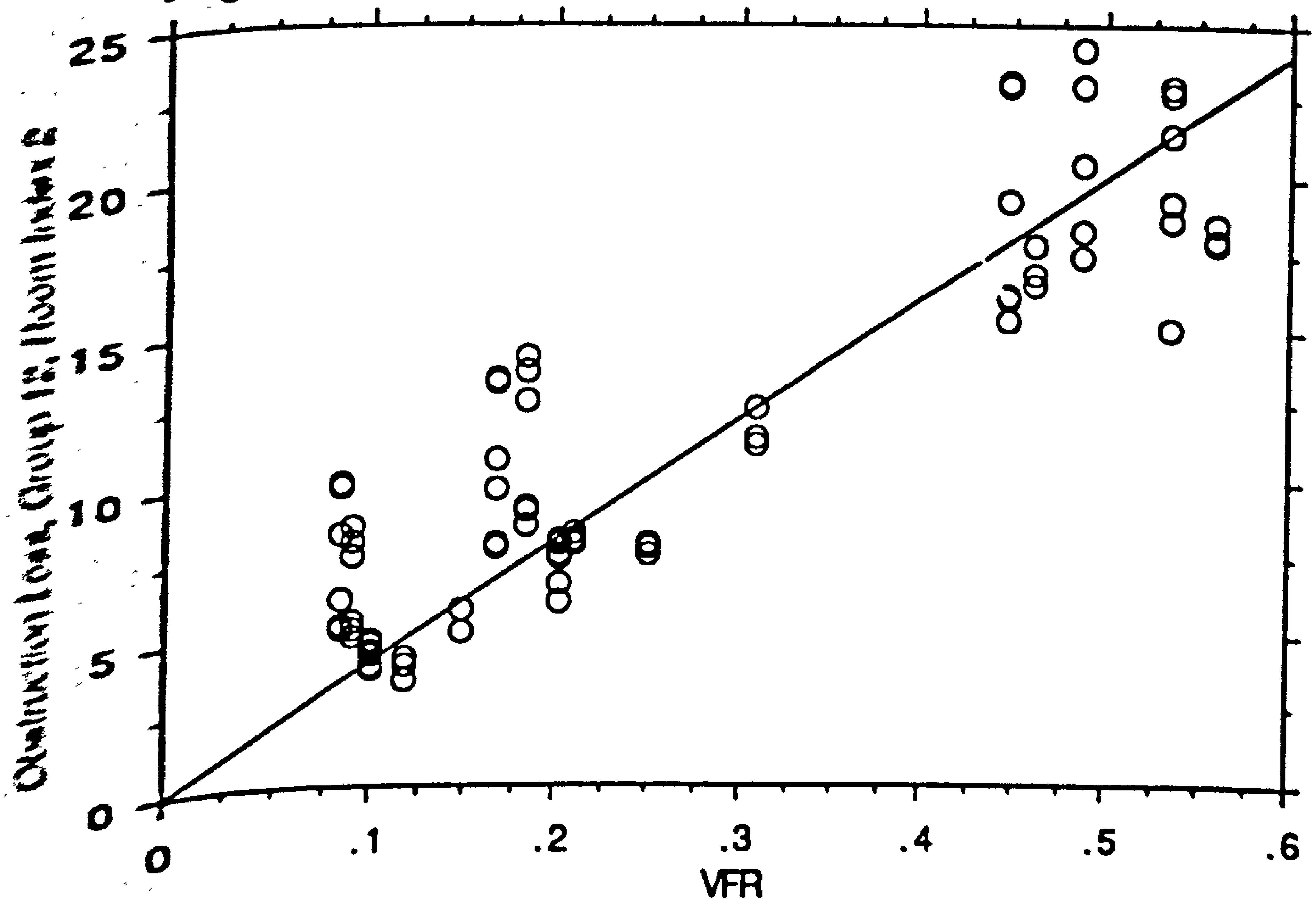
ANOVA Table
Obstruction Loss, Group 12, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	14273.729	14273.729	1.567E3	<.0001
Residual	80	728.882	9.111		
Total	81	15002.611			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	40.069	1.012	1.087	39.581	<.0001

Regression Plot



$Y = 0 + 40.069 * X; R^2 = .951$

Regression Summary
Obstruction Loss, Group 12, Room Index 3 vs. VFR

Count	54
Num. Missing	0
R	.987
R Squared	.974
Adjusted R Squared	.973
RMS Residual	1.994

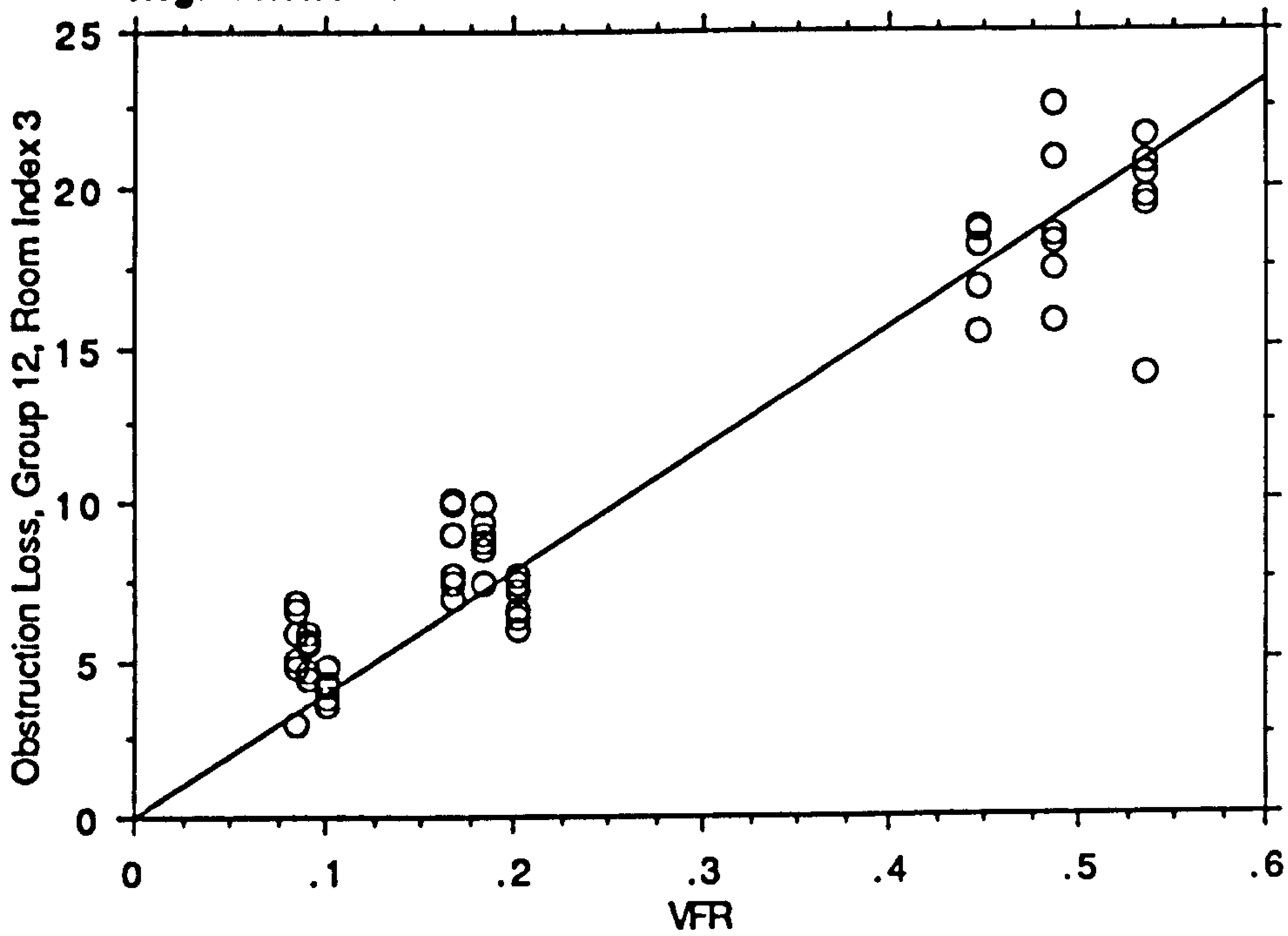
ANOVA Table
Obstruction Loss, Group 12, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7765.485	7765.485	1953.614	<.0001
Residual	53	210.671	3.975		
Total	54	7976.156			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.036	.883	1.099	44.200	<.0001

Regression Plot



Y = 0 + 39.036 * X; R^2 = .974

Regression Summary
Obstruction Loss, Group 12, Room Index 4 vs. VFR

Count	54
Num. Missing	0
R	.993
R Squared	.987
Adjusted R Squared	.986
RMS Residual	1.456

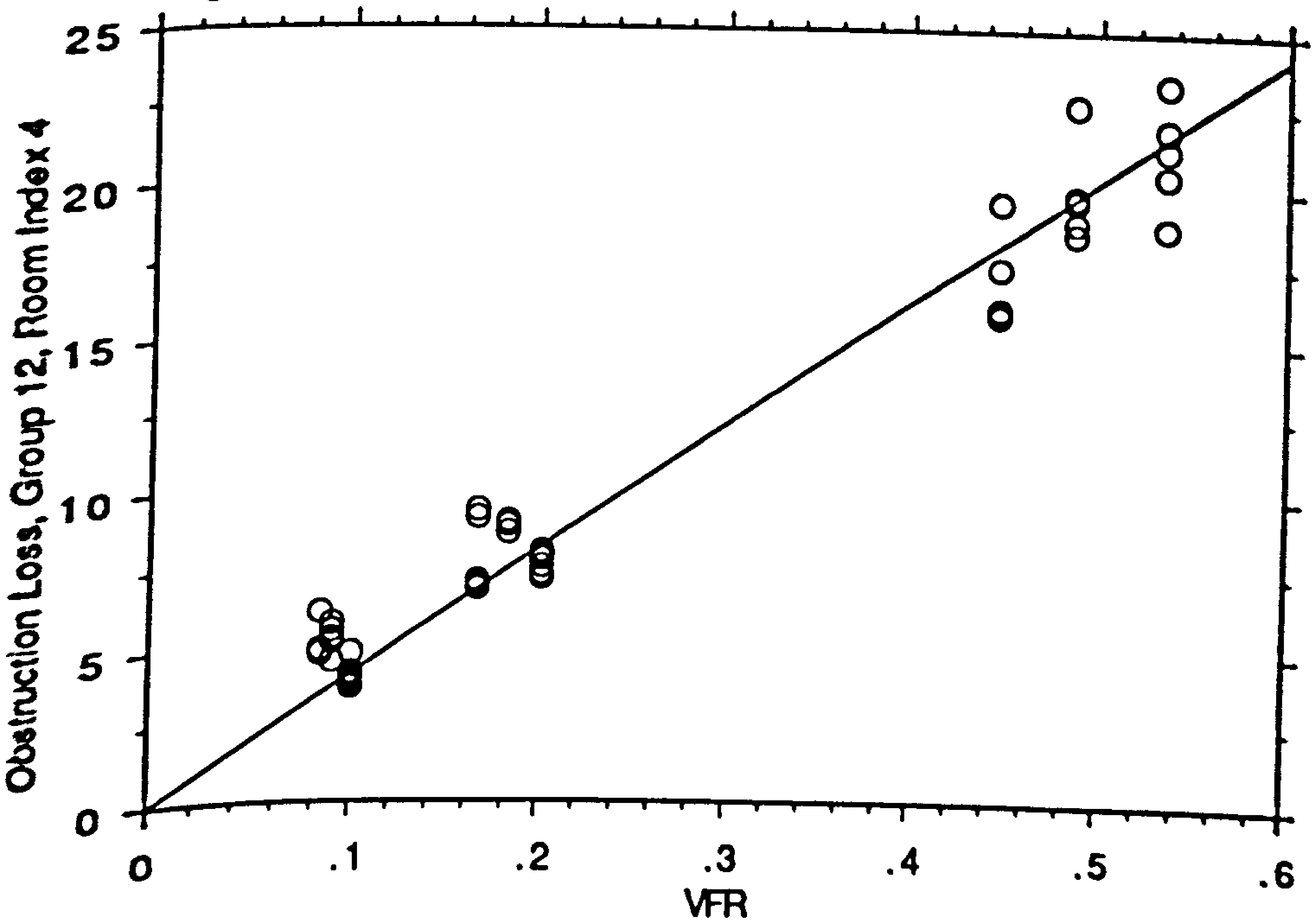
ANOVA Table
Obstruction Loss, Group 12, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8350.446	8350.446	3940.938	<.0001
Residual	53	112.302	2.119		
Total	54	8462.747			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	40.480	.645	1.089	62.777	<.0001

Regression Plot



Y = 0 + 40.48 * X; R^2 = .987

Regression Summary
Obstruction Loss, Group 12, Room Index 5 vs. VFR

Count	46
Num. Missing	8
R	.992
R Squared	.985
Adjusted R Squared	.984
RMS Residual	1.468

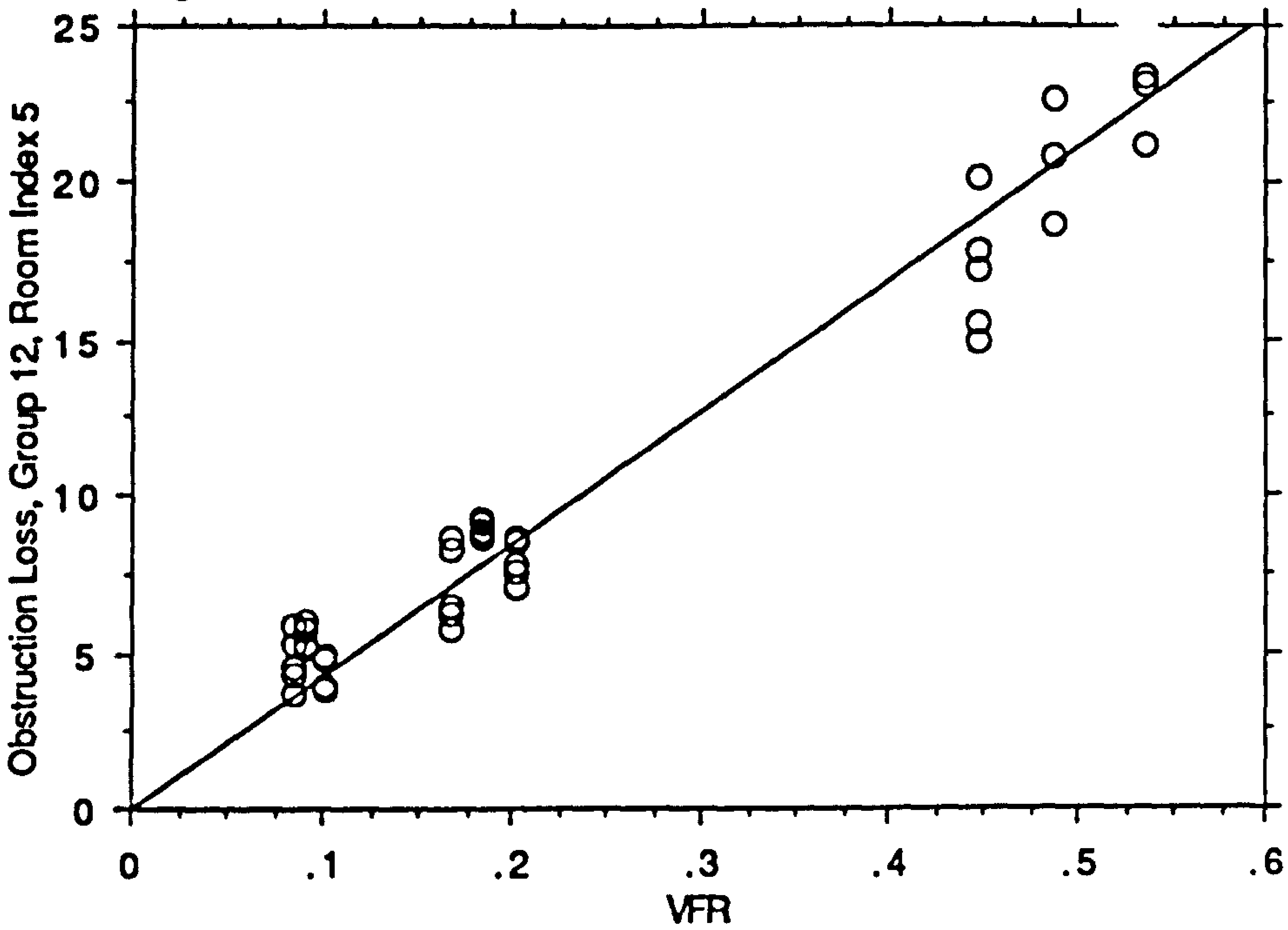
ANOVA Table
Obstruction Loss, Group 12, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6206.450	6206.450	2879.757	<.0001
Residual	45	96.984	2.155		
Total	46	6303.434			

Regression Coefficients
Obstruction Loss, Group 12, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	42.241	.787	1.072	53.663	<.0001

Regression Plot



Y = 0 + 42.241 * X; R^2 = .985

Regression Summary
Obstruction Loss, Group 15, Room Index 1 vs. VFR

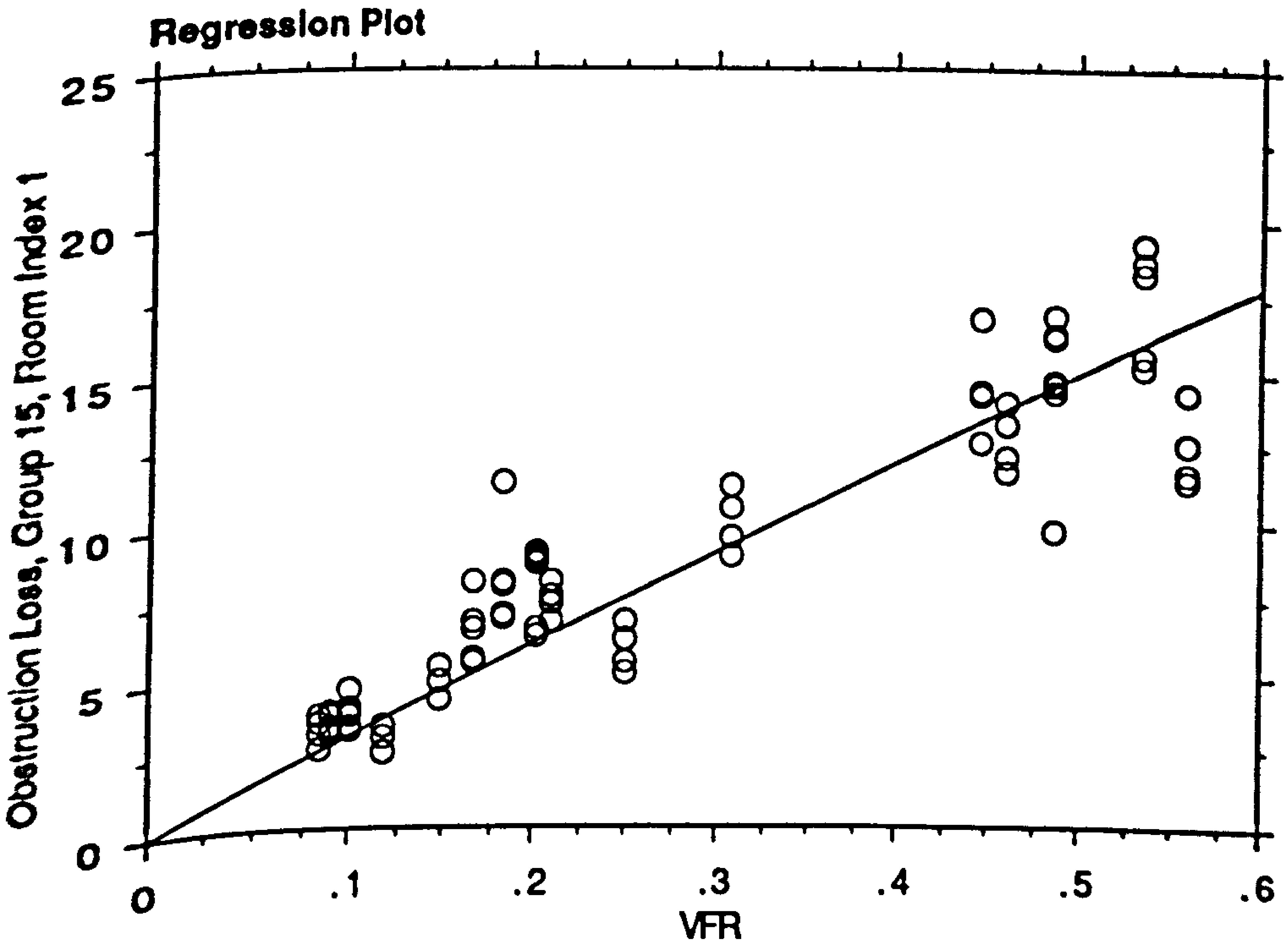
Count	108
Num. Missing	0
R	.978
R Squared	.957
Adjusted R Squared	.957
RMS Residual	2.087

ANOVA Table
Obstruction Loss, Group 15, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10468.979	10468.979	2404.566	<.0001
Residual	107	465.856	4.354		
Total	108	10934.834			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	29.718	.606	1.082	49.036	<.0001



Y = 0 + 29.718 * X; R^2 = .957

Regression Summary
Obstruction Loss, Group 15, Room Index 1.25 vs. VFR

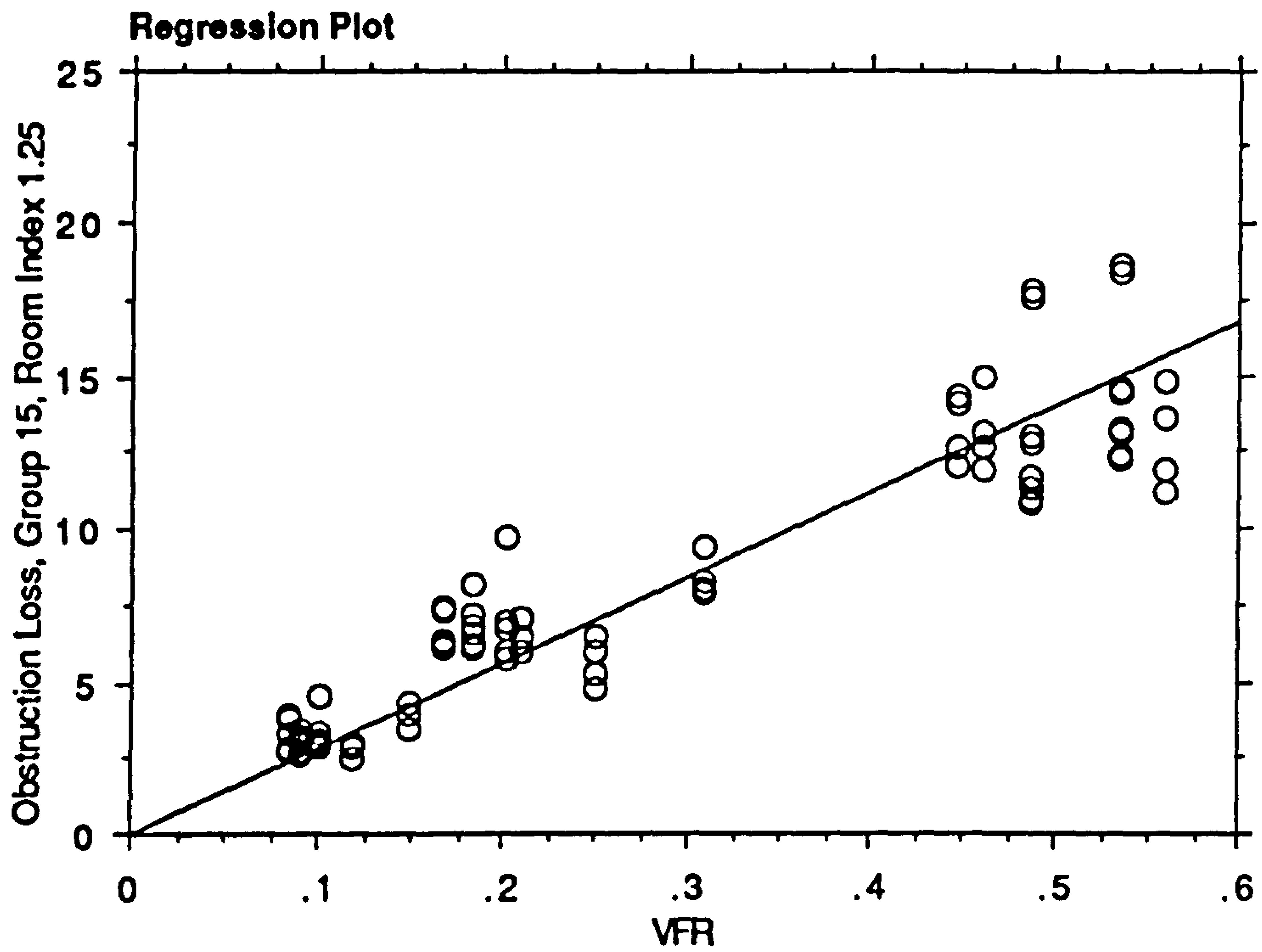
Count	108
Num. Missing	0
R	.983
R Squared	.967
Adjusted R Squared	.966
RMS Residual	1.729

ANOVA Table
Obstruction Loss, Group 15, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	9280.437	9280.437	3106.183	<.0001
Residual	#	319.687	2.988		
Total	#	9600.124			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	27.980	.502	1.069	55.733	<.0001



$Y = 0 + 27.98 * X; R^2 = .967$

Regression Summary
Obstruction Loss, Group 15, Room Index 1.5 vs. VFR

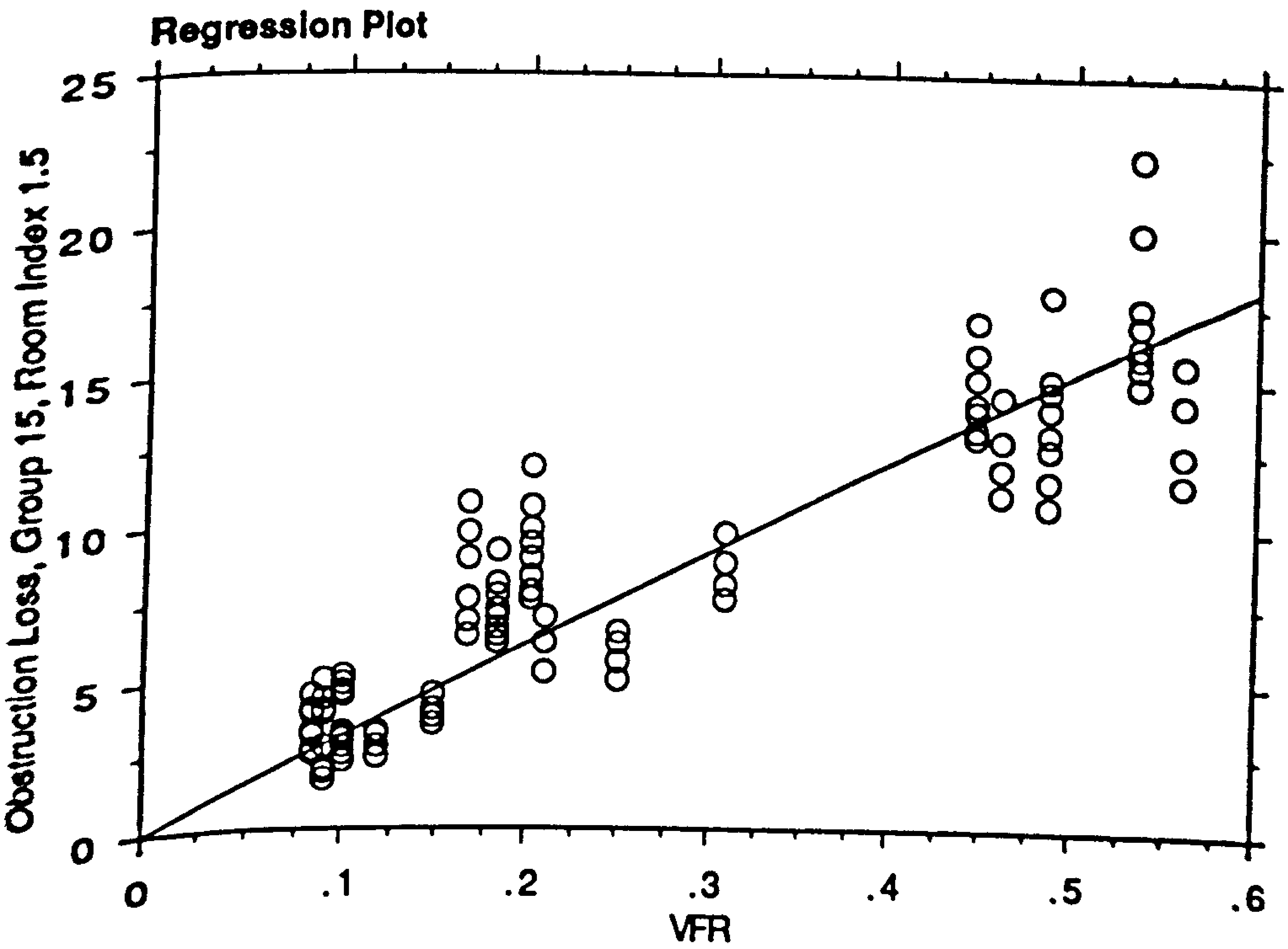
Count	108
Num. Missing	0
R	.975
R Squared	.951
Adjusted R Squared	.950
RMS Residual	2.280

ANOVA Table
Obstruction Loss, Group 15, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10775.835	10775.835	2072.306	<.0001
Residual	#	556.392	5.200		
Total	#	11332.227			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	30.151	.662	1.060	45.523	<.0001



Y = 0 + 30.151 * X; R^2 = .951

Regression Summary
Obstruction Loss, Group 15, Room Index 2 vs. VFR

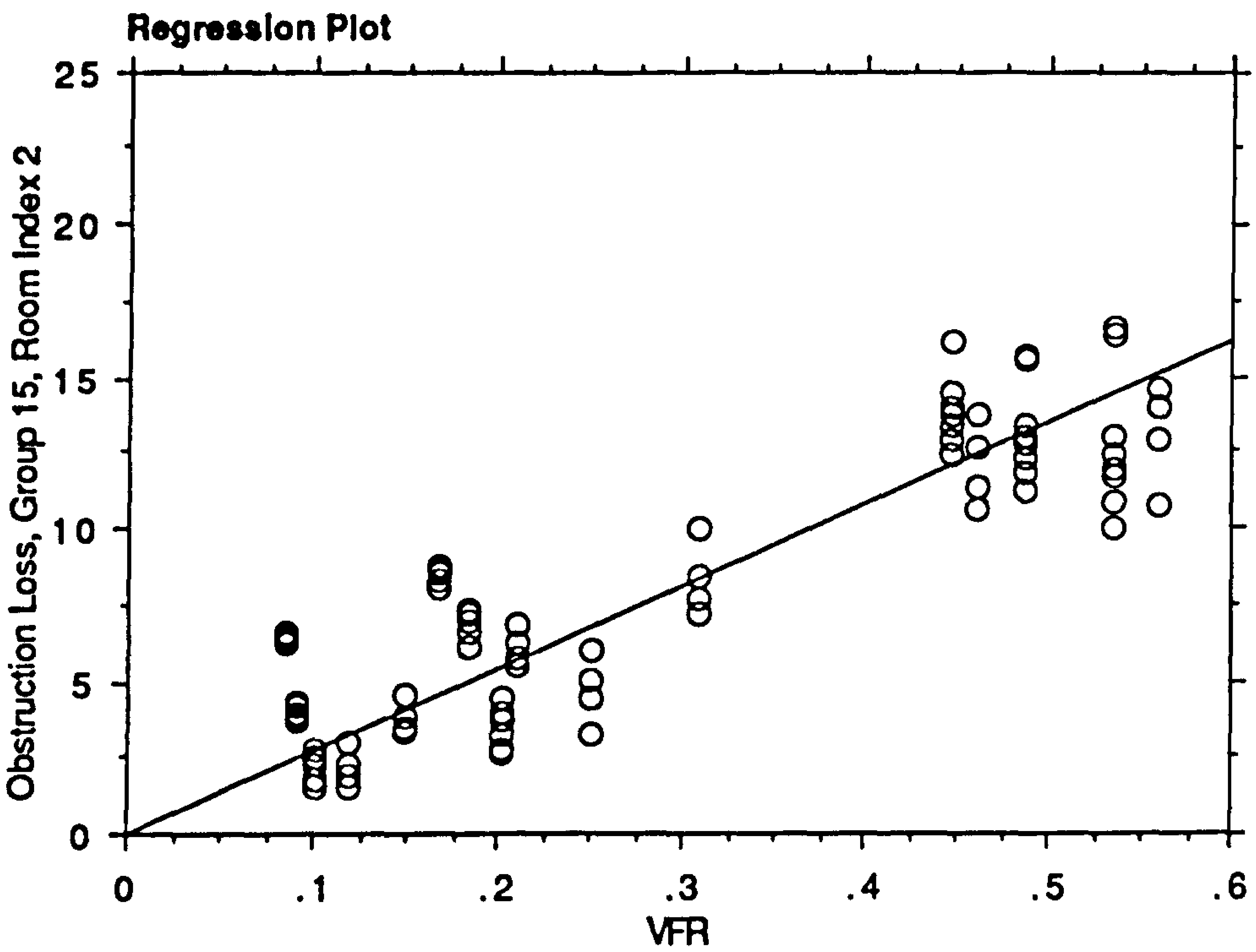
Count	108
Num. Missing	0
R	.968
R Squared	.937
Adjusted R Squared	.937
RMS Residual	2.313

