A TECHNICAL AND COMMERCIAL ANALYSIS OF THE MANUFACTURE SUPPLY AND PROPERTIES OF NOISE CONTROL FOAMS

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ABSTRACT

Plastic foams are used extensively for the reduction of unwanted noise. With recent changes to the types of foam available and the market for sound absorbers it is possible that a large increase in demand for cellular plastic will occur. By understanding how a foam absorbs sound, methods of increasing performance for a specific application can be suggested.

This work investigates how changes in market forces affect the demand for acoustic materials. As alternative materials can also fulfil any new demand, the way in which foam manufacturers are utilising market changes is investigated. The primary factors influencing changes in the demand for acoustic absorbers are technological developments, legislation and public opinion.

In recent years there has been an increase in the types of foams available to compete for the noise control market. The newer, high performance, foams have properties which overcome the disadvantages that foam has relative to its competitors. Properties and performance of high performance foams are reviewed.

A number of parameters in a foam control its sound absorbing properties. By holding all but one of these parameters constant it is demonstrated how changes have an effect on acoustic absorption. With information on how individual parameters influence acoustic absorption behaviour the possibilities of tuning a foam to a specific application is investigated. The investigation is conducted using models suggested by several authors. Only one model is found to be applicable to cellular plastics and there are limitations to its application.

Increased demand for acoustic absorbers and an understanding of how foams absorb sound would indicate a large increase in the demand for acoustic foam. Due to economic reasons the implementation of technology can be too costly. Using foams in preference to other, usually less expensive, materials requires a transference of information to end users. There appears to be a shortage of expertise in the foam industry to communicate this cost justification. Potential for improvement of foam performance for specific application is possible. Equally possible is an increase in foam production brought about by greater demand for acoustic absorbers. In the next few years observation of the industry will reveal whether potential is translated into profit.

Acknowledgments and thanks.

My most grateful thanks must first go to Dr N.Hilyard, not only for his guidance but also patience and tolerance. Over the duration of the project he has injected enthusiasm and insight without excessive interference. The only thing he was unable to teach me was the difference between effect and affect. I should also like to thank my other supervisors for their contributions; Dr. B Quatermain for his acoustic expertise and Mr. W. Neal for his commercial accounting expertise.

I would like to thank all the people in industry who assisted with advise information and samples. Many of the contributing people are listed in Appendix 1. However special thanks should go to Paul Hanscombe of Pritex, Roger Rodwell (now with W R Grace), Stephen Duffy and Tony Griffiths of Hyman and Robert Belcher of Manrose. At all of these Companies I was made to feel welcome by all their staff. To any Company that I have not mentioned specifically I apologise but you were so many.

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CHAPTER 1

INTRODUCTION

When sound energy impinges on a porous material a portion of the energy is reflected and the remainder is absorbed or transmitted. Technical/scientific investigations of this phenomenon have been documented as far back as Rayleigh [53]. The original porous media investigated were fibrous in nature or made up from small particles. With the development of plastics a new type of porous material became available: CELLULAR POLYMERS, or as they are usually known plastic foams. Plastics technology and hence foams has developed steadily together with our understanding of their acoustic behaviour. Work has been reported relating the physical and mechanical properties of a plastic foam and its acoustic behaviour (e.g. [23],[5],[84]). Similarly there have been studies into the commercial influences affecting the foam market [81] [37]. The primary objective of this investigation is to bring together the study of the technical and commercial aspects of the acoustic foam industry.

(a) Scope of the project

The project investigates current ideas on acoustic absorption theory and the factors within a foam that govern the absorption behaviour. From a knowledge of these factors, methods of optimising foam characteristics can be established so as to provide the best absorption performance for a given sound environment. As we live in the real, highly competitive world it is also important to know whether changes suggested are economically viable. Economic viability involves a study of the manufacturing routes, the current markets for acoustic foams and how developments (e.g. National and EEC legislation) might affect the future situation with regard to, for example noise emission and harmful substances used in foam manufacture.

(b) Reasons for undertaking the project.

Many changes have been taking place over the last few years that have affected the demand for acoustic materials, primarily a concern over problems associated with excess noise. These problems fall into three categories - disturbance, annoyance and noise induced hearing conditions, such as deafness, tinnitus etc. From a noise control point of view the situation is divided into three sectors (i) Industrial Noise, (ii) Environmental Noise and (iii) Noise emission from household products. Legislation and public worry about noise have been increasing. A major use for foam is in noise management systems and hence an in-depth knowledge of all aspects involved with acoustic foams will be of great importance to foam producers and acoustic engineers.

Several adverse market forces have discouraged the use of plastic foams. These influences require investigation. To overcome the adverse publicity about the flammability of PUR and CFC blown foams the plastics industry has been developing new types of foams. In some cases the development has concerned the modification of existing polymer matrices. Other development include new matrix materials and new production or processing techniques. Many factors affect the acoustic foam market, all of which have been investigated individually. Because of the diversification of the disciplines required there has not been an complete study of the acoustic foam market. To fully understand the market requires investigation of acoustics, polymer chemistry, mechanics, business environments and many other disciplines. Although this project cannot hope to fully cover every aspect of acoustic foams it does bring together an overview of most of the diverse aspects.

(c) Methodology

An initial strategy for the project was devised involving the understanding of basic concepts. These concepts include foams (their structure, chemistry, production) and acoustic theory related to absorption processes. On the commercial side it was necessary to develop an understanding of market analysis, costing concepts etc. With these basic tools contacts with industry were made and test samples (both standard foams and speciality foams) obtained. With hindsight it is clear that approaching acoustic foam manufacturers directly was not a good idea. In Chapter 2 the size, structure, segmentation, and the highly competitive nature of the industry are discussed. All these factors contributed in making contact difficult. Initially samples were obtained but very little technical or commercial information was forthcoming. The original strategy therefore had to be modified. There is within the foam industry a very elite group of specialists who deal in acoustics, usually only one in each large company. It was after one of these specialists had been identified that a direction for future work was formulated. Most subsequent discussions with the foam industry have been through these acoustic engineers. They were generous with both technical and commercial information on their products and on foams in general. Care had to be taken with some information and possible conflict of interests when dealing with competitive companies. The transfer of information was not only one way. Most of the personnel in the foam industry have little academic acoustic contact and the acoustic foam engineers were extremely interested in discussing their work as well as current foam projects being undertaken at Sheffield City Polytechnic. The role of the acoustic engineer within the structure of the foam industry will be discussed further in Chapter 2. Because most of the information about the acoustic foam industry has been obtained through a single type of source there will be an element of bias. This bias has been noted and taken into consideration wherever possible.

The investigation of the two sectors of work (commercial and technical) has been conducted concurrently. Although in the past they have usually been treated as separate subjects, in reality they are highly interdependent. If an idea is technically sound but commercialy un-economic it is not worth pursuing. Similarly if a commercial idea is technically impossible then it cannot be pursued.

Technical work began with the development of an understanding of the fundamental aspects of acoustic absorption. These fundamentals were then applied to predictive models. To ascertain the usefulness of the predictive models laboratory measurements were undertaken and the results analysed. From the theoretical studies and measured data, critical factors that can be used to modify a foams acoustic absorption properties were deduced.

Commercially, after ideas on the type of information required had been deduced a programme of how to obtain this information was devised. The programme was deliberately designed with a large degree of flexibility due to the initial problems found in instigating industrial contacts. To obtain the required information a series of interviews with several acoustic foam engineers were arranged. Before the interview took place research on the individual who was to interviewed and their company had been undertaken. This helped twofold, first in wording the questions and secondly as a check to see if the answers were in any way biased. Visits to the company were structured as follows: a general discussion on the company and technical considerations, followed by a more formal interview which was taped. The questions asked at the formal interview were devised before the interview took place. Transcripts of some of the interviews are referenced in Chapter 2. The interviewee has been given a copy of the interview transcript to check for validity and to see if any commercially restricted information that he did not want publishing had been included. The structure of the interview worked well. Information gained from the interviews, from reviewing trade press and other sources have been brought together to understand and predict the future of the acoustic foam market. Within the assessment of the future for foams in acoustic application a comparison is made of what the technical analysis identifies as being necessary, with what the industry plans for the future.

CHAPTER 2

COMMERCIAL ANALYSIS

2.1 Introduction

Polyurethane slabstock is the foam most commonly used for acoustic absorption applications. Details of manufacture and post manufacture technology are given in Appendix 7. To estimate the proportion of the cellular plastic market occupied by acoustic foam is problematic as foams suitable for acoustics application are also used for many other purposes. When foam manufacturers sell their product they are unsure of the end use of a material. Some of the technical service acoustic engineers employed by two major U.K. foam manufacturers have, from experience, estimated the proportion of their slab stock production that is eventually used for acoustics applications. Using information gained from these sources and information from other persons interviewed an estimate of the total turnover of acoustic foam in the U.K. is obtained. Future prediction of market share is more difficult. Although there will be an increase in demand for acoustic materials, foams are one of many materials that can fulfil this demand. If the anticipated changes in the foam and acoustic markets are correctly exploited, then there will be a large increase in demand for acoustic foams. Figure 1 shows the diverse applications for flexible foams. Acoustic applications, as well as having its own sector, feature heavily in all the other sectors.

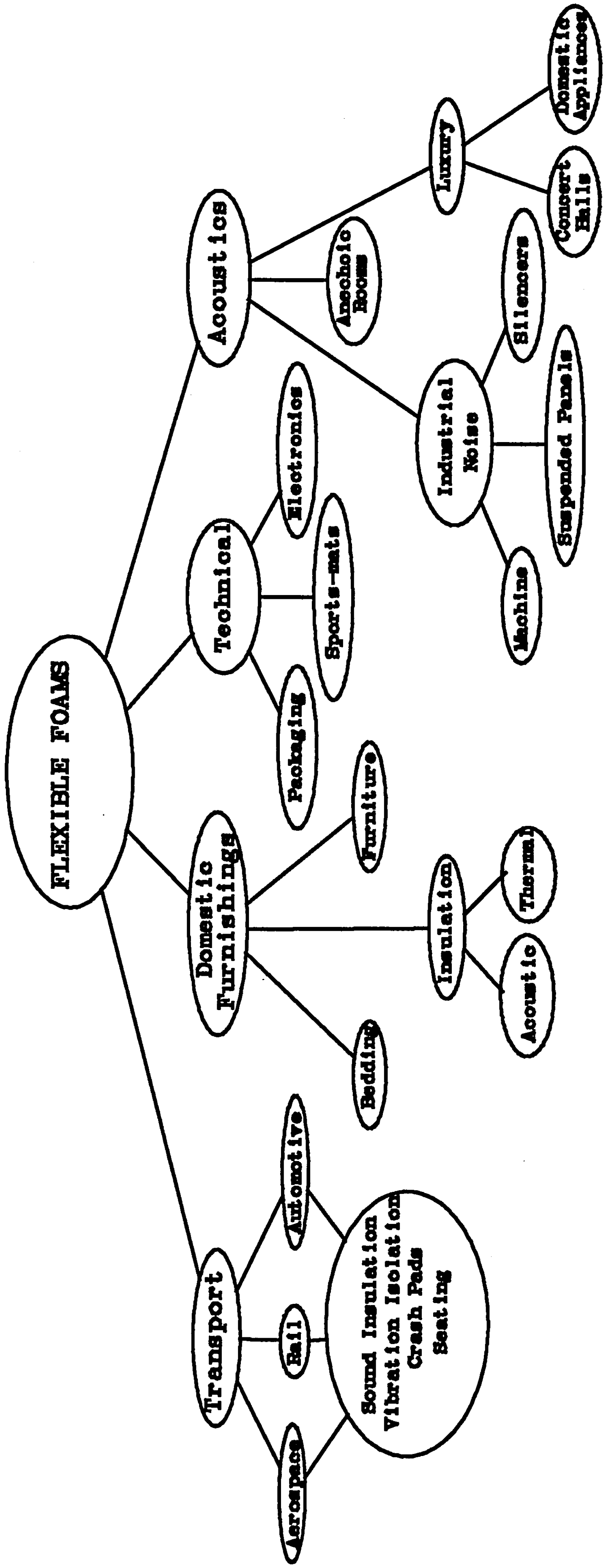


Figure 1 Sectors of application of flexible foams.

The prevalence of acoustic awareness is due to a general increase in the level of luxury goods (low noise is a luxury) now demanded by society and an increase of regard for health. Standards of living enjoyed by the majority of people in the U.K. and Europe have over recent years been steadily increasing. There have been slight regressions but what was once thought of as luxury are now household necessities. Most households have washing machines, at least one television and at least one car. Exploitation of noise reduction as a luxury has mainly been in the area of transportation with all major car manufacturers, constantly through the media, informing the public how quiet their products have become.

An office environment is another area where the luxury of noise control is becoming expected. The dividing panels in open plan offices incorporate a foam layer for acoustic absorption purposes.

The second area were there has been an increased awareness of noise is that of health. Noise induced hearing loss is the commonest form of industrial illness. Although there has been awareness of the problem for many years it is only relatively recently that serious positive action has been taken with the introduction of legislation (1974 Health and Safety at Work Act)[63]. Further EEC legislation has been implemented or is being proposed for implementation in the near future. A large market sector included within the sectors of Figure 1 are military applications. In addition to noise reduction in military transportation being needed for operational reasons it is also important for stealth.

2.1.1 Structure of the Foam Industry.

The various types of foam that are used for acoustic applications have been described in Appendix 7. To discuss the production and marketing process of all the commercially available foams is beyond the scope of this piece of work. For the following analysis PUR slabstock foam will be used.

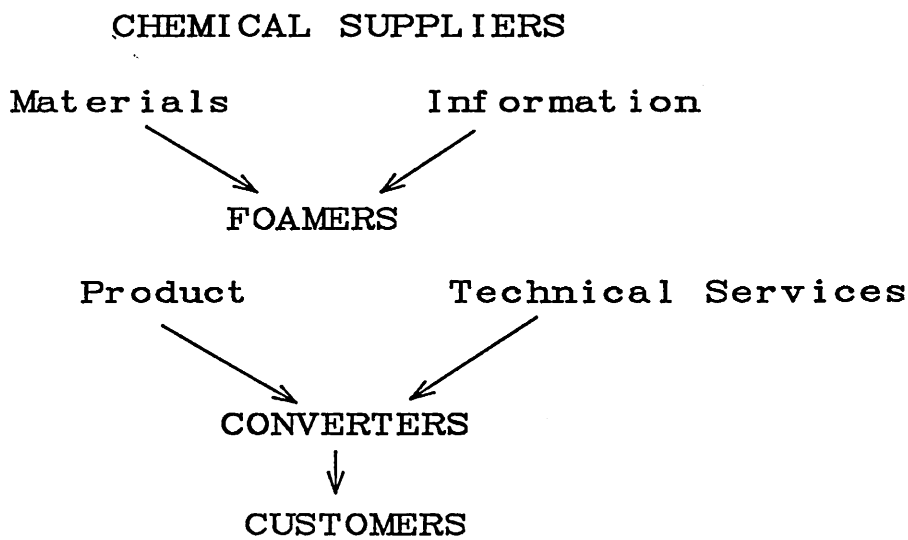


Figure 2 Schematic representation of the components in the foam industry.