ANOVA Table
Obstruction Loss, Group 15, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	8582.982	8582.982	1603.735	<.0001
Residual	107	572.650	5.352		
Total	108	9155.632			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.908	.672	1.052	40.047	<.0001



Y = 0 + 26.908 * X; R^2 = .937

Regression Summary
Obstruction Loss, Group 15, Room Index 3 vs. VFR

Count	71
Num. Missing	1
R	.960
R Squared	.921
Adjusted R Squared	.920
RMS Residual	2.603

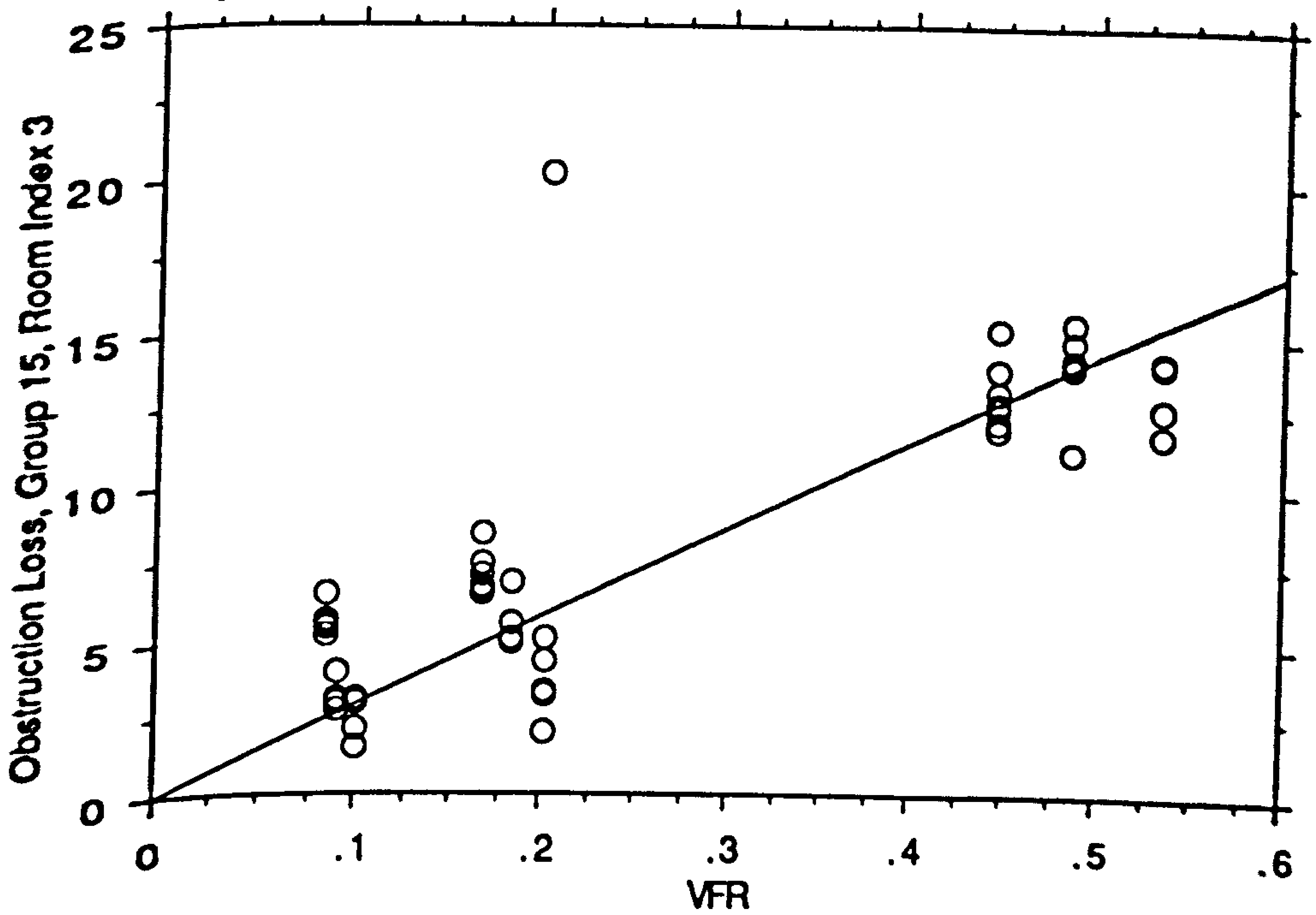
ANOVA Table
Obstruction Loss, Group 15, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5527.651	5527.651	815.510	<.0001
Residual	70	474.471	6.778		
Total	71	6002.122			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	28.540	.999	1.044	28.557	<.0001

Regression Plot



Y = 0 + 28.54 * X; R^2 = .921

Regression Summary
Obstruction Loss, Group 15, Room Index 4 vs. VFR

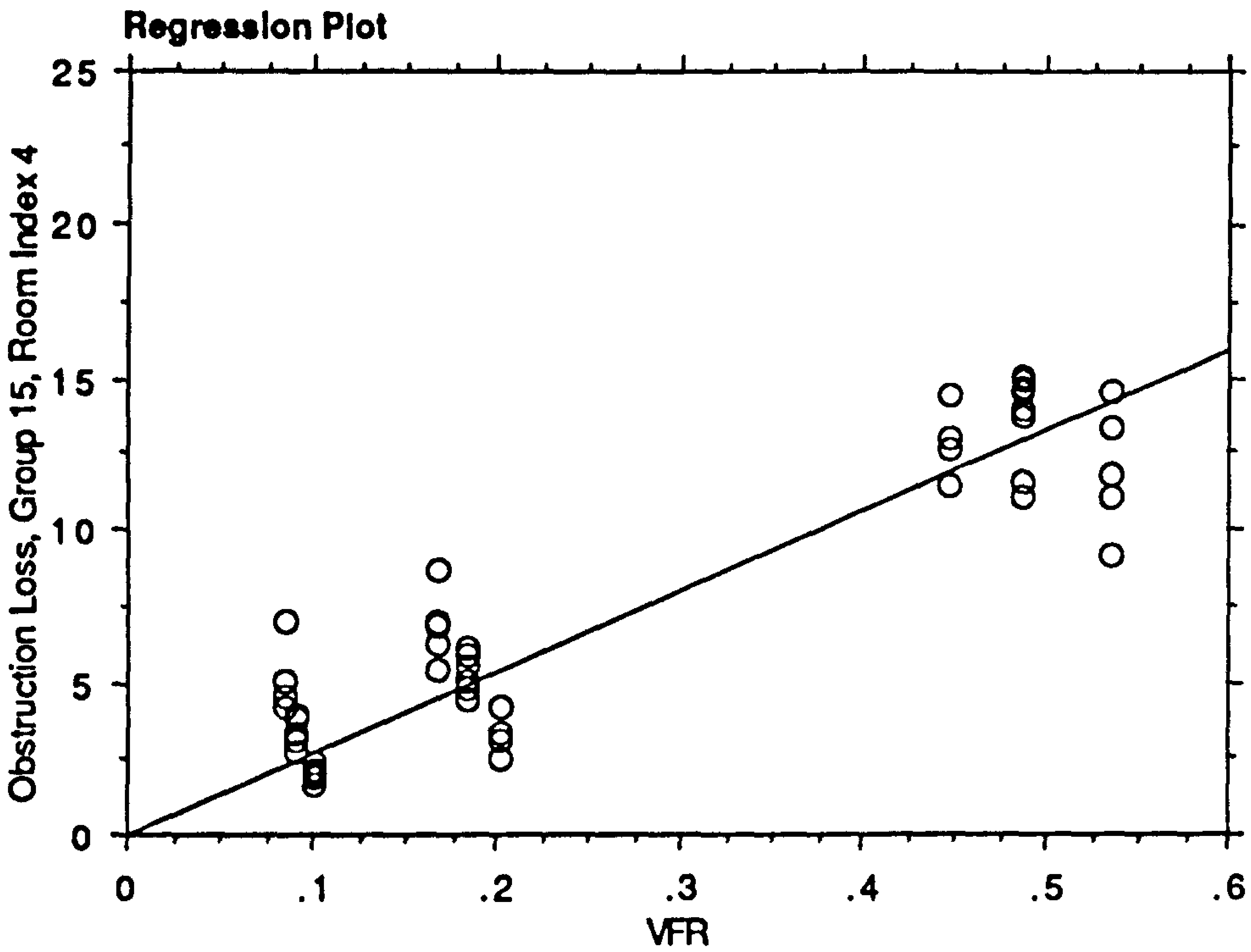
Count	72
Num. Missing	0
R	.970
R Squared	.940
Adjusted R Squared	.939
RMS Residual	2.073

ANOVA Table
Obstruction Loss, Group 15, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	4788.048	4788.048	1114.086	<.0001
Residual	71	305.139	4.298		
Total	72	5093.187			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.546	.795	1.042	33.378	<.0001



Y = 0 + 26.546 * X; R^2 = .94

Regression Summary
Obstruction Loss, Group 15, Room Index 5 vs. VFR

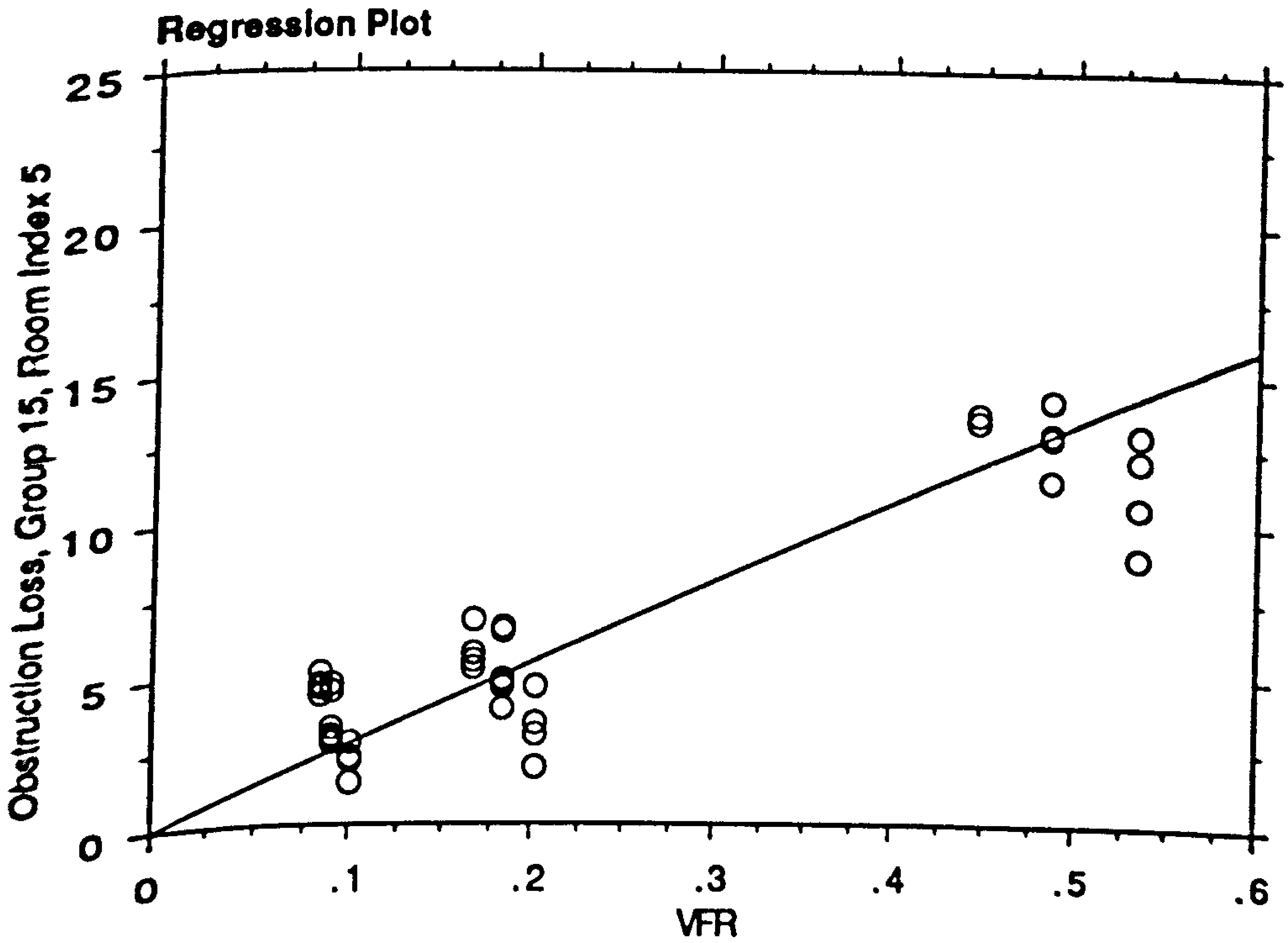
Count	64
Num. Missing	8
R	.971
R Squared	.943
Adjusted R Squared	.942
RMS Residual	1.785

ANOVA Table
Obstruction Loss, Group 15, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	3304.674	3304.674	1036.766	<.0001
Residual	63	200.811	3.187		
Total	64	3505.485			

Regression Coefficients
Obstruction Loss, Group 15, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	26.500	.823	1.011	32.199	<.0001



Y = 0 + 26.5 * X; R^2 = .943

Regression Summary
Obstruction Loss, Group 16, Room Index 1 vs. VFR

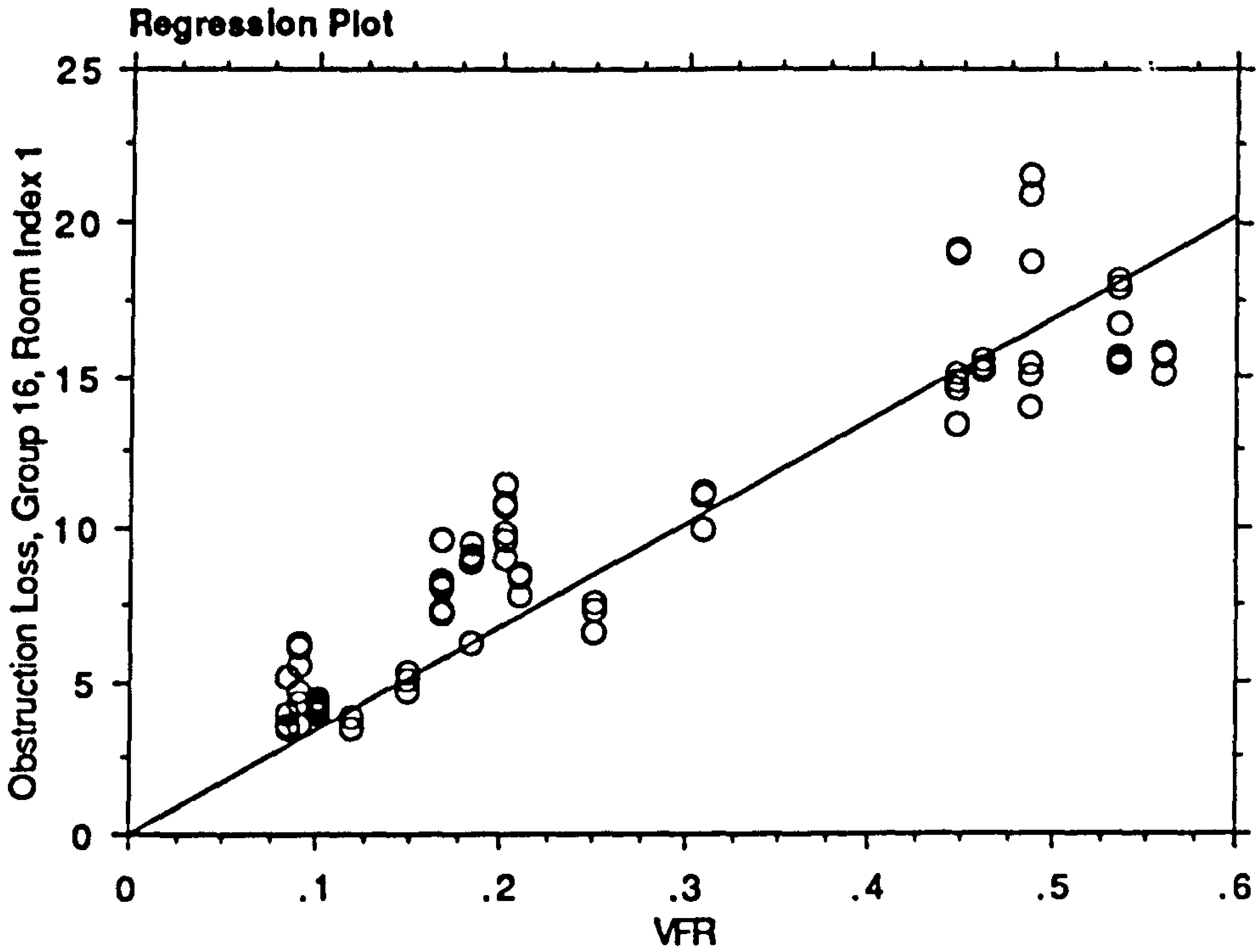
Count	81
Num. Missing	0
R	.981
R Squared	.962
Adjusted R Squared	.961
RMS Residual	2.247

ANOVA Table
Obstruction Loss, Group 16, Room Index 1 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	10214.076	10214.076	2022.614	<.0001
Residual	80	403.995	5.050		
Total	81	10618.071			

Regression Coefficients
Obstruction Loss, Group 16, Room Index 1 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	33.895	.754	1.142	44.973	<.0001



Y = 0 + 33.895 * X; R^2 = .962

Regression Summary
Obstruction Loss, Group 16, Room Index 1.25 vs. VFR

Count	81
Num. Missing	0
R	.991
R Squared	.982
Adjusted R Squared	.981
RMS Residual	1.602

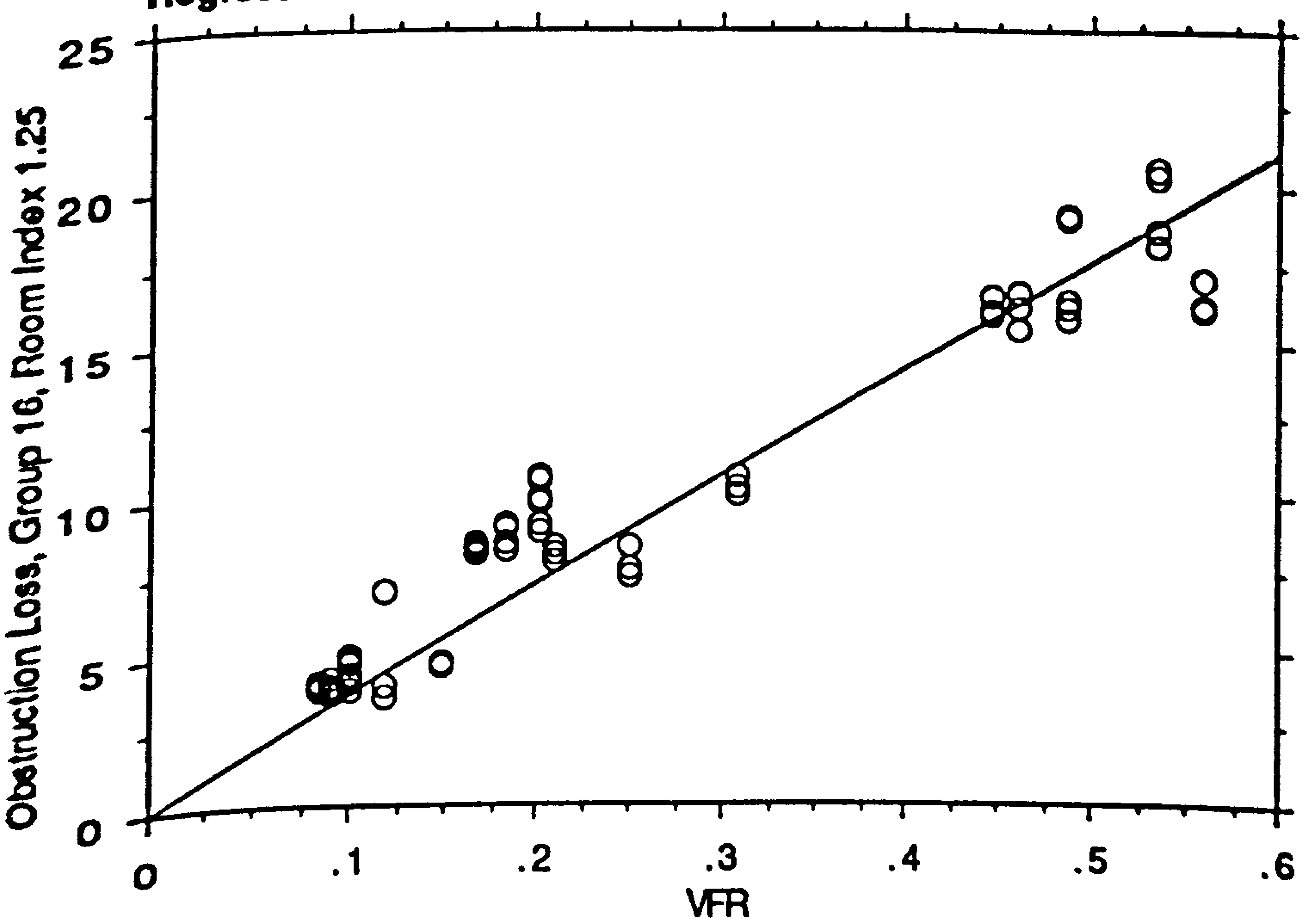
ANOVA Table
Obstruction Loss, Group 16, Room Index 1.25 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	11016.286	11016.286	4291.095	<.0001
Residual	80	205.379	2.567		
Total	81	11221.665			

Regression Coefficients
Obstruction Loss, Group 16, Room Index 1.25 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	35.201	.537	1.112	65.506	<.0001

Regression Plot



Y = 0 + 35.201 * X; R^2 = .982

Regression Summary
Obstruction Loss, Group 16, Room Index 1.5 vs. VFR

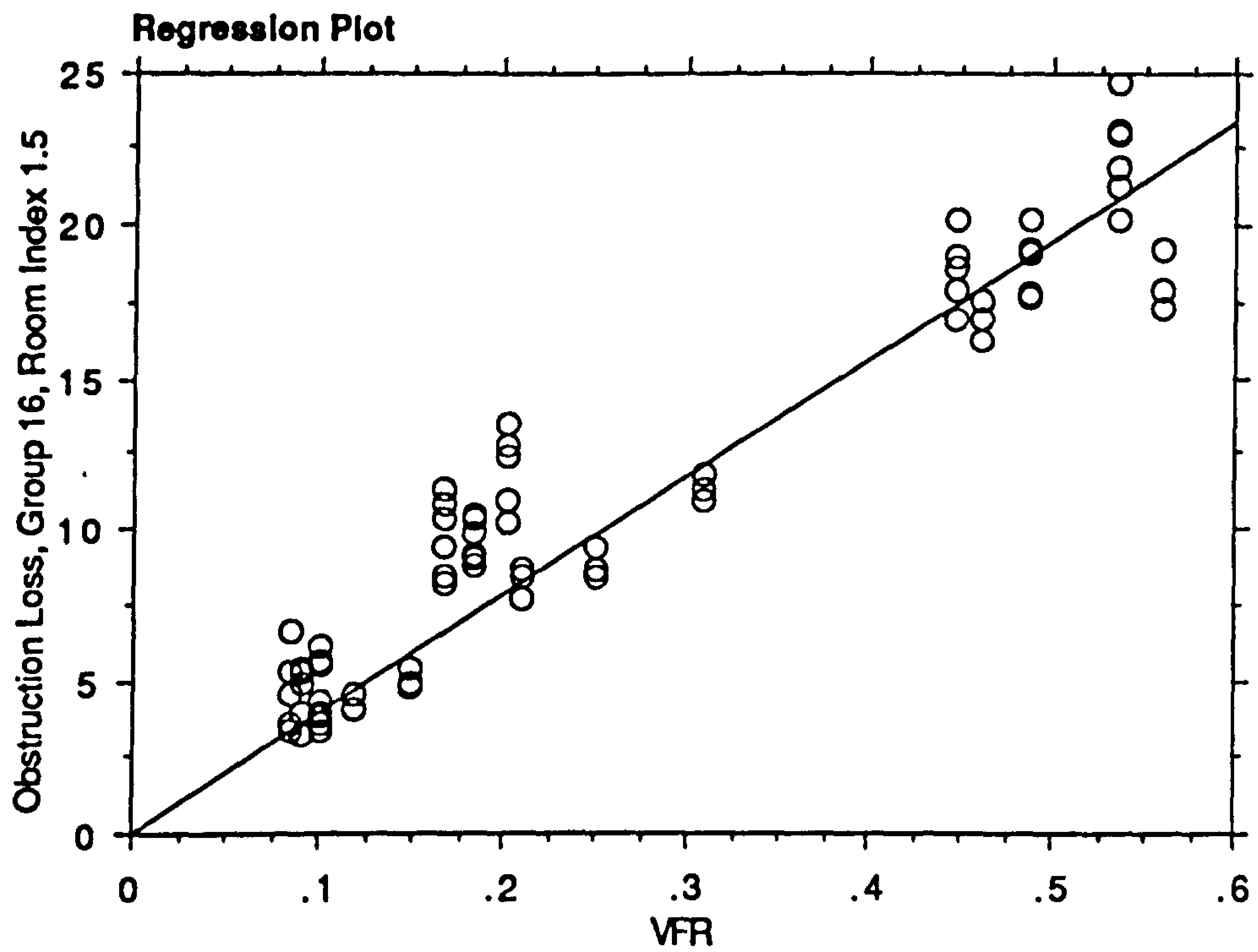
Count	81
Num. Missing	0
R	.985
R Squared	.971
Adjusted R Squared	.970
RMS Residual	2.261

ANOVA Table
Obstruction Loss, Group 16, Room Index 1.5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	13621.831	13621.831	2664.866	<.0001
Residual	80	408.931	5.112		
Total	81	14030.762			

Regression Coefficients
Obstruction Loss, Group 16, Room Index 1.5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.143	.758	1.106	51.622	<.0001



Y = 0 + 39.143 * X; R^2 = .971

Regression Summary
Obstruction Loss, Group 16, Room Index 2 vs. VFR

Count	80
Num. Missing	1
R	.991
R Squared	.981
Adjusted R Squared	.981
RMS Residual	1.782

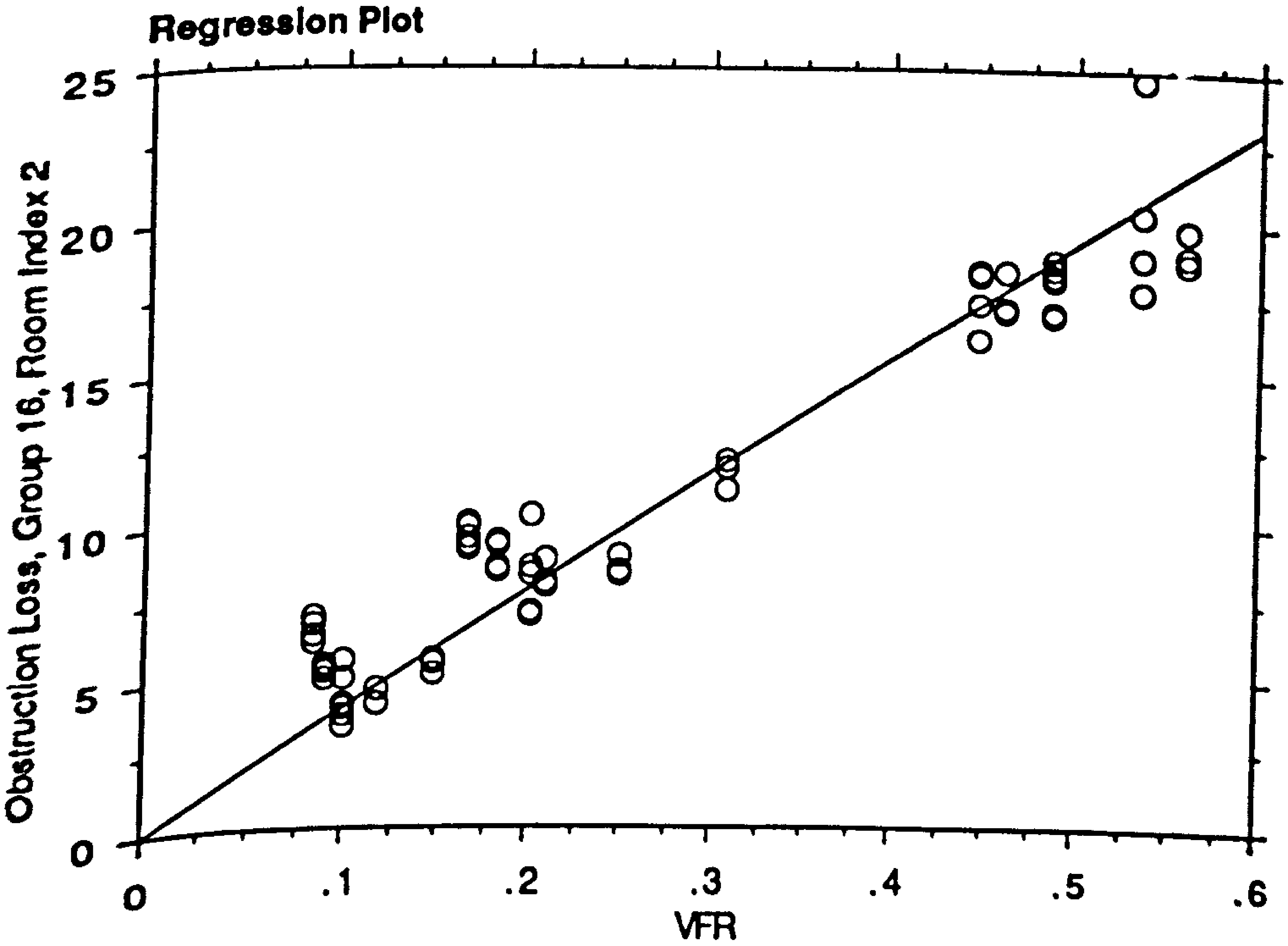
ANOVA Table
Obstruction Loss, Group 16, Room Index 2 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	13155.315	13155.315	4144.070	<.0001
Residual	79	250.785	3.174		
Total	80	13406.100			

Regression Coefficients
Obstruction Loss, Group 16, Room Index 2 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	38.556	.599	1.107	64.374	<.0001

Regression Plot



Y = 0 + 38.556 * X; R^2 = .981

Regression Summary
Obstruction Loss, Group 16, Room Index 3 vs. VFR

Count	51
Num. Missing	3
R	.978
R Squared	.957
Adjusted R Squared	.956
RMS Residual	2.678

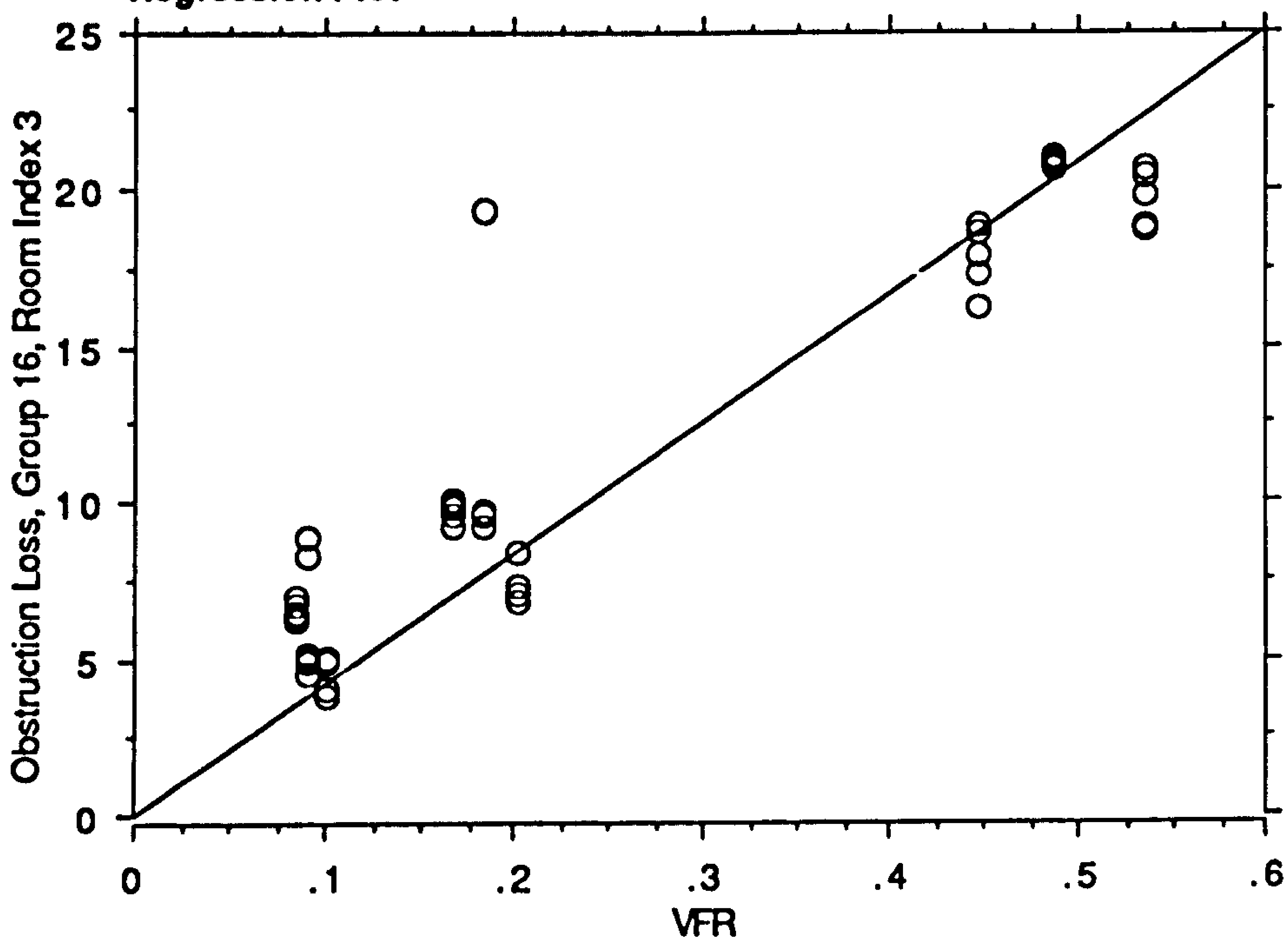
ANOVA Table
Obstruction Loss, Group 16, Room Index 3 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	7997.181	7997.181	1114.808	<.0001
Residual	50	358.680	7.174		
Total	51	8355.861			