The manufacturing route of polyurethane slab stock foam, from initial chemicals to the consumer, is in three stages (a consumer in this case is defined as a company using the foam as a method of reducing sound within their own product e.g. a vehicle manufacture.) (i) The raw chemical suppliers,(ii) the foamers, and (iii) the converters. These three categories of company are often separate and autonomous. Appendix 2 shows most of the current U.K. companies involved with foams. Company groups such as Harrison and Jones include foamers and converters.

A raw chemical supplier will manufacture and sell the base chemicals to the foamer (details of chemistry of polyurethane production are given in Appendix 7.2.1). The chemical suppliers also calculate base formulations. Chemicals supplied to the foamer have most of the additives included. Only slight modifications to formulations are required when a foam is produced. The modifications are intended to overcome the influences of atmospheric conditions. J.R.Sandham [71] discusses these variations and the models that can be used to predict how changes in ambient conditions affect the foam characteristics. Additionally the manufacture of polyurethane chemicals also provide a comprehensive network of advice and technical expertise on foam production. All the chemical suppliers are large multi-national companies and hence have the resources and expertise needed for product development. The help and advice given to the foamer will always involve the increased use of the advising companies products. Chemical suppliers will benefit greatly by a growth in the market brought about by new technology.

The second group involved in producing slab-stock polyurethane foam are the foamers. There are approximately 8 foamers in the U.K., varying from companies like Relyon with a single machine, to companies like Hyman with 3 machines (this can vary as Hyman also develop foam producing machines and might have machines on test). A foamer puts the advice given by the chemical supplier into effect, however it is the foamer that has ultimate control of foam properties. Density and air flow resistance are the main quality control parameters used to assess a finished blocks suitability as an acoustic foam (the relationship between acoustic absorption and air flow resistance is discussed in Chapter 3). Although air flow resistance varies greatly within the finished block if it is within set limits the foamers will consider the foam suitable for noise control applications. An acceptance of the variability, not only from batch to batch but within the same cross section of a foam, of all characteristics (e.g. cell size, cell shape, air flow resistance, etc.) has made the foamers reluctant to fine tune their foam to optimum acoustic performance. It is preferred to select a material from the variations within batches. Additional costs will be incurred in the implementation of theoretical optimisation procedures in their subsequent changes in manufacturing technology. Increased demand for both quality and quantity of acoustic grade foams may change these attitudes.

The final group of companies involved in the foam production are the converters. Foamers produce large blocks of material that require reduction in size, some post production processing (details of which are given in Appendix 7.3.3) and then conversion into individual components as specified by the customer. Some of the processing reduce the size while others such as impregnation, densification etc. alter the physical properties and hence the acoustic characteristics of the material. A further post production processes is the manufacture of composites, ie bonding layers of other material to the foams (e.g. a thin layer of plastic might be added for ease of cleaning). These additions affect the foams acoustic performance.

The three company sectors, described above and as shown schematically in Figure 2, have the following relationships. First the raw chemical suppliers will not produce foam on any large scale; some have small scale plant used for research (e.g. BASF U.K. has a small research/production centre at Alfreton, called Elastogran). A company manufacturing polyurethane will require a large customer base as the machinery used to produce the initial chemicals (polyol and isocyanate) requires large scale production before it is economic. Total world wide production of polyurethane in 1987 was 3.1 million tonnes of which 1.8 million tonnes was for foam (Wouters [81]) for which there are only six major suppliers. The supplier of chemicals has a higher profitability than foam production but requires a higher level of initial investment. As the outlets for foam are already being adequately covered by existing foamers there would be little financial gain for the chemical supplier to enter the foaming market. Additionally if the chemical suppliers produced foam they would also create a conflict of interest with the customers they supply. Should they enter what is a highly competitive market it would create bad will between them and the foamers. There are few very large companies and groups involved in general polyurethane production. Should a chemical supplier upset one of these groups by entering the foam manufacturing sector it could hamper the sale of non-foam polyurethane chemicals that are also bought by the group. An example of these large groups is the Recticel group. Recticel has a turnover of 21.5 billion Belgium francs (approximately £ 0.34 Billion) and deals nearly exclusively in polyurethane, both solid and cellular (details from Recticel annual brochure 'Recticel: Facts and Figures' 1989). The opposite of the segregation maintained between the chemical suppliers and foamers is the integration between foamers and converters. A foamer will produce large blocks of material which for many customers will require further reduction before becoming a saleable product. When a cutting machine has been purchased it can further be utilised for more specialist foam conversions. Further machines for simple converting are relatively inexpensive. It is a logical consequence that foamers enter the converting industry.

Converters can not easily enter the foaming industry due to the initial set up costs. Converters, such as Tmatt usually have other interests and produce special foam products or foam components for their own products.

2.2 Markets For Acoustic Foams

2.2.1 Consumption Data.

The information used in this analysis comes from three main sources (i) Kompass [43] (ii) EXTEL [30] (iii) Interviews with company representatives (transcripts of the interviews are given in Appendix 1). The major U.K. foam manufacturers and converting companies are listed in Appendix 2. Table 1 below summarises data on the proportion of output used in acoustic applications for the two main acoustic foam suppliers.Duffy (Appendix 1 details discussion with S.Duffy) is of the opinion that these two companies have the highest profile in acoustic foams and command about 50% of the U.K. market. From this it is estimated that the current turnover in the U.K. for PUR foams is about £ 2.54m. The error in these estimates can be attributed to two main sources: (i) The data from private communications are subjective and (ii) The final application of foam is not known to the foam manufacturers unless he is also converting a specific piece of foam.

Table 1 Estimates of turnover in acoustic foam for two major suppliers.

Firm	Turnover (1989)	Proportion of output used in Acoustic Application	Estimated Acoustic Turnover
Pritex	£5.8m [30]	30% (a)	£1.74m
Ranwal	£4.0m [30]	20% (b)	£0.8m

(a) P.Hanscombe (1989) private communication, Appendix 1.
(b) R.Rodwell (1989) private communication, Appendix 1.

A cursory examination of the flexible foam market from the time of time of its initial growth period, about 1953, indicates that it should be in the mature stage of its product life cycle. This is

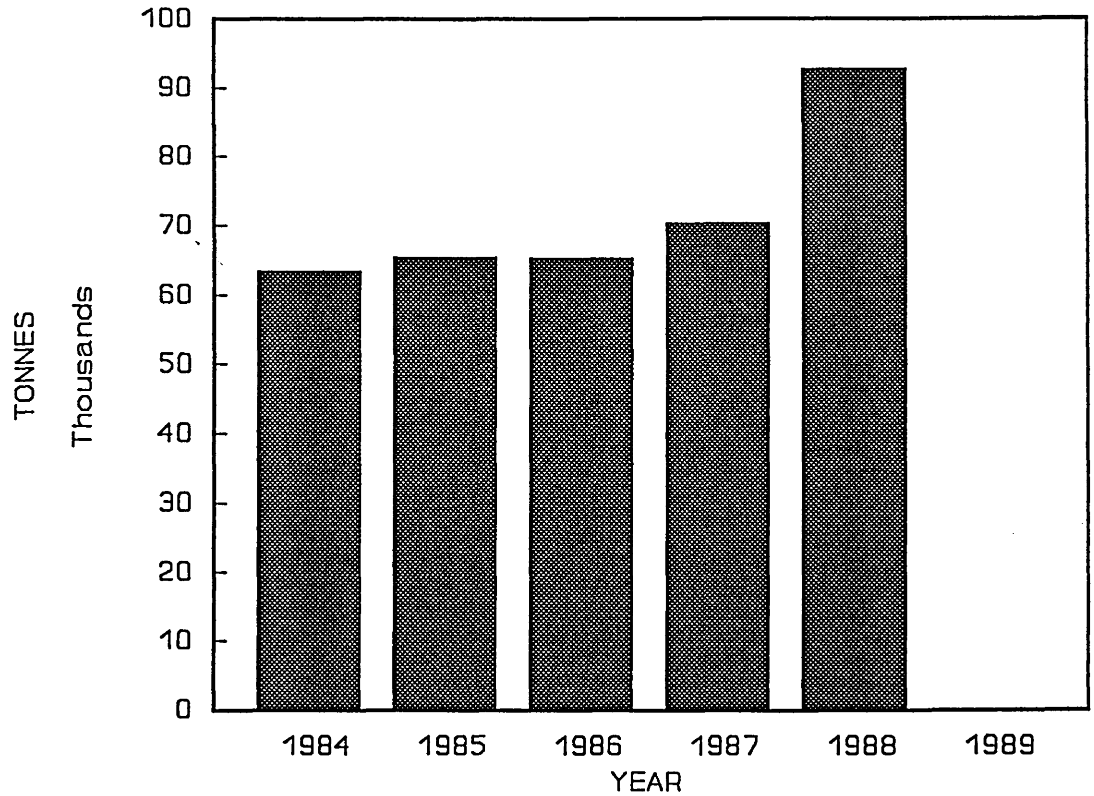


Figure 3 Graph of consumption of flexible foam in the U.K. Data from Business Monitors PQ2415 and 4832 1990.

however incorrect. The product and the markets have not remained static. They have been driven by (a) technical developments, (b) legislation and (c) consumer demand.

Over the last few years 1981-1987 the global market for flexible foams has grown by about 20% ,Figure 3. This represents an annual increase in consumption from $1.8x10^6$ tonnes to $2.2x10^6$ tonnes. Although there have been good and bad years the trend is for an increase in demand. Some factors such as adverse publicity over the flammability of foams will affect all foam production (for example the Manchester air disaster in 1982). Other factors, such as the increases in demand for acoustic material will affect only facets of the overall demand. To demonstrate the large potential that can be fulfilled by foam, a case study of the opportunity in the automotive industry is given in Section 2.5 below.

2.2.2 Factors Influencing Consumption.

As discussed in the introduction to this chapter above and as shown schematically in Figure 1 there is a large variety of applications where acoustic foams are used.

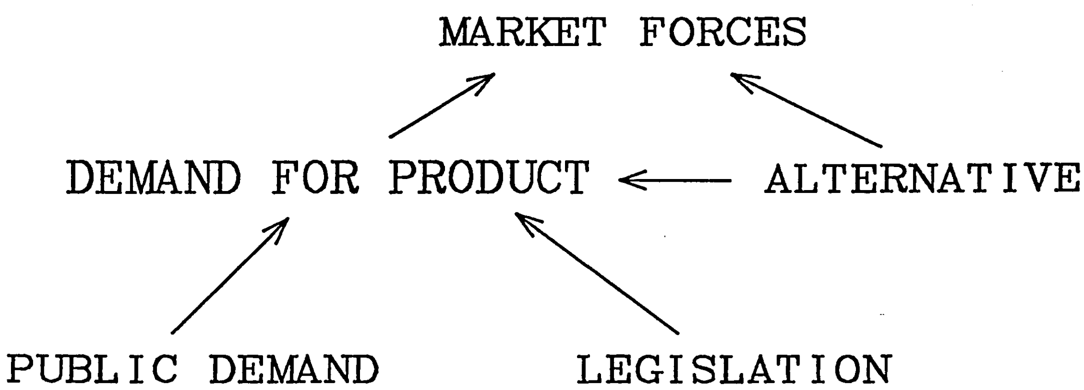


Figure 4 Market forces affecting the demand for acoustic foams.

The key market forces effecting acoustic foams can be divided into two areas (1) increases or decreases in demand for the product. (2) competition from other goods capable of performing the same function. In the case of acoustic foams the first market force (change in demand) can again be further subdivided into two main sectors: demand due to public desire and demand brought about by legislation. Examples of these two market pushes are typified in automotive industry. The interior of a car is required to be quiet by public demand whereas the noise emitted from the car (kerb side or drive past noise) is required to be low by regulation [29]. Details of legislation on curbside noise follows in Section 2.3.3.

2.2.3 Increase in demand due to public pressure.

The public pressure for decreased noise in not only in vehicles. Over the last few years there has been an increase in general awareness of noise. Examples of this can be seen in the London

Docklands development (e.g. 25/7/88 Guardian), where the most crucial factor in the airport design was the amount of noise emitted from the aircraft. It is publicity from issues like the London docklands development that make the general public more aware of noise. Another contributing factor to people's awareness is when an employer fulfils its legal commitment to educate in the hazards of noise. Legislation is discussed below. However by far the largest contributor to public awareness of noise is still the automotive manufacturers. All major automotive manufacturers are using the low interior noise level of their vehicles as a critical portion of their technical sales/marketing strategy. Originally noise reduction developments were in the larger luxury car sector. As with all automotive developments, what was a luxury is now becoming standard and cellular plastics play a major role in the achievement of vehicle specification.

2.2.4 Increase in Demand Caused by Legislation.

Historically attitudes by management to noise emitted from industrial machine have been poor, as it is an intangible problem. Management, from its quiet offices, find it difficult to appreciate the reasons why a quiet factory is required. There is no perceived return on investment in noise reduction procedures. With larger, faster, more powerful and hence noisier machines being required for more economic production the noise problem is increasing. An awareness of the problems caused by long term exposure to excess noise is well established and legislation is changing with the changes in awareness. When more stringent legislation on levels of noise allowable in any situation is introduced there will be an affect on the demand for noise reducing materials ie acoustic foams. Some of the new legislation related to noise reduction is reviewed below.

Legislation

Current legislation on noise at work is very general and based on the 1974 Health and Safety at Work Act. The act is designed to reduce all types of risk at work. The Health and Safety Executive (HSE) which enforces these regulations uses the " Code of Practice for the Reduction of Employed Persons to Noise" [14] as its interpretation of the noise section of the 1974 act. Since the act's introduction the HSE has increased its efforts to enforce the legislation as can be seen in Figure 5. The graph shows the number of notices issued by HSE inspectors in respect of noise. Data for the graph were obtained from [27]. It was not until 1983 that the first immediate prohibition notice was issued but after 1983 they were being issued on a regular basis. From the graph a general trend of increase in concern regarding noise levels is deduced. However the HSE has always wanted tighter regulations and in 1981 it submitted new draft regulations and guidance documentation [63] [77]. Because of the initiative for the unification of the European market the 1981 draft documents were put aside in favour of an EEC directive [18]. This was adopted in 1986 for implementation in 1990. Differences between the Code of Practice currently being used by the HSE and the EEC directive are not large, although where there are differences the directive is tougher. When one compares the two documents, the main difference is that the code of practice states a level of 90 dB (A) at which something must be done. In the EEC directive there are three action levels;

(i) <85 dB(A),

(ii) > 85 dB(A) < 90 dB(A)

(iii) >90 dB(A)

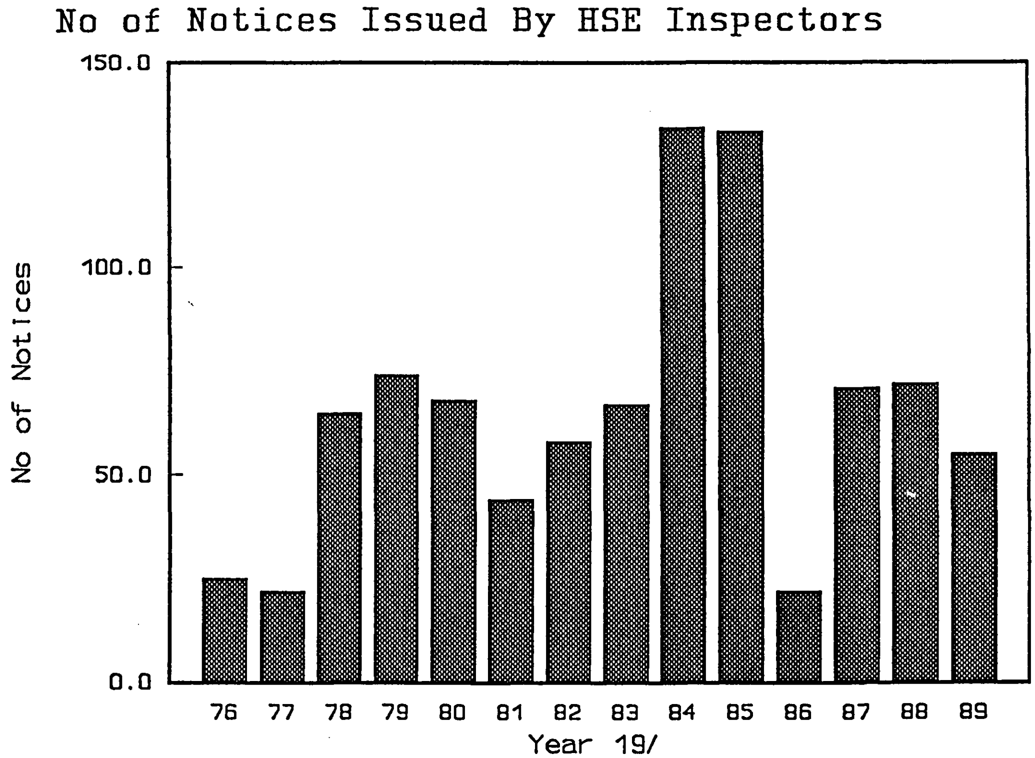


Figure 5 Graph to show the number of notices served by the Health and Safety Executive, related to noise.

It is the introduction of the 85 dB(A) action level that major differences will occur. At this level over twice as many workers will be covered by the legislation. Approximately 630,000 workers are exposed to noise levels above 90 dB(A), whereas 1.7 million are exposed to over 85 dB(A) (data from Health and Safety Executive [27]). Other changes include peak action levels. The HSE still considers the new legislation inadequate and it is due for review in 1994 when further reduction more in line with the 1981 proposed changes will be considered. A level of 85 dB(A) was originally proposed by the commission but lobbying by the CBI (who estimated a cost to British industry of 500 million pounds for 85 dB(A)) increased the level to 90 dB(A) [79]. Other noise related health risks, not including hearing loss, are still covered by the 1974 HSW act.

To assist in the tightening of noise control, legislation on the noise emission from all machines used in the U.K. is being implemented. On 15 June 1989 the European council adopted a directive [17] which is intended to be implemented in December 1992. The directive requires machine manufacturers to report and label all machines capable of producing 70 dB(A) and above. Legislation on specific types of machinery are already in operation and a resume of some of these machines and relevant directives are given in Table 2.

Table 2 A selection of EEC regulation on noise emissions.

Directives	No
Directive on the determination of noise emission of construction plant equipment.	79/113/EEC 81/1051/EEC 85/404/EEC
Common provision for construction plant equipment.	84/534/EEC
Tower cranes.	84/405/EEC amended 87/405/EEC
Compressors.	84/533/EEC
Welding Generators.	84/535/EEC
Power Generators.	84/536/EEC
Concrete breakers and picks.	84/537/EEC
Lawnmowers.	84/538/EEC amended 88/180/EEC and 88/181/EEC
Dozers and excavators.	86/622/EEC
Agriculture or forestry tractors.	77/311/EEC
Powered industrial trucks.	86/663/EEC
Household appliances.	86/594/EEC
Machinery directive.	89/595/EEC

When legislation is introduced the demand for acoustic absorption material will increase as noise from the current plant is reduced by barrier and enclosure techniques. When the plant is replaced it will be designed with acoustics as a prominent selling feature. After plant has been replaced the rate of increase in demand will decline until growth is at the pre legislation rate but at a much higher level.

The expected increase in demand for noise reduction has already become apparent and can be seen in the increased advertisement in the trade journals for acoustic related positions. In the foam industry all the persons interviewed stated that from their experience, acoustic related work was consuming more of their time than previously.

So far only the legislation on noise levels affecting workers has been discussed. There is also legislation regarding annoyance noise imposed on the general public. This type of environmental noise is covered by the 1974 "Control of Pollution Act (Sections 56-58)" and enforced by local Environmental Health Officers. Reduction of noise emitted from an industrial premises uses little sound absorbing materials (typical noise sources are compressed gas outlets that require mechanical silencers). Also there is no change in regulation anticipated in the near future, therefore legislation on environmental noise will have little effect on the acoustic foam market. Information of environmental noise was obtained from an interview with M.Bayley, Environmental Health Officer for Rotherham district Council.
A second area where legislation is implemented is noise emission from vehicles. The legislation has been slowly decreasing. A direct comparison is difficult as the categories for vehicles is has not been kept constant. (e.g. 84/372/EEC classifies vehicles according to weight whereas newer legislation 84/424/EEC categorises in terms of engine power). A general reduction of 5 dB in the noise levels

permitted to be measured as a vehicle drives past a stationary observer has been introduced over the last 15 years. The figures of 5dB is approximate, being taken from EEC documents 84/424/EEC and 84/372/EEC. Below is an example of the typical changes in the legislation.

Legislation

84/372/EEC	84/424/EEC		% reduction in Sound Intensity
3.5-12 tons 86dB	Upto 100 hp	81 dB	66
	100-200 hp	83 dB	50
> 12 tons 88dB	>200 hp	84 dB	66

Although it is not required by the EEC that the new legislation be brought in to effect until April 1991 in many European countries the legislation is already being implemented. All of Europe will have implemented the directive by January 1992. Other non EEC countries have also accepted the directive as standard.

2.3 Cost analysis of foam production.

The following discussion is on factors involved in the cost efficiency of production of PUR foam for use in acoustic applications. When the costs have been ascertained an estimate of return on investment will be made. The technique used will be Net Present Value (NPV). From NPV the Internal Rate Of Return (IRR) will then be calculated. The discounted cash flow methods were selected in preference to other cost analysis techniques (e.g. pay back periods) as they represent a more realistic analysis (taking into consideration the fact that cash in hand is worth more than promised cash in the future). Details of NPV and IRR can be found in standard accounting or business text books. Data on which NPV evaluation is to be applied have been obtained from several sources. A summary of the sources and a justification for the data are discussed below. PUR is the most widely used foam, hence the analysed is on this type of foam.

Land and labour costs are regionally dependent, hence the NPV evaluation has been conducted with cost taken from around the Sheffield area.

Three different machines used for PUR slabstock production will be assessed; Max foam, Vertifoam and Miniflex. These machines have been described in Appendix 7.2.2. Miniflex is a smaller, more compact version of Vertifoam. Details of machine production capabilities were obtained from data sheets supplied by Viking PTI Ltd. of Stockport, an engineering company that specialises in the manufacture of machines used in slabstock production. Further details of manufacturing quantities have been deduced from production manuals distributed by Shell and Dow chemicals.

Within the umbrella of PUR there are many types of foams and variations in selling price. The least expensive is sold by the foam manufacturers for approximately £80.00 per cubic metre. This type of foam is very crude with little uniformity in material characteristics. Often this inexpensive material will be the front of a production run before the parameters in the foam have stabilised. With the addition of additives, higher control testing and post production treatments the trade selling price can rise to £300.00 per cubic metre. All grades of material are employed for acoustic applications, however the most commonly used has a trade selling price of approximately £110.00 per cubic metre.

The cost of chemicals will vary greatly with quantity. Additionally because the chemicals are petrochemical derivatives costs will be highly dependent on oil prices. Figures for base chemicals used in this evaluation were originally obtained from ICI and Shell via. telephone conversations. These were then verified by conversations with foam manufacturers (Pritex and Hyman).

Wage prices where obtained from Government published figures. Building costs were estimated by the Information Service of the Royal Institute of Chartered Surveyors, in Kingston upon Thames. They stressed that prices are extremely volatile in today's economic climate.

Information on rateable value came from the Sheffield development agency. Figures obtained are for buildings erected after 1 April 1990 when a new system of rate assessment was implemented. Older buildings will gradually be phased into the new rate assessment system. Assessment of rates are dependent on many factors however a figure obtained from comparison with a recently constructed factory is £25.00 per square metre. This is then multiplied by the uniform business rate of 34.8 pence in the pound to give a cost of £8.70 pounds per square metre of factory space. A summary of the values used in the NPV analysis is given in Table 3.
Output from the three machine types will vary. For analysis, two output rates for each machine have been calculated. Results are given in Table 4. Output rate has a maximum upper limit, however machines are rarely set at these rates. A rate has to decided upon at which all the foam produced can be sold. If production is below the chosen level, storage and other facilities are under utilised, presenting additional costs. Should there be a possibility of un-satisfied demand there will be a loss of possible revenue or

Table 3 Summary of values used to calculate cost of foam production.

Characteristics	Miniflex	Vertifoam	Maxfoam
Max output /tonnes per year	1000	4000	3000
No of tech workers	1	1	2
No of manual workers	2	3	4
Cost /£	300000	430000	590000
(*)Machine Housing /£	1900000	2300000	3000000
(*) Rates /£	18500	24700	33400

* based on Area

opportunity cost. Because the product has a large volume an increase in output will require subsequent large increase in storage area. Due to the additional safety precautions required the cost of having storage facilities available for over production becomes uneconomical. The storage of this high volume product can make a large increase in cost and according to Paul Hanscombe (see Appendix 1) it is not unusual for material to go from raw chemicals to finished product (cut formed etc.) in 3 days. Calculations of space used in the NPV analysis is slightly higher than the chosen output as production cannot be at maximum all the time.

Table 4 Expected returns for investment in three different foam manufacturing plants.

Performance	Miniflex	Vertifoam	Maxfoam
NPV (0.2) 1000 tonnes	680000	120000	-31000
IRR 1000 tonnes	25.9	20.9	12.5
IRR 3000 tonnes	-	91.2	66.9
IRR 4000 tonnes	-	127.7	-

Examples of the calculation of NPV set at 0.2 for each machine is given in Appendix 5 for each machine and at a production rate of 1000 tonnes per year.

From the discounted cash flow analysis above the following conclusions can be drawn. For small quantity production, around 1000 tonnes, the most suitable machine would be the Miniflex. Production quantities above 1000 tonnes would appear to be more suitable for the vertifoam type of machine. This point was put to P.Hanscombe (Appendix 1) who runs a Maxfoam type machine. Foam from a Vertifoam is not as 'tight' as that from a Maxfoam. A much more open foam is produced which is less suitable for acoustic use. The analysis is sensitive to changes in material and selling cost. In the present economic climate these are extremely variable. Demand for the product is also extremely variable.

2.4 Alternative Materials.

Above, a case is made for a large increase in demand for quietness brought about both by public demand and legislation. Acoustic absorbing materials are the primary method of reducing noise. However there are several other types of acoustic absorber, apart from foam, capable of satisfying this demand. Any consumer, when purchasing a product, will evaluate alternatives, balancing good points against bad points and arriving at a product that will maximise their utility. There are many factors that have to be considered. A bias that each consumer puts on each factor will vary. Key factors are shown schematically in Figure 6. Before these factors are discussed, a brief description of the main alternatives to foam will be given.

There are other methods of reducing sound energy levels apart from using porous media e.g. product design, addition of silencers or resonators machined into a construction panel. Further details of these methods are given in References [5] and [75]. These types of

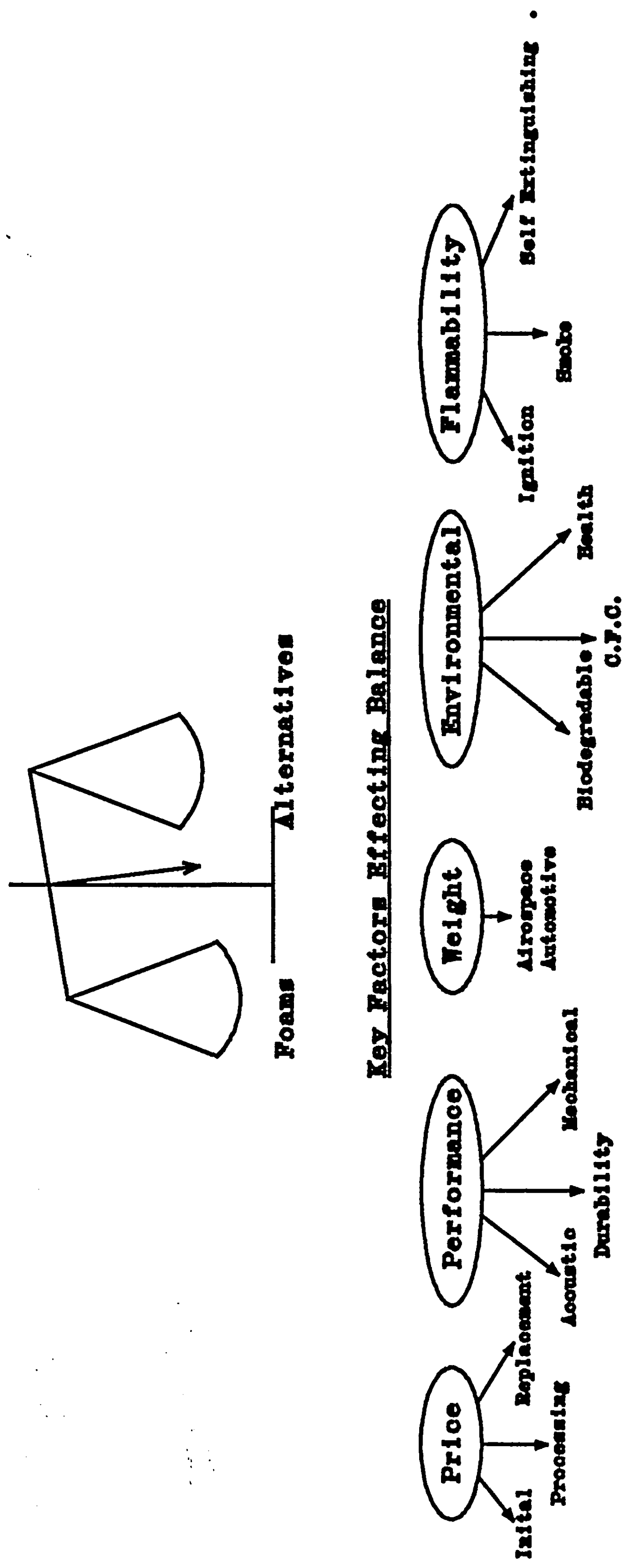


Figure 6 Schematic representation of factors influencing a consumers choice of acoustic material.

noise reduction are used in a few specialist applications. Originally, fibrous materials were used as porous sound absorbers, however with advances in the plastics industry and the advent of cellular materials the fibrous type material are being gradually superseded. Fibre felts, mineral wools and natural materials alternatives to foams for acoustic absorbers. Characteristics are shown Table 5.

The information given in Table 5 is from manufacturers' information sheets. Information on random incident absorption was not available for Felts. Manufacturers' data for felts are normal incident absorption on 10mm samples. In Chapter 3 the theoretical effects of sample thickness on absorption are discussed. Therefore when one compares absorption of materials, equal thickness are required. Felts are compared with a rigid foam in part B of Table 5.