P **Regression Coefficients**
Obstruction Loss, Group 16, Room Index 3 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	41.743	1.250	1.166	33.389	<.0001

Regression Plot



Y = 0 + 41.743 * X; R^2 = .957

Regression Summary
Obstruction Loss, Group 16, Room Index 4 vs. VFR

Count	42
Num. Missing	12
R	.987
R Squared	.975
Adjusted R Squared	.974
RMS Residual	1.994

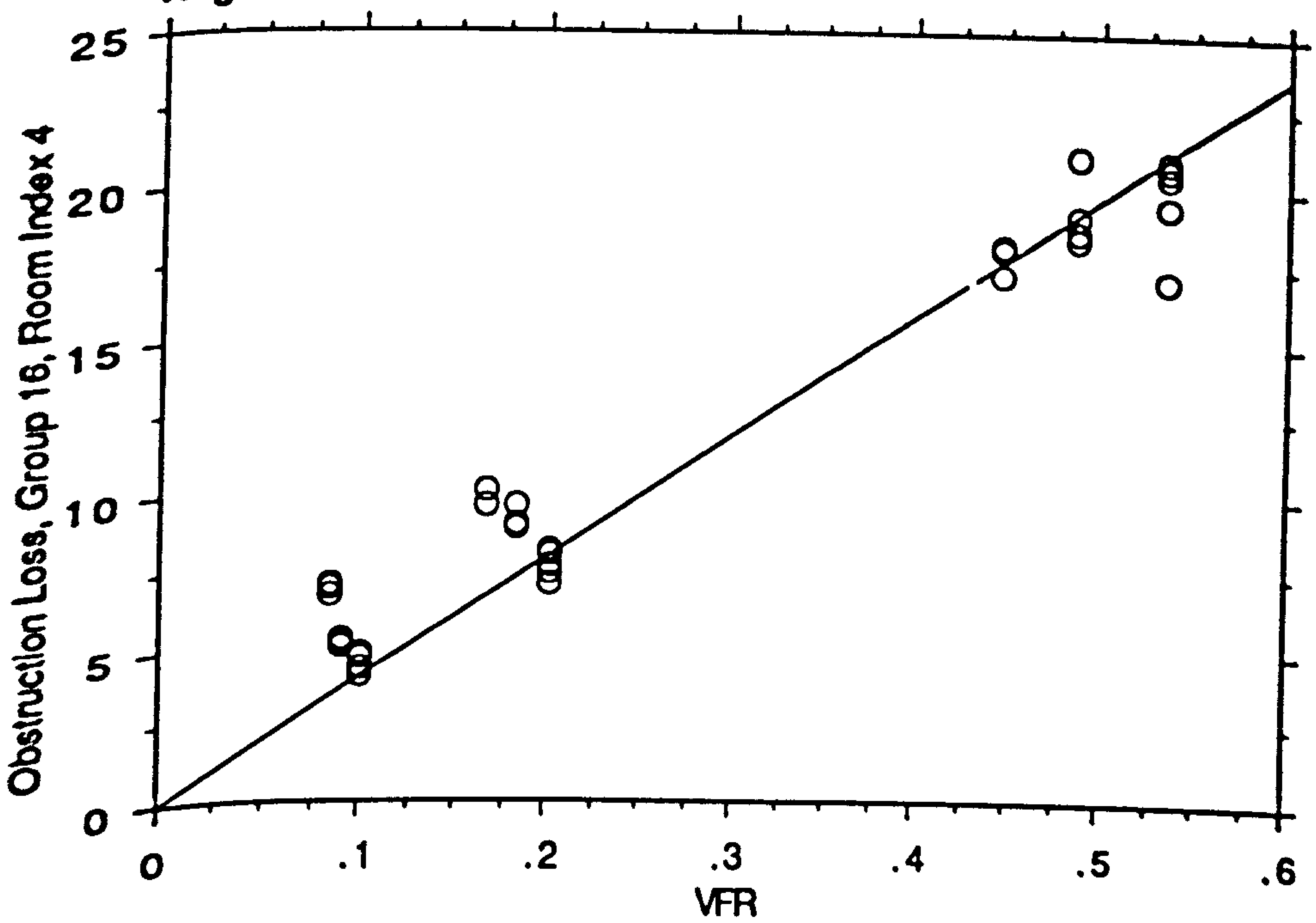
ANOVA Table
Obstruction Loss, Group 16, Room Index 4 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	6360.303	6360.303	1600.352	<.0001
Residual	41	162.947	3.974		
Total	42	6523.250			

Regression Coefficients
Obstruction Loss, Group 16, Room Index 4 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	39.526	.988	1.164	40.004	<.0001

Regression Plot



$Y = 0 + 39.526 * X; R^2 = .975$

Regression Summary
Obstruction Loss, Group 16, Room Index 5 vs. VFR

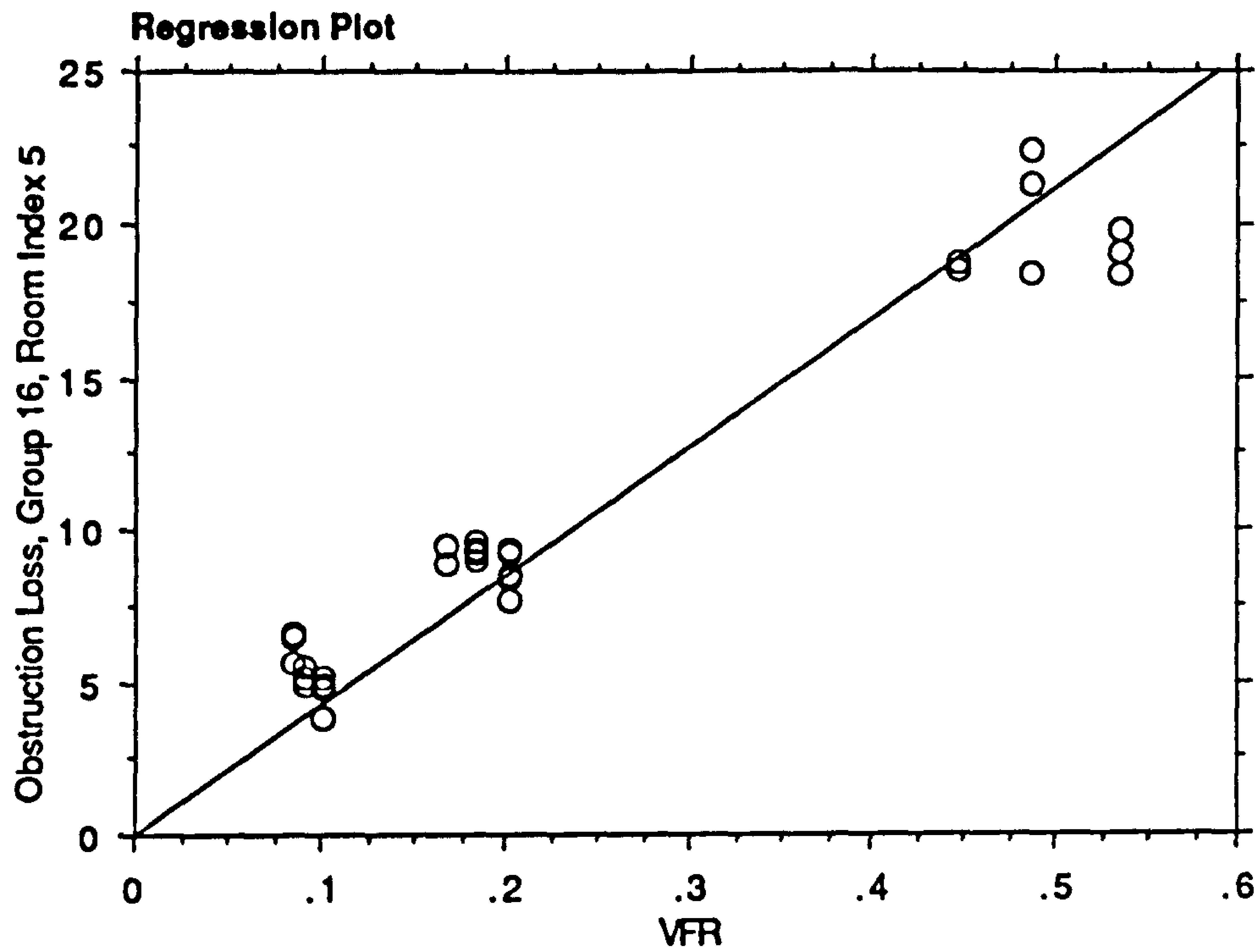
Count	39
Num. Missing	15
R	.989
R Squared	.979
Adjusted R Squared	.979
RMS Residual	1.799

ANOVA Table
Obstruction Loss, Group 16, Room Index 5 vs. VFR

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	5760.680	5760.680	1780.157	<.0001
Residual	38	122.970	3.236		
Total	39	5883.650			

Regression Coefficients
Obstruction Loss, Group 16, Room Index 5 vs. VFR

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
VFR	42.398	1.005	1.157	42.192	<.0001



Y = 0 + 42.398 * X; R^2 = .979

Appendix Three

Published papers

1. *A.S.M. Leung, M.J. Lupton and D.J. Carter*, "Standard obstructions for lighting calculations", *Lighting Research and Technology*, 26(3) pp. 161-165 (1994).

2. *M.J. Lupton, A.S.M. Leung and D.J. Carter*, "Measured light losses in real interiors", *CIBSE National Lighting Conference*, Cambridge, pp. 91-97 (1994).

3. *D.J. Carter, M.J. Lupton and A.S.M. Leung*, "A lighting design method for non-empty interiors", *23rd Session of the CIE*, New Dehi, India, pp. 168-171, (1995).

4. *M.J. Lupton, A.S.M. Leung and D.J. Carter*, "Advances in lighting design methods for non-empty interiors", *accepted for publication in Lighting Research and Technology*, (1996).

5. *D.J. Carter, M.J. Lupton and A.S.M. Leung*, "Lighting design calculations for non-empty interiors", *accepted for publication in CIBSE National Lighting Conference*, Bath, (1996).

Lighting Res. Technol. 26(3) 161–165 (1994) Printed in Great Britain L281

Summary This paper puts forward the concept of 'standard obstructions' for interior lighting calculations. Standard obstructions may be used as the basis of the calculation of light loss factors for use in the design of lighting for interiors whose ultimate use is not known. They may also be used as benchmark validation tools for interior lighting analysis computer programs that have a capacity to handle internal obstructions

Standard obstructions for lighting calculations

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1 Introduction

In general lighting terms an obstruction may be considered to be an object which is between luminaire plane and working plane. In a commercial building they may include visual display terminals, filing and storage cabinets panels and screens used for dividing offices into work stations, and also users of the office when seated at desks.

Previous work at Liverpool addressed the problem of the size and configuration of the elements of office obstruction set out above. A series of 'light', 'medium', and 'heavy' standard obstructions were put forward to represent the range of obstruction density in office interiors. The standard obstructions were developed from analysis of data on room contents collected by surveys of a number of office buildings and from information provided by major office equipment manufacturers and the sizes of the elements of the standard obstructions are shown in Table 1. The elements are arranged into the configurations set out below:

- light standard obstruction: person, desk and VDT
- medium standard obstruction: person, desk, VDT and filing cabinet
- heavy standard obstruction: person, desk, VDT, filing cabinet and partition.

Floor area per standard configuration may be 8,10 or 12 m^2.

Standard obstructions were developed for use in the calculation of luminaire spacing and light losses for use in the design of lighting for obstructed interiors. They may also have a use as benchmark validation tools for interior lighting analysis computer programs that have a capacity to handle internal obstructions. For both uses there is a need for standardised data on internal obstruction and the aim of this paper is to put forward standard obstructions for this purpose.

2 Light loss prediction using standard obstructions

Lighting design methods currently in use are based on the assumption that the volume between task and lighting equipment is empty. This has implications for specifiers, designers, and users of lighting installations since obstructions that project above the task plane will adversely influence the illumination of the interior. Previous work at the University of Liverpool has developed a modified lumen method procedure for producing designs for general lighting installations for obstructed interiors capable of, firstly, spacing the luminaires at an appropriate distance to overcome the anticipated effects of obstructions on illuminance uniformity and, secondly, to take account of the likely light losses caused by obstructions. The core of the lumen method of lighting design is the spacing-to-height ratio (SHR) which determines luminaire layout. The modification to this calculation enables the designer to space the luminaires at an appropriate distance to allow illuminance uniformity to be maintained in areas containing the various standard obstructions[1]. A lumen method calculation is then possible using a modified spacing-to-height ratio(SHR_{obs}) selected by the designer as being appropriate to the interior being considered. The second element of the modified lumen method is compensation for the obstruction light loss over the working plane[2]. To predict this, a specially written computer program was used to enable illuminance conditions for specific combinations of room size, room contents and light source to be determined. This was used to calculate the obstruction loss (OL), the percentage reduction in average working plane illuminance caused by uniformly distributed standard obstructions, for a range of interiors lit by point or linear source luminaires. Some typical predicted values of OL extracted from Reference 3 are given in Table 2. The design process then proceeds in an orthodox manner using OL as a multiplier to the utilisation factor to ensure

Table 1 Elements of standard obstructions

Element		Length (m)	Width (m)	Height (m)	Vertical surface area (m^2)	Reflectance
Filing cabinet		0.64	0.48	1.35	1.34	0.3
Partition		1.5	0.025	1.75	3.06	0.6
VDT		0.4	0.4	0.4	0.64	0.3
Person	—head	0.1	0.2	0.55	0.53	0.3
	—body	0.1	0.5	0.34	—	0.4
Desk		0.76	1.41	0.75	NA	0.3

Table 2 Some typical predicted values of OL (%) for installations with linear luminaires installed near SHRmax

	Degree of obstruction		
	Light (VFR=0.1)	Medium (VFR=0.25)	Heavy (VFR=0.45)
Diffuser	2.5	7	14
Wide distribution reflector	2	5	11
Narrow reflector	1.5	5	10

acceptable average working plane illuminance and SHR_{obs} as the luminaire spacing criterion to ensure acceptable working plane illuminance uniformity.

The development of the modified lumen method demonstrated that prediction of light losses in obstructed interiors based on a knowledge of the nature of the contents is feasible.The dominant factor in interior light loss was the size and disposition of the room contents and a number of measures of obstruction density have been investigated[4]. It was conclud- · ' that the ratio of obstruction vertical surface area to floor a (VFR) gave the best indication of the influence of room contents on overall working plane light loss. The VFR method was used to generate data for the modified lumen method using standard obstructions having a VFR range from 0 to 0.7 as 'room contents'. To verify that standard obstructions were representative of obstruction densities commonly found in commercial buildings, a number of surveys of room contents in offices were conducted. The surveys consisted of physical measurement of the rooms and their contents from which vertical surface area, floor areas and hence VFR values were calculated. The results, shown in Table 3, indicate a range of VFR in actual interiors from 0.15 to 0.69, these being within the range of VFR created by the standard obstructions. In terms of this measure of obstruction, therefore, standard obstructions are capable of replicating conditions found in actual furnished interiors.

Table 3 VFR values for some real interiors

Installation	Actual VFR
·ping company general office	0.15
·h authority general office	0.28
Insurance company general office	0.34
Bank general office	0.34
Consulting engineers general office	0.38
Bank data processing office	0.42
University administration office	0.44
Insurance company general office	0.57
Consulting engineers design office	0.58
Electricity company general office	0.60
University accounts office	0.63
Transport authority engineering office	0.64
University computer unit	0.69

The standard obstruction concept was also used for measurement of light loss in a range of interiors that contain lighting equipment that is representative of good modern practice. Some of the installations were equipped with surface-mounted diffusers, some with luminaires designed specifically for VDT areas, and the rest with surface-mounted or recessed wide distribution reflector luminaires with either wedge or cross-blade louvres which are classified in the *CIBSE Code for interior lighting* as 'surface modular' or 'recessed modular'[5]. The surface reflection factors for all installations were within the *CIBSE Code* recommendations. The measurements are made in the installations firstly in their empty state, secondly filled with 'standard obstructions', and finally, in some cases, in their working state after occupation by the building users. For the purpose of the surveys the standard obstructions were constructed of suitably painted cardboard, polystyrene,and wood (see Figure 1). The results, shown in Table 4, indicate for all installations the same general pattern of OL rising as VFR increases. The average OL values over all the measured installations of 1.8% for light standard obstruction, 6.2% for medium standard obstruction, and 11.8% for heavy standard obstruction are in good agreement with the predicted results shown in Table 2. In four of the five cases where the OL was measured under working conditions the value corresponds to that measured using the standard obstruction configuration having a VFR similar to that of the working condition. In addition, in the shipping company general office the illuminance was measured on a 0.25 m square grid over a 0.5 m square 'task area' located immediately in front of the human occupant for a randomly located workstation for each standard obstruction case and working case. The average uniformity ratio (minimum/average) over the task area for the working case (0.8) was similar to those measured using the randomly located standard obstructions (light case 0.89, medium case 0.86, and heavy case 0.77). There may, therefore, be potential for not only predicting light losses over the whole working plane, but also for giving some indication of likely task illuminance conditions.

The practical significance of the differences in light loss characteristics for the different types of luminaire may best be illustrated by an example. A heavily obstructed office (VFR=0.5) lit by diffusing or batten luminaires would have a predicted OL of 14%. The same installation lit by narrow reflector luminaires of a type typically used to light offices containing visual display terminals would have a predicted OL of 10%. Thus, if the installation is designed for an average working plane illuminance of 500 lux the predicted average losses would be 70 lux and 50 lux respectively. The magnitudes of the reduction in average working plane illuminance under these circumstances are large enough to cause user complaints as a result of local reductions in illuminance, and to cause the installation not to meet a design specification written in terms of maintained illuminance. It is clear that some method of incorporating this type of data into routine lighting design should be investigated.

On the evidence of the simulation and surveys of illuminance conditions within obstructed spaces it appears that the standard obstructions concept appears to have potential as a predictive tool for both overall light loss and task illuminance conditions for the working state of an installation containing obstructions. Standard obstructions have also been used for measurement of effective floor cavity reflectance[6].

3 Computer program validation

Computer programs are increasingly used for appraisal of proposed designs. With the many programs and algorithms available there is a need for a process of validation of the programs so that they may be used with confidence by designers. The validation process includes review of the underlying assumptions of the program, including data used, and also testing of programs using standard 'benchmark' data. Some work has already been done in this area to test programs based on the lumen method using as standard conditions an empty office lit by defined luminaires. The programs are

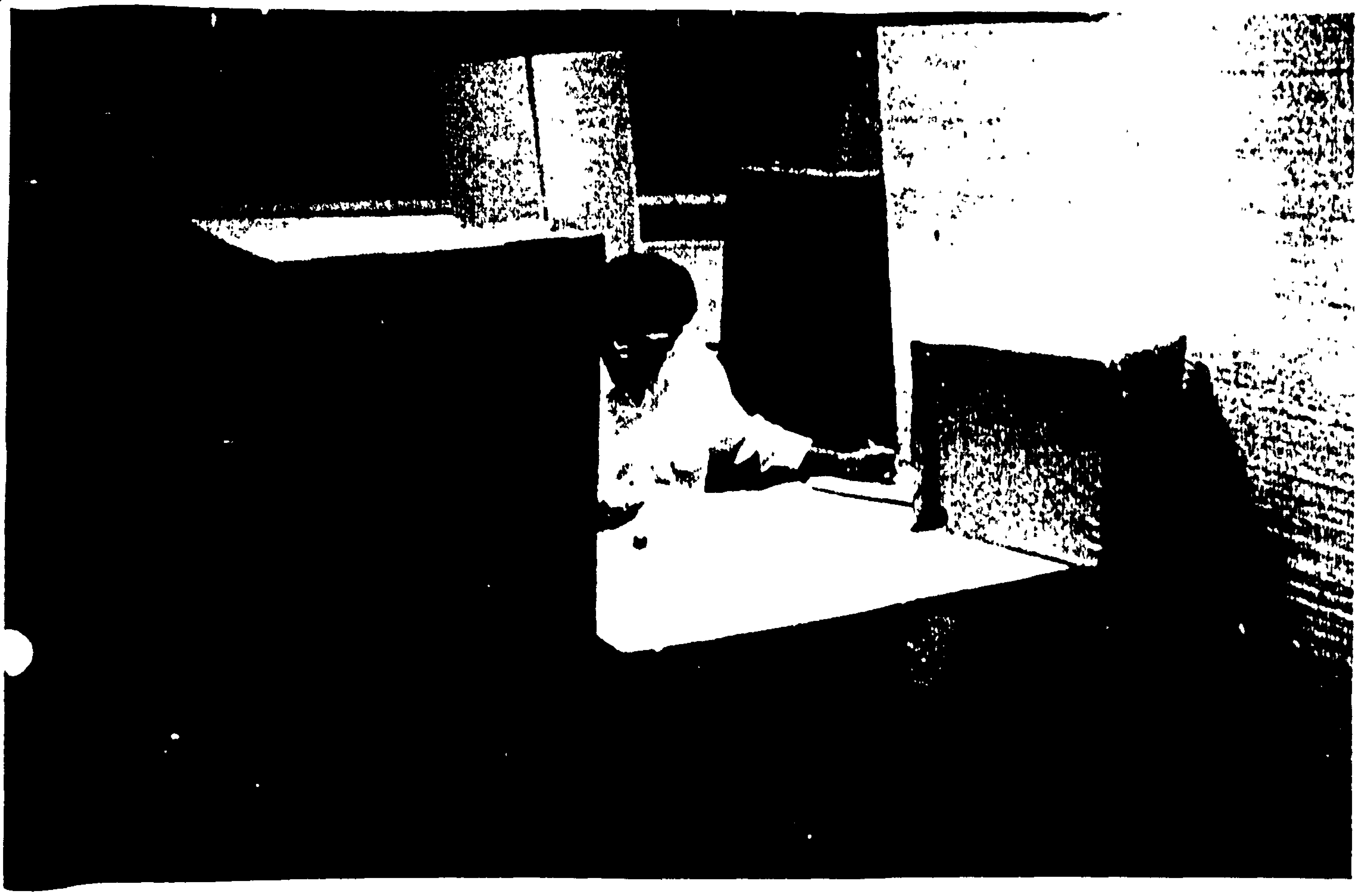

Figure 1 Standard obstructions used for measurement of light losses

evaluated against an acceptable range of limits of working plane illuminance parameters which acts as the main validation device[7]. The test models used to date have all assumed an empty space despite the fact that many programs are available which have the capacity to define internal surfaces such as partitions and to take account of these in the illuminance calculation process. There exists no standard data for internal obstructions for test purposes and the standard obstructions put forward in this paper are suitable for this purpose. Standard obstructions are simple enough to create using the orthogonal geometry systems that are in common use in lighting design programs yet are capable of being used to predict light losses caused by room contents.

4 Discussion

There is currently much debate within the Commission Internationale de l'Eclairage and elsewhere about the need for realistic assumptions in lighting design. It has been shown that the results produced using standard obstructions are capable of being used as a source of realistic design data for prediction of illuminance conditions with a working space. Whilst much work remains to be done in computer validation models it is arguable that the use of a test model which incorporates obstructions is of greater value in producing reliable practical design aids than the simple empty case models. This paper puts forward the standard obstruction configurations for both purposes.

References

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2 Carter D J and Bougdah H A lumen method for obstructed interiors *Lighting Res. Technol.* 24(1) 15–24 (1992)

3 Ratelli M R and Carter D J A designers guide for the electric lighting in obstructed interiors *Proc. 7th Lux Europa Congress, Edinburgh* Vol. 1 pp220–232

4 McEwan I and Carter D J A survey of lighting in obstructed spaces *Proc. 21st Session of Commission Internationale de l'Eclairage (CIE), Venice, Italy* Vol. 1 p226 (1987)

5 *CIBSE Code for interior lighting* (London: Chartered Institution of Building Services Engineers) (1994)

6 Cook G K and Hill S The influence of the floor cavity: a block to energy efficient lighting design *Proc. 2nd European Conf. on Energy Efficient Lighting Arnhem* pp823–837 (1993)

7 Bommel W J M and de Man M J G Test model for computer programs used in interior lighting *Proc. 7th European Lighting Congress Lux Europa, Edinburgh* Vol. 1 p462 (1993)

Discussion

G K Cook (University of Reading)

The authors of this paper are to be commended for addressing the need for a more accurate and usable method of quantifying the influence of obstructions above the working plane

Table 4 Summary of light losses for installations

Installation	Luminaire type	Obstruction type	VFR	Obstruction loss (OL) (%)
University teaching room	Diffuser	Light	0.1	4
		Medium	0.19	6.4
		Heavy	0.5	11.5
University teaching room	Surface modular louvred reflector	Light	0.1	1.3
		Medium	0.19	2.9
		Heavy	0.5	7.7
Luminaire manufacturer demonstration area	VDT Category 1	Medium	0.34	9.2
		Heavy	0.95	9.8
	VDT Category 2	Medium	0.34	12.8
		Heavy	0.95	17.0
	Recessed modular louvred reflector	Medium	0.34	15.8
		Heavy	0.95	19.0
Health authority general office	Recessed modular louvred reflector	Light	0.09	3.0
		Medium	0.21	7.0
		Heavy	0.47	12.0
		Actual	0.28	10.0
[illegible]rance company general office	Recessed modular louvred reflector	Light	0.12	0
		Medium	0.27	2.0
		Heavy	0.56	3.0
		Actual	0.57	11.0
Insurance company general office	Recessed modular louvred reflector	Light	0.12	0
		Medium	0.25	3.0
		Heavy	0.54	8.0
		Actual	0.34	8.0
Transport authority engineering office	Recessed modular louvred reflector	Light	0.1	0
		Medium	0.23	5.0
		Heavy	0.5	10.0
		Actual	0.64	12.0
Speculative office	Recessed modular louvred reflector	Light	0.12	1.0
		Medium	0.25	2.0
		Heavy	0.55	8.0
Speculative office	Recessed modular louvred reflector	Light	0.15	5.0
		Medium	0.31	5.0
Shipping company general office	Diffuser	Light	0.14	5.0
		Medium	0.30	12.0
		Heavy	0.66	20.0
		Actual	0.15	7.0

vorking plane illuminance. Although the advice concern-[illegible] obstructions given in Section 4.5.3.4 of the *CIBSE Code for Interior Lighting*[5] is useful, it does not offer a method of quantifying their effect.

The paper is focussed on commercial office accommodation, an interior which is well suited to the lumen method of artificial lighting design. There are many other obstructed interiors which remain to be investigated and these include interiors where significant differences in the type and orientation of obstruction apply, e.g. shops, hospitals and industrial interiors. This would also allow the VFR concept to be tested across a wider range of interiors, and also to compare the influence of other factors. Work is currently underway at Reading University which is concerned with quantifying the effect of the floor cavity on working plane illuminance[8].

The earlier work carried out at Liverpool and described in the paper provides for uniformity and an acceptable illuminance on the working plane of obstructed interiors. While recognising the obvious need for these requirements there is also a need to provide interest and variation for the occupants. These factors could be provided in some way by the obstructions which would then become factors in any wider assessment of lighting quality.

All of the luminaire types listed in Table 4 have significant DLORs. Uplighting has been provided in many offices and it would be interesting to compare the effect of standard obstructions under these conditions. Table 4 confirms the good agreement between four of the cases where VFR and OL was measured under working conditions. Has further work been carried out to identify the reasons for the significant differences in the remaining interior?

The need for 'benchmark' data in order to validate lighting design computer programmes is directly related to the work of CIE TC3-29 *Computer Calculations*. Is it proposed that the standard obstructions described in this paper should be adopted as a CIE standard? If so, it has not been made clear how the confidence limits of the site measurements could be defined. The relative simplicity of computer programme validation for unobstructed interiors has, with certain exceptions[9, 10], failed to provide the required accuracy necessary to produce a CIE standard.

References

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9 Slater A I, Wilkins J P and Stockmar A W A comparison of computer calculated lighting distributions and measurements *Proc. 21st CIE Session, Venice* Vol 1 pp198–201 (1987)

10 Egger W Comparison of computed and actual measured illuminances and CRFs *Proc. CIBSE National Lighting Conf.* pp 39–64 (1988)

The Revd Dr A R Bean

This paper describes a very useful piece of work and deals with a problem well known to lighting engineers. Until the advent of the computer the type of calculation required to determine the effects of obstruction was, in general, too time-consuming to be undertaken. The authors have demonstrated that it is now possible to deal with the problem of potential obstruction in a reasonable way.

However, lighting design is littered with many good ideas unused because of commercial pressure and anything which increases the number of luminaires required is not welcome in competitive tendering situations. It would need the specifier or consultant to ask for this modified method of calculation to be employed by all those tendering before it would find significant use.

Another aspect is the accuracy with which the recommended illuminances meet the real needs of the users of the space. In most situations 500 lux is very satisfactory for offices and the writer has found quite a few offices where 400 lux was considered good by the occupants. This was in spaces where VDUs, filing cabinets etc., were present, i.e. the lighting levels seemed already to take into account the normal types of office obstruction.

Perhaps the best thing, at the moment, would be to make adjustments only where heavy obstruction was expected and to assume that the lighter obstructions are accommodated for within the recommended average illuminance values.

This particular paper demonstrates the value of an ongoing programme of work which tackles a particular practical problem and proceeds steadily towards a solution.

Authors' reply to discussion

The authors thank the discussors for their contributions. We will attempt to answer their points in turn.

J K Cook

The authors agree that the problem of light losses caused by obstruction afflicts many types of building interior and not just offices. The VFR concept is useful for designers of lighting for any interior where the precise nature of the contents is unknown and for which the standard obstruction method enables reasonable design assumptions to be made

Regarding uplighting, the authors have undertaken one set of laboratory measurements to compare OL values for the same room lit in turn by VDT downlights, uplights and wall washers. The OL for the heavy obstruction cases were 1%, 10% and 5% respectively. These results follow the general pattern in that light from small downlight sources is not intercepted to the same degree by vertical obstructions as that from sources with more diffuse intensity distributions — in this case walls and ceiling. No field measurements have yet been made within an actual uplighter installation.

We have been unable to investigate the reasons for the poor agreement for the fifth case where VFR and OL were measured under working conditions because we have been unable to get further access to the building for security reasons.

We hope that in due course the standard obstruction could be adopted as part of the 'benchmark' data for a CIE standard. The field measurements used in the work to date have been performed to enable OL to be established for design purposes and their accuracy is probably not sufficient for validation of a standard. For this purpose laboratory photometric measurements of illuminance conditions in spaces with standard obstructions would be required.

The Revd Dr A R Bean

The authors agree that the work has commercial implications. It is our hope that the results will eventually find their way into codes where they will form the basis of recommendations for good practice which will be available to specifiers, consultants and clients.

Dr Bean's point about the effect on the occupants of a space of small percentage drops in average illuminance is well made and we agree that most of the user complaints encountered have been in the more heavily obstructed interiors. The other important aspect of this work are its implications, in a litigation-conscious world, for compliance with specifications, particularly those written in terms of maintained illuminance. The prospect of a client armed with a lightmeter is indeed a terrifying one!

MEASURED LIGHT LOSSES IN REAL INTERIORS

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This paper is concerned with measurement of the amount of light absorbed by room contents in commercial premises. The furniture, equipment and personnel that occupy a working office will cause light losses in terms of both local variation of illuminance uniformity across working areas and an overall reduction in average working plane illuminance. This problem has been investigated in simulation studies which have put forward theoretical values of light absorption but little work has been undertaken to measure light absorption. A series of photometric surveys of illuminance within modern office buildings are described which were undertaken firstly in the empty spaces; secondly, furnished with simulated 'standard obstructions'; and thirdly, in their working state. The installations were selected so as to include examples of common types of luminaire, and different types of room furniture system. The results show typical magnitudes of light loss and give an insight into the relative importance of the various parameters that influence light absorption - notably obstruction type and size, and luminaire type. The influence of the results on current design practice are indicated.