Felts are animal and manmade fibres which, when compressed or needle punched form a fibrous mat. A similar material, falling into this category, is animal fibres (horse hair etc.) bonded together with rubber. These materials are still being used today, but to a limited extent. Other commonly used sound absorbing materials are mineral wools, which are thin fibres spun from molten rock or glass, a similar process to candy floss manufacture. Naturally occurring materials are also commonly used, for example cork. Details of the forms and typical applications are given in Table 6. Other alternative materials will not be discussed due to their limited use, e.g. curtains, acoustic tiles.

The key factors affecting the decision a prospective user of sound absorbing material would make are shown in Figure 6.

Random Incident Acoustic Absorption of Selected Materials

Table A

	Material	Thickness /cm	Density /Kg m^-3	125 /Hz	250 /Hz	500 /Hz	1000 /Hz	2000 /Hz	4000 /Hz	NRC
Foam										
	Fireflex S30	50	28-32	0.16	0.77	1.04	0.98	0.98	0.99	0.94
	T31	50	28-32	0.14	0.69	1.10	1.02	0.97	0.96	0.95
	IMF	50	27-30	0.10	0.60	1.07	1.00	0.95	0.98	0.90
	T29/60 D	50	26-28	-	0.45	1.03	1.02	0.91	0.95	0.85
	Firend T360	25	>60	-	0.20	0.50	0.70	0.79	0.72	0.55
	Audioprene		28-30	0.26	0.61	0.97	1.11	1.07	1.02	0.94
	Audioprene R		27-30	0.26	0.70	1.10	1.06	1.06	1.10	0.98
Rock wool										
	Slab RW3	50	60	0.11	0.60	0.96	0.94	0.92	0.82	0.86
	Slab RW6	50	140	0.20	0.75	0.90	0.85	0.90	0.85	0.85
Glass wool										
	S100	50	16	0.25	0.45	0.80	0.80	0.85	0.85	0.73
	S200	50	32	0.15	0.50	1.00	1.00	1.00	1.00	0.88
	Sonic Liner	50	20	0.30	0.90	1.00	0.95	0.95	0.98	0.95

Table B

Material	Thickness /cm	Density /Kg m^-3	Normal Incident Acoustic Absorption /Hz											
			200 /Hz	315 /Hz	500 /Hz	630 /Hz	800 /Hz	1000 /Hz	1250 /Hz	1600 /Hz	2000 /Hz	3150 /Hz	4000 /Hz	5000 /Hz
PU Foam	14.5	68	0.08	0.09	0.19	0.25	0.32	0.41	0.25	0.45	0.5	0.77	0.94	0.96
Felt A	11.5	144	0.06	0.05	0.13	0.13	0.18	0.23	0.1	0.44	0.47	0.75	0.79	0.89

Table 5 Random incident absorption characteristics of materials commonly used for noise control applications.

Table 6 Materials that compete with foam, their most popular use and maximum continuous operating temperature.

Alternative - Competitive Materials			
Materials	Form	Major Applications	Max. Operating Temp /°C
Foam (PUR & PVC)	Sheet, Blocks, Mouldings, Composites	Automotive, Marine, Industrial	100
Speciality Foams	Sheets	Military, Aerospace	300
Rock Wool & Glass Wool	Blocks Blankets Rolls	High Temperature, Building, Under Bonnet	230
Felts	Blankets	Under Carpet Automotive & Domestic	100

Cost Superficially the cost of foams relative to other materials does not make them a realistic alternative.

Table 7 Approximate cost factor of sound absorbing materials.

Materials	Cost Factor
Foam	1
Felt	2/3
Mineral Wool	1/2

When one compares materials, it is seen that felts are approximately two thirds of the price of foam and mineral fibres in the region of half the price. It is the manner in which foams are used which makes them economic alternatives, creating cost reductions via:

(1) Reduced number of components

(2) More efficient usage of materials

(3) Optimum coverage of sensitive areas

(4) Reduced assembly and installation time

(5) Design flexibility

(6) Potential for robotic assembly of finished components

(7) Lightness in weight

(8) Retention of performance over long periods

(9) Resistance to chemical and biological degradation

(10) An ability to tailor properties

Foams have the ability to be cut, formed, moulded, or injection moulded into complex shapes that cannot easily be obtained from alternative materials. Also foams can be easily bonded to other materials, creating composites with a set of properties not otherwise available. By correctly using the properties of foam and foam composites, products are created that can replace several components with one new component. Single components have a reduced assembly cost, making foam/composites more cost effective than traditional materials.

<u>Performance</u> A sound absorbing material's absorption capabilities are not always the highest priority. For example if two materials are being considered for an application and the least expensive is a inferior sound absorber, by using more of this material, the required absorption is obtained and costs reduced. Other performance considerations are how a material will perform over time in the physical and chemical environment in which it is required to function. Performance of a material after exposure to excess heat or chemicals affect the material selected for a given application. Often a material used for acoustic applications will perform

secondary functions which, together with durability, make mechanical strength, tear resistance and fatigue resistance contributing factors.

<u>Weight</u> is of primary importance in acoustic problems related to transportation. Any weight increase is directly related to increased fuel consumption and hence running costs. In aerospace, especially, weight is especially important, taking precedence over many other factors. When both sound transmission and acoustic absorption are considerations additional mass can be an advantage.

<u>Environmental</u> "Green" or environmental issues are becoming more prominent daily. At the forefront are factors such as biodegradability, recycling and the ozone layer. These issues are of significance where foams are concerned. In common with most plastics, polymer foams are not biodegradable. Many study groups have been set up to examine the feasibility of recycling. A specific example related to foams was reported in the 1987 UTEC conference [81] where a group had been set up in the USA to consider the problems of urethane. One major effect of the unification of the European market in 1992 is the greater concern regarding biodegradability that the Europeans have, compared with the U.K.

The other major environmental issue affecting foam producers is CFCs. CFCs are used as a blowing agent during foam production (Appendix 7 gives further details of foam production). Twenty percent of the world's 1988 CFC consumption was used for foams [37]. Since the Montreal protocol on CFC reduction, foam manufacturers have found alternative methods of blowing foams [16] [83] and water blown foams are quite common. Generally the use of CFC in flexible foam has been phased out.

Health A very important reason why foams are preferred over alternative materials is a general fear of fibrous material. Many people associate material like rock wool with asbestos. In America, legislation has been introduced classifying Rockwool etc. as hazardous materials. If they are used anywhere in a product, full safety literature must be supplied. The health hazard is not great, the main problem for suppliers being public attitudes, and few people are willing to purchase any product with fibrous material in it. Cellular plastics are clean, easily machined, moulded or formed, light, and now reasonably fire resistant. Fibres can also cause irritation and be difficult to clean.

Flammability: Polymers are all combustible to varying degrees and can rarely tolerate temperatures above 150° C. With the large amount of air in foam, a fire would have an oxygen supply readily available. Similarly other base materials (animal and manmade) used in acoustic products will also contain air, making excellent oxygen sources for any fire. Minerals used in mineral fibre sound absorbing blankets have excellent fire resistance.

Of all the acoustic absorbing materials, foams (particularly PU foams) have the greatest problem with flammability. Not only do they burn readily, but there has been a large amount of press coverage concerning the fires where foams are held to be the cause of death. There was a large increase in the bad press in the late 70's early 80's with incidents like the Manchester air disaster (1982), Mansfield leisure centre fire in Belfast (1984) [13] and the Woolworth department store fire (1978) [13]. In all these fires many people lost their lives. It was not just the fire that killed but the dense choking black smoke and noxious gasses (e.g. hydrogen cyanide) that are given off when PUR foams burn. Further details on all aspects of "Fire in Cellular Polymers" can be found in a book by that name edited by J.M.Buist et al [13]. The publicity given to foam fires has forced the foam manufacturers to modify their products. Many manufacturers have turned this bad press around and use the flame resistance of modified foams as a positive selling point. References [60] and [61] are typical of the articles written on foam flammability, in relation to new flame retardant foams.

At this stage it is important to note that the fires involved mainly furniture (the Mansfield leisure centre fire involved foam gymnasium mats). The resulting publicity and development will, however, affect all foams. Regulations on the flammability of foams at present only relate to furniture, however there is much concern from any foam purchaser with regard to flammability. The manufacturers interviewed (see Appendix 1) indicated that because of the high profile of foam flammability, a consumer of any type of foam would require that foam be flame retardant. Legislation on the flammability of foam in furniture was introduced in February 1988 with "Furniture and Fittings (Fire)(Safety) Regulations 1988 (Statutory Instrument 1988 No 1324)". This legislation does not directly affect acoustic grade materials. Indirectly, however, the legislation will affect acoustic foams as they are usually manufactured in the same batch as furniture foams.

To reduce a foam's hazard in a fire situation, several techniques are employed, the most popular of which are:

(i) addition of melamine powder, which will, char forming a surface non flammable barrier.

(ii) addition of alumina trihydrate which upon heating produces water to extinguish the fire.

(iii) Designing the foam so it shrinks away from any flame source.

(iv) Using different base polymers for the foam (see Appendix 7).

There are other methods used but at present the above are the most popular. All the methods will affect the physical properties and generally put additional cost onto the selling price of the foam.

Felts have similar flammability problems and are therefore usually treated to increase their flame resistance.

2.5 Case study: The Automotive Industry

Noise control is taking a higher and higher profile in all types of transportation. The car is an excellent example of this and clearly demonstrates consumer 'pull' for lower interior noise levels, and legislation 'push', to achieve lower exterior noise levels.

The Main Noise sources in a car are;

(i) Engine

(ii) Exhaust

(iii) Road Noise (tyres)

(iv) Wind Noise

Ideally, noise should be eliminated at source. This is often attempted and an example of this is in better car aerodynamics which reduces wind noise. All current vehicle manufacturers are producing cars with reduced drag coefficients, reducing petrol consumption and noise. Progress is also being made in other areas. Despite these reductions there is still considerable unwanted noise. Noise created within the car falls into two categories;

1. Air Borne
2. Structure Borne

Foams can be used to reduce both these types of noise: sound absorbing foams can reduce interior noise and heavier viscoelastic foams are used for noise insulation and vibration damping.

However foams are not as prevalent as they could be. Areas where noise reduction materials could be or are employed are illustrated in Figure 7 to Figure 12. In all these applications the current use of foam is limited. To estimate the potential market for acoustic foams in cars the major areas used for sound controls are considered separately.

1. Floor carpet composites panels

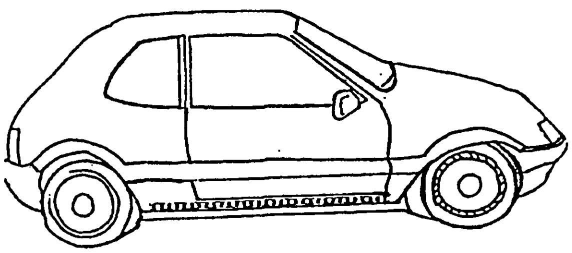


Figure 7 Areas in a car where acoustic floor coverings are used.

Floor panels are multi-functional, having to be decorative, hard wearing, easy to clean as well as being able to absorb and insulate sound and vibrations. In most modern cars, these objectives are satisfied by a carpet backed by an acoustic layer. Traditionally the acoustic layer was of felt or fibre blanket. Foams are replacing these materials although some large manufacturers still prefer the traditional materials (e.g. Ford mainly use fibre felt as a sound absorber).
From an ICI News Letter [39] it can be deduced that there is on average 3.5 m^2 of carpet in every car. A typical specification for the thickness of the absorbing layer [40] is between 3-25 mm (an average of 12mm is assumed.)

The average quantity of foam used under carpets in cars is therefore about 0.42 m^3. Additional septum layers of heavy rubber or bitumen are added for damping. These, as suggested by Zwinselman and Bachmann [87], could be replaced by viscoelastic or highly filled foams.

2. Door Panels

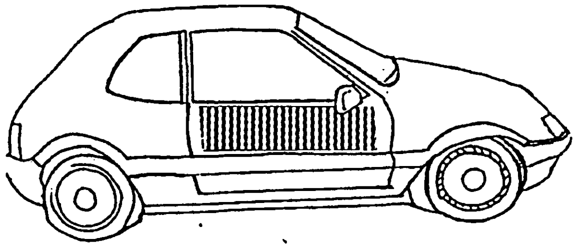


Figure 8 Areas in a car where additional sound absorbing material could be used, door panels.

Most door panels are moulded plastic or hardboard covered with a decorative layer. There is available space behind a door panel which is rarely used for sound absorption. With the increased use of electric windows door panels will no longer be required to incorporate the window closing mechanism in the door panels. The door panels will then be continuous, with additional room for acoustic sound absorbers.

In company specifications door panels [40] are between 10 and 20 mm thick (assume an average of 15 mm). An estimate of the area of each door is 0.7 m^2. If four doors are included the total volume of sound absorbers that could be used in doors will be 0.42 m^3.

3. Headliners

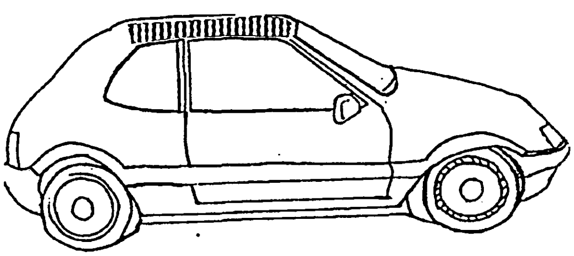


Figure 9 Areas of a car where additional sound absorbing material could be used, headliners.

Headliner materials have undergone many changes. The reasons for these changes include cost, ease of installation and acoustic properties. Historic developments of headliners can be found in [24]. The typical modern headliner is a self-supporting fibreglass and foam composite with a decorative layer. From [66], [44], the thickness of foam in a headliner is between 10 and 20 mm (assume an average of 15mm). An estimate of the average area of a head liner is 1.1 m^2. Therefore 0.165 m^3 of foam could be used in the average car. This estimate is based on current production methods; any new headliners could include a greater use of foam as long as the criteria of cost, self-supporting and acoustic properties were improved. Modern head liner production incorporates rigid polyurethane foams.

4. The engine compartment (under bonnet).

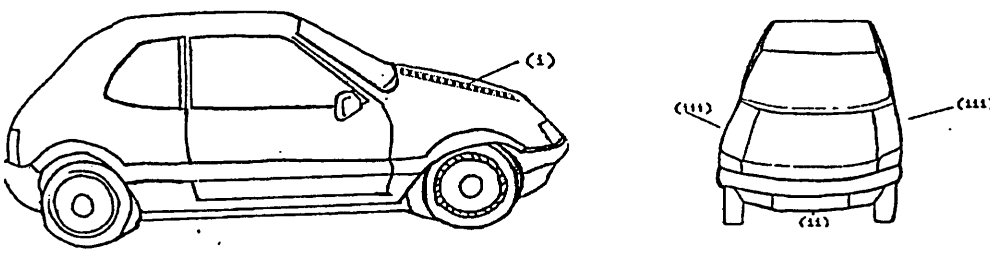


Figure 10 Areas in a car where additional sound absorbing material could be used, around the engine (so called under bonnet treatment applications).