INTRODUCTION

Traditional lighting calculation methods assume a clear room volume without allowance for light losses caused by room contents. Whilst this clear space approximation permits sophisticated means of calculating luminaire spacing to height ratio and average working plane illuminance the lack of realism in the outcome has become an increasing concern within the international lighting community (1). Recent developments in lighting equipment, prompted by the visual problems of VDTs and the pressure to increase energy efficiency tend to increase the risk of obstruction losses. Much use is now made of mirrored and louvred luminaires, designed for use at wider spacings, whose directional lighting characteristics mean that areas of the working plane remote from luminaires are particularly prone to shadows caused by room contents. Additionally, proposed changes in lighting design standards involve specifying 'maintained illuminance' at the task - the minimum average illuminance at which maintenance must be carried out - which exposes the deficiencies of the current lighting design methods and enables installations to be more easily checked for compliance with a performance specification.

Lighting is arguably the only major branch of building services where the design process is undertaken making no allowance for building occupancy. The most common technique of lighting design worldwide is the 'Lumen' or' Zonal Cavity' method which enables an average illuminance to be provided over the horizontal working plane of an empty interior whilst attempting to limit the variation of illuminance by control of the spacing of luminaires (2). In practice, although the uniformity of illuminance on an unobstructed working plane may be satisfactory, room contents may cause areas of shadow and light loss which may influence visual performance,worker morale and, in extreme cases even safety. The work described in this paper indicates the magnitude of light losses caused by internal obstructions in a number of real building interiors and the way in which this information may be used by a designer of general lighting systems is indicated.

PREDICTION OF OBSTRUCTION LIGHT LOSSES

The two main approaches to prediction of light losses have been either computer simulation or field measurement.

<u>Computer simulation</u>
In recent years computer based methods of analysis of illuminance conditions within building interiors have been developed including some that are capable of modelling obstructions. These analysis methods use variously, finite element, Monte Carlo simulation, or ray-tracing techniques, and a number have visual simulation output capability. They are however of limited use in practical lighting design since the input data for the room contents is unlikely to be available when lighting design is undertaken. Work at Liverpool University has recognised the need for a general representation of light loss caused by building contents using only information available at the early design stage (3). To this end a procedure has been developed for design of general lighting installations which is capable, firstly, of spacing the luminaires at an appropriate distance to overcome the anticipated effects of obstructions on illuminance uniformity and, secondly, to take account of the likely light losses caused by obstructions.

The first part of this procedure is a modification to the spacing to height ratio (SHR) calculation which enables the designer to space the luminaires at an appropriate distance to allow illuminance uniformity to be maintained in areas containing "standard obstructions" which are representative of the range of room contents in commercial interiors. These consist of a desk surrounded variously by human form, filing cabinets and partitions. The computer based technique permits the calculation of a modified SHR for any luminaire appropriate to the size and shape of the obstructions that are likely to be placed in the space. A lumen method calculation is then possible using a modified SHR (SHROBS) selected by the designer as being appropriate to the interior being considered. The light loss over the working plane has been investigated using a computer program which enables illuminance conditions for specific combinations of room size, room contents and light source to be determined. This was used to calculate the Obstruction Loss (OL), the percentage reduction in average working plane illuminance caused by obstruction, for a limited range of interiors lit by point or linear source luminaires. In addition for each interior the ratio of obstruction vertical surface area to floor area (VFR) was calculated. This has been shown to be the most convenient and reliable measure of obstruction density (3,4). For the limited sample of installations investigated it was demonstrated that prediction of light losses in obstructed interiors based on a knowledge of the contents was feasible and that luminaires could be grouped into broad generic groups each of which had similar light loss characteristics over a range of practical room sizes and room surface reflectance. Some typical predicted values extracted from Reference 5 are given in Table 1. The design process would then proceed in an orthodox manner using OL as a multiplier to Utilisation Factor to ensure acceptable average working plane illuminance and SHROBSMAX as luminaire spacing criterion to ensure acceptable working plane illuminance uniformity

Field measurement

Photometric surveys have been undertaken by a number of researchers to investigate both lighting conditions in particular furniture configurations or overall light loss within a furnished space.
The surveys reported by Briggs (6) were primarily intended to as the basis of a new NAIES calculation technique for predicting illuminance levels in spaces equipped with cellular partitions. Siminovitch et al (7) analysed the reduction in working plane illuminance due to a number of different work station geometries using scale model of office interiors. The results indicated local light losses on task areas of up to 70%. Kajima et al (8) and McEwan and Carter(4) reported the results of surveys of measurements across the whole working plane of modern offices in empty and furnished conditions. The former reported losses of 20% in one room, the latter losses of between 8 and 10% in four different installations but in both cases details of the room and its equipment were not included or the reasons for the losses explained.

Losses of the magnitudes quoted above have clear implications for the lighting designer particularly when using the maintained illuminance concept. Surveys to investigate losses are however time consuming and are only able to address a limited range of geometric and photometric variables. Computer simulation overcomes this problem but designers need to be confident that data produced in this way is capable of representing real conditions.

PHOTOMETRIC SURVEYS

Any modification to lighting design methods to take account of obstruction depends critically on the assumptions made. The Liverpool proposal is based on calculated values of OL for installations assumed to be occupied by Standard Obstructions. To date no attempt has been made to measure light loss due to Standard Obstructions to enable comparison to be made with the calculated values or to relate them to losses in actual interiors. Measurements of these values are thus important for three reasons. The first is to add to the sparse information on the magnitude of losses in commercial buildings. The second is the need to verify that the simulated and measured values of OL are of the same magnitude, and the third is to check whether illuminance conditions in actual installations in their working state can be replicated using the various "Standard Obstruction" configurations.

The surveys investigated illuminance levels in a range of interiors that contain lighting equipment that is representative of good modern practice. Two of the installations were equipped with surface mounted diffusers and two with luminaires specifically for areas with VDTs. The rest of the installations were lit using surface mounted or recessed wide distribution reflector luminaires with either wedge or cross-blade louvres and which are classified in the CIBSE Code (9) as "surface modular" or "recessed modular". The surface reflection factors for all installations were within the CIBSE Code recommendations. The measurements are made in the installations firstly in their empty state, secondly filled with 'Standard Obstructions', and finally in their working state after occupation by the building users. This paper reports results for 14 installations and it is planned that a large number of additional installations will be surveyed over the period of the research.

Standard Obstructions

In general lighting terms an obstruction is defined as an object which is between the luminaire plane and working plane.

In an office this can be taken as:

a) Visual display units
b) Filing and storage cabinets
c) Panels and screens used for dividing offices into work stations.
d) Users of the office when seated at desks.

Previous work at Liverpool addressed the problem of the size and configuration of the elements of office obstruction set out above. A series of" light", "medium", and " heavy " standard obstructions were put forward to represent the range of obstruction density in office interiors. The standard obstructions were developed from analysis of data on office furniture provided by two major office equipment manufacturers. The sizes of the standard obstruction elements to be used for the calculation of OL and for the photometric surveys are shown in Table 2. Figure 1 illustrates the Standard Obstruction configurations.These are:
Light standard obstruction -Person + Desk + VDU
Medium standard obstruction -Person + Desk + VDU + Filing cabinet
Heavy standard obstruction -Person + Desk + VDU + Filing cabinet + Partition
Floor area per standard configuration is 12 square metres

These standard obstructions can be used to represent obstruction densities having ratios of vertical surface area to floor area (VFR) from O to 0.5. Typical values of VFR for modern office buildings were within the range 0.22 to 0.57 and thus the standard obstructions should be capable of simulating obstruction densities within most working interiors. For purposes of the surveys were constructed of painted cardboard, polystyrene, wood and are designed for easy transport in small sections

Survey locations
Getting access to suitable installations for measurement purposes is a major task. The problem is not only one of selecting suitable installations in terms of size and equipment but also one of persuading the building designers, owners, and users to allow access at the various stages of the surveys. Information on the installations is given below and in Table 3.
Installations 1 to 4
General purpose room located in the University of Liverpool. 7.7m by 6.8m by 3.0m high, furnished with four standard obstructions only. Lit by a regular array of 3 x 3 ceiling mounted luminaires, switched such that two luminaire configurations could be used with different SHRtransverse- 0.89 and 1.79. Two different luminaire types were used; a prismatic base, opal sided diffuser and a modular louvred reflector luminaire.
Installations 5 to 7
A demonstration area owned by a luminaire manufacturer 9.5m by 6.8 by 2.7m high. Only half of the room was used for measurement and each half was furnished with four standard obstructions. Each half could lit in turn by regular arrays of three different types of luminaire - LG3 CAT1, LG3 CAT3, and recessed modular reflector all having SHRaxial of 1.2 and SHR transverse of 0.75
Installations 8 and 9
A medical records centre and general office equipped with recessed modular louvred luminaires. Installation 8 was 9.3m by 5.6m by 2.6m high and lit by a regular array of 2 x 3 luminaires and furnished with 4 standard obstructions. Installation 9 was 8.4m by 8.5m by 2.6m high, lit by a 3 x 3 grid of luminaires and was furnished with 6 standard obstructions. Installation 8 is a medical file/record store equipped with three 2m high by 3m long file stacks and Installation 9 is a general office. Working plane illuminance measurement was also recorded for the working condition.
Installations 10 and 11
The rooms surveyed were representative sections of large open plan offices of an insurance company. The section of the room in Installation 10 was 7.2m by 13.1m by 2.7m high and and in Installation 11 a 11.2m by 8.9m by 3.1m high section of the room was used. In both cases 10 standard obstructions were used and measurements were also made for the working condition. Installation 10 was lit by a regular array of 7 x 3 recessed modular reflector luminaires. Installation 11 was lit by a regular array of 3 x 3 surface mounted modular luminaires suspended from the timber trusses at 3.8m centres below a white plastered ceiling void.
Installation 12
A ground floor office suite measuring 13.5m by 7.4m by 2.75m high lit by a regular array of 6 x 4 flush mounted modular luminaires. The room was furnished by 9 standard obstructions and contained two large supporting columns.
Installations 13 and 14
The rooms were part of a show suite of a new office development. Installation 13 was a 9m by 4.5m by 2.8m high section of the main open plan office area, and installation 14 was a smaller (5.45m by 5.9m by 2.8m high) adjoining conference room. Both installations were lit by a 1.5m square array of recessed profiled reflectors with a 24w PL lamp. The installation was used as a show suite and therefore could not be surveyed in the actual working conditions. Four Standard Obstructions were used in each space.

Survey methods
The first part of a survey consists of gathering physical photometric details of the room and its lighting equipment. Each survey consists of measuring horizontal working plane illuminance on a square grid of points (usually 0.5m centres) over the whole room empty, again when furnished with the various standard obstructions, and finally, in its working state. All daylight is excluded during measurement. A cosine and colour corrected photocell is mounted on a tripod and positioned over grid points at desk top height (approx. 0.7m above floor). The average working plane illuminance was calculated as the area weighted arithmetic average of the grid point illuminance. The obstruction loss (OL) was calculated as the percentage reduction in average working plane illuminance and is shown in Table 3.

DISCUSSION OF RESULTS

The results for all installations show the same general pattern in that OL rises as VFR increases. The average OL values over all the measured installations of 1.8% for Light Standard Obstruction, 6.2% for Medium Standard Obstruction, and 11.8% for Heavy Standard Obstruction are in good agreement with the the predicted results shown in Table 1. It thus appears that the methods of simulation and prediction of light losses for obstruction described earlier could be the source of realistic design data for actual interiors.

The different luminaires used have varying propensity for light loss for similar degrees of obstruction. It is apparent from the results from Installations 1 to 4 that the diffusing luminaires have higher OL for a given VFR than the Modular Louvred luminaires, and similarly that the LG3 CAT 3 and Modular Louvred luminaires have higher light losses than LG3 CAT 1. The reason for this is presumably that light from luminaires with direct light distributions is not intercepted to the same extent by vertical obstruction than that from luminaires with pronounced sideways intensity distributions.

There is some evidence that OL varies with SHR. The results from Installations 1 to 4 indicates that higher OL values occur when the luminaires are spaced near to their SHRMAX and that underspacing the luminaires substantially reduces obstruction light loss. Installations 13 and 14, which are equipped with a large number of small lumen output luminaires installed at well below their SHRMAX, have very low OL values.

e magnitude of OL for Installations 5,6,7 and 8, is higher than for the others and a number of factors may cause this. is unlikely that the luminaires account for the differences since the Installations 7 and 8 are photometrically similar to the other Modular Louvred luminaires, but give very different results in terms of OL. Rooms 5 to 7 are however smaller than the rest of the installations and the smaller floor area/workstation gave higher VFR values. Additionally Installation 8 contains the medical record racks. There was thus not only more obstruction in these rooms to intercept light but also a greater proximity of the room wall surrounding each work station which also served to absorb light. Luminaires in installations 5 to 7 were all underspaced and it is conceivable that the OL values could have been higher had they been spaced near their maximum SHR. On the other hand those rooms with Room Indices of greater than 2(Installations 9 to 12) generally had lower than average values of OL.

The range of VFR values created for the measurements ranged from 0.1 to 0.95 (with the exception of Installation 8). Results of the surveys of modern office buildings cited earlier indicated that typical values of VFR for room contents ranged from 0.22 to 0.57 when calculated on the same basis and hence the measurements could be considered to be made under conditions that ranged from the current design condition of an empty room, through that of the actual finished state for a typical office, to that of a grossly over obstructed space which is unlikely to intentionally occur in a commercial building but which could occur in an industrial environment. On the limited evidence of four surveys it may be concluded that the VFR and OL for offices in their working state could best be represented by the Medium Standard Obstruction. OL values up to 15% might reasonably be expected in commercial interiors given a particular combination of luminaire and contents. Losses of this magnitude have clear implications for the lighting designer when trying to meet a specification written in terms of average working plane illuminance.

CONCLUSIONS

would be foolish to attempt to draw up general rules based on the results of a limited number of surveys but the results of the work do point to some tentative conclusions. The range of the magnitude of the measured values are generally similar to those of the predicted values produced using the Liverpool simulation programs. Simulation of design data for real interiors is thus feasible. The major factor influencing OL is size and density of obstructions. Luminaire type is the next most important influence but there are differences in performance between types of luminaire in obstructed interiors. Large rooms generally have smaller values of OL than small rooms. The maximum influence of obstructions on OL is when luminaires are spaced near their SHRMAX and light loss can be reduced by underspacing the luminaires. It may be tentatively concluded that Medium Standard Obstructions are capable of replicating illuminance conditions in office interiors but work is continuing to confirm this.

ACKNOWLEDGEMENT

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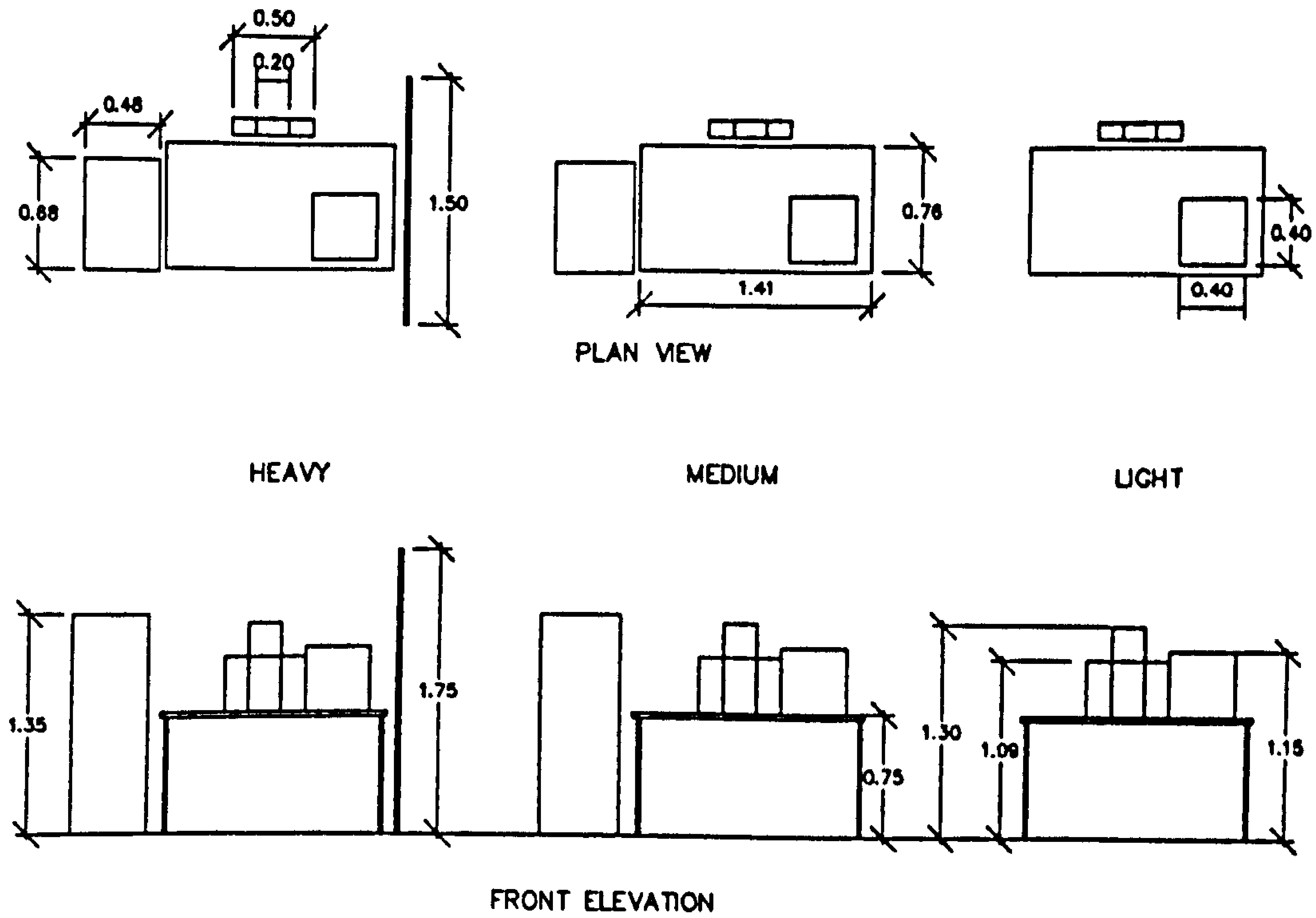

Figure 1 Layout of Standard Obstructions

Element	Length (m)	Width (m)	Height (m)	Vertical Surface Area (m2)	Reflectance
Filing Cabinet	0.64	0.48	1.35	1.34	0.3
Partition	1.5	0.025	1.75	3.06	0.6
V.D.U.	0.4	0.4	0.4	0.64	0.3
Person - head	0.1	0.2	0.55	0.53	0.3
- body	0.1	0.5	0.34		0.4
Desk	0.76	1.41	0.75	N/A	0.3

Table 2 Details of Standard Obstructions

	Degree of Obstruction		
	light V.F.R. = 0.1	medium V.F.R. = 0.25	heavy V.F.R. = 0.45
Diffuser	2.5%	7%	14%
Wide Distribution Reflector	2%	5%	11%
Narrow Reflector	1.5%	5%	10%

Table 1 Some typical predicted values of OL for installations with linear luminaires installed near SHRMAX.

Installation	Type of Luminaire	Room Index	SHR Transverse		Obstruction Type and V F R		Obstruction Loss (OL %)
			Maximum	Actual			
1	Diffuser	1 6	≈1 7	0 89	light	0.1	1
					medium	0 19	3 8
					heavy	0 5	7 7
2	Surface Modular Louvred Reflector	1 6	1 8	0 89	light	0 1	1 2
					medium	0 19	3 7
					heavy	0 5	7 0
3	Diffuser	1 6	≈1 7	1 79	light	0.1	4
					medium	0 19	6 4
					heavy	0 5	11 5
4	Surface Modular Louvred Reflector	1 6	1 8	1 79	light	0 1	1 3
					medium	0 19	2 9
					heavy	0 5	7 7
5	VDT Cat 1	0 9	1 26	0 75	medium	0 34	9 2
					heavy	0 95	9 8
6	VDT Cat 3	0 9	1 67	0 75	medium	0 34	12 8
					heavy	0 95	17 0
7	Recessed Modular Louvred Reflector	0 9	1 62	0 75	medium	0.34	15 8
					heavy	0 95	19 0
8	Recessed Modular Louvred Reflector	1 8	1 87	1 6	light	0 11	4 0
					medium	0 23	8 0
					heavy	0 53	14 0
					actual	1 64	30 0
9	Recessed Modular Louvred Reflector	2 2	1 87	1.6	light	0 09	3 0
					medium	0 21	7 0
					heavy	0 47	12 0
					actual	0 28	10 0
10	Recessed Modular Louvred Reflector	2 3	1.25	1 1	light	0 12	0
					medium	0 27	2 0
					heavy	0 56	3 0
					actual	0 57	11 0
11	Recessed Modular Louvred Reflector	2.1	1.25	1 0	light	0.12	0
					medium	0 25	3 0
					heavy	0 54	8 0
					actual	0 34	8 0
12	Recessed Modular Louvred Reflector	3 6	1 25	1.0	light	0.10	0
					medium	0.23	5 0
					heavy	0 50	10 0
13	Recessed Modular Louvred Reflector	1 3	1.7	0.8	light	0.12	1 0
					medium	0.25	2 0
					heavy	0 55	8 0
14	Recessed Modular Louvred Reflector	1 2	1 5	0.8	light	0.15	5 0
					medium	0 31	5 0

Table 3 Summary of installations and results

A LIGHTING DESIGN METHOD FOR NON-EMPTY INTERIORS

D J Carter, A S M Leung, M J Lupton

ABSTRACT

The lumen method is the most popular design tool used for interior general lighting schemes due to its simplicity, economy and ready availability of design data. This paper puts forward proposals for modifying the existing procedure to enable the designer, to take account of the consequences of the likely average light losses caused by obstructions.

LA CONCEPTION D'ÉCLAIRAGE POUR LES INTÉRIEURS ENCOMBRÉS

RESUME

La méthode "Lumen" est la plus courante des moyens de conception utilisés dans la préparation des installations d'éclairage intérieur général à cause de sa simplicité, son économie et la disponibilité des donnees de conception. Cette publication propose des modifications à la méthode actuelle qui permettent au ingénieur de conception de considérer les conséquences des déperditions moyennes de lumière probables dues aux encombrements.

METHODE FÜR BELEUCHTUNGSENTWÜRFE FÜR VERSTELLTE INNENRÄUME

ZUSAMMENFASSUNG

Die Lumenmethode ist das beliebteste Entwurfverfahren für allgemeine Innenbeleuchtungseinrichtungen wegen ihrer Einfachheit, Sparsamkeit und der leichten Verfügbarkeit von Entwurfdaten. Dieser Artikel schlägt Änderungen für ein schon entwickeltes Verfahren vor, die es dem Beleuchtungsplaner ermöglichen sollen, die Auswirkungen der wahrscheinlichen Beleuchtungsverluste durch Verbauung zu berücksichtigen.

KEYWORDS

Calculations, interior lighting, light loss, lighting design and specification,office lighting

1 INTRODUCTION

Arguably the most significant failing of lighting design methods in current use is the assumption that interiors are empty. The lumen method is the most used lighting design method worldwide due to its simplicity, ready availability of design data, and economy of designers time. This paper presents a modified lumen design method that takes account of the likely light losses under working conditions caused by the contents of a room. In office buildings these may include furniture or partitions which project above the working plane and cause the actual illuminance levels in the space to be lower than those predicted using the "empty room" assumption.To overcome this the modified lumen method includes a multiplier to the Utilisation Factor, called the Obstruction Factor, which increases the installed flux to compensate for light absorbed by typical room contents. The Obstruction Factor data is general enough to acknowledge the range of luminaire types, room sizes and obstruction configurations likely to be found in practice, and is in a form suitable for design use.

2 LIGHT LOSS ANALYSIS

2.1 Background to the work

The relationship between average light loss over the working plane and the various parameters of general lighting installations have been investigated using both computer simulation[1] or photometric survey[2]. The results indicated that some parameters have a greater effect than others. Specifically density of obstructions had the largest effect followed by that of variation in luminaire type. Variation of room and obstruction surface reflectance had a negligible effect on total light loss. The effect of room size was shown by survey results to be influential. The density of obstructions - size and disposition - was quantified by expressing the vertical surface area of furniture and other room contents above the working plane as a ratio of the floor area of the room, a ratio termed the Vertical surface area to Floor area Ratio - VFR. It was further established that luminaires having the same physical and photometric properties had a similar relationship between obstruction density in terms of VFR and obstruction light loss (OL) the percentage reduction of average working plane illuminance in an obstructed space to that in the same space in an empty state. Light losses for photometrically different classes of luminaire, on the other hand, varied considerably. In general diffusing luminaires exhibited consistently higher losses than more direct luminaire types.

2.2 Data generation

The previous work indicated that luminaires could be grouped into broad generic groups each of which have similar light loss characteristics and that the same OL/VFR relationships held for that group over a range of practical room sizes and room surface reflectance. This pointed the way to reducing the almost infinite number of data sets associated with the vast range of commercially available luminaires into a compact body of knowledge suitable for design purposes. Light loss data was generated using a computer program previously developed at Liverpool to calculate average working plane illuminance in a series of installations of different sizes and degrees of obstruction lit in turn using examples from the luminaire generic groups[3].

The selection of generic luminaire groups, each having similar physical and photometric characteristics, was made using the classification in the CIBSE Code for Interior Lighting, section 3.3.2. "Luminaire characteristics" (4). Sixteen categories of interior luminaire were identified using this method and a selection of examples for each category from four multinational manufacturers was made. Care was taken to ensure that the luminaires selected from each category had similar luminous intensity distributions and spacing characteristics. The empty interiors were designed using conventional lumen design techniques. The obstructed interiors were fully occupied by 'Standard Obstructions' and lit by the various luminaires spaced according to conventional spacing to height ratio rules. The standard obstructions represent workstations made up of a desk surrounded variously by human form, VDT, filing cabinets and partition. A series of 'Light', 'Medium' and 'Heavy' standard obstructions have been put forward to represent the range of obstruction density in offices[5]. The standard obstructions used to represent the room contents in the calculations give a VFR range from 0 (empty) to 0.70 (Heavy case standard obstruction), these being representative of the range of obstruction conditions in modern commercial office buildings. A typical room configuration is shown in Figure 1. The data was produced for the full range of room index over which Utilisation Factor is calculated - that is up to room index 5. The calculation of OL for the various installations involved permutations of room index, VFR, and luminaire type. For each luminaire type modules of floor area of 8, 10, and 12 square metres each containing a Light, Medium, or Heavy standard obstruction were created to give a range of VFR from 0.15 to 0.7. The modules were then combined into "rooms" of different sizes to vary room index over the range 1 to 5. A macro program was used to run the program for each combination of modules to generate OL/VFR data for the 16 classes of luminaire (7644 cases).

2.3 Results

The results were plotted as graphs of OL/VFR for the various luminaires for all room indices and an example is given in Figure 2. The data was processed by linear regression techniques which assumed a true zero and the results of this analysis confirmed that a straight line passing through the origin could be fitted to the data with measures of fit (r squared) of the order of 0.98. The greater the slope of the graph the greater the value of OL for a given value of VFR and hence the greater the propensity for light loss. The slopes of the graphs for the different types of luminaire vary considerably with the bare batten types having the highest losses. The graphs for the luminaire types equipped with louvre systems (those suitable for VDT locations; and recessed modular luminaires with louvres) indicate that these luminaires have the lowest losses. The reason for this is that light from luminaires with direct light distributions is not intercepted to the same extent by vertical obstruction than that from luminaires such as battens which have a pronounced sideways intensity distribution. The rest of the luminaires which have a OL/VFR slope between the extremes of battens and VDT are semi direct luminaires that have a degree of optical control using prismatic controllers, painted reflectors, or recessed modular luminaires. The slopes of the graphs also varied with room index for some conditions.

3. USE OF RESULTS IN LIGHTING DESIGN

The light loss simulation produced too large a data set to be directly useful for practical design purposes. A number of alternative methods of producing a compact body of data capable accounting for different light loss characteristics of luminaires in rooms of different sizes were investigated. The solution was to plot the slope of the OL/VFR graph (m - the obstruction loss characteristic) for the luminaire groups as a function of room index and luminaire spacing, the former accounting for room size and the latter being dependent on the photometric characteristics of the luminaires in the group. Figure 3 shows the data in this manner with room index plotted on the Y axis and luminaire spacing on the X axis in terms of CIBSE SHR [6]. The SHR data used to plot Figure 3 was calculated as the arithmetic average of the maximum values of SHR for the actual luminaires used from each classification group used in the simulation. Ideally design data should be easy to understand and simple to use if mistakes and misunderstandings are to be avoided and the proposed method of presentation of data achieves this. At the first stage the designer would decide the illuminance level and luminaire type. Next the designer is required to either calculate or estimate VFR for the proposed installation. This is done by expressing the vertical surface area of furniture and other room contents above the working plane as a ratio of the floor area of the room. Where there is little information on the ultimate use of the room default values of VFR may be assumed. For example for most office interiors in the UK which do not contain cellular dividing partitions a value of 0.35 may be used, the value for the medium standard obstruction. Finally using the maximum permitted luminaire spacing and room index for the proposed installation the value of m can be read off Figure 3 and the Obstruction Factor calculated as follows:

$$\text{Obstruction Factor} = (1 - (\text{VFR} \cdot m)/100).$$

This may then be used in the lumen method as a multiplier to the Utilisation Fac`··

4. COMPARISON OF RESULTS WITH SURVEY MEASUREMENTS

A limited amount of photometric survey data from installations in their actual working state was available from Reference 2 for comparison with predictions made using Figure 3. Table 1 summarises the measured and predicted data and it is clear that the agreement is good.

5. CONCLUSION

This work has developed an easily implemented method of prediction of light loss data for a representative range of interior luminaires for installations of different sizes and with varying degrees of interior obstruction. There is encouraging evidence that the results of the survey and simulation work give similar results. A format for this data for design purposes has been developed and the design method is currently being field tested.

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Installation	Obstruction Loss (%)	
	Predicted	Measured
Health authority general office	10	11
Insurance company general office	11	14
Insurance company general office	8	8
Transport authority engineering office	12	16
Shipping company general office	7	5

Table 1: a) Comparison of measured and predicted results.
b) Vergleich von gemessenen und berechneten Ergebrissen.
c) Comparaison entre les résultats mesurés et les prédictions.

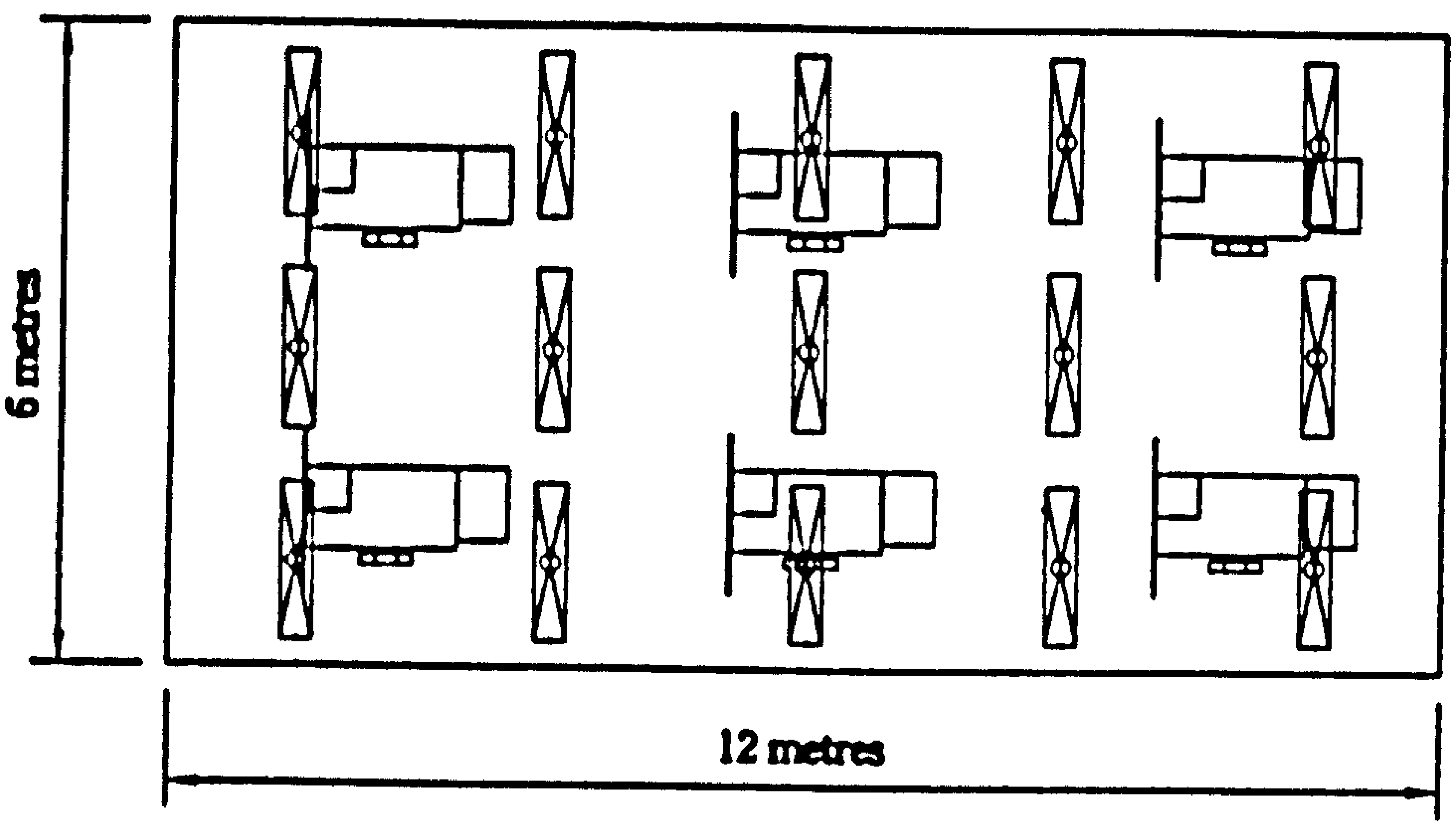

Figure 1 a) Typical room configuration made up of six 4m by 3m modules lit by 15 luminaires.
b) Typische Zimmergestalt, aus sechs 4 x 3 m² Elementen gebaut und mit 15 Beleuchtungskörpern ausgestattet.
c) Composition typique d'une pièce éclairée à quinze luminaires, construite de six modules de 4 mètres sur 3.