Three areas will be considered: (i) the underside of the bonnet, (ii) under the engine and (iii) the engine side bulkhead compartment as shown in Figure 10. Control of noise emission from the engine has become increasingly relevant with the growing popularity of the noisier diesel engine and EEC legislation concerning drive past noise. All three of these areas have problems associated with heat, oil and petrol. Details of the aggressive environment together with material resistance are discussed by Rigby [66]. Therefore standard polyurethane foam cannot be used unless it is treated or covered. Alternatively, other types of high performance foam could be used. Consider first (i) bonnet attached panels. These are becoming very popular, especially with the more expensive vehicles. Because of the heat and solvent problem these panels have traditionally been made from mineral fibres. Under the bonnet, there is often space for a thicker layers of absorbing material, between 4 and 45 mm, [4] (average thickness 20mm). If one estimates the area of sound absorber that can be attached under the bonnet to be 1 m^2, the volume of absorber used under the bonnet in the average car would be about $0.02m^3$. The second area, under the engine, has the additional function of smoothing the under surface of the vehicle, reducing drag and air noise. Low drag improves the vehicle's economic performance and in addition noise reduction is obtained by limiting the source air noise. Because these panels have to be light and easily removed for maintenance they have traditionally been thin, approximately 5mm thick. An estimate of the area of an "under engine panel" would be $1m^2$ giving a potential volume per car of absorber equal to 0.005 m^3. (iii) The compartment around the sides of the engine can be used for sound absorption. An estimate for possible consumption of foam in this area would be 0.002 m^3 per vehicle.

5 Other Areas

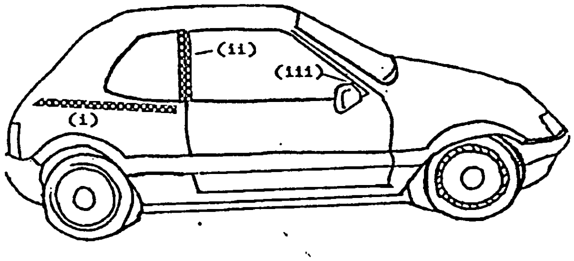


Figure 12 Other areas in a car where additional sound absorbing material could be used.

In addition to the applications already identified other areas could be considered, such as those shown in Figure 12, the posts and contrails (ii). Extra components which could be made more efficient sound absorbers are the parcel shelf (i) and behind the dash board (iii). In a vehicle there are many possible sound absorbing areas and leakage paths. A summed estimate for the usage per car of absorber in all these small areas would be about 0.04 m^3.

Summary:

There are many areas within a vehicle where acoustic panels and acoustic foam treatments can be incorporated, each having acoustic and non-acoustic performance requirements. Foams are one of several types of materials that can be used for these application.

Table 8 gives an estimate of the potential utilisation of sound absorbing materials in automotive applications. This is based on manufacturers specifications, in Western Europe, and the number of cars sold in 1990.

Notes: the type of polyurethane foam used for automotive acoustic applications will vary according to where it is to be used. Under carpet treatment is typically RIM moulded on to

Table 8 Table of quantities of acoustic absorbing material used in car production.

Component	Area $/m^2$	Thickness $/m\ 10^{-2}$	No	Total Volume$/m^3$
Floor Panels	3.5	12	1	0.042
Door Panels	0.07	15	4	0.042
Headliners	1.0	15	1	0.0165
Bonnet	1.0	20	1	0.02
Under Engine	1	5	1	0.05
Side Engine				0.02
Others				0.04
Total Volume per Vehicle				0.23
Total Weight per Vehicle (a)				9.22 Kg
U.K. Demand (b)				1.84×10^4 tonnes
Western Europe Demand (c)				1.11×10^5 tonnes
Machine time (Western Europe) (d)				$5.2\text{x}10^7$ hours
Total No. of new machines required				

(a) Average density 40 Kg/m^2
(b) Based on 2 million cars per year [34]
(c) Based on 12 million cars per year [34]
(d) Based on Vertifoam Machine.

the back of carpet (details are given in reference [52]). The density of this foam is in the order of 80 Kg m^{-3}. Other applications such as foams used in headliners will be low density, rigid polyurethane of the order of 11 Kg m^{-3}. Although the analysis above uses slabstock for calculation a variety of different types of foams will be used.

An example of how noise control is affecting the marketing of vehicles is the advertising campaign of Ford for their Cargo-Q trucks. In an advertisement for the truck, noise has taken highest priority above all other features. The initial paragraph is related to noise and reinforcement statements are also included in the last paragraph. Priority is given above cost and environmental features. The aspect of noise that is concentrated upon is drive past legislation (EEC 84/424) and how the Ford Cargo-Q 'easily conforms to next year's noise legislation (1992)'. Additional statements with less prominence are also made regarding the interior noise. Further information is available from Ford on the legislation and how Cargo-Q meets the required standards in a free booklet. Information is given in the booklet in a non-technical format with comparisons of other noises. A table of old and new levels of drive past noise for trucks is also included. A paragraph on interior noise specifically mentions the use of foam in noise reduction. 'The Noise shields and foam are designed to absorb noise energy not just channel it.'

This is just one example of how legislation is being used by a vehicle manufacturers as a positive market force. The increasing awareness will generate a requirement for increased quantities of noise control material, foams.

2.6 Costing of a Commercial Ventilator.

An example of a ventilator is used to demonstrate how the use of foam as an alternative to other acoustic absorbing material will produce a more marketable product.

The product is a device for the introduction of fresh air into a building while excluding noise external from that building. By passing air through a u shaped passage lined with an acoustic absorbing material fresh air can be introduced while excluding noise. Details of the criteria for design of the fan is given in Appendix 1 (an interview with Mr R.Belcher the MD of Manrose a company proposing to manufacture this type of ventilator).

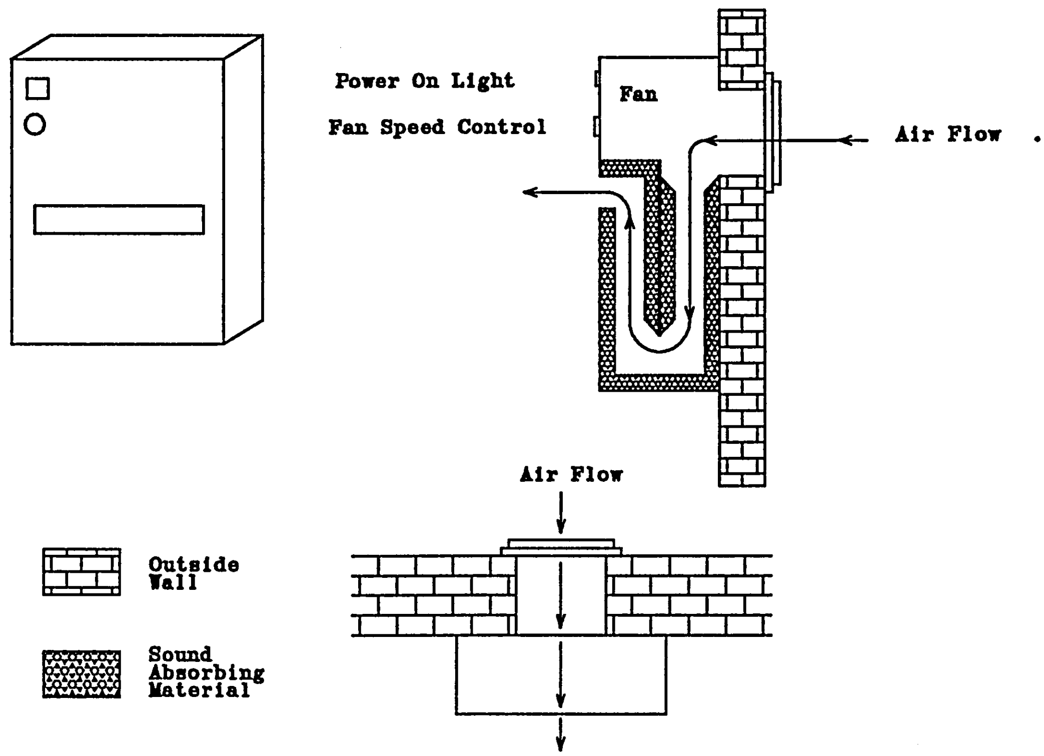


Figure 13 Schematic representation of a noise reduced ventilation fan.

A major objective of this exercise is to reduce costs by using foams. The acoustic material presently being used in this type of ventilator is Rockwool. From the foams available Basotec (see Appendix 7 for material specifications) is suggested as more suitable than Rockwool. In designing a new ventilator several other non-acoustic modifications will be made to give the product a an extra competitive edge. Details of other product modifications will not be included in this discussion as the objective is to demonstrate the advantages and cost savings obtained from using foam. Cost savings will be brought about by several of the foam's characteristics: it is self supporting, it does not require a surface cover and it permits easier handling of the material.

Manufacture of the unit starts with a metal shell. Panels of Rockwool are cut and then coated with black lantor material (a protective covering) . The covering is to prevent loose fibres from being blown into the building. Each cut slab of Rockwool is then sprayed with an adhesive and put into the metal shell. In the design of old unit (Figure 13) there is a central metal sheet with Rockwool glued to both sides.
Several differences in production will be possible when using Basotec. By careful design the cut slabs of Basotec will be able to slot together without the use of glues. The central metal panel will also not be required as Basotec is self supporting. No loose fibres are free to be blown into buildings hence the material no longer requires a covering.

Original costing obtained from Manrose included 75 individual items. The majority of these will be constant, independent of the type of sound absorber used and hence will be combined under sundries.

Quotes for labour are from Remploy. The cost of case production was quoted from a metal working shop opposite the Manrose factory in Slough. It is expected that further reductions in these two costs could be made after prototypes have been constructed. Only estimates were required initially

Table 9 Costings for ventilator with two different sound absorbing materials.

COSTINGS (Old)		
Components	Cost each /£	Cost /£
Sundries	29.53	29.53
Rockwool (0.75 of slab)	1.57	1.18
Black Lantor (0.8 sheet)	0.19	0.15
Spray adhesive (.02 litre)	1.94	0.04
Solvent (0.02 litre)	1.83	0.04
Metal Shell	12.32	12.32
Labour	14.27	14.27
Total		57.53

COSTING (New)		
Sundries	29.53	29.53
Basotec (0.6 of slab)	2.63	1.57
Metal Shell	10.22	10.22
Labour	11.14	11.14
Total		52.16

to ascertain the feasibility of the proposed changes. When final production prototypes have been constructed and tested a more vigorous costing exercise will be undertaken. Other ideas such as having the front section of the case plastic moulded will also further reduce the production cost.

Total cost saving obtained by the use of Basotec is £5.37. As a minimum thirty percent mark-up is required, this implies that the product could be sold for £6.98 less than if manufactured with Rockwool. In the discussion with Mr Belcher (see Appendix 1) for his marketing strategy a minimum of a ten pounds reduction in the selling price is required. Although the use of a foam has not brought the selling price down to the required level it has made the required reduction from other modifications much less. It was estimated by R. Belcher that the level of saving brought about by additional non-acoustic modification would be approximately equal to those obtained from using foam instead of Rockwool. The two types of cost savings will not only make the new marketing strategy possible, but it will also create additional profitability. In conclusion the product initial objectives of this exercise have been more than fulfilled and the product can now be made more profitable. Mr Belcher had not originally thought of using foam and would have abandoned the modification project had these discussions not been entered into.

CHAPTER 3

THEORETICAL MODELS OF ACOUSTIC ABSORPTION

3.1 Introduction.

In this chapter, some of the many models used to predict acoustic performance from simply measured characteristics of a material are investigated. Most of these models were not originally concerned with foam but with fibrous porous materials. The purpose of this investigation is to find a realistic theoretical approximation with variables that can easily be measured. Methods used to attain different characteristics are discussed in Appendix 7. Once an adequate model has been identified, the effects of physical parameters on acoustic absorption can be investigated and a method of optimising each variable established.

The earliest model was constructed by Rayleigh [53]. By considering a porous medium as containing parallel cylindrical capillary pores running normal to the surface Rayleigh builds his model. This investigation will not begin with the original Rayleigh model but with the first model put forward by Zwikker and Kosten [86]. These models are also based on a simple case of idealised pores in a solid medium. The analysis is of a modified homogeneous isotropic fluid in terms of viscous and heat conduction processes. Models based on these ideas introduce phenomenological frequency dependent parameters without identifying methods of their calculation or measurement. All the models investigated include at least one of these parameters. However in more recent models most variables can be either calculated or measured. It would not be productive to look at every model that has been developed. Five models have been selected for detailed discussion. Others which have made important contributions will be mentioned.

In addition to the theoretical models, empirical models are also discussed. Delany and Bazley [23] originally suggested this approach with specific reference to fibrous materials. Other authors have adapted the earlier work for use with foams.

3.2 Zwikker and Kosten model

3.2.1 Introduction : the theory is taken from Reference [86] page 15 in which the model represents the wave impedance of an impervious medium with internal friction. According to Zwikker and Kosten there are three material parameters that affect the impedance: a) the density, b) stiffness and c) the loss angle. The fourth factor included in the model is thickness. Each of these factors and its effect on the impedance will be discussed.

3.2.2 The Model

To construct their mathematical model Zwikker and Kosten first considered a homogeneous solid. Using Newton's second law, they set up the equations of motion and set up the equations of continuity by applying the law of mass conservation. From these calculations an expression for the characteristic impedance of the homogeneous solid is derived. By taking internal damping into consideration, in the expression for characteristic impedance, the equation below for the wave impedance of impervious media with internal friction is obtained.

$$Z=W\coth\gamma l=\rho c(1+j\delta)\coth\left\{j\frac{\omega l}{c}\left(1-j\frac{\delta}{2}\right)\right\} \quad (1)$$

where Z=specific acoustic impedance

W=material characteristic acoustic impedance of the material

W_o=characteristic acoustic impedance of free air

γ=propagation constant

δ=loss tangent of the material

ω=angular velocity

ρ=bulk material density

c=velocity of propagation

$=\sqrt{K_r/\rho}$

K_r=compression modulus of the material

$$\alpha_o=1-|r|^2=1-\left|\frac{Z-W_o}{Z+W_o}\right|^2 \quad (2)$$

3.2.3 Discussion

Calculation of first minimum and maximum. Equation (2) will convert the impedance values calculated by the model and give a value of normal incidence acoustic absorption. We consider the two vectors as shown in the Argand diagram below.

3.2.4 Graphical representation of α_o in the complex plane.

The locus described when the modulus of $Z-W_o/Z+W_o$ (the complex reflection coefficient r) is held constant is a circle. Hence the value of the normal incidence absorption coefficient will also be constant for all values of Z on the locus. The argument of r represents the phase angle by which the incoming and reflected pressure wave differ. Plotting the locus of constant argument will describe circles different from the

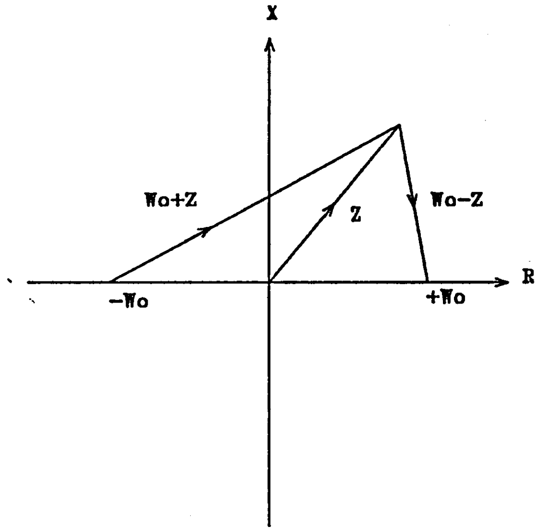


Figure 14 Argand diagram representing the modulus and argument of Z.

constant absorption circles. When sets of different values for the constant modulus and constant phase difference are plotted we obtain a map of circles as shown in Figure 15. Plotting curves for the measured values of the Z over theses circles enables the normal incidence acoustic absorption and phase angle to be read off. The diagram can also be used in the interpretation of theoretical models.

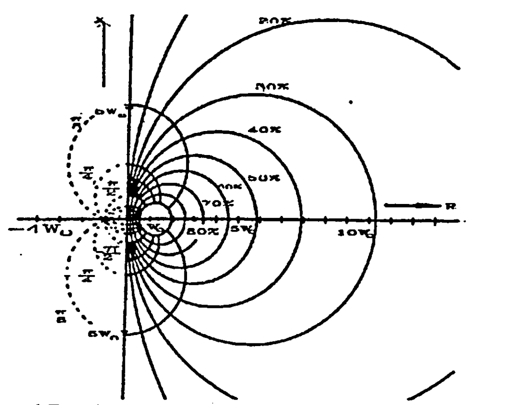


Figure 15 Chart of constant modulus and phase difference.

3.2.5 Expected shape of impedance curves.

It can be shown that a function coth (a+jb) will describe approximately a logarithmic spiral ([86] page 8). The spiral will have centre at unity and gradient b/a. By inspection it can be seen that equation (2) will therefore approximate a logarithmic spiral with centre $(\rho c, \delta\rho/2)$ and gradient $\delta/2$. Using this information it is possible to predict how changes in the loss tangent, length, density, and stiffness will affect the complex impedance and hence the acoustic absorption.

From the plots of constant acoustic absorption coefficient (Figure 15) it can be seen that the approximate minimum modulus of the quotient $Z-W_o/Z+W_o$ (hence maximum absorption) vectors will occur on an impedance spiral when Z crosses the real axis. By putting the imaginary part of Equation (1) equal to zero we find that maximum absorption is when:

$$\frac{\delta}{2}\sinh\left\{\frac{\delta\omega l}{c}\right\}=\sin\left\{\frac{2\omega l}{c}\right\} \qquad \textbf{(3)}$$

Because the left hand side of the above expression is periodic between zero and one, several solutions are expected. We also note that at low frequencies the right hand side is very small and can be approximated to zero. Hence the first solution to Equation (1) can be approximated by:

$$2\sin\left\{\frac{2\omega l}{c}\right\}=0 \quad \Rightarrow 2\frac{\omega l}{c}=\pi \qquad \textbf{(4)}$$

Once the position of the first maximum is found experimentally the above relationship with details in equation (1) can be used to calculate K_r, the dynamic stiffness of the material.

3.2.6 Changes in parameters.

Note: In the following graphs length (l) is in metres, density ρ is in kg m^{-3} and dynamic stiffness K_r is in N m^{-2}.

To assist in the explanation of this relationship, several graphs are presented. The impedance curves have been constructed from Equation (1), by varying the frequency between 100 and 2000 Hertz, while holding other parameters constant. Further curves were then drawn by altering other parameters and then re-drawing the curve. Three sets of curves are plotted for small changes in one parameter. A final set of graphs is then created to show how these changes affect the normal incidence acoustic absorption coefficient.

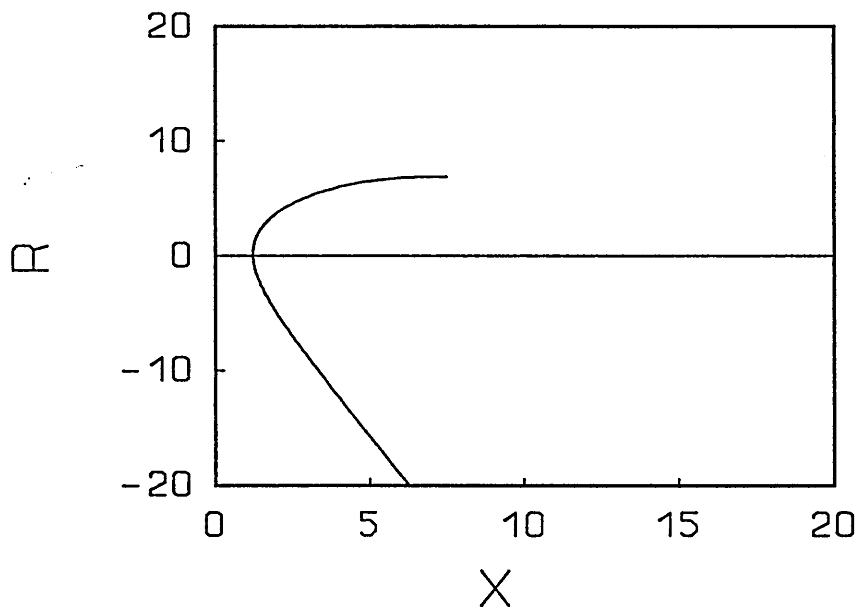


Figure 16 Graph of impedance predicted from the Zwikker and Kosten model, l=0.01 m, δ=0.3, ρ=50 Kg m^{-3}, Kr=1E5 N m^{-2}.

Length changes will only have an effect on the coth term in Equation (1) since l is not a part of the expression for either the gradient or the centre of the spiral and we conclude that the shape will remain constant for changes in l. However the length of the spiral will change and the frequencies where the spiral intersects with the real axis will decrease with increased length. Consequently when length changes are translated into changes in the absorption/ frequency relationship we see a stretching of the curve. Maxima and minima will have the same amplitude for all lengths but an increase in length will increase the frequencies at which maxima and minima occur. The increases in spiral length are shown graphically in Figure 16, Figure 17 and Figure 18 and how they then translate into absorption is shown in Figure 19.

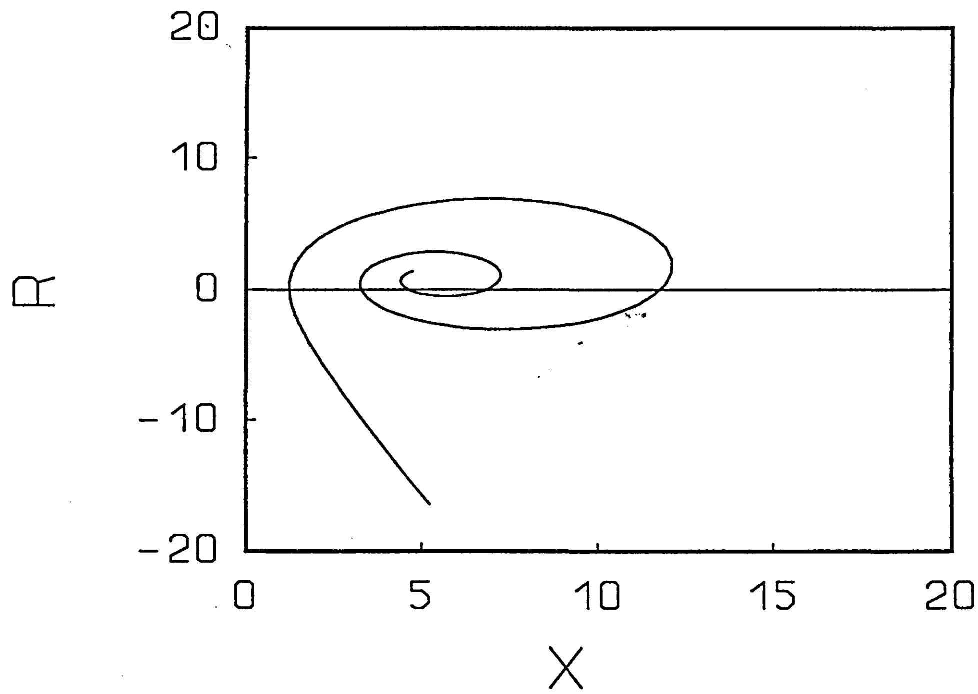


Figure 17 Graph of impedance predicted by the Zwikker and Kosten model, l=0.03 m, δ=0.3, ρ=50 Kg m^{-3}, Kr=1E5 N m^{-2}.

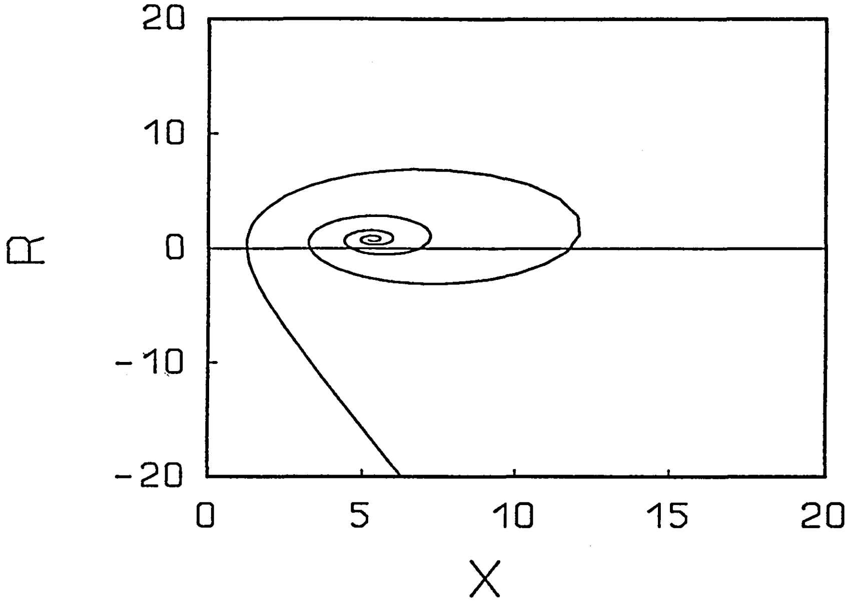


Figure 18 Graph of impedance predicted using the Zwikker and Kosten model, l=0.05 m, δ=0.3, ρ=50 Kg m^{-3}, Kr=1E5 N m^{-2}.

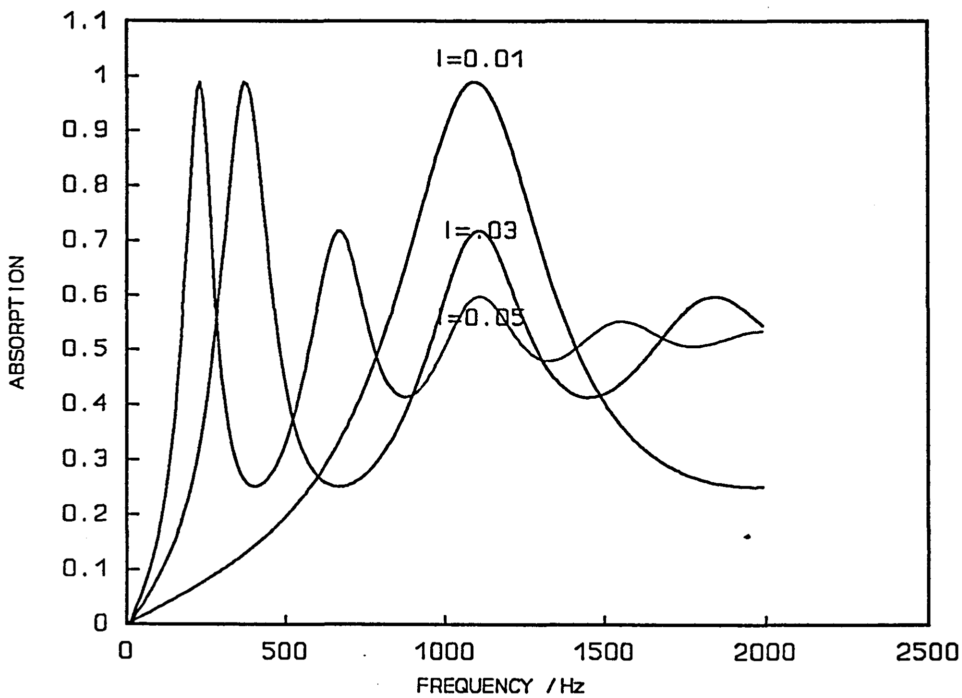


Figure 19 Graph of absorption against frequency using the Zwikker and Kosten model, length varying, Kr=1E5 N m^{-2}, δ=0.3, ρ=50 Kg m^{-3}.

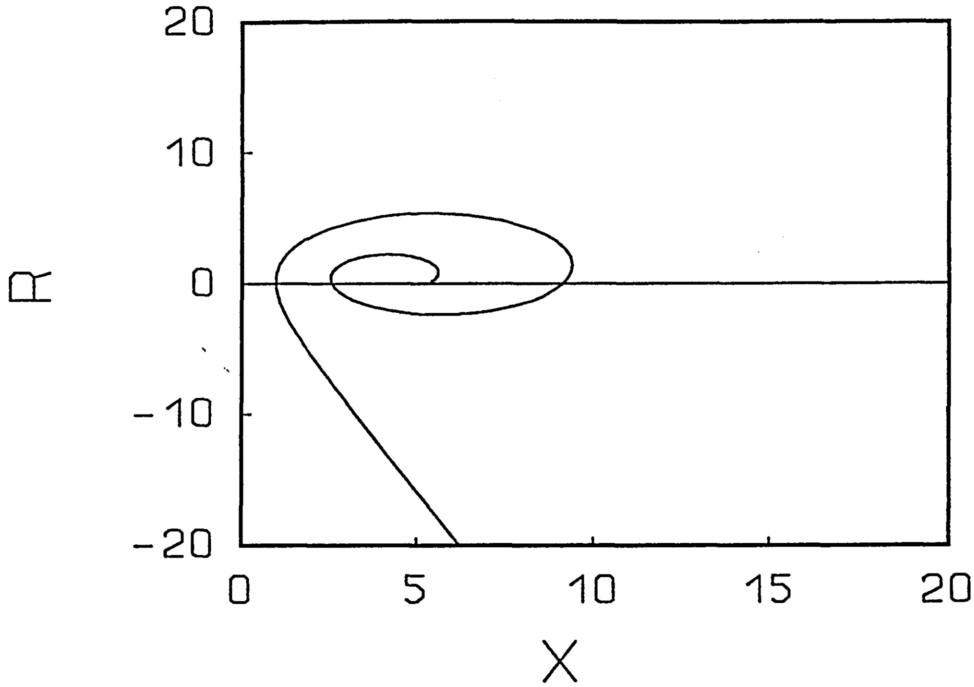


Figure 20 Graph of impedance predicted using the Zwikker and Kosten model, l=0.03 m, Kr=1E5 N m^{-2}, δ=0.3, ρ=30 Kg m^{-3}.