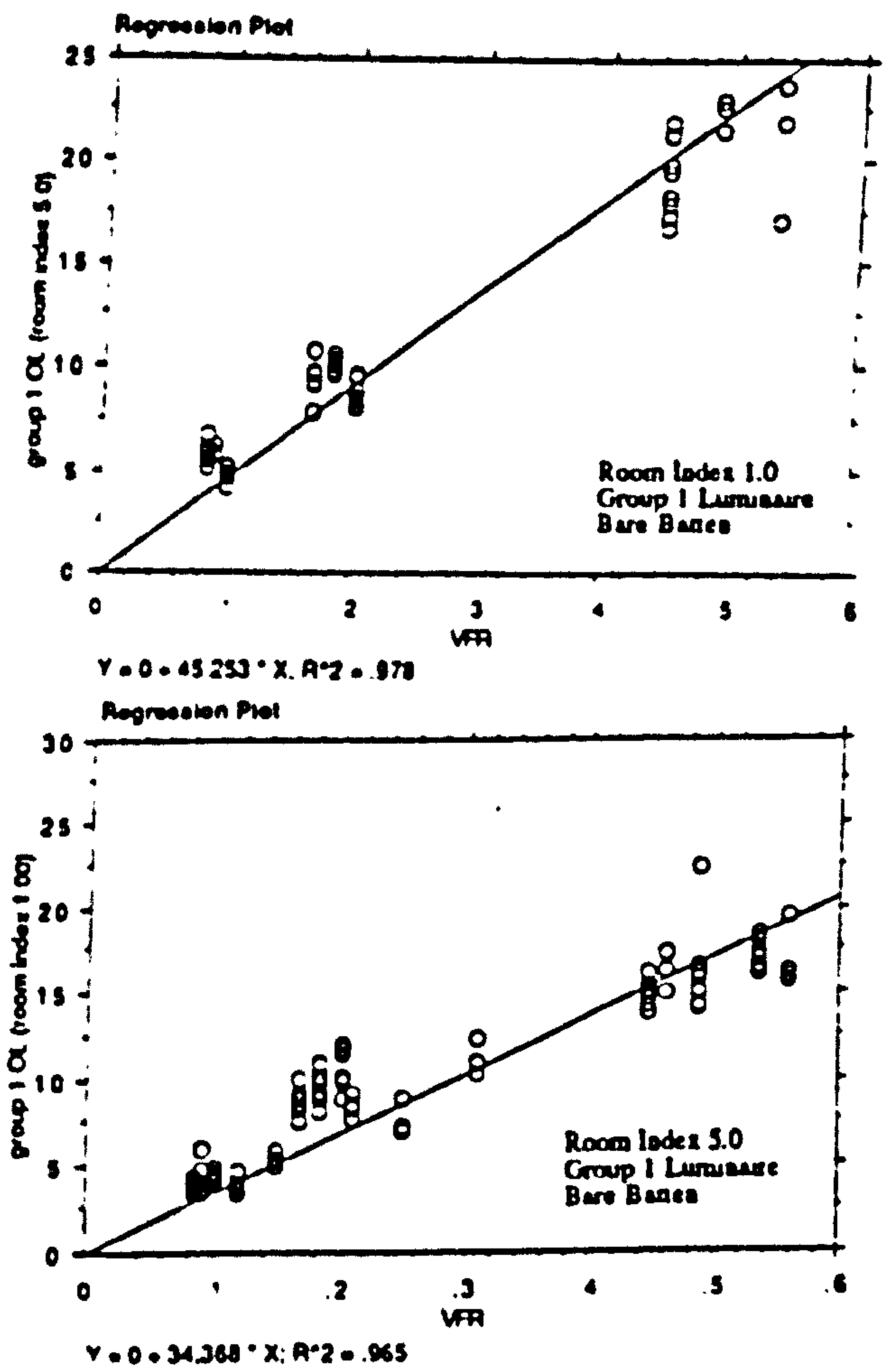

Figure 2 a) Example graphs of OL/VFR data.
b) Beispielsgraphe von OL/VFR Daten.
c) Exemples des graphiques des données OL/VFR.

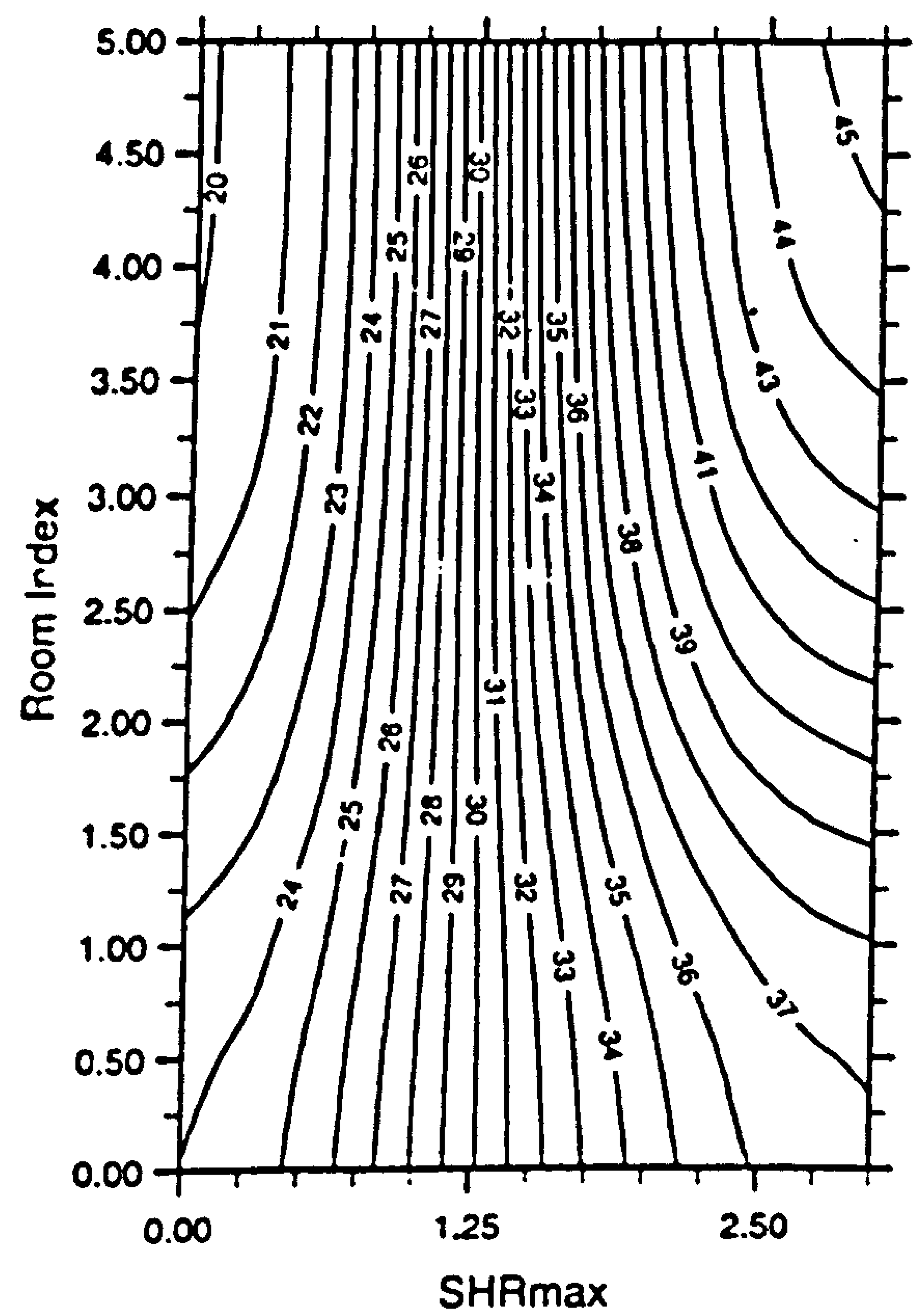

Figure 3 a) Obstruction loss characteristic as a function of room index and luminaire spacing.
b) Versperrungsverluste als funktion des Zimmerindexes und des Beleuchtungskörperabstandes.
c) Déperditions dues aux encombrements montrés comme fonction du indice d'une pièce et d'espacement des luminaires.

Advances in lighting design methods for non-empty interiors

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Summary

Traditional lighting design techniques assume an empty room despite the fact that room contents such as equipment, furniture or machinery may adversely influence illuminance conditions within an interior. The last decade has seen a considerable research and development effort to produce tools and guidance for designers seeking to produce lighting solutions for non-empty interiors.This paper reviews the many advances that have been made, including the now widely available computer based design methods, and summarises the design guidance promulgated on the subject in the major codes and standards. A number of limitations in the existing work are identified and areas of necessary future development identified.

1 Introduction

Traditional lighting design techniques assume an empty room despite the fact that interiors will contain obstructions such as equipment, furniture or machinery which may adversely influence illuminance conditions. A paper in this journal some ten years ago reviewed the subject of the treatment of obstruction in interior lighting design (1). The work on the subject at that time consisted of a limited number of photometric surveys of installations, some hand calculation methods based on empirical data and simulation of installations based mainly on finite element computing techniques. In general the simulation methods were analysis tools for specialist applications and research and as such were neither suitable for, or available to, practising designers. The hand calculation techniques were similarly limited in their range of application and were mainly used for particular design problems such as offices equipped with cellular partitions.

In the last ten years there has been much work in the subject area. Recent developments in lighting equipment prompted by the need for energy conservation, or to address the problems of lighting areas equipped with VDTs, have tended to increase the potential problems caused by obstructions. A considerable amount of research has been undertaken in many parts of the world and a range of design tools have been developed that acknowledge, and attempt to overcome, the problems of lighting interiors containing significant amounts of interior obstruction. Most of the new design methods are based on computer software and the wider availability of computer technology to designers in the various sectors of the lighting and building services industry has meant that the subject is of concern to a wider audience than a decade ago.In addition a number of codes and standards now seem to recognise that the problem exists and offer a variety of guidance.

This paper reviews the many advances that have been made over the last decade in the 'quantitative' approaches of modelling of obstructed spaces, namely computer based design methods, measured photometric data and empirical design methods.'Qualitative' aspects of visual conditions in obstructed spaces are identified. In addition the design guidance promulgated on the subject in the major codes and standards is summarised. A number of limitations of existing work and areas of necessary future development are identified.

2 Codes and Standards

The problems caused by obstruction did not feature greatly in lighting codes and standards until comparatively recent years except in the case of specialist applications. The guidance on the design of library lighting, for example, makes recommendations regarding the siting of luminaires relative to shelving systems and recommends the use of local lighting to make good deficiencies in illuminance provided by the general lighting system (2). A number of recent developments have forced the producers of Codes to address the problem. Much use is now made of mirrored and louvred luminaires, designed for use at wide spacings, whose characteristics mean that light will be directed at relatively flat angles of incidence to areas of the working plane remote from luminaires. This will cause shadows from any room contents. Additionally, changes in European lighting design standards involve specifying 'maintained illuminance' at the task - the minimum average illuminance at which maintenance must be carried out - which exposes the deficiencies of the current lighting design methods, which are largely based on the 'empty room' assumption, and enables the resulting installations to be checked for compliance with a specification. This section outlines the guidance on the subject set out by the various major lighting authorities.

2.1 Chartered Institution of Building Services Engineers

The CIBSE Code for Interior Lighting (3) notes that local reductions in illuminance will be caused if large objects of furniture or equipment project substantially above the working plane and contains a general warning about the inadvisability of spacing luminaires at or near maximum under such circumstances. In its section on design, the use of the lumen method for empty rooms is described. It is pointed out that 'absorption of light by room contents such as furniture and equipment may reduce the achieved illuminance on the working plane' but apart from two references does not elaborate in quantitative terms.

The CIBSE Lighting Guide 7 'Lighting for Offices' (4) contains a paragraph on the subject. It makes the point that most of the problems in offices are encountered after occupation due to the day to day clerical activities but, rather optimistically, suggests that relocation and tidying will solve many of the problems. It then goes on to point out the dangers of the use of extreme spacing of luminaires in areas equipped with dividing screens or partitions and the likelihood of light absorption by contents but without mentioning likely magnitudes.

The CIBSE Lighting Guide 1 'The Industrial Environment' (5) recognises that obstruction caused by machinery, overhead conveyors, pipe work,and the like, is a common feature of many industries.It recommends three approaches to reduce the problem.The first is to site the luminaires below any overhead obstruction and the second the use of at least two luminaires to light any part of a space. Finally a reduction in luminaire spacing is recommended, typically one third of the maximum spacing to height ratio, but depending on size, reflectance and number of obstructions.

2.2 Illuminating Engineering Society of North America

The NAIES Handbook (6) contains general guidance relating to design and recommendations specific to applications. The document states that the actual illuminance in partitioned spaces will be less than that predicted by using the the empty room approach, recommends that partitions be included in appropriate calculation methods, one of which is described in Section 4.2. The section on office lighting contains detailed guidance on both quantitative, and qualitative and psychological lighting issues. The problems of calculation of illuminance in open plan offices are discussed and it is pointed out that predictions based on the empty room assumption can be misleading. Light losses of between 10 and 50% are quoted for 'an average density of partitions 150cm high', depending on reflectance. Point by point computer calculation methods or mock-ups are recommended for illuminance prediction in partitioned workstation areas so that the designer may maintain the appropriate luminance ratios between task, surround and background. The problems of the requirement for flexibility in office planning for lighting design are pointed out in that lighting systems tailored to specific furniture configurations may become afflicted by problems of shadowing or glare if, at some later date, the furniture layout is radically changed. Finally the psychological effect of the elements of an office space are briefly mentioned (see Section 5).

2.3 Other lighting bodies

The DIN 5035 Part 1 specifies 'nominal illuminance' values over task areas equipped ready for use and that these values should take into account the influence of objects in a fully furnished room (7). The standard points out that most design methods are based on the empty room and that (unspecified) corrections are necessary to the standard lumen method to account for this.The CIE Guide on Interior Lighting (8) and the Australian Interior lighting Standard(9) make no specific mention of the problem apart from a general warning about shadows on task areas from some types of source.

3 Quantitative Methods

This section describes quantitative approaches to solution of the problems of obstruction in interior lighting. Important recent advances in modelling techniques are outlined and the use of computer software for the production of both design data and design solutions is discussed.

3.1 Modelling of obstructed spaces

3.1.1 Finite element methods

Finite element methods are now used in many branches of engineering as the basis of computer programs for the solution of analysis and design problems. The method used in lighting consist of a set of discreet, non-overlapping areas or 'elements which represent surfaces or light sources.The elements are either whole surfaces - floor, ceilings, walls, room contents or working plane - or discrete divisions of these surfaces. The photometric behaviour of each element is analysed in turn, and the contribution of all elements is summed. The resulting set of simultaneous equations is solved by matrix methods. When obstructions are placed in a space the number of elements is increased and the radiant exchange between room surfaces is modified due to the reduced ability of elements to 'see' others. In practical terms the realism of the results is related to the size and distribution of the element mesh - generally larger numbers of small elements give more accurate results but at the cost of increased computer time. A number of applications of the finite element method were described by McEwan and Carter(1). Research work over the last decade has concentrated on extension of the method into new applications and attempts to improve the computational efficiency and decrease run time. Efforts to extend the approach to the analysis of interiors having non-diffuse surfaces have, however, proven extremely difficult (10).
Numan and Moore developed a method to assess the flux exchange in obstructed spaces based on the finite element method (11). Partially obstructed surfaces were considered to be composed of zones without obstructions, separated by dummy planes projecting from the edge of the obstruction, which have full view of all surfaces of the zone they separate. These dummy planes were considered as transparent windows through which radiation travels from one surface to an other. The method uses the form factor concept between fully viewed surfaces in order to approximate the form factor between partially obstructed surfaces. The radiation travelling between surfaces of neighbouring zones is first received at a dummy plane and then distributed to the surfaces of neighbouring zones. If the dummy plane is assumed to be a secondary diffuse source, the fractions of the radiant energy received on each of the surfaces, through the dummy plane, can be determined by the form factor between the dummy plane and the surfaces under consideration.
Zhang and Ngai describe a finite element techniques for application to lighting calculations in a multi-partitioned space (12). The research used a concept developed by Mistrick- the use of two superimposed finite element systems in order to reduce calculation time (13). Zhang and Ngai's procedure is divided into three stages. Firstly, a global finite element mesh is established consisting of an array of elements on each room surfaces, the size and arrangement of which depends on priority of the surfaces. Secondly, a finer element mesh is created which is superimposed on surfaces where detailed lighting distribution data is required. Figure 1 illustrates this concept. Finally, a series of flux exchange equations are derived with the superimposed fine element mesh acting as both receiving and transmitting surfaces. The initial exitances and the form factors of the superimposed fine mesh are updated as the calculation proceeds, without changing the characteristics of the global finite element mesh in the entire system. The authors compared the results of the new procedure with the standard finite element method for both direct and indirect lighting systems and comparable results with reduced run time was claimed.
Ikemoto and Isomura (14) developed a number of simplifications to the finite element method with the aim of reducing run time whilst retaining computational accuracy. The most important modifications were to limit to 25 the number of elements on any surface, which in turn limited the number of form factor calculations, and to terminate the interreflection calculation after the second bounce. A reduction in accuracy of about 1% and of run time of 90% compared with other finite element applications was claimed.

3.1.2 Monte Carlo methods

In the last decade lighting researchers have investigated the potential of the Monte Carlo technique for lighting calculations in an effort to overcome some of the drawbacks of finite element methods. The basis of the Monte Carlo method is the tracing of the actual path of a particle of light from its source to its eventual absorption at a surface. At each change of direction of a particle, caused by reflection or transmission, the new direction is calculated according to statistical probabilities defined by the properties of each surface. Light sources may be simulated in two ways. The first is the use of scaled random numbers which represent the emitted particles in proportion to the luminous intensity distribution of the luminaire or alternatively, the assignment to each particle of a weighing proportional to the luminous intensity in the direction of travel with particles emitted evenly over equi-angular steps. Specular surfaces and obstructions are treated in the same manner as diffuse surfaces and room surfaces. The illuminance of an area of a room or obstruction surface is proportional to the total number of times a surface intercepts a particle paths taking into account the particle weighing value. In general the accuracy of the simulation is proportional to the square root of the number particles traced and the resulting amount of computation is large. A rectangular coordinate system for all room and obstruction surfaces used defined with respect to an arbitrary origin.

Tregenza (15) and Stanger (16) developed techniques for the application of the method in lighting. Both established that the technique could potentially be used to model complex interiors but that the major drawback was that accurate results required a lot of computer time. More recently Kajiyama and Kodaira (17) investigated the illuminance distribution over the working plane of the room equipped with low partitions. Good agreement between computed and measured results was claimed, however the computation time, despite using several techniques to improve speed, was enormously long , of the order of 18 CPU hours for a small office 6.9m by 4.75m by 2.88m containing four cubicles and four luminaires.

3.1.3 Ray tracing methods

The ray tracing approach includes parts of both finite element and Monte Carlo techniques and is capable of modelling a wide range of geometrically complex natural and artificial lighting installations. The various program algorithms are based on the technique of 'backward ray tracing' in which a light ray is traced back from the point of measurement to the source. Each ray of light acts as a luminance value resulting either directly from an emitting source or indirectly from a surface using information on surface reflection properties.This has been much used in computer graphics to produce realistic, but not necessarily photometrically accurate, images but has been little used in lighting. Ward and Rubinstein applied this technique to a particular application for computing luminance called synthetic imaging, which is a two-dimensional map of calculated luminance values as viewed from a selected point (18,19). To determine direct illuminance rays are traced to each light source and an intersection test for to check for any surfaces in the path of the ray performed. If the surface considered is unobstructed, the photometric characteristics of the source, the installation geometry and the surface properties are used to determine the outgoing luminance. If the surface is totally obstructed, the direct illuminance is zero, but in the case of partly obstruction a Monte Carlo method is used to determine the indirect illuminance by sampling the area around the source. The computation of indirect illuminance is also performed by sampling radiated luminance values over a hemisphere defined by the surface element position and normal direction. Both diffuse and specular surfaces may be dealt with in this manner. The Radiance computer program incorporating these calculation methods produces impressive images of the scene, but consumes enormous amounts of computation time. Modelling an office scene lit by four fluorescent tubes, with a desk containing a number of objects and a chair took of the order of 20 CPU hours on a workstation to produce a high resolution image.

3.2 Computer based design methods

The last decade has seen three linked developments which together has done much to establish CAD as a major element of the lighting design process: improved hardware with the introduction of personal computers; the availability of comprehensive photometric data; and improved software. Little needs to be said here about developments in PC hardware. Photometric data became more readily available and (albeit different) standard formats were published in the UK, USA and elsewhere. The major improvements in software related to the user interface and improved program capabilities. The original lighting programs written for mainframe computers often assumed a user knowledge of computing and were written with economy of machine time rather than designers' time in mind. User interfaces consisting of worksheets have now largely been replaced by interactive input usually based on a standardised operating systems such Windows. This has greatly reduced designer learning time and widened the user base of such programs. Most contemporary CAD programs contain features other than a basic working plane illuminance calculations and some now include a consideration of some effects of objects such as furniture and work stations located in the room. Given the ever increasing importance of CAD in lighting much of the basic research on obstruction will enter practice in this way. The purpose of this section is to review some of these applications in the context of both of the research on obstruction that has been undertaken and the requirements of the tools needed by the designer.

Most commercial interior lighting software is mainly based on lumen/zonal cavity or point-by-point/finite element methods. Some programs combine these two types into modules of the same program, using the lumen method for "quick" calculations and finite element methods for more realistic calculations that include inter-reflected light. Programs that are based on the lumen method are simple in operation and can operate efficiently on inexpensive equipment to predict the number of luminaires needed or average illuminance. Most suites of software offered for sale by software houses or consulting engineers include a program of this nature but an ever increasing number of luminaire manufacturers distribute this type of program free to interested organisations usually equipped with a database of the manufacturers' products. This development means that lighting design software of this type is reaching a wider range of users than previously. Non lighting specialists who are unlikely to buy software may be tempted to use free software for design purposes possibly without realising the consequences.The second type of program accurately simulate inter-reflected light between the various room surfaces and have been used as research tools for a number of years but are increasingly included in suites of purchased software or distributed as free software. Output for these types of program is by tabulated information, 2D or 3D contour plot, or visualisation routines and most have the capacity to define interior obstructions of varying degrees of complexity and to acknowledge their presence in the calculation process.

3.2.1 Obstruction in computer-aided lighting design

This section reviews some of the features of commercially available software currently available to designers that are relevant to obstruction. In general the majority of programs are lumen/zonal cavity based ,mostly distributed free by manufacturers, but very few examples of this type handle obstructions. Programs purchased as part of a software package are generally more likely to address the problems of interior obstruction.Table 1 lists the main features of six examples of software that handle obstructions - four lumen/zonal cavity based programs, of which one is currently free distribution, and two programs which are intended primarily as research tools which have been included for comparison purposes only. Table 1 is not intended to be an exhaustive list of available programs since this information is ephemeral and is available elsewhere (see for example the annual survey published by NAIES (20). Most programs offer a multitude of features but the four main variables relating to the the way the software treats obstruction may be summarised as follows:

(i) Obstruction definition

The manner in which the individual obstructions are constructed influences both input routines and calculation method. Most programs use rectangular planes to build up solid objects so that, for example, a cube may be defined as six single surfaces each of which is treated as separate for calculation purposes. The alternative definition is of an obstruction as a predefined three-dimensional object which is then broken into appropriate planar surface areas by the calculation procedure. All of the programs in Table 1, with the exception of Radiance, construct the internal obstructions as a combination of horizontal or vertical orthogonal surfaces. Luxicon provides the user with a limited set of preconstructed items comprising either structural members such as columns or furniture. In most programs room and obstruction surfaces must be aligned orthogonally and this clearly limits the degree of realism of an actual interior that can be modelled. Complex surfaces including curves can be defined using irregular areas defined by surface nodes. Radiance users may construct furniture geometry may be made up from combinations of N-sided polygons, spheres, cones and discs in this way.

(ii) Number of Obstructions

The total number of obstructions that can be defined as input also influences both the maximum size complexity and degree of realism to which an actual interior that can be modelled. Table 1 gives the maximum number of obstruction elements which may be either three dimensional blocks or surfaces. For comparison the contents of a typical office having a room index of 1.6 and furnished with desks, chairs, VDTs and a small number of filing cabinets could be modelled using 240 vertical and 70 horizontal rectilinear surfaces (21). It is clear that some programs described in Table 1 are generally capable of modelling a room of this size but that the maximum number of furniture items that can be accommodated depends on the degree of sophistication used in the modelling of the objects.

(iii) Calculation Methods

The basis of the calculation methods that have been implemented in the coding of the various examples has been discussed in Section 3.1. The majority use a point-by-point calculation technique, combined with a check for light interception by obstructions, to determine the direct lighting contribution, and a flux interchange routine for calculation of indirect illuminance. Linear and area light sources are generally modelled by subdivision into smaller portions which are then treated as point light sources, the direct lighting contribution received on any surface element from each individual point source being the total from all sources the element can "see". The inter-reflected component is calculated using the "radiosity" or "finite element" method. The main difference between the programs in this process is the criterion for termination of the "bouncing" of light between surfaces which influences accuracy and run time. Most programs continue the process a set number of times(usually three) until all but a negligible proportion can be assumed to have been absorbed by the room surfaces, but some software (Oasys-BEANS for example) will allow the user to enter the number of bounces.

The Radiance program, based on the technique of backward ray tracing , has the advantage of being able to model a range of complex geometries and materials. Interior obstructions may be modelled to a high degree of accuracy. The output is in the form of photo-realistic images. However the program was developed as a research tool, for which it is much used worldwide, but its commercial use is limited by a user interface that requires large amounts of time consuming data input and by its large appetite for computer time. Whilst advances in computer technology may go some way towards overcoming these disadvantages, a more fundamental limitation is that like all 'analysis' methods the Radiance user is required to input precise details of the installation and its contents. Such details are unlikely to be available at the time when most lighting schemes are undertaken.

(iv) Type of Output

There are a number of common types of output, some of which are used in combination. Illuminance grids or contour plots in text or graphic form, either for a horizontal working plane or, increasingly, as three dimensional plots, are features of all programs, although the practical use of the latter is far from clear (see Figure 2). Three of the programs have the capacity for graphic visualisation output of which Figure 3 is an example. The Lumen Micro and Luxicon programs produce a monochromatic image from a fixed viewpoint and have the capacity to present a series of such images as a "walk through". Visualisation in the form of photo-realistic images is the main form of output of Radiance. The generation of visualisation output is an major consumer of computer time - an image for a typical small office interior can take tens of hours for both data input and computation.

3.2.2 Program validation

Programs are increasingly used for appraisal of proposed designs. With the proliferation of programs and algorithms available there is a need for program validation so that they may be used with confidence by designers. Any validation process includes a review of the underlying assumptions of the program, including data used, and also testing of programs using standard "benchmark" data. Some work has already been done in this area to test programs based on the lumen method using as standard conditions an empty office lit by defined luminaires, the programs being evaluated against an acceptable range of limits of working plane illuminance parameters as the main validation device (22). The results give provisional acceptability limits but further work is required to include the full range of types of program, a wider range of input conditions (e,g, luminaires other than direct downlighters) and alternative output criteria (e.g. vertical illuminance).

The test models used to date have all assumed an empty space. The addition of obstructions to the input data must be considered an essential modification to the test model. Currently there exists no standard data for internal obstructions for test purposes and the standard obstructions put forward in Section 3.3.1 are suitable for this purpose being simple enough to be created using the orthogonal geometry systems that are in common use in lumen design programs yet capable of being used to predict light losses caused by room contents.

3.3 Simulation of lighting in non-empty interiors - design data

The various modelling techniques have been used,often in combination with some of the empirical techniques described in Section 4 to derive data that may be used in the design of lighting in non-empty spaces.

3.3.1 Work at Liverpool University

A number of researchers at the University of Liverpool have developed simulation methods for various aspects of lighting in non-empty interiors over the last ten years. The work has developed, firstly, a technique for spacing luminaires in general lighting installations at an appropriate distance to overcome the anticipated effects of light losses caused by obstructions on illuminance uniformity and, secondly, to predict and compensate for the magnitude of the likely light losses caused by obstructions.

The first study developed the idea of extending the existing design guidance for empty rooms by modifying the maximum spacing to height ratio to allow for some 'standard obstruction loss' which could be used by designers in addition to the normal maximum spacing to height ratio (23) This work took as a starting point the standard UK method for calculation of SHR in empty rooms which was then modified to take account of defined obstructions positioned within the central area of the 4x4 square luminaire array and was then implemented by means of a computer program. The obstructions, based ostensibly on the results of a survey carried out in an open plan office, represented a desk with either a partition or a filing cabinet at one end with a person seated at the desk. For each SHR value of the preferred series the program calculated the illuminance conditions within the central area of the luminaire area taking into account the presence of the obstructions. The work addressed the problem of the size and configuration of the elements of obstruction. A series of "light" , "medium", and " heavy " obstructions were developed to represent the range of obstruction density in office interiors (see Figure 4). These "Standard Obstructions" were developed from analysis of data on room contents collected by surveys of a number of office buildings and from information provided by major office equipment manufacturers and the sizes of the elements of the Standard Obstructions are shown in Table 2 . The elements are arranged into configurations set out below·

Light Standard Obstruction -Person + Desk + VDT.
Medium Standard Obstruction -Person + Desk + VDT + Filing cabinet.
Heavy Standard Obstruction -Person + Desk + VDT + Filing cabinet + Partition.
Floor area per standard configuration may be 8,10 or 12 square metres.

The representation of the human form was found to have a major influence on task illuminance conditions and the CIE standard for "body shadow" used in Contrast Rendering Factor computation was adopted as this is capable of acknowledging the separate contributions of head and body to obstruction. The program introduced the standard obstructions either parallel or perpendicular to the luminaire axis. For each SHR value of the preferred series, at each point on a 0.10 m square grid over the task, the illuminance from each of the 16 luminaires was calculated taking into account the presence of obstructions. The uniformity ratio based on minimum/maximum illuminance over the task area, excluding a 0.10 m wide edge strip, was then calculated. The edge strip was excluded from the uniformity ratio calculation since this would not in practice be used for visual tasks. The effect of obstructions was a major element in the illuminance calculation procedure and was assessed by separate consideration of how much of the luminaire, if any, may be "seen". For luminaires which were assumed to be point sources they are either "seen" or "not seen" and for linear luminaires checks were initially required to determine if a luminaire was partly or totally blocked by an obstruction The illuminance was calculated using a point -by-point calculation

To study the effects of the various standard obstructions the uniformity ratios for the preferred series of SHR set out in CIBSE TM5 were calculated for a number of examples. The results are summarised in a series of graphs similar to Figure 5 for both linear and symmetric point source luminaires The examples include standard obstructions positioned such that the axis of the work station is either

parallel or perpendicular to those of the linear luminaires. Results for the Heavy standard obstruction configuration are denoted by "H", those for Medium standard obstruction configuration with VDT by "V",and with filing cabinet by "F", and those with the Light standard obstruction configuration by "L". To provide a reference for the obstructed cases the uniformity ratios for the empty case identified by "E" are also shown. There were large differences in SHRMAX (the maximum permitted spacing to height ratio) for the luminaires between empty and obstructed cases and smaller but significant differences between the various obstructed cases (see Table 3). The effect of an an individual obstruction component was greater when perpendicular rather than parallel to a linear luminaire.
McEwan and Carter also developed a computer program capable of investigating the lighting conditions within spaces lit by any defined range of artificial lighting equipment (24) . Bougdah demonstrated that this program could be used to investigate the influence of different luminaire types and spacings on the illuminance conditions within a space for known obstruction conditions, and using a larger dataset attempted to develop some general rules regarding the behaviour of light in obstructed spaces (25). The results showed that obstruction size and density had by far the greatest influence on reduction in average illuminance over the working plane (the 'OL') of up to up to 14%. The next most important factor was luminaire type which caused losses of up to approximately 6% depending on type of luminaire. Specifically diffusing luminaires have a greater propensity for light loss than those which have more narrow downward light distributions. Variation of the reflectance of room and obstruction surfaces, room index, and mounting height were thought to have a negligible effect on light loss. A linear relationship between 'obstruction density' (expressed in terms of Vertical surface area of obstruction above the working plane to Floor area Ratio - VFR) and light loss was put forward for each of three luminaire types for a range of room sizes (see Figure 6). The VFR values may be calculated for the proposed room contents by summing for a typical workstation in the room the total area of vertical surfaces above the working plane, including a human form, and dividing this by the floor area occupied by the workstation including associated circulation space. Values of VFR for the various Standard Obstructions are in the range 0 to 0.7. Results of surveys of modern office buildings indicated that typical values of VFR for room contents ranged from 0.15 to 0.69 when calculated on the same basis as the Standard Obstruction (26). In terms of this measure of obstruction therefore, Standard Obstructions were capable of replicating conditions in actual furnished interiors.Raitelli and Carter extended the work in two different ways (27). Firstly the computer simulation was successfully carried out using general purpose commercially available software to investigate the light loss characteristics of obstructions of different shapes and sizes. Additionally rooms were modelled containing a regular grid of partitions such that the working plane was covered by square "cells" or with 'furniture like' obstructions. The results for the two types of obstruction were similar and confirmed the major influence of obstruction type on light loss.