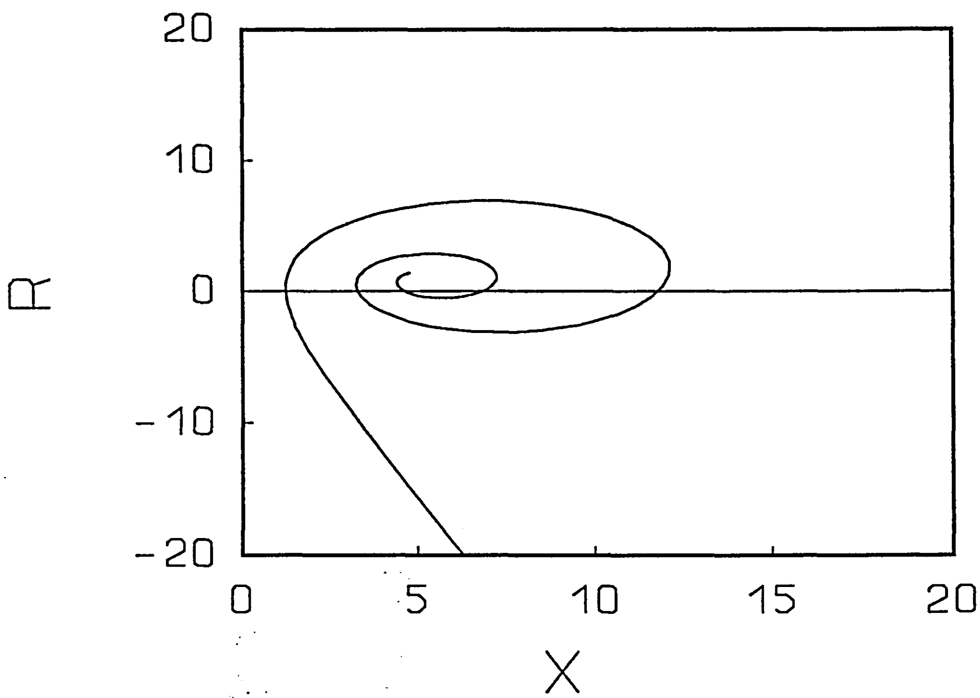


Figure 21 Graph of impedance predicted using the Zwikker and Kosten model, l=0.03 m, Kr=1E5 N m^{-2}, δ=0.3, ρ=50 Kg m^{-3}.

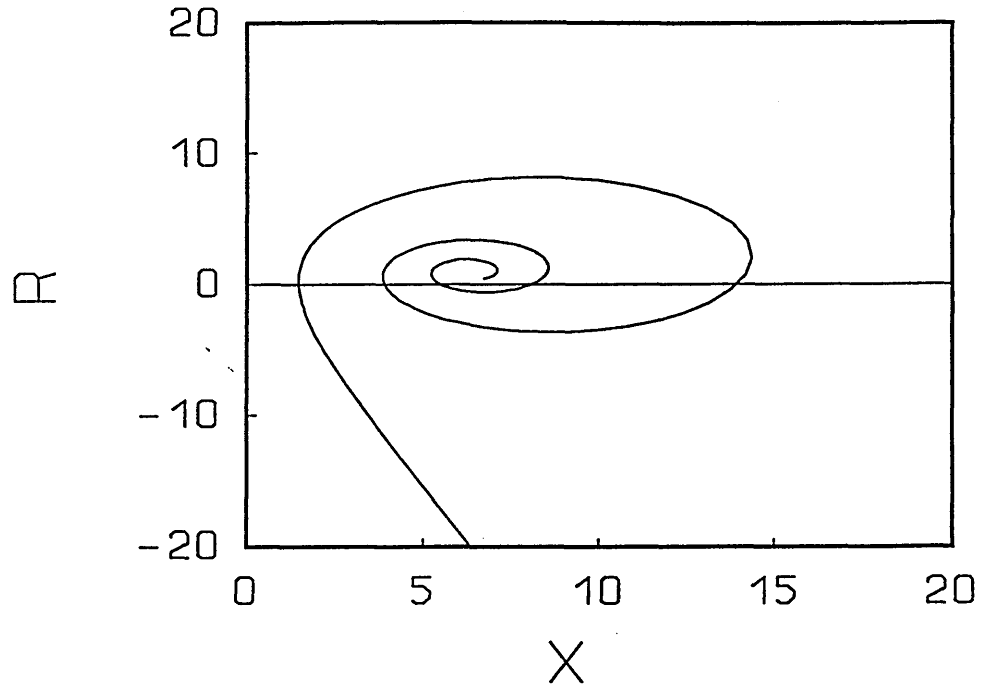


Figure 22 Graph of impedance predicted by the Zwikker and Kosten model, l=0.03 m, δ=0.3, Kr=1E5 N m^{-2}, ρ=70 Kg m^{-3}.

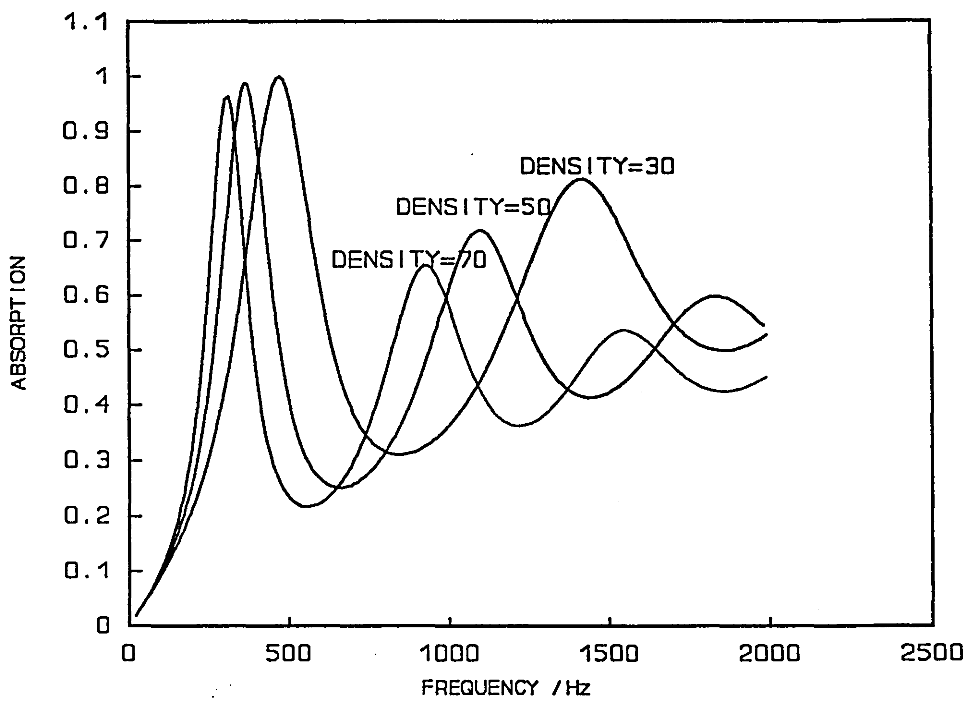


Figure 23 Graph of absorption against frequency using the Zwikker and Kosten model, density varying Kr=1E5 N m^{-2}, δ=0.3,l=0.03 m.

Changes in density affect the factor c in Equation (1) and, since $c=\sqrt{K_r/\rho}$ an increase in density brings about a decrease in c. Inside the coth term, c will have no effect on the gradient but as with length there is an increase in spiral length. The ρc term at the beginning of Equation (1) will increase as density increases, enlarging the spiral and shifting its centre further in the positive x direction. This shift in centre will increase the modulus of Z at its intersects the real axis hence a decrease in the amplitude of the first maximum. The effect on the absorption due to the increased spiral length will be an elongation of the frequency/absorption curve. A size increase and centre shift will affect the magnitude of the turning points within the frequency absorption relationship. Changes in the impedance curves can be seen in Figure 20, Figure 21 and Figure 22. How these changes translate into normal incidence absorption can be seen in Figure 23.

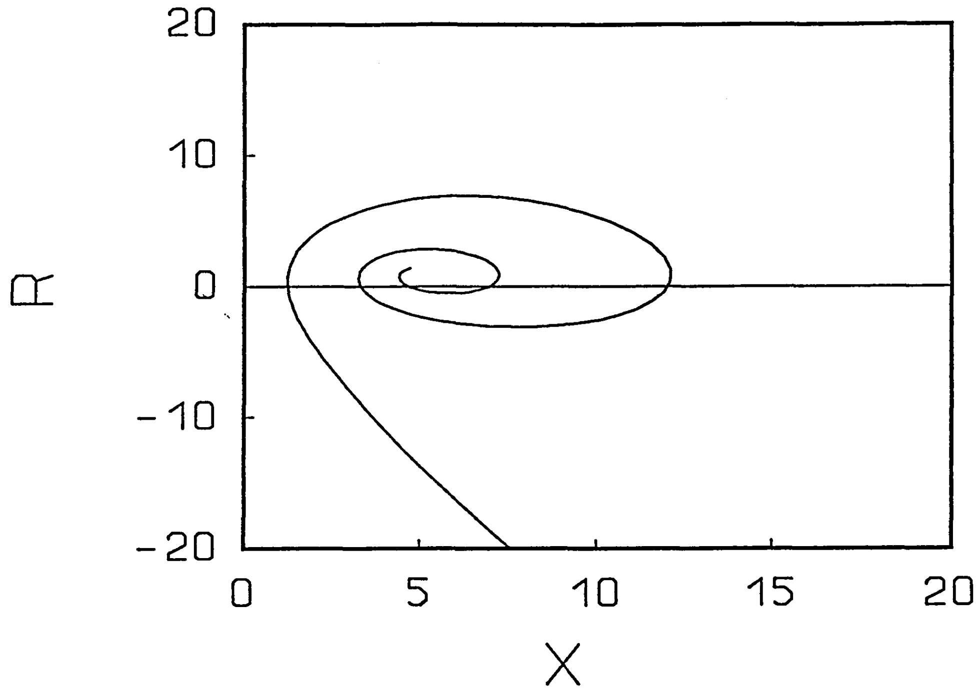


Figure 24 Graph of impedance predicted using the Zwikker and Kosten model, l=0.03 m, δ=0.3, ρ=50 Kg m^{-3}, Kr=1E5 N m^{-2} .

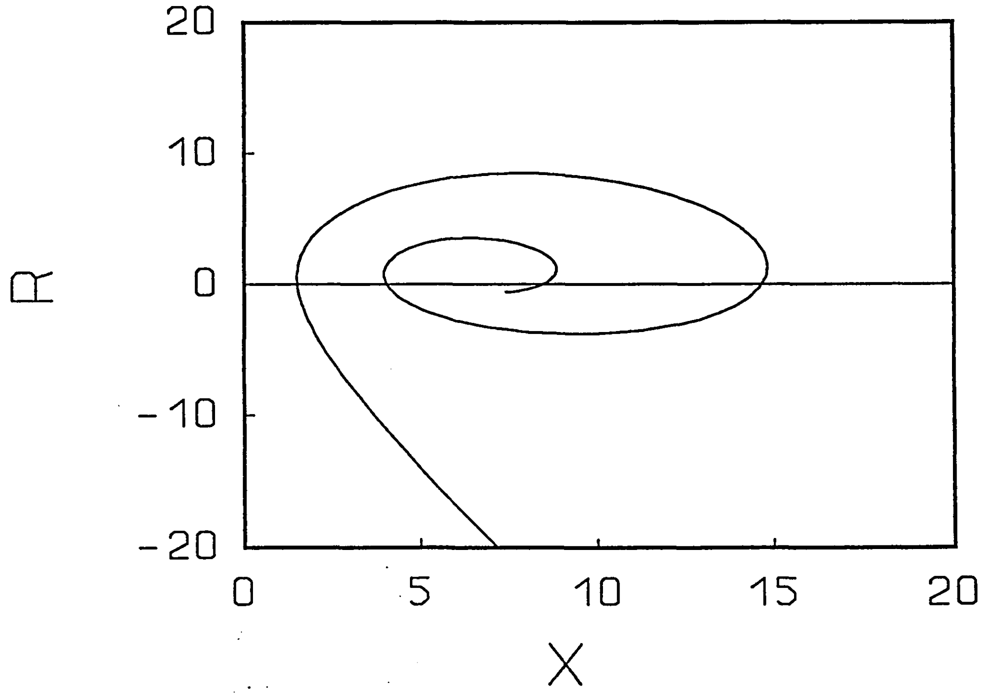


Figure 25 Graph of impedance predicted using the Zwikker and Kosten model, l=0.03 m, δ=0.3, ρ=50 Kg m^{-3}, Kr=1.5E5 N m^{-2} .

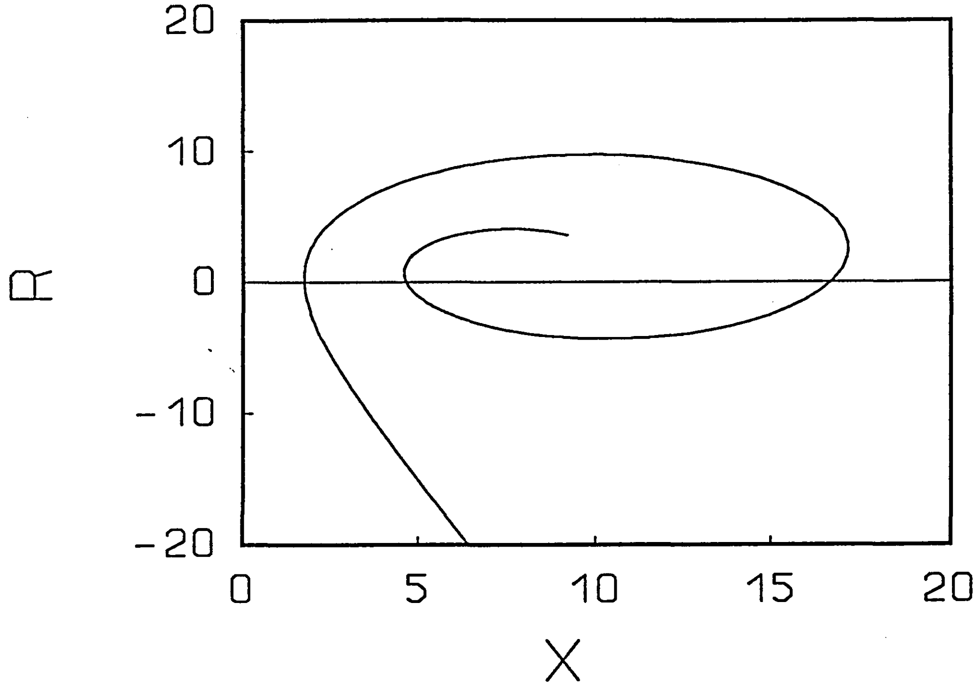


Figure 26 Graph of impedance predicted using the Zwikker and Kosten model, l=0.03 m, δ=0.3 ρ=30 Kg m^{-3}, Kr=2E5 N m^{-2} .

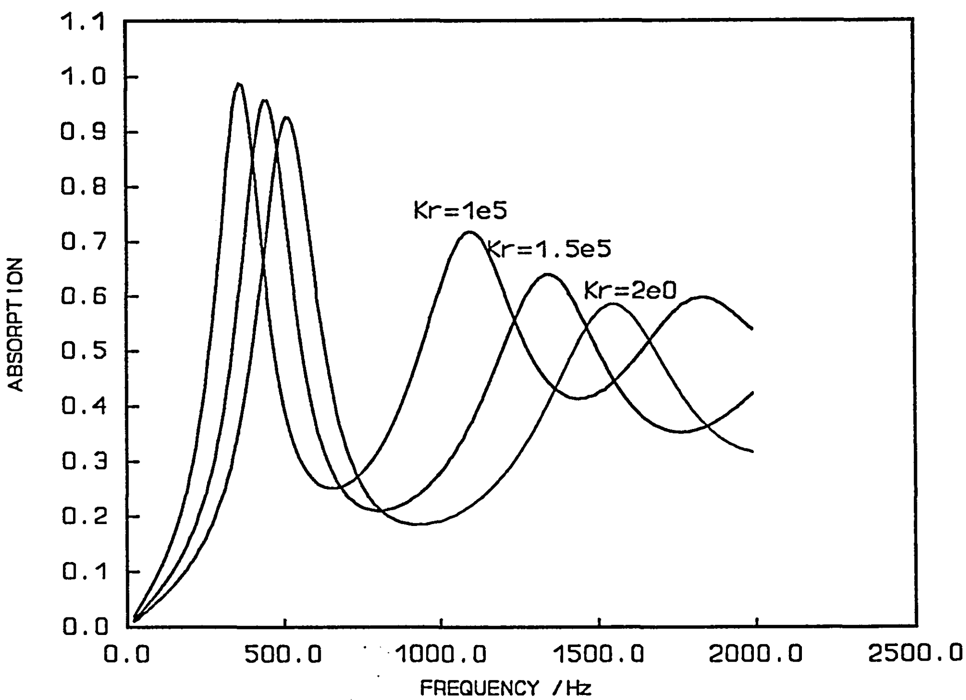


Figure 27 Graph of absorption against frequency varying stiffness using Zwikker and Kosten model, δ=0.3, l=0.03 m, ρ=30 Kg m^{-3}.