3.3.2 Choi and Mistrick(28)

The work is a study of both working plane illuminance reduction and task uniformity in offices with uniform height cubical partitions equipped with some furniture. The study is interesting in that although it only deals with this restricted range of room contents it does examine the effects of different types and position of luminaires and provides information that could be of direct use to designers of open plan offices equipped with cubical partitions. The work was based on simulation of a 12.5m square room equipped with 25 cubicles. Detailed analysis was performed in the centre cubical only, the others being accounted for in the calculations by regarding their top surfaces as an imaginary surface. The results thus purport to represent conditions in the body of a room but not, arguably, the worst case of the corner cubicles. A specially written computer program was used to investigate four luminaire layouts (a single luminaire over the centre of the cubical, a line of luminaires along the axis of the cubical, a single luminaire straddling the cubical walls and a line of luminaires straddling the cubical walls) and three luminaire distributions (direct, indirect and direct/indirect). Additionally three heights of partition and four partition reflectances were simulated.
The fraction of working plane average illuminance relative to that for the empty room was determined for a cubical with a desk only and also for a desk and overhead cabinet. From all types of luminaire the obstructions caused light loss of up to the order of 50% on the desk only and 65% on desk with overhead cabinet - enough to require supplementary task lighting. In general the loss increased with partition height and decreased with partition reflectance. Luminaires having a direct distribution had least light loss with low partitions but maximum with high partitions. Overall the direct/indirect type had the least light loss.The luminaire layout also had an effect on the magnitude of light loss with straddled

layouts having least loss and centred luminaires the most. The Illuminance uniformity predictions were made,curiously, over the whole cubical rather than just the desk (which was located at one side of the cubical),and thus the results probably underestimate uniformity. The values of uniformity are considerably affected by luminaire layout and type. The straddled layout and indirect luminaire giving the best uniformity, whereas centred layout and direct luminaires had the lowest uniformity

4 Empirical approaches

The empirical approach to the problem of obstructed spaces has been adopted by a number of investigators. Photometric measurements have been undertaken in both simulated and real obstructed interiors in order to better understand light distributions within such spaces and to form the start point for design methods. This section examines both the results of the various photometric surveys and comments on their significance, and describes design methods based on empirical data.

4.1 Measurement of Light Losses

The published investigations of lighting conditions in obstructed spaces have been undertaken for a variety of reasons. These may be as part of an assessment of interior environmental quality; to verify design criteria; for software validation; or to act as the basis of a design method. Research of this nature has usually been undertaken by photometric survey supplemented in some cases by computer simulation to expand the original data set.

Cook and Hill (29,30) investigated the influence of obstructions located in the floor cavity on the illuminance distribution on the working plane. The work describes illuminance surveys of a number of large rooms firstly empty and then furnished with tables and chairs. For each of condition values of floor cavity reflectance were calculated using standard techniques(CIBSE Code) In one room, furnished with a combination of desks and chairs, the reduction in average working plane illuminance was 14% whilst in the second room, furnished only with leather backed chairs, showed no light loss The authors attempted to derive a relationship between horizontal working plane illuminance and the effective reflectance of the floor cavity. It was concluded that no simple relationship existed and that the present methods of determining the influence of floor cavity obstructions on working plane illuminance did not necessarily produce predicable results using lumen calculations for some types of cavity obstruction. The nature of the cavity obstructions was found to influence flux transfer within the cavity. The relationship was more reliable when closed sided or solid objects occupied the cavity than for more open sided obstructions such as desks.

Measurement of light losses has been undertaken at the University of Liverpool. Initially four surveys of actual office interiors, before and after furnishing, were undertaken in order to obtain information on illuminance distributions over the working plane (31). Detailed measurements of furniture configurations, room characteristics and horizontal working plane illuminance were made in each office. The results related the maximum and average reduction in working plane illuminance to a number of room variables (such as average reflectance of room and furnishings), and a number of indices, notably ratio of vertical obstruction surface area to floor area, ratio of height of obstruction to mounting height,and area of working plane with a uniformity ratio lower than 0.8. Based on these results tentative proposals regarding the relationships between light loss and furniture characteristics were put forward. Generally it was noted that designer should be prepared for reductions in average working plane illuminance in the order of 10% due to the introduction of office type room furnishings

Secondly Raitelli and Carter made a series of measurements to investigate the general trends indicated by the results of the earlier computer simulations (27) The measurements were made in a room which allowed permutations of two luminaire types and two spacing to mounting height ratios It was furnished, in turn, by four different 'furniture like' configurations; ranging from an empty room to a heavily furnished condition. The results confirmed the dominant roles of obstruction size and luminaire type over light loss, but in addition illustrated that reduction in luminaire spacing to mounting height ratio could overcome some of the influence of the obstructions. Table 4 illustrates some typical predicted values of OL for installations with linear luminaires installed near maximum SHR.

The final piece of Liverpool work to date by Lupton et al was a series of photometric surveys within modern commercial interiors which were undertaken firstly in the empty space; secondly, furnished with simulated 'standard obstructions'; and thirdly in their working state (21). The results of the surveys show that reductions of up to 15% in average working plane illuminance might be quite reasonably be expected in modern commercial interiors. The results showed good agreement with the typical magnitudes of light loss indicated by the Liverpool simulation work, further confirmed the primary importance of obstruction density on obstruction induced light loss, but also showed that room size had an important influence on light loss.

Kajima et. al. undertook photometric measurements in a number of office buildings as part of an investigation of a variety of issues relating to the visual environment (32). In one building three offices, each lit by regular arrays of fluorescent 40W x 2 lamp batten open reflector luminaires, were surveyed both before and after the installation of furnishings, and a reduction in average working plane illuminance of 22%, 21% and 19% respectively noted. The authors concluded that the reductions due to the furnishings were a significant design consideration. They proposed a correction factor (called the 'office furniture factor') to be applied to the 'lighting coefficient' (utilisation factor) as shown in Equation 1. On the basis of their measurements a value of office furniture factor of 0.8 was put forward.

Actual mean illuminance = Design mean illuminance of empty room x office furniture factor
Equation 1

If some assumptions are made about the furnishing within each space based upon the published plans of the rooms it is possible to compare results of Kajima et. al. to those of the Liverpool researchers. The three rooms of Kajima et. al. have estimated VFRs of 0.44, 0.40 and 0.51 respectively and these compare well with Bougdah's predicted results for a surface mounted diffusing luminaire 9 (See Figure 6).

Siminovitch et al undertook a series of studies to investigate the luminous environment within enclosed workstations lit by general lighting systems with the aim of developing geometric relationships between task and lighting layout such that good visual conditions were maintained (33,34). The first study involved measurement in a scale model of a 13m x 13m interior,equipped with model workstation furniture and illuminated by a regular grid of scale model 600mm x 1200mm diffusing luminaires. Horizontal illuminance was measured at different viewing angles for four different workstation configurations. Reductions in average working plane illuminance, when compared with similar measurements for the empty space, of up to 36% for a 25 degree viewing angle, and 70% in the 40 degree viewing angle were obtained. A second investigation developed the initial work by the use of a full scale photometric simulation facility to investigate the effect of various obstruction configurations and orientations on both Contrast Rendering Factor and horizontal illuminance from the 2 x 2 array of fluorescent direct downlighter luminaires illustrated in Figure 7. A workstation with the four configurations (unobstructed desk; desk and person; desk, person and 1.2m partition; desk, person, and partition with a storage unit). was placed in the four orientations with respect to the luminaire array. Measurements of Contrast Rendering Factor and illuminance were recorded at various point on the desk. Large variations of Contrast Rendering Factor were noted (with values as low as 40 recorded for some viewing angles) which may be explained by the degree to which the various obstructions were configured to partially or wholly occlude the luminaires. Horizontal illuminance was measured along the central axis of the desk at viewing angles of up to 45 degrees. Reductions for the obstructed cases compared with the empty case ranged from 40% to 80%. The authors found that the highest level of illuminance reduction occurs when the task plane is positioned between two luminaires located along the axis of viewing (see Figure 7 position 1). The lowest reductions occurred when the luminaire is located directly over the task plane and with the task between two luminaires located perpendicular to the line of sight (see Figure 7 position 2). These results are similar to the Liverpool simulations of task illuminance conditions made as part of the study of luminaire spacing to height ratio for obstructed spaces. Siminovitch et al put forward the concept of pre-defining interior lighting layouts and workstation task geometries coupled with local task lighting as methods of ensuring adequate illuminance and contrast and gave examples of suitable configurations. The major drawbacks of this approach are its lack of flexibility and its inapplicability to the design of interiors where detailed information on the furniture is unavailable.

4.2 Empirically based design methods

The Lumen or Zonal-Cavity method is the most widely used method of design of general lighting It enables an average illuminance to be provided over the working plane of an empty interior whilst attempting to limit the variation of illuminance by control of the spacing of luminaires. The number of luminaires to give the average illuminance is determined by Equation 2, and the subsequent luminaire layout set out using the appropriate spacing to height ratio (SHR).

$$E(s) = \frac{UF(s) \times N \times F \times MF}{\text{Area of Surfaces S}} \qquad \text{Equation 2}$$

where

UF(s) is the Utilisation Factor for the reference surface S
N is the total number of lamps in the installation
F is the bare lamp flux
MF is the maintenance factor of the installation

There have been a number of proposals to modify the lumen method to account for the influence of room contents. These have usually involved the inclusion in Equation 2 of an additional term, a multiplier to the UF(s), which increases the initial installed flux to compensate for light absorbed by room contents and the adjustment of the SHR to acknowledge the presence of obstructions This section examines these proposals.

Steffy (35) put forward a ' partition factor', used as a multiplier to UF in Equation 2, to compensate for light absorbed by vertical free standing partitions and thus not reaching the working surface No explanation is given as to the origin of the data. The partition factor, shown in Table 5, depends only on ceiling and partition height.

According to Steffy the partition factor is "usually lower (worse) for direct, well-controlled luminaires and usually higher (better) for indirect, widespread distribution luminaires" but no magnitudes of these adjustments are quoted. This piece of advice is in general agreement with the results of Choi and Mistrick but, interestingly, is at variance with the results of the Liverpool work which was based on furniture configurations that do not include cellular partitions. The major limitation of the partition factor is that it accounts only for height of partition and ceiling but not for number and location of partitions. The influence of luminaire type is ignored. The results of the surveys of Kajima et al (described in Section 4.1)) were also used to determine the value of a multiplier for the UF. The term,called the 'office furniture factor', had a value of 0.8 and appeared to be intended for use in the design of general lighting for offices only.

Ballman and Levin (36) put forward a number of calculation procedures for installations equipped with cellular partitions. The first estimates the value of a multiplier for the UF in order to calculate average illuminance over the whole floor area of such an installation. The multiplier, also known as the 'Partition Factor', ranges from 0.6 to 0.8 depending on partition height, reflectance, cell size and ceiling height. The same authors devised a calculation method for total average illuminance in an individual cubicle which employed the technique of separating the room into an upper cavity that extends from the top of the partitions to the luminaire plane, and the second that is the cavity within the partitioned space and using the lumen method to calculate the average illuminance on the top of the partitions. Next the UF for the area within a single cubical is determined assuming that the source is a diffuse 'virtual luminaire' , the appropriate surface reflectance and a zero effective ceiling reflectance. This technique may be extended to give the indirect illuminance at any point within the cubical by simply undertaking the calculation of the average illuminance on the plane of the top of the partitions twice, once as above to give total illuminance ,and secondly to give direct illuminance by assuming black walls and ceilings. A second lumen calculation gives average illuminance in the cubical This method is included in the recommendations in the NAIES Handbook (6). The final calculation method of interest is a graphic technique to check which luminaires in an installation contribute to the direct illuminance at a given point within a cubical. The magnitude of the direct illuminance is then calculated using the inverse square law.

Although there seems to be a consensus in a number of Codes that some adjustment of the SHR to acknowledge the presence of obstructions is necessary there is little published quantitative advice except for a number of 'rules of thumb'. CIBSE LG3 recommends a reduction of one third in the maximum SHR as suitable for most industrial applications. Steffy simply suggests more luminaires, spaced closer together in order to provide task illuminance from multiple sources. Williams (37) describes an empirical method of adjusting manufacturers recommended spacing to height ratio for application for the design of lighting for areas with cubical partitions. The modification to the published maximum spacing is shown in Equation 3.

$$\text{Maximum spacing} = ((Ws - Wp)/Ws) \times SHRmax \times (Hm + Ld) \qquad \text{Equation 3}$$

Where:	Ws =	width of the smallest panelled workstation
	Wp =	vertical distance from working plane to top of panel
	SHRmax =	maximum spacing to height ratio
	Hm =	mounting height of luminaires above working plane
	Ld =	Luminaire dimension (in same direction as SHR)

5 Subjective effects

Research over the past few years has given some clues as to which factors create subjective visual impressions of interiors. The work, notably by Flynn(38) and Loe (39) illustrated that luminance patterns on walls, ceilings and floors can influence how people perceive a given space and the results of this work can, with some difficulty, be translated into design guidance for desirable room surface luminance.The work may be criticised for its concentration on the luminance conditions of the bounding surfaces of empty rooms since large open spaces create an entirely different feeling from that of , say, partitioned workspaces. In a typical room which contains furniture or equipment a view inside the room is likely to be a combination of room surface and horizontal and vertical surface of the room contents. The luminance patterns on room contents are likely to be influenced by factors other than just the lighting system within the space (for example : layout, shape, colour, texture) and the users' view of the obstructed interior may be completely different from that of the same installation in an empty state. Under these circumstances even the modest amount of design guidance that exists in the form of preferred room surface luminance is inappropriate except for the special case of rooms equipped with regular cubical workstations which take on many of the visual aspects of a small room. Since most working interiors contain a variety of objects it is a matter of concern that little is known about how a view of room contents changes the subjective impressions of the whole interior and it is clear that some work is required in this area.

6 Discussion

Most of the recently published lighting codes and standards allude to the problems of light loss caused by interior obstruction and appear to recognise that this is of concern to designers. The guidance they offer however is usually confined to general warnings about the dangers of light loss and shadowing caused by room contents and advice on overcoming these problems is typically a recommendation to use reduced luminaire spacing or increased installed flux in conjunction with traditional empty room design methods. The NAIES on the other hand offers detailed advice on calculation techniques for spaces equipped with partitions. This otherwise laudable attempt to address the problems suffers from two disadvantages, namely that its application is clearly very limited and that it requires more information, in the form of precise furniture layouts, than is typically available at the design stage. Arguably the most important issue is that having identified obstruction light loss as a problem the various codes ignore the commercial implications. The nature of the problem is that absorption of light by contents must be compensated for by an increase in installed flux if it is necessary, for example, to achieve a specified working plane illuminance. Under conditions of commercial competition designers are attempting to achieve a solution within a cost limit but there is little guidance in the codes on which to base design assumptions. Unlike other aspects of lighting design (such as utilisation factor and maintenance factor) there is little agreed numerical design data or design assumptions relating to obstructions and thus the scope for commercial dispute is large.

Over the last ten years computer-aided-methods have become widely available in lighting. The available software ranges from lumen method to finite element and many programs offer some facility to include interior obstruction. Most of the programs permit definition of obstructions by combination of orthogonal surfaces to a degree of realism that depends on the variables of the program. The results of these programs may in some cases give only a crude indication of the effect of the obstructions but it can be argued that even this is beneficial in that it causes the designer to think about the problems of obstruction at an early stage. As noted above there is a need for agreed validation processes for programs and information in codes to enable the designer to interpret program output and relate it to code recommendations. All of the programs only permit analysis of an installation - that is the input data must include precise details of the room contents. Where the designer has no prior knowledge of the contents there is a need for some agreed obstruction configuration as input.

Despite two decades of research effort only two large scale data sets of light loss information using representative ranges of luminaires have been published. The various pieces of work at Liverpool lead to a proposal for a lumen method that allowed for both modified luminaire spacings and increases in installed flux to account for light absorbed by obstructions and Choi and Mistrick generated light loss data for spaces divided using cellular partitions and lit by a range of luminaires. The main limitations of this work are the non "designer friendly" nature of their data and its application only to office interiors. Light loss is a major problem in industrial interiors and similar general light loss data is required for this application.

It is apparent that the two least researched aspects of obstructed interiors are luminaire spacing and subjective effects. Two approaches to the spacing problem have been put forward. Bougdah's proposed method, based on the CIBSE TM5 method of calculation of spacing to height ratio, required computer calculation for each luminaire and has not been adopted by the industry. The 'rule of thumb' approach of Williams on the other hand requires only a basic knowledge of height and arrangement of partitions. In is clear that neither method completely addresses the problem and that more work in this area is required. The studies of subjective effects of lit interiors have yielded some clues about the impressions created by different luminance patterns on room bounding surfaces. The nature of obstructed interiors is such that some or all of the bounding surfaces may be obscured by the contents of the room and this would change the subjective impression of the space. This may be an important issue in some types of interior and some work is required to investigate this topic.

7 Conclusion - the next ten years?

A large body of knowledge exists on the nature obstruction loss in interior lighting design. The various factors that cause light loss have been identified and their relative importance established for a limited range of types of interior. Methods of analysis of illuminance in obstructed interior have been developed and design methods which attempt to overcome the effects put forward. There is a need for more development and better presentation and dissemination of the results of the work however before the 'empty room' assumption can be rendered invalid. Specifically effort is required in three areas. The first is the continued development of appropriate calculation methods , not only of those mounted on computer software, but also of the hand calculation techniques which are arguably used for the majority of lighting design. Secondly studies of the effects of obstruction should be extended to include interiors other than offices and commercial buildings. The problems of obstruction are of major importance in the lighting of industrial buildings for example and these contain a range of objects which could not be modelled using the existing techniques. Finally the whole question of obstruction light loss and its consequences must be addressed more fully in codes and standards. It is desirable that such documents include numerical data on light loss as a basis for design assumptions, advice on the available calculation methods including interpretation of results and sets out the commercial implications of the subject.

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Figures

Tables

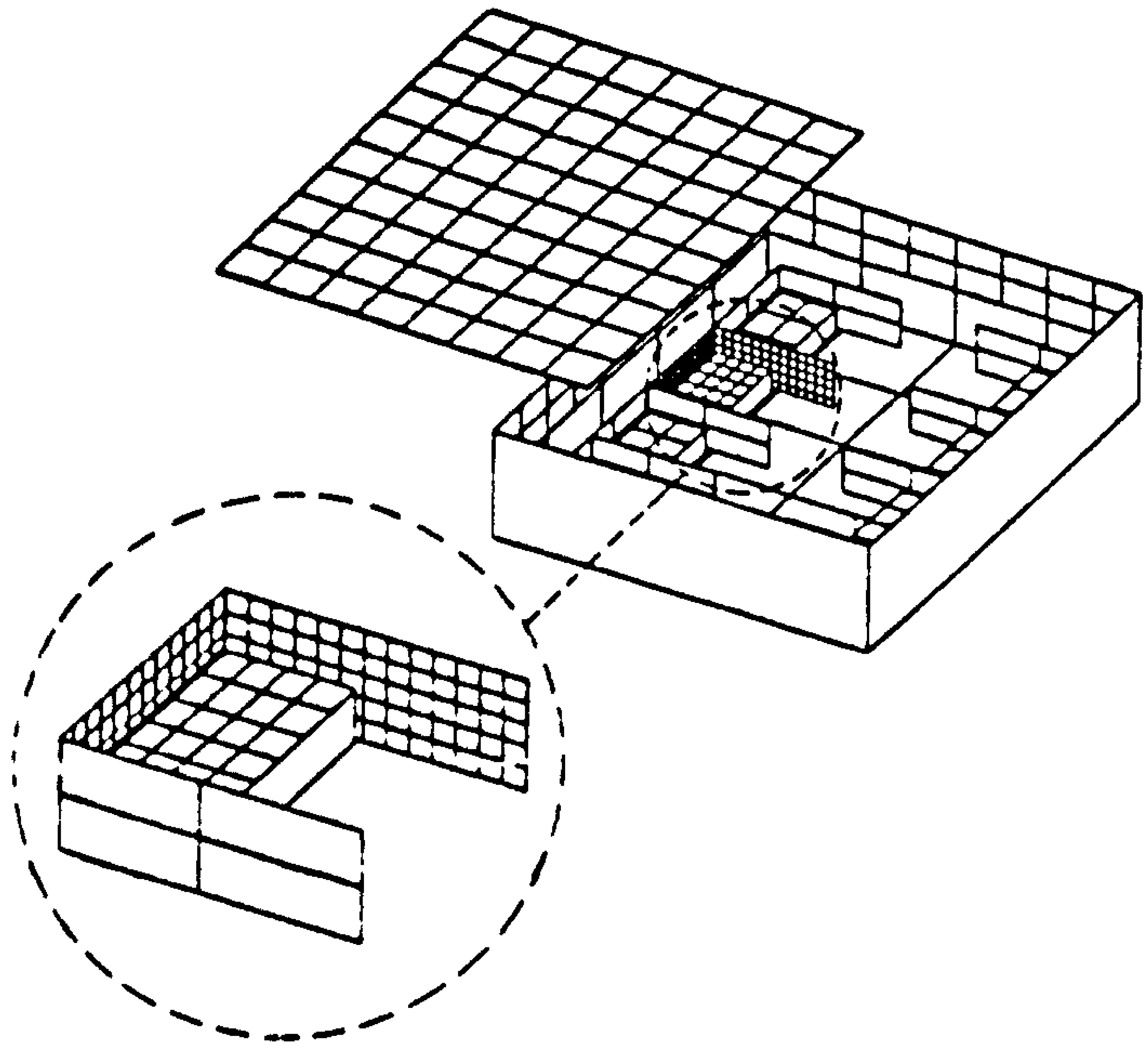


Figure 1: Zhang and Ngai's discrete element system showing the second fine mesh superimposed on the global mesh at a prioritised location.

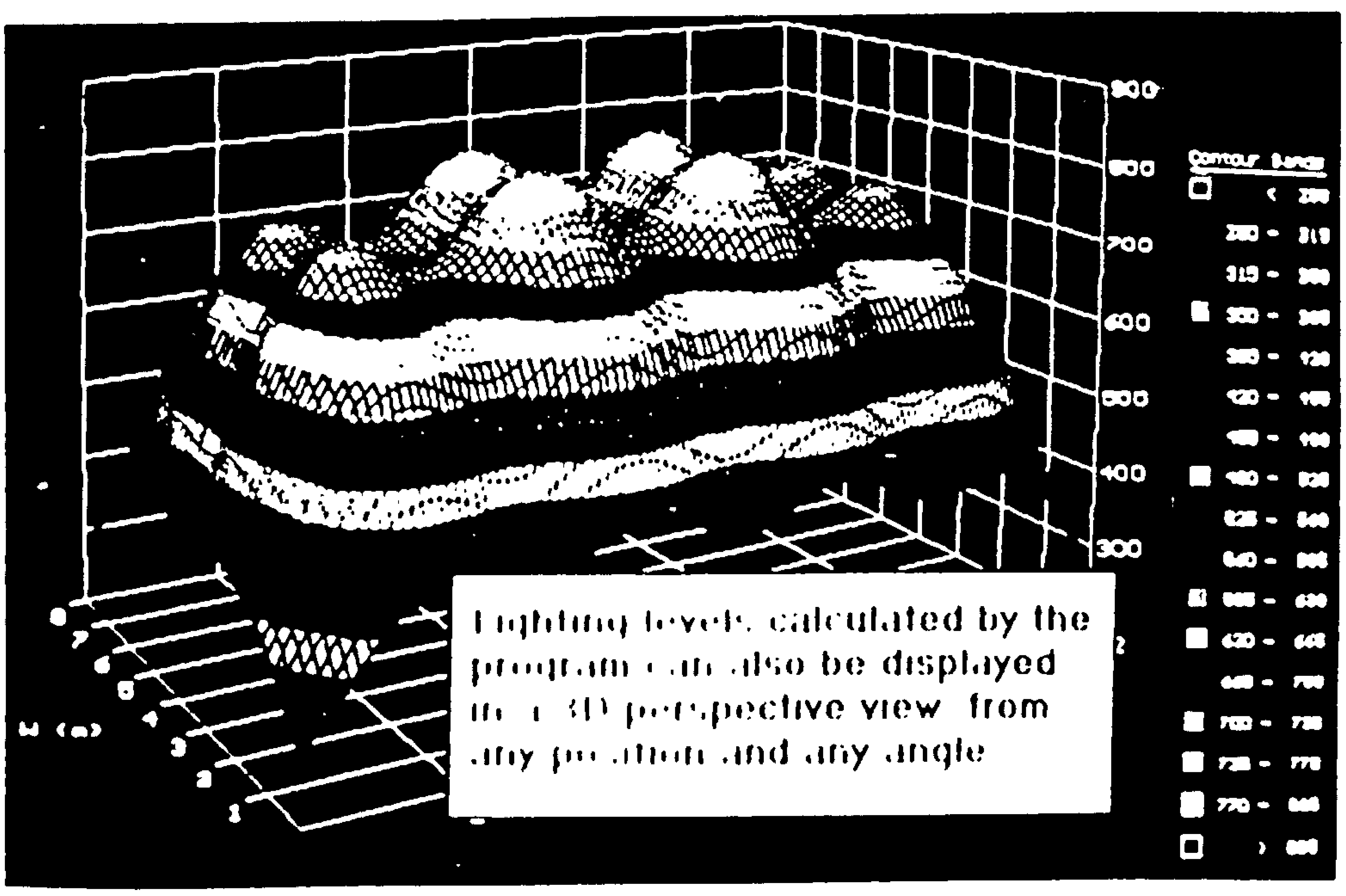
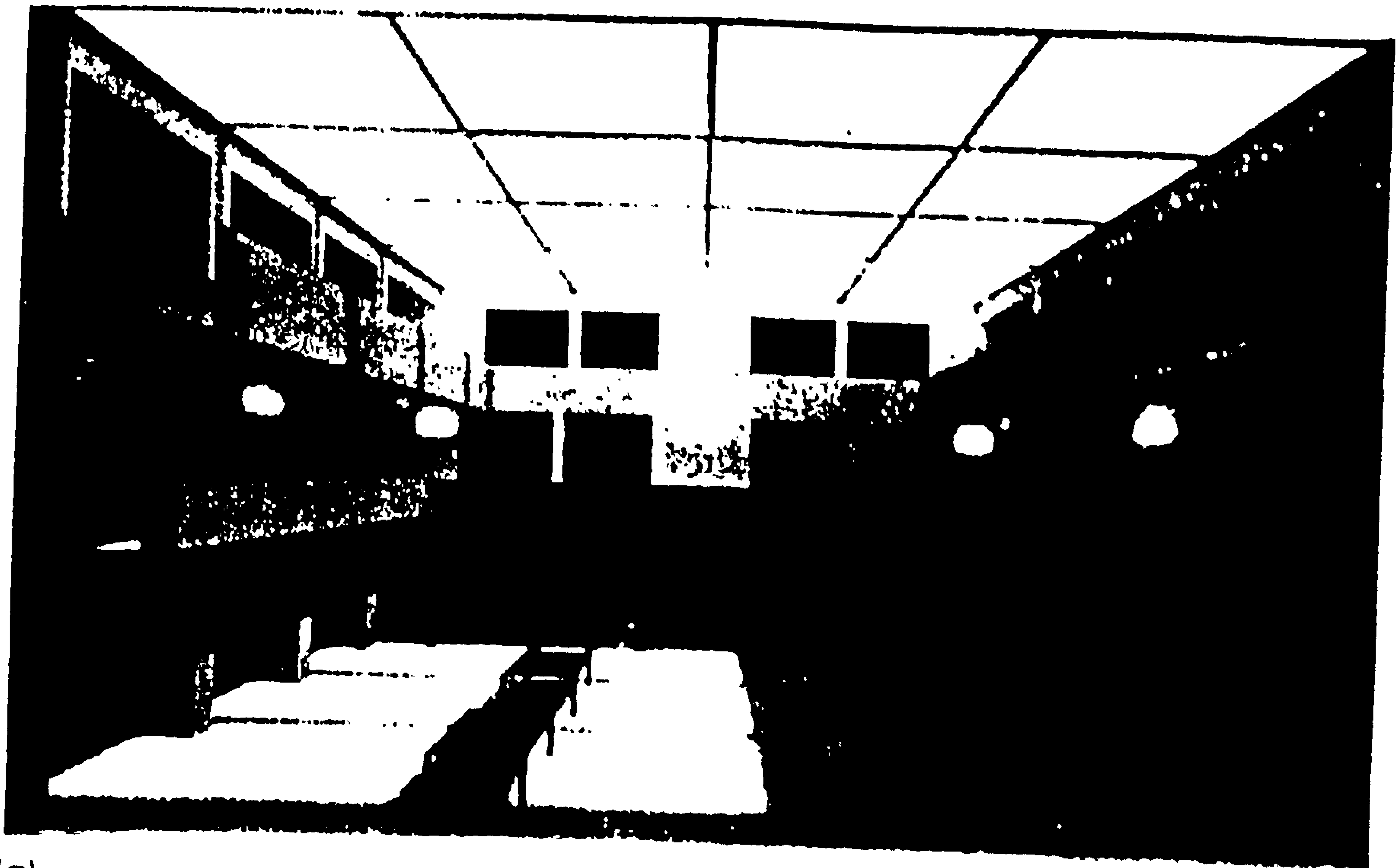
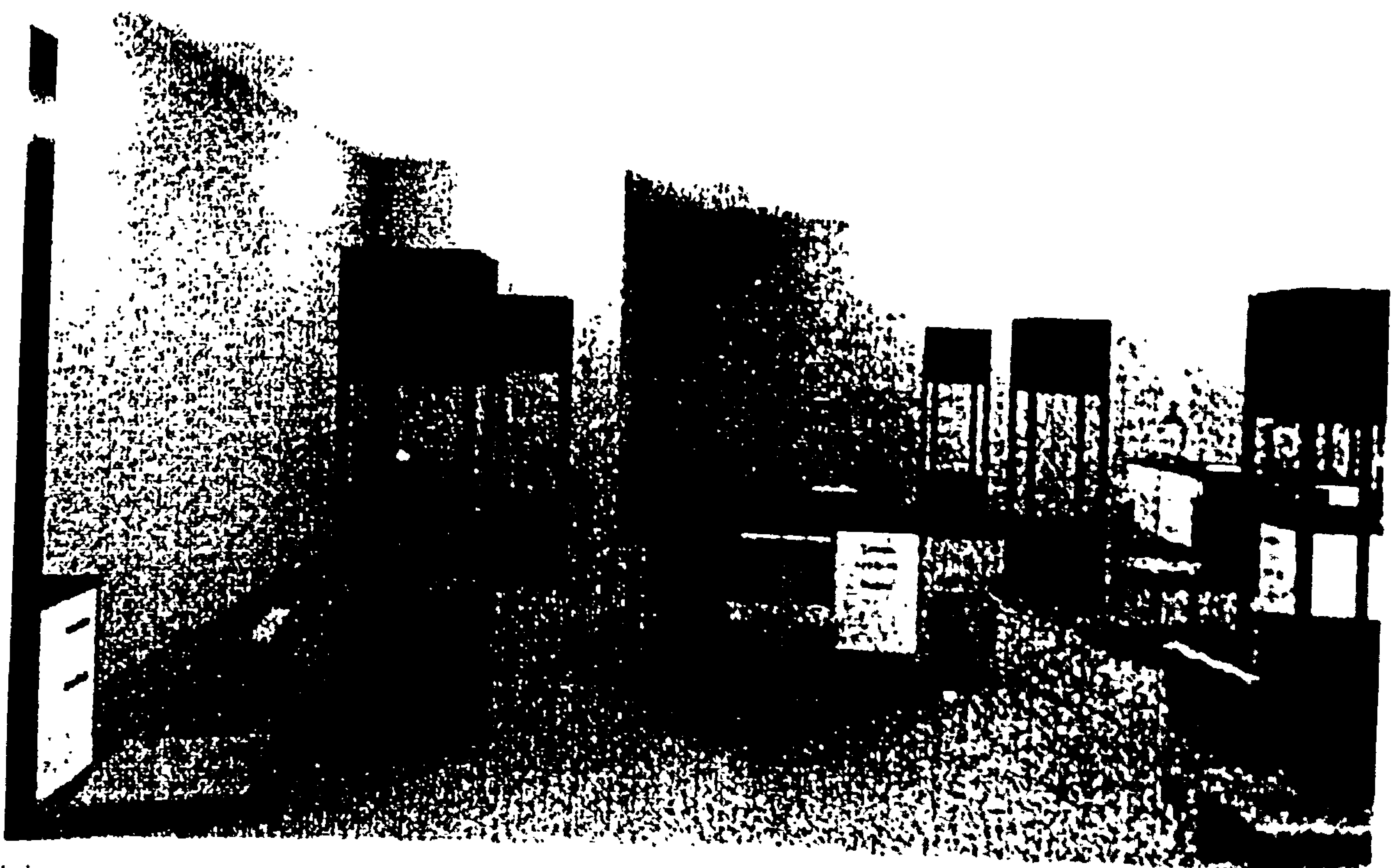


Figure 2: Example of 3D contour plot output from FACET lighting design package.



(a)



(b)

Figure 3: Examples of visualisation output from (a) Lumen Micro and (b) Radiance 2.4.

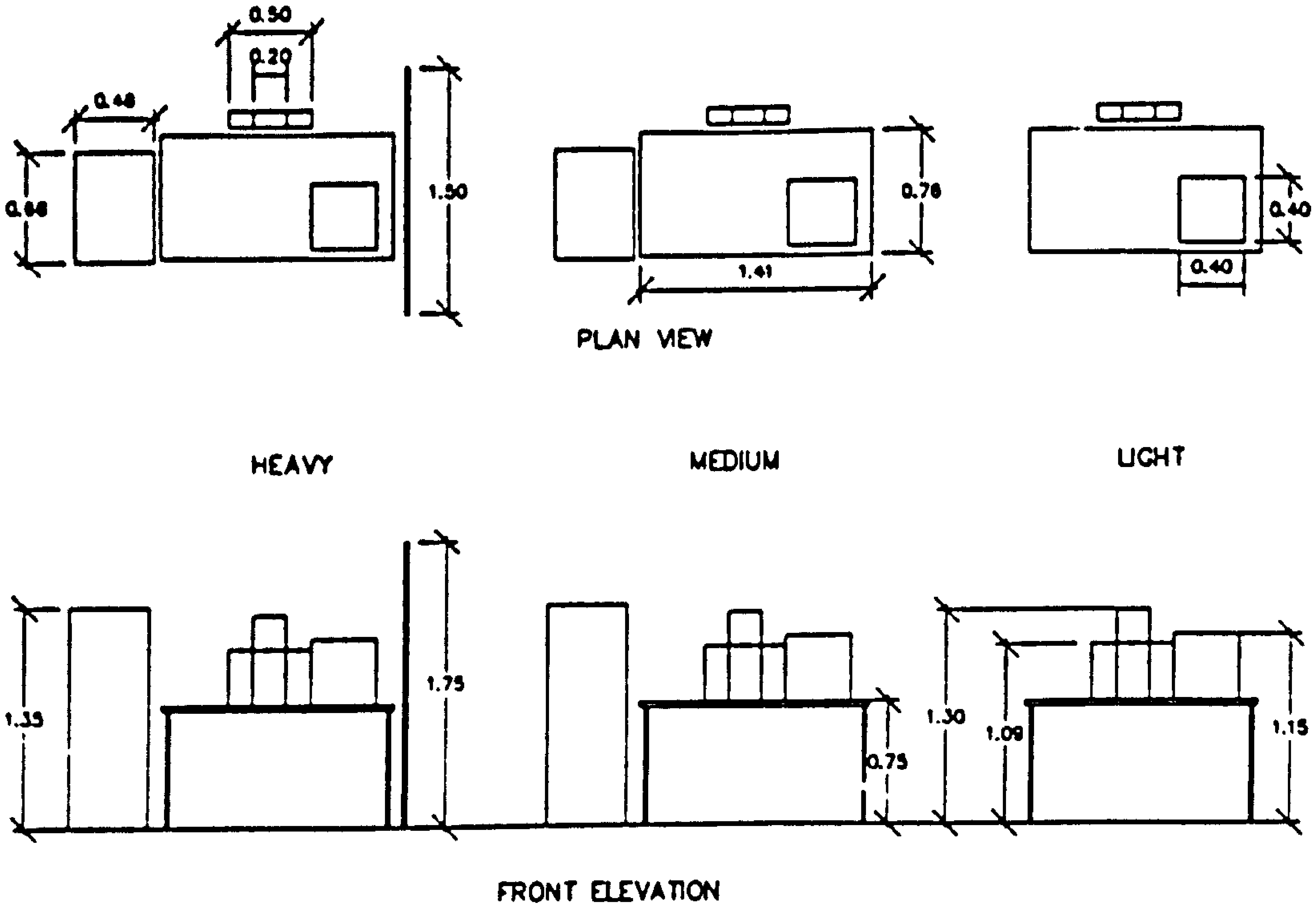
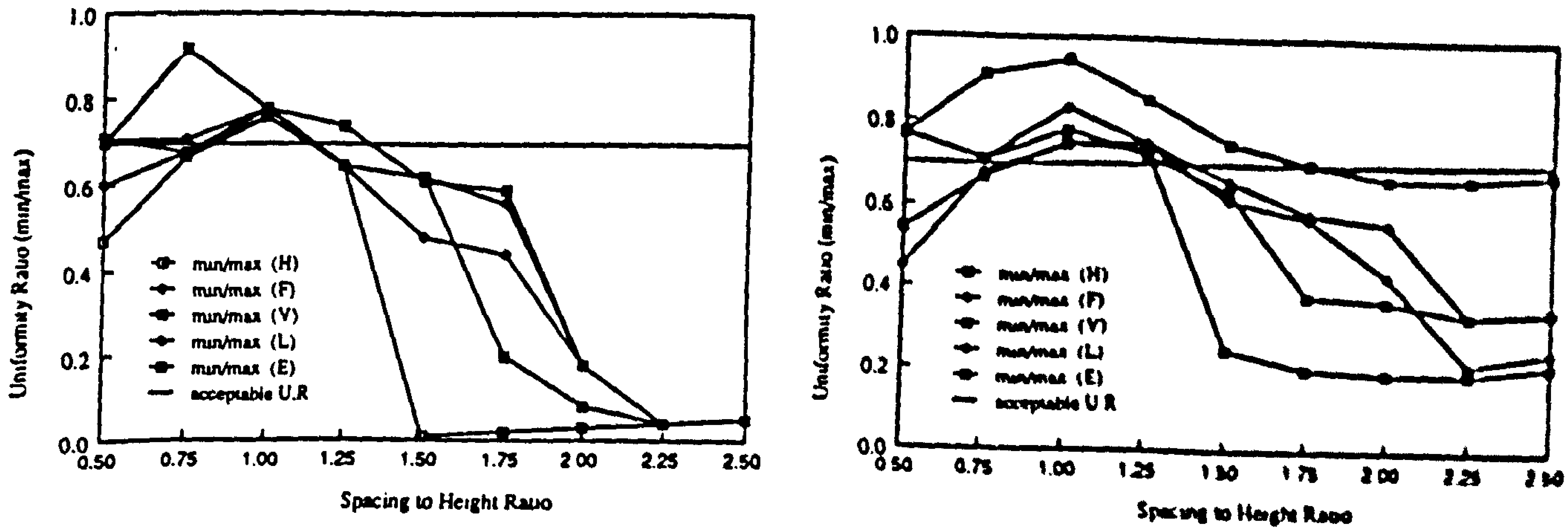
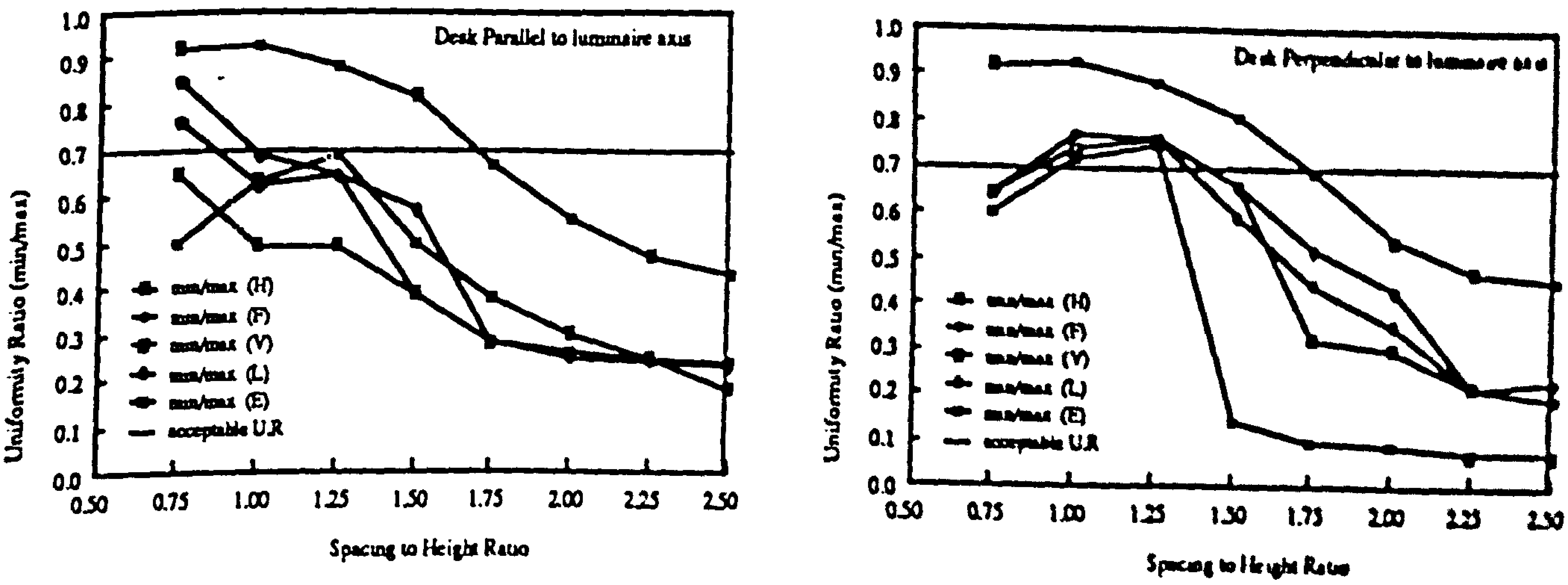


Figure 4: Diagram of standard obstruction layouts and sizes.



(a)



(b)

Figure 5: Variation of uniformity ratio as a function of luminaire spacing for (a) point source luminaires and (b) linear prismatic panel diffuser.

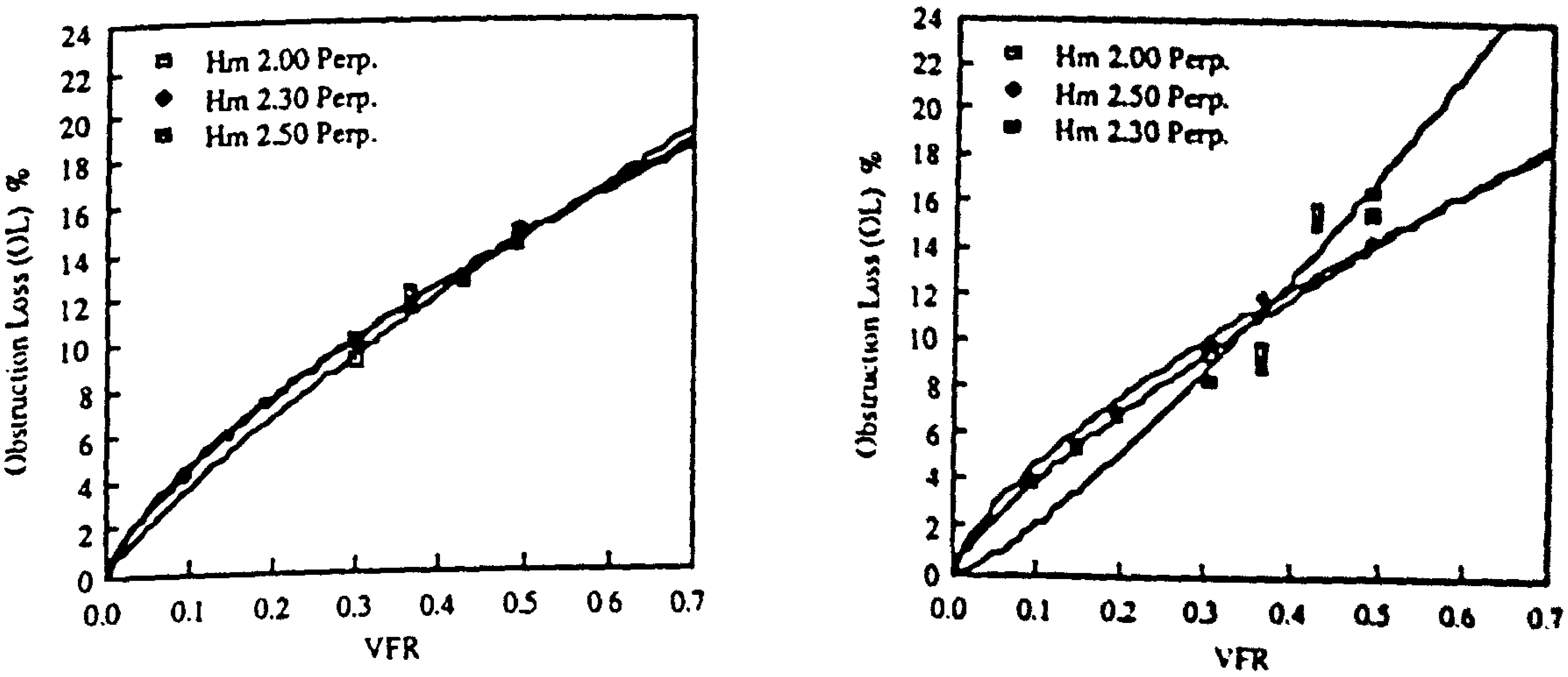


Figure 6: OL/VFR characteristic for surface mounted broadspread luminaire.

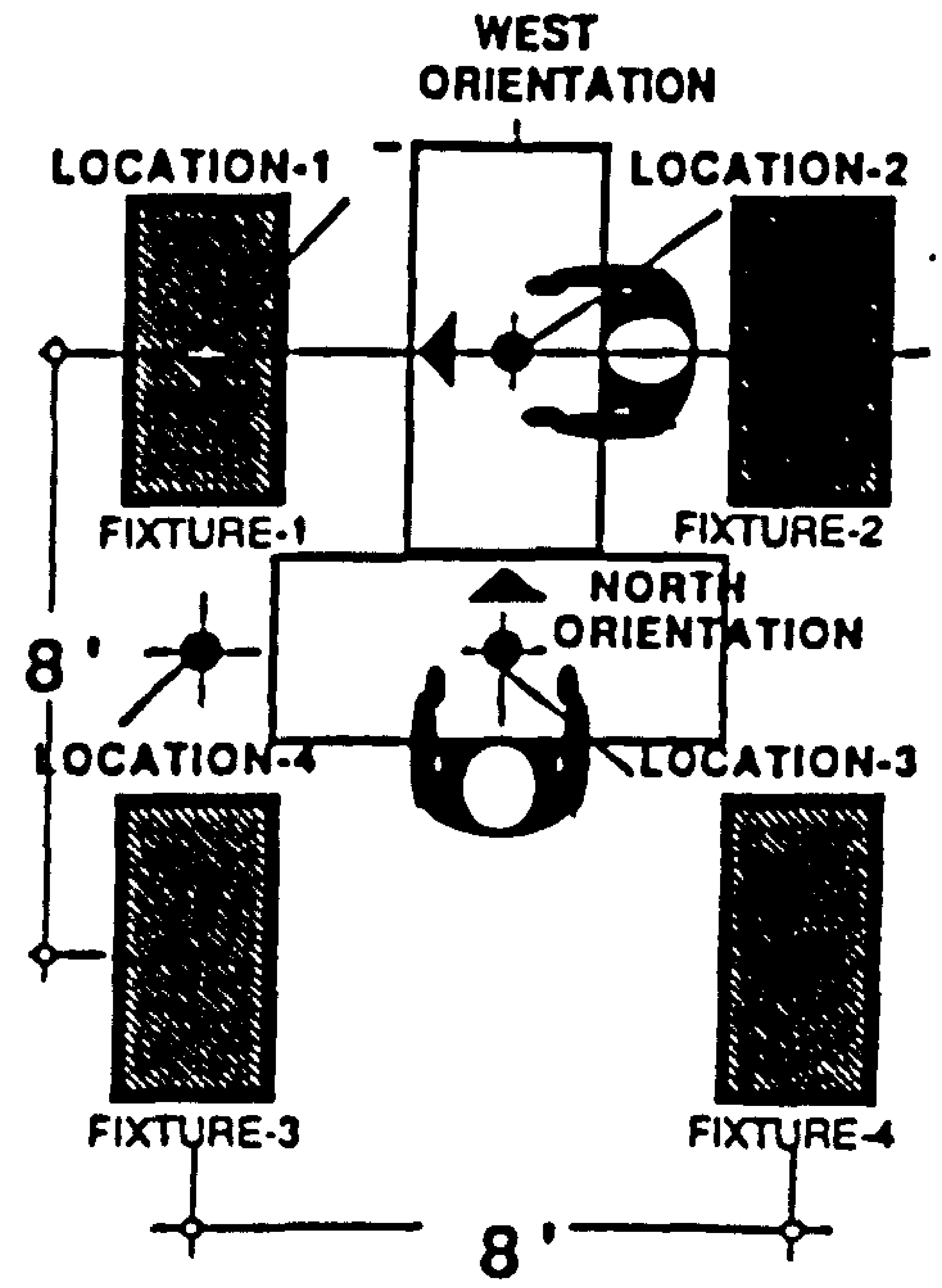


Figure 7: Layout of test suite used by *Siminovitch et al* in the evaluation of luminous environment within enclosed workstations.

	Lumen-Micro[40]	Luxicon[41]	Oasys-BEANS[42]	FACET[43]	Radiance 2.4	UoL Lighting Analysis
Hardware Platform	486DX PC 2Mb Ram	486DX-50 PC 12Mb Ram	486DX PC 2Mb Ram	486DX PC 2Mb Ram	UNIX workstation	UNIX workstation
Data Formats	IES/TM14	IES/Luxicon	TM14	IES/TM14/ASCII	radiance/IES	UoL/TM14
Maximum Obstructions	500	>500	50	>100	unlimited	100
Room types	rectangular	rectangular	complex	complex	complex	rectangular
Light sources	Artificial and natural	Artificial and natural	Artificial and natural	Artificial and natural	Artificial and natural	Artificial
Surface types and properties	diffuse reflecting solids	diffuse reflecting solids	diffuse reflecting solids or part transmitting	diffuse reflecting solids	specular, diffuse, dielectric, BRDF	diffuse reflecting solids
Obstruction types	single orthogonal surfaces	single orthogonal surfaces	complex orthogonal surfaces (up to 10 defining nodes	complex 3D boxes or surfaces	complex unlimited defining nodes	orthogonal 3D boxes
Calculation technique	Lumen/point-by-point and finite element techniques	Lumen/point-by-point and finite element techniques	Lumen/point-by-point and finite element techniques	Lumen/point-by-point and finite element techniques	hybrid combination of Monte Carlo and deterministic ray tracing	point-by-point and finite element techniques
types of output	report, contour plots, visualisation	report, contour plots, visualisation	numerical grids, contour plots	report, contour plots	photorealistic visualisations	report

Table 1: Summary of some properties of lighting design computer programs that handle internal obstructions.

Element	Length (m)	Width (m)	Height (m)	Vertical Surface Area (m²)	Reflectance
Filing cabinet	*0.64*	*0.48*	*1.35*	*1.34*	*0.3*
Partition	*1.50*	*0.025*	*1.75*	*3.06*	*0.6*
VDT	*0.40*	*0.40*	*0.40*	*0.64*	*0.3*
Person - head	*0.10*	*0.20*	*0.55*	*0.53*	*0.3*
- torso	*0.10*	*0.50*	*0.34*		*0.4*
Desk	*0.76*	*1.41*	*0.75*	*N/A*	*0.3*

Table 2: Dimensions and reflectances of standard obstruction elements.

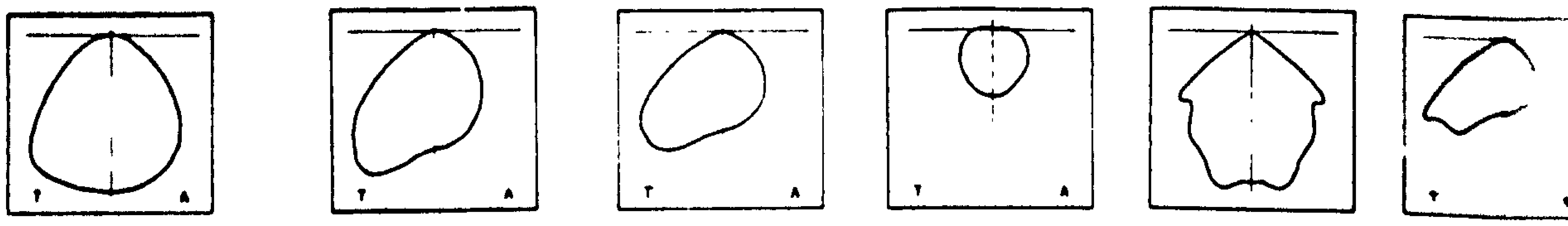
Configuration	Luminaire type								
	1 Prismatic panel diffuser		2 Surface mounted broadspan reflector		3 Recessed broad-span reflector		4 Surface mounted diffuser	5 Recessed diffuser	6 Recessed reflector
									
Position of workstation relative to luminaire axis	Perpen-dicular	Parallel	Perpen-dicular	Parallel	Perpen-dicular	Parallel	Perpendicular or parallel	Perpendicular or parallel	Perpendicular or parallel
Empty case	1.70	1.70	1.90	1.90	2.08	2.14	1.75	1.32	1.80
Light obstruction case	1.40	1.00	1.52	1.00	1.56	1.51	1.40	1.17	1.66
Medium obstruction case VDU	1.40	—	1.50	—	1.51	1.00	1.40	1.17	1.55
Medium obstruction case FC	1.33	0.85	1.25	—	1.25	1.00	1.27	1.17	1.44
Heavy obstruction case	1.27	—	1.25	—	1.25	1.00	1.25	1.15	1.29

Table 3: SHRmax for standard obstructed interiors lit by different types of luminaire

Luminaire type	Degree of Obstruction		
	Light VFR ≈ 0.1	Medium VFR ≈ 0.25	Heavy VFR ≈ 0.45
Diffuser	*2.5%*	*7%*	*14%*
Wide distribution reflector	*2%*	*5%*	*11%*
Narrow reflector	*1.5%*	*5%*	*10%*

Table 4: Some typical predicted values of OL for installations with linear luminaires installed near to their respective SHRmax.

Ceiling Height (m)	Partition Height (m)	Approximate Partition Factor
Between 2.60 and 2.75	*Less than 1.05*	*1.0*
	1.05 to 1.35	*0.95*
	1.35 to 1.63	*0.85*
	1.63 to 2.0	*0.75*
Between 2.75 and 2.90	*Less than 1.05*	*1.0*
	1.05 to 1.35	*0.97*
	1.35 to 1.63	*0.90*
	1.63 to 2.0	*0.80*
Between 2.90 and 3.05	*Less than 1.05*	*1.0*
	1.05 to 1.35	*0.97*
	1.35 to 1.63	*0.95*
	1.63 to 2.0	*0.85*

Table 5: Partition Factors according to Steffy.

LIGHTING DESIGN CALCULATIONS FOR NON-EMPTY INTERIORS

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The lumen method is the most popular design tool used for interior general lighting schemes due to its simplicity, economy and ready availability of design data. This paper puts forward proposals for modifying the existing procedure to enable the designer to both modify luminaire spacing and take account of the consequences of the likely average light losses caused by obstructions.

INTRODUCTION

Arguably the most significant failing of lighting design methods in current use is the assumption that interiors are empty. The lumen method is the most used lighting design method worldwide due to its simplicity, ready availability of design data, and economy of designers time. Erstwhile it has enabled the average illuminance to be provided over the horizontal working plane of an empty interior whilst attempting to limit the variation of illuminance by control of spacing of luminaires. In practice although the uniformity of illuminance on unobstructed working planes may be satisfactory, room contents may cause areas of shadow and light loss that may influence user visual performance, worker morale and, in extreme cases, safety. Additionally light losses of this nature frequently cause contractual disputes between designers and building users when specified illuminance levels are not achieved at the commissioning stage.

This project has developed a modified lumen design method that takes account of the likely light losses caused by the contents of a room under working conditions. In commercial buildings these may include furniture or partitions which project above the working plane and cause the actual illuminance levels in the space to be lower than those predicted using the "empty room" assumption.To overcome this the modified lumen method includes a multiplier to the Utilisation Factor, called the Obstruction Factor, which increases the installed flux to compensate for light absorbed by typical room contents. The Obstruction Factor data is general enough to acknowledge the range of luminaire types, room sizes and obstruction configurations likely to be found in practice, and is in a form suitable for design use. The modified method includes guidance on the effects of luminaire spacing on working plane illuminance variation.

LIGHT LOSS ANALYSIS

Background to the work

The relationship between average light loss over the working plane and the various parameters of general lighting installations have been investigated using both computer simulation[1] or photometric survey[2]. The results indicated that some parameters have a greater effect than others. Specifically density of obstructions had the largest effect followed by that of variation in luminaire type. Variation of room and obstruction surface reflectance had a negligible effect on total light loss. The effect of room size was shown by survey results to be influential. The density of obstructions - size and disposition - was quantified by expressing the vertical surface area of furniture and other room contents above the working plane as a ratio of the floor area of the room, a ratio termed the Vertical surface area to Floor area Ratio - VFR. It was further established that luminaires having the same physical and photometric properties had a similar relationship between obstruction density in terms of VFR and Obstruction light Loss (OL) the percentage reduction of average working plane illuminance in an obstructed space to that in the same space in an empty state. Light losses for photometrically different classes of luminaire, on the other hand, varied considerably. In general diffusing luminaires exhibited consistently higher losses than more direct luminaire types.

Data generation

The previous work indicated that luminaires could be grouped into broad generic groups each of which have similar light loss characteristics and that the same relationships between OL and VFR held for that group over a range of practical room sizes and room surface reflectance. This pointed the way to reducing the almost infinite number of data sets associated with the vast range of commercially available luminaires into a compact body of knowledge suitable for design purposes. Light loss data

→ was generated using a computer program previously developed at Liverpool to calculate average working plane illuminance in a series of installations of different sizes and degrees of obstruction lit in turn using examples from the luminaire generic groups[3].

The selection of generic luminaire groups, each having similar physical and photometric characteristics, was made using the classification in the CIBSE Code for Interior Lighting, section 3.3.2. "Luminaire characteristics" [4]. Sixteen categories of interior luminaire were identified using this method and a selection of examples for each category from four multinational manufacturers was made. Care was taken to ensure that the luminaires selected from each category had similar luminous intensity distributions and spacing characteristics. The empty interiors were designed using conventional lumen design techniques. The obstructed interiors were fully occupied by 'Standard Obstructions' and lit by the various luminaires spaced according to conventional spacing to height ratio rules. The standard obstructions represent workstations made up of a desk surrounded variously by human form, VDT, filing cabinets and partition. A series of 'Light', 'Medium' and 'Heavy' standard obstructions have been shown to represent the range of obstruction densities encountered in offices[5]. The standard obstructions used to represent the room contents in the calculations give a VFR range from 0 (empty) to 0.70 (Heavy case standard obstruction), these being representative of the range of obstruction conditions in modern commercial office buildings. A typical room configuration is shown in Figure 1. The data was produced for the full range of room index over which Utilisation Factor is calculated - that is up to room index 5. The calculation of OL for the various installations involved permutations of room index, VFR, and luminaire type. For each luminaire type modules of floor area of 8, 10, and 12 square metres each containing a Light, Medium, or Heavy standard obstruction were created to give a range of VFR from 0.15 to 0.7. The modules were then combined into "rooms" of different sizes to vary room index over the range 1 to 5. A macro program was used to run the program for each combination of modules to generate OL/VFR data for the 16 classes of luminaire (3822 cases).

Results

The results were plotted as graphs of OL/VFR for the various luminaires for all room indices and an example is given in Figure 2. The data was processed by linear regression techniques which assumed a true zero (i.e. no obstruction light loss in an empty room) and the results of this analysis confirmed that a straight line passing through the origin could be fitted to the data with measures of fit (r squared) of the order of of 0.98. The greater the slope of the graph the greater the value of OL for a given value of VFR and hence the greater the propensity for light loss. The slopes of the graphs for the different types of luminaire vary considerably with the bare batten types having the highest losses. The graphs for the luminaire types equipped with louvre systems (those suitable for VDT locations; and recessed modular luminaires with louvres) indicate that these luminaires have the lowest losses. The reason for this is that light from luminaires with direct light distributions is not intercepted to the same extent by vertical obstruction than that from luminaires such as battens which have a pronounced sideways intensity distribution. The rest of the luminaires which have a OL/VFR slope between the extremes of battens and VDT are semi direct luminaires that have a degree of optical control using prismatic controllers, painted reflectors, or recessed modular luminaires. The slopes of the graphs also varied with room index for some conditions.

INFLUENCE OF LUMINAIRE SPACING ON ILLUMINANCE VARIATION AND LIGHT LOSS

Luminaire spacing

A major concern of designers is that of limiting the variation of illuminance over the working plane. The 'uniformity ratio' and 'diversity' are used to quantify illuminance variation over task areas and the whole working plane respectively. The main device used to control illuminance variation is spacing of luminaires usually by means of a spacing to height ratio (SHR). A number of methods of calculation of SHR exist worldwide but each is based on the 'empty room' assumption. British (CIBSE) practice is to calculate and publish two SHR values for each luminaire at which the uniformity criterion is satisfied - a ' nominal' value on a preferred series of increments and a ' maximum' [6]. The likely effects of obstructions are acknowledged in some codes and standards but the guidance on countering these rarely extends beyond suggestions to reduce spacing. The magnitudes of the reductions for particular sets of variables are not stated. A modified SHR calculation method that accounted for the presence of standard obstructions was developed at Liverpool some ten years ago [7]. The method is based on the criterion of task uniformity and the results in terms of maximum SHR showed large differences in achieved conditions between types of luminaire and between empty and obstructed conditions. Despite this the modified method has not become part of routine design practice because of the lack of availability of manufacturers' data. There is thus a need to attempt to frame some design guidance for obstructed interiors in terms of the more widely available SHR data that is based on the empty room assumption.

Investigation

Computer simulation was used to analyse task uniformity, diversity and obstruction loss as a function of luminaire type and spacing, and obstruction density. The calculations were made for a space filled with standard obstructions and intended to represent conditions in the centre of a large open plan office (see Figure 3). The calculations were made on the same basis as other SHR methods, that is, considering direct illuminance only and ignoring the influence of the walls. Illuminance calculations were made on a fine grid of points for two task areas (in the centre of the room and at the edge of the luminaire grid), and over a larger grid for purpose of determining diversity and obstruction loss. Six of the categories of luminaire described in section 2.2 were selected as being representative of the range of photometric performance, these being battens, surface modular and VDT louvre luminaires.

Results

Figure 4 shows uniformity ratios for a task area at the edge of the luminaire grid (the worst case) as a function of SHR for a louvred VDT luminaire. Uniformity ratio decreases as SHR increases. The variation in uniformity between the two task locations and between the different obstruction cases is small but the difference between the furnished and empty cases is substantial. Figure 4 also shows the values of the CIBSE SHR nominal and maximum, and the obstructed SHR maximum values from the modified Liverpool SHR method. The results in general indicate that task uniformities fall below the threshold of 0.7 around the CIBSE SHR nominal or the maximum Liverpool modified SHR. Since the calculation process uses direct light only, which would tend to underestimate actual uniformity, the use of SHR nominal is likely to produce satisfactory conditions in most occupied interiors.In cases where extreme illuminance variations are likely to occur - for instance where high partitions are to be used - one step below SHR nominal will be necessary.
The increase in core area illuminance diversity with SHR for a surface modular luminaire is shown in Figure 5. The magnitude of this increase as a function of VFR was greatest for diffusing or batwing type luminaires, whereas direct luminaires exhibited the greatest rise in diversity with SHR. In general the study indicated that only then using diffusing or batwing type luminaires must the designer take extra care to check diversity conditions and that in all other cases, as long as CIBSE SHR maximum is not exceeded, the criterion will be satisfactory.
An example of the variation of OL across the whole room as a function of SHR is shown in Figure 6. For all luminaire types there is a negligible variation in OL with SHR for each VFR.

USE OF THE RESULTS IN LIGHTING DESIGN

The light loss simulation described in Section 2 produced too large a data set to be directly useful for practical design purposes. A number of alternative methods of producing a compact body of data capable accounting for different light loss characteristics of luminaires in rooms of different sizes were investigated. The best solution was to plot the slope of the OL/VFR graph (m - the obstruction loss characteristic) for the luminaire groups as a function of room index and luminaire spacing, the former accounting for room size and the latter being dependent on the photometric characteristics of the luminaires in the group. Figure 7 shows the data in this manner with room index plotted on the Y axis and luminaire spacing on the X axis in terms of CIBSE SHR. The SHR data used to plot Figure 7 was calculated as the arithmetic average of the maximum values of SHR for the actual luminaires used from each classification group used in the simulation.
Ideally design data should be easy to understand and simple to use if mistakes and misunderstandings are to be avoided and the proposed method of presentation of data achieves this. At the first stage the designer would decide the illuminance level and luminaire type. Next the designer is required to either calculate or estimate VFR for the proposed installation. This is done by expressing the vertical surface area of furniture and other room contents above the working plane as a ratio of the floor area of the room. Where there is little information on the ultimate use of the room default values of VFR may be assumed. For example for most office interiors in the UK which do not contain cellular dividing partitions a value of 0.35 may be used, the value for the medium standard obstruction. Finally using the maximum permitted luminaire spacing and room index for the proposed installation the value of m can be read off Figure 7 and the Obstruction Factor calculated as follows:

Obstruction Factor = (1 - (VFR . m) /100).

This may then be used in the lumen method as a multiplier to the Utilisation Factor. The luminaire layout is then determined using the published CIBSE SHR values modified if necessary in accordance with the results of Section 3.

VALIDATION AND TRIAL USE OF THE METHOD

Validation of the tools used in the design method has been carried out as an integral part of their development. For instance validation of the analysis computer program and of standard obstructions are described in References [3] and [5] respectively. The complete design method was validated by comparison with photometric survey data from installations in their actual working state and by comparison with relevant parts of other design tools. Trials of the method were then conducted in the cooperating organisations.

Comparison of results with survey measurements

The surveys investigated illuminance levels in a range of interiors that contained lighting equipment that was representative of good modern practice. In an item additional to the original programme, 27 sets of measurements are made in the installations firstly in their empty state, secondly filled with 'Standard Obstructions', and finally in their working state after occupation by the building users. Each survey consisted of measuring working plane illuminance on a square grid of points (usually 0.5m centres) over the empty room, and again when furnished with the various standard obstructions. These are constructed of painted cardboard, polystyrene, wood and are designed for easy transport in small sections. All daylight is excluded during measurement. A photocell was positioned over grid points at 0.7m above floor. The average working plane illuminance was calculated as the area weighted arithmetic average of the grid point illuminance. The obstruction loss (OL) was calculated as the percentage reduction of empty case average illuminance. A limited amount of data from those installations surveyed in their working state was available for comparison with predictions made using Figure 7. Table 1 summarises this measured and predicted data and it is clear that the agreement is good.

Comparison with other published methods

The modified method is capable of accounting for the effects of a wide range of obstruction configurations but the small amount of published information which can be used for comparison purposes relates to the particular case of cellular partitions. Reworking the example quoted by Steffy [8] using the modified method gives an obstruction factor of 0.92 compared with 0.9, and a similar exercise on the example quoted in the Handbook of the Illuminating Engineering Society of North America [9] results in a similar number of luminaires required to light the occupied room.

→ Trial use In Industry

As part of their agreed contribution Thorn Lighting Ltd and Moorlite Electrical Ltd each commented the format of the design method on and subsequently used it on a trial basis.
Thorn assesses the validity of the design data by comparison with values of obstruction loss calculated using their in-house software(VLS). A series of rooms was set up in VLS each furnished with heavy, medium and light standard obstructions. The analysis was undertaken using three levels of subdivision of room surface namely, in decreasing order of accuracy, 'adaptive' (ie according to luminance gradient) and fixed subdivision of 0.25m and 1.0m square elements. Table 2 shows the results of the simulations compared with predicted OL values found using Figure 7.The Thorn results computed using the adaptive method compare favourably with those using the design method.
Both cooperating organisations contributed comments on the draft design method and subsequently used the method to devise 'shadow' solutions for live projects. These were produced by designers who had no previous exposure to the modified method. Nevertheless they found the method to be easy to understand and use on a number of office lighting projects. At the comment stage the main point of contention was that the inclusion of the obstruction factor in the lumen method would place the designer at a commercial disadvantage since the method at first sight involves the specification of more luminaires than would be the case using the empty room assumption. In general however the application of the modified method did not result in an increases in numbers of luminaires compared with the comparable design using the empty assumption. This was largely due to practical constraints such as ceiling grid sizes which determined luminaire types and layouts. The designers commented that a knowledge of likely light losses enabled them to 'fine tune' the design, particularly in respect of lamp size, and to have confidence in discussing with clients the likely range of performance of the scheme in use. The trial use of the scheme is continuing.

CONCLUSION

This work has developed an easily implemented method of prediction of light loss data for a representative range of interior luminaires for installations of different sizes and with varying degrees of interior obstruction. There is encouraging evidence that the results of the survey and simulation work give similar results. A format for this data for design purposes has been developed and the design method has been successfully field tested. The development and field testing of the method raised a number of issues. Installations designed using the conventional 'empty room assumption' and subsequently filled with furniture will have areas of low illuminance and shadow which are sources of customer complaint. The perceived quality of lighting systems has long been linked to user productivity, satisfaction and visual comfort and thus the use of the method can be 'sold' to clients as contributing significantly to lighting quality, particularly since staff costs far exceed any other operating cost within a typical commercial building. There is evidence that with careful planing and design the costs of an installation designed using this method increases roughly in line with the level of light loss. It is likely that the results of this work will in time be included in Interior Lighting Codes and Standards and will thus be available to all designers, manufacturers and users. Once this information is in the public domain it is likely to become the de facto standard and thus no commercial disadvantage will accrue from its use.

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9 Illuminating Engineering Society of North America, Lighting Handbook 8th Edition, IESNA, New York 1994

Installation	Obstruction Loss (%)	
	Predicted	*Measured*
Health authority general office	10	11
Insurance company general office	11	14
Insurance company general office	8	8
Transport authority engineering office	12	16
Shipping company general office	7	5

Table 1: Comparison of measured and predicted results

Furniture Density	*Design Method Prediction*	LVS Simulated Values		
		Adaptive sub-division	*Fixed sub-division (0.25 x 0.25)*	*Fixed sub-division (1.0 x 1.0)*
High	0.82	0.77	0.73	0.70
Medium	0.85	0.83	0.77	0.75
Low	0.94	0.94	0.88	0.87

Table 2: Comparison of Liverpool and Thorn LVS obstruction factors

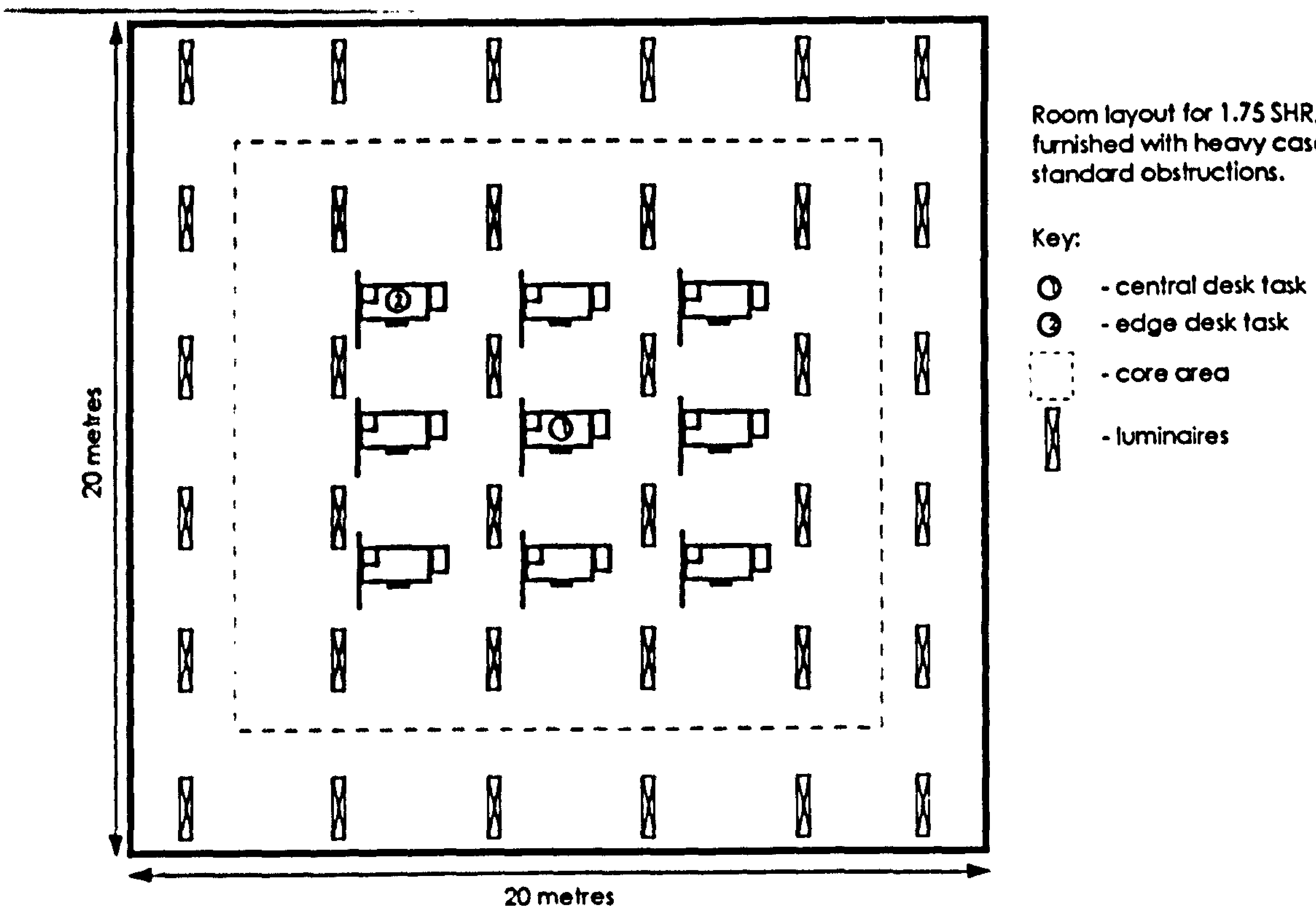

Figure 3 Room layout with heavy case standard obstructions – luminaires at 1.75 SHR

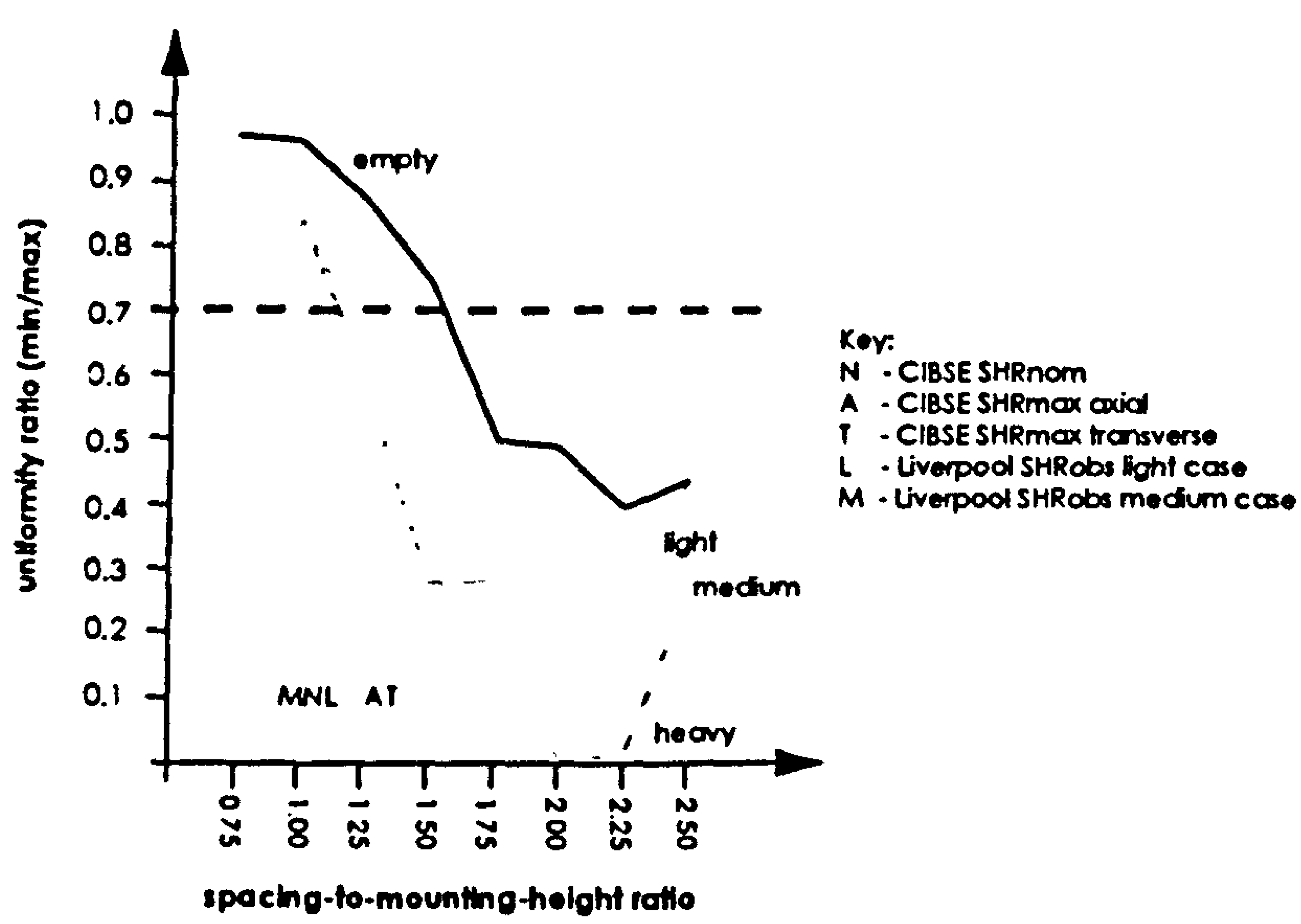

Figure 4 Task uniformity/SHR on edge desk for VDT luminaire

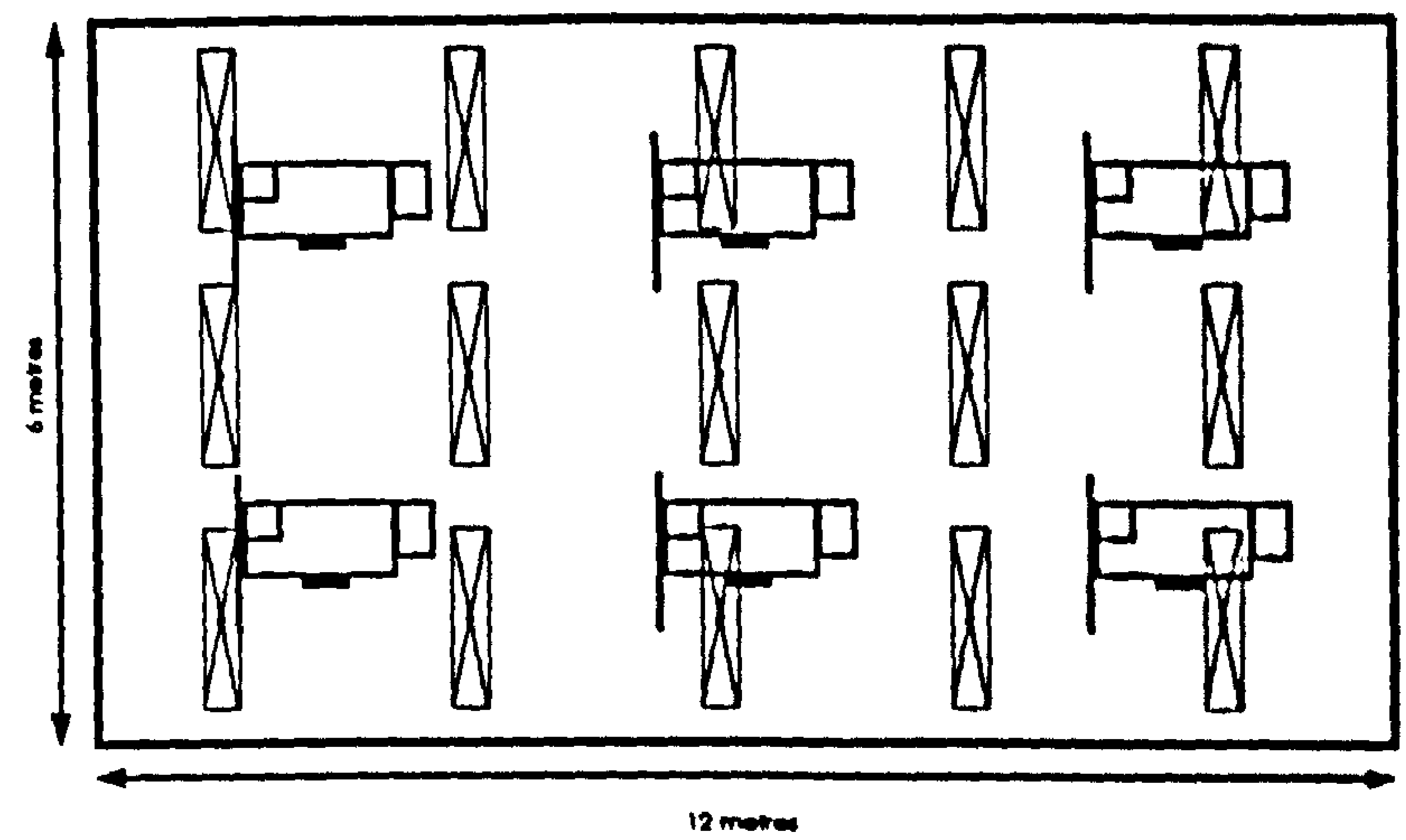

Figure 1: Typical room configuration made up of six 4m by 3m modules lit by 15 luminaires

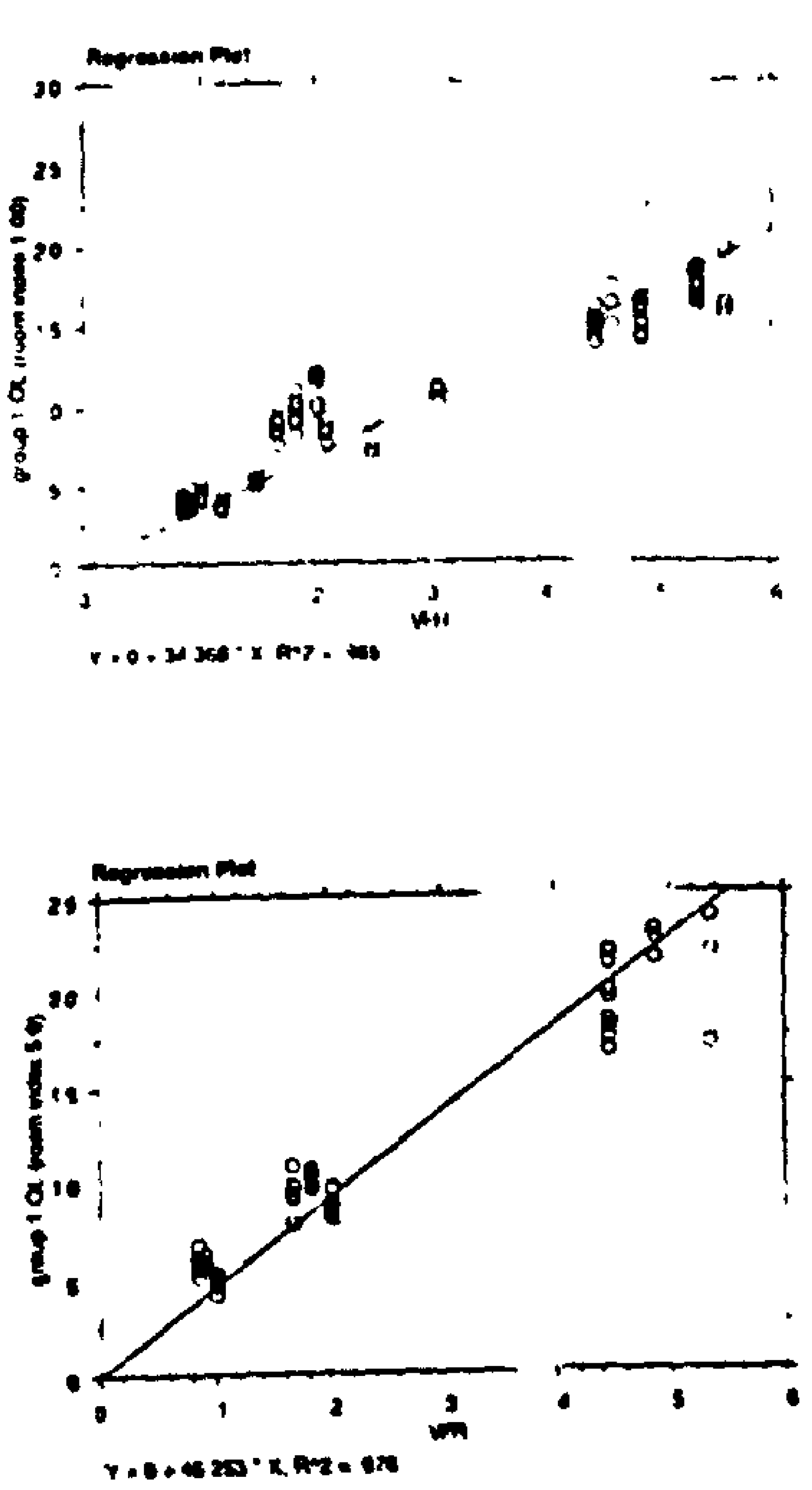

Figure 2: Example graphs of OL/VFR data

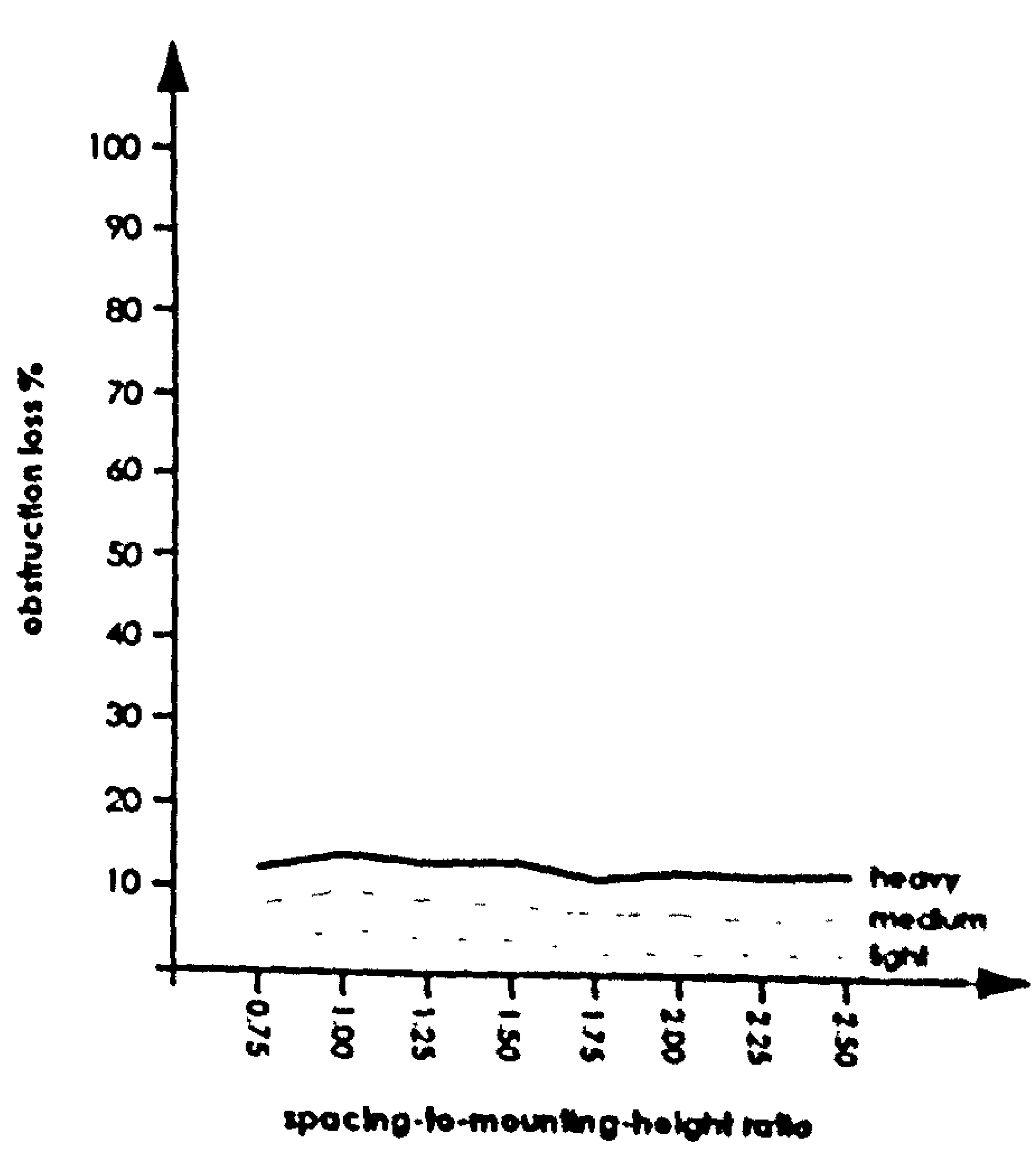

Figure 6: OL/SHR for diffusing luminaire

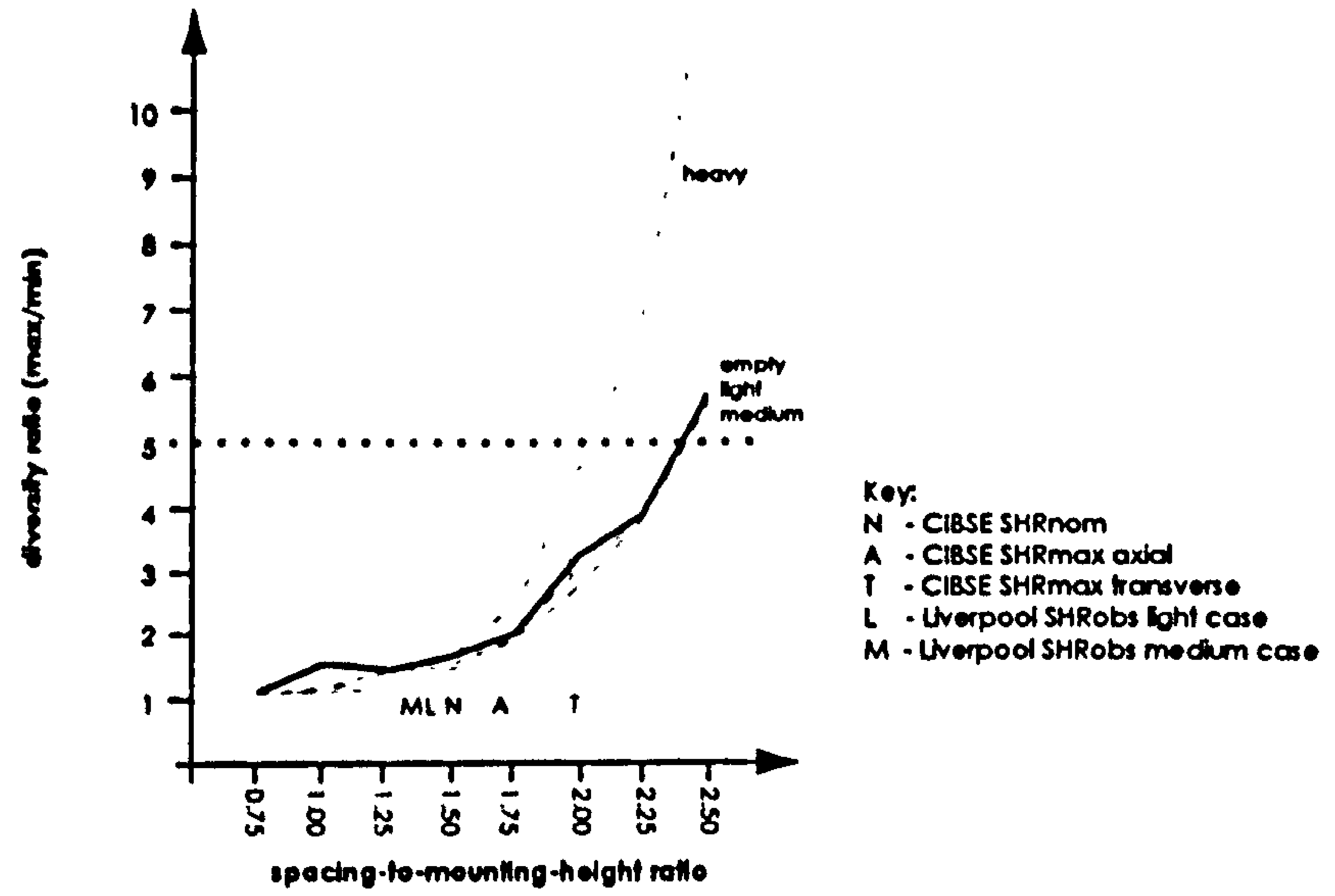

Figure 5. Diversity/SHR for surface modular luminaire

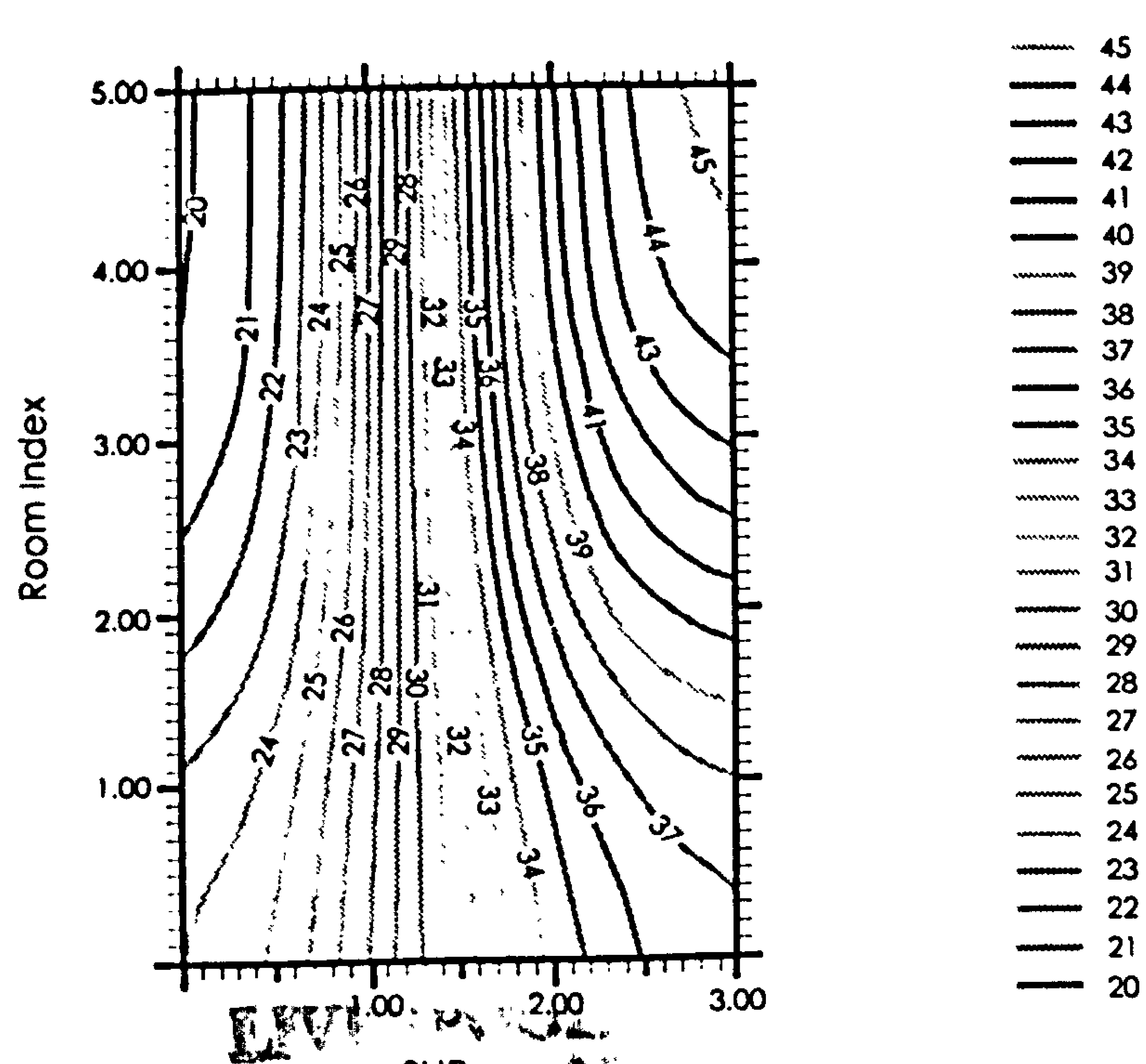

Figure 7. Obstruction loss characteristic as a function of room size and luminaire spacing