Changes in K_r will have a similar effect on the size and position of the spiral to that produced by changes in density. Within the coth term, however, the effects will be opposite, ie an increase in stiffness will decrease the value of c. Hence increases in the value of K_r will decrease the length of the spiral. This can be seen in Figure 24, Figure 25 and Figure 26. As stiffness increases the spiral gets shorter in length but the overall magnitude will increase and the centre moves to in the positive x and y directions. The graphical representation of how these changes affect absorption are shown in Figure 27.

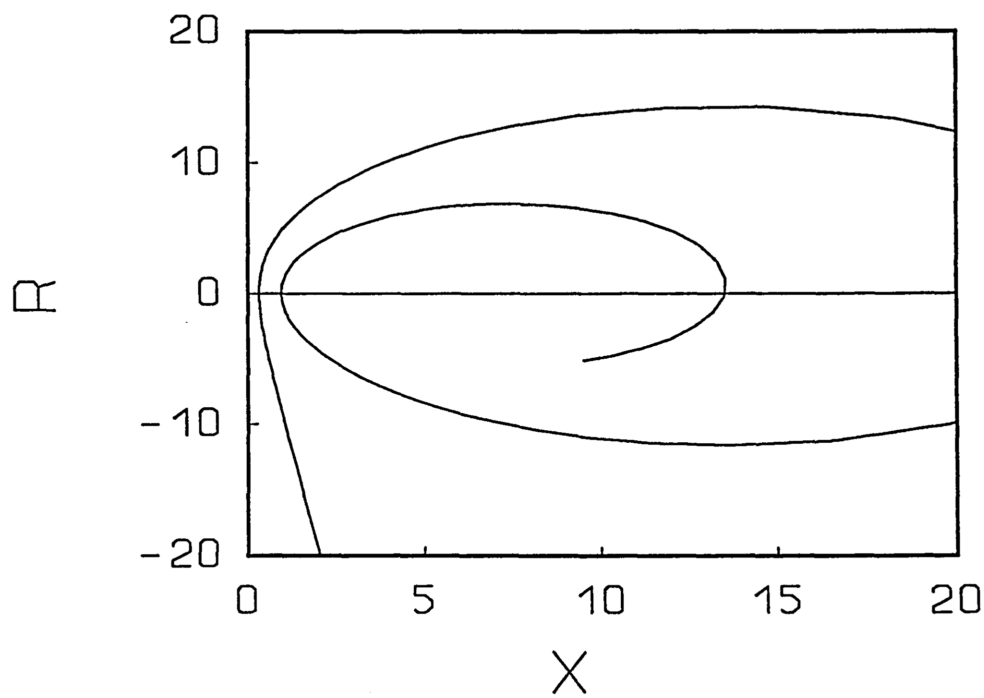


Figure 28 Graph of impedance predicted using the Zwikker and Kosten model, l=0.03 m, ρ=30 Kg m^{-3}, Kr=1E5 N m^{-2} , δ=0.1.

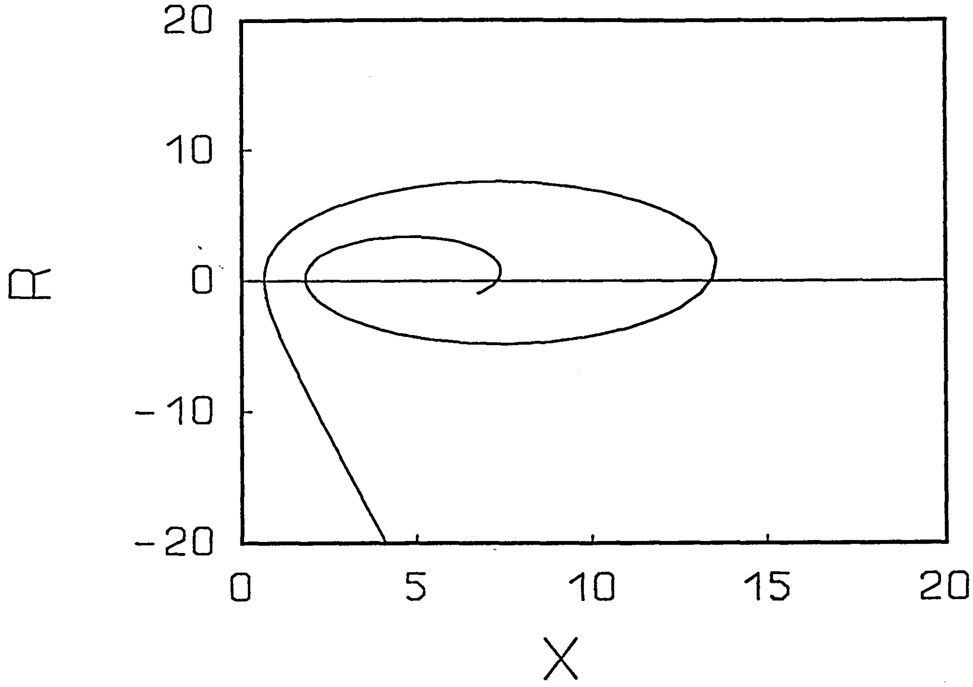


Figure 29 Graph of impedance predicted by the Zwikker and Kosten model l=0.03 m, ρ=30 Kg m^{-3}, Kr=1E5 N m^{-2} , δ=0.2.

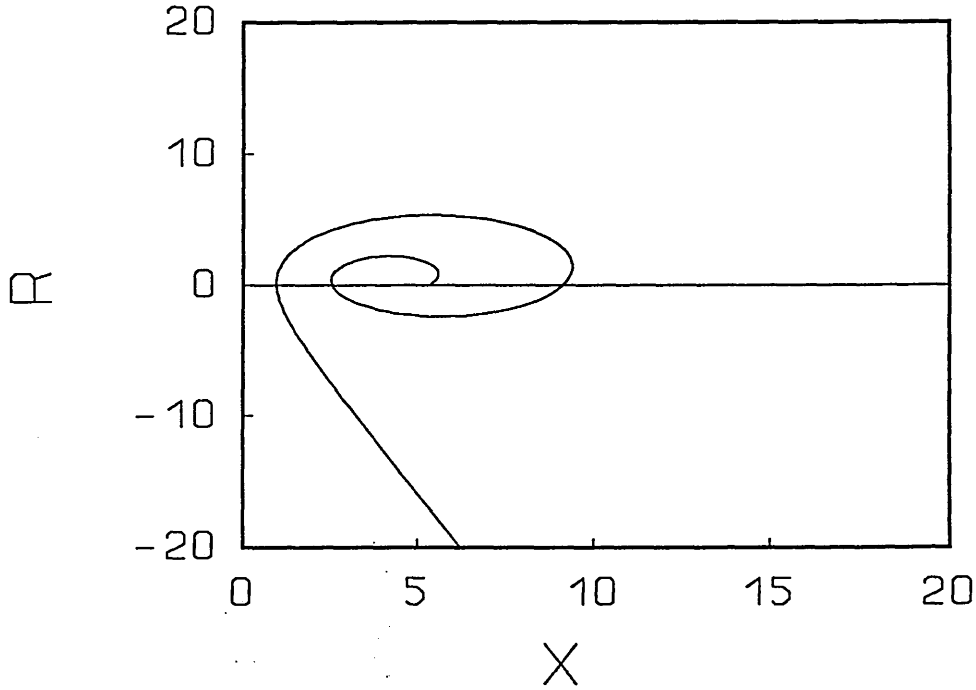


Figure 30 Graph of impedance predicted by the Zwikker and Kosten model, l=0.03 m, ρ=30 Kg m^{-3}, Kr=1E5 N m^{-2} , δ=0.3.

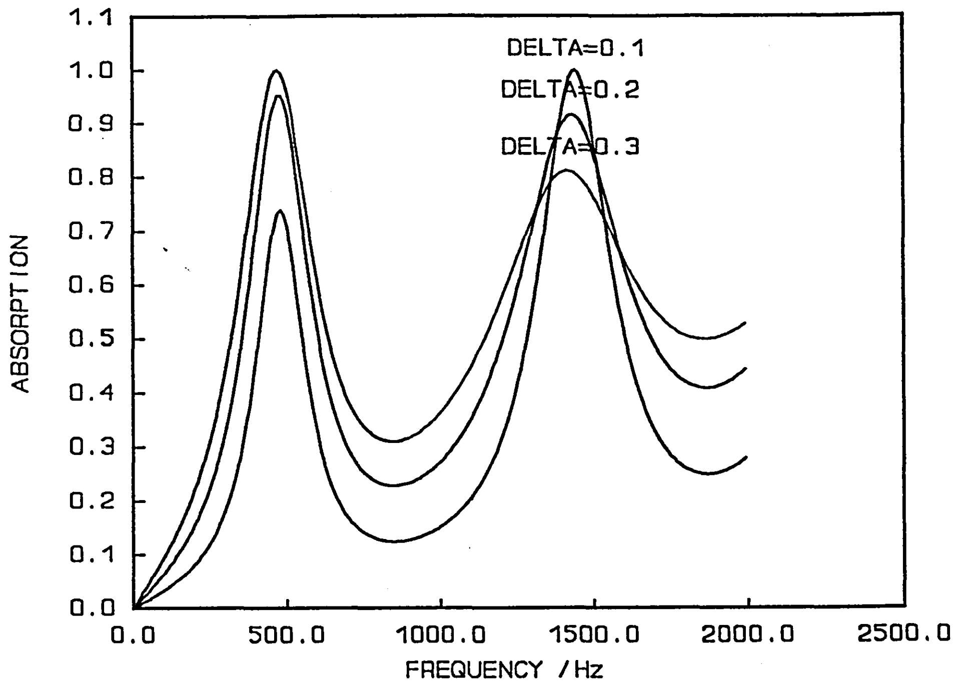


Figure 31 Graph of absorption against frequency varying δ using Zwikker and Kosten model l=0.03 m, ρ=30 Kg m^{-3}, Kr=1E5 N m^{-2} .

The final parameter in this model is loss tangent (δ). The effect of increase in loss tangent will be bring the impedance spiral centre closer to the real axis. Changes in the position of the centre will be minimal compared to those brought by a increase in gradient. As the loss tangent increases so will the gradient of the spiral, thereby reducing the size of the spiral. Changes in the impedance spiral due to changes in loss tangent can be seen in Figure 28, Figure 29 and Figure 30. How these changes translate into normal incident acoustic absorption can be seen in Figure 31.

The majority of theoretical work on this topic is based on two longitudinal wave types found in acoustic absorbing materials, air borne and matrix borne. Initial work was carried out by Zwikker and Kosten and was later developed by Beranek.

3.3 Beranek Model

3.3.1 Introduction: The theory is taken from reference [5], pages 257-279, and from an older paper by Beranek [6]. A model is suggested for a homogeneous porous material. Several factors are used within the model: flow resistance, density, porosity, a structural factor and length. All these factors will be discussed, and their effects on the normal acoustic absorption analysed. Due to the complexity of the model the implications of change in the parameters will not be as well-defined as with the Zwikker and Kosten model considered previously.

3.3.2 The Model

By considering a material to be made from many idealised elemental cells Beranek formulated an equation for air flow through the material. Each cell includes a section of solid material the remaining volume is occupied by air and continuity equations are obtained under steady state conditions. It is assumed by Beranek that the air behaves isothermally. The forces acting on the solid and gaseous section are applied with the continuity equations to form a mathematical model for the prediction of normal incident acoustic impedance.

$$Z_o = \frac{-jKb}{\omega Y}$$

For rigid tiles

$$b = j\omega\sqrt{\frac{\rho_o k Y}{K}}\sqrt{1-\frac{R_1}{\rho_o k \omega}}$$

For flexible blankets $K>20Q$

$$b = \sqrt{\frac{Y}{K}}\sqrt{\langle\rho_1\rangle - j\frac{\langle R_1\rangle}{\omega}}$$

where

$$\langle R_1\rangle = \frac{R_1\left[1-\rho_o\frac{(1-Y)}{\rho_m}\right]}{\left[1+\frac{\rho_o(k-1)}{\rho_m}\right]^2\left[1+\frac{R_1^2}{\rho_m^2\omega^2[1+\rho_o(k-1)/\rho_m]^2}\right]} \qquad (5)$$

$$\langle\rho_1\rangle = \rho_o k\left\{\frac{R_1^2\frac{\left[Y+\frac{\rho_m}{k\rho_o}\right]}{\left[\rho_m\omega\left(1+\frac{\rho_o(k-1)}{\rho_m}\right]\right.} + \frac{1}{\left[1+\frac{\rho_o(k-1)}{\rho_m}\right]}}{1+\frac{R_1^2}{\left[\rho_m\omega\left(1+\frac{\rho_o(k-1)}{\rho_m}\right)\right]^2}}\right\}$$

Where R_1=air flow resistance per unit thickness.

ρ_m=bulk density of material

ρ_o=air density

Y=volume porosity

K=volume coefficient of elasticity of air

Q=volume coefficient of elasticity of material

k=structural factor

c=speed of sound in air

Z_o=Characteristic acoustic impedance of material

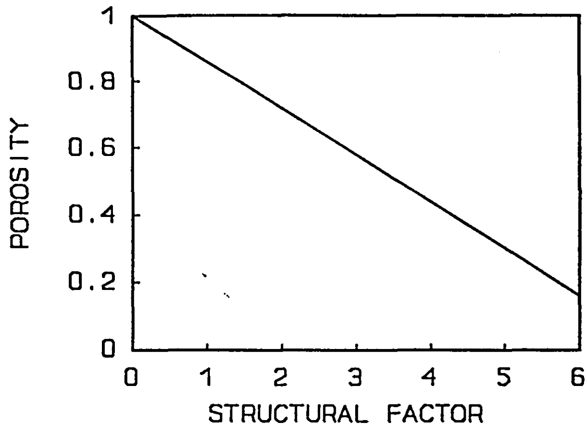
3.3.3 The Parameters; before the model as a whole is discussed difficulties associated with the parameters will be identified. Most of the terms are relatively simple to measure and are described in chapter 4. However two parameters that are difficult to calculate or measure are the structural factor and the effective porosity.

Porosity, defined as the ratio of voids to the total volume of a material, is calculated from the formula given below:

Y= 1-Mass of sample/(volume of sample x density of matrix)

The density of the porous material is calculated in the usual way. Matrix density is difficult to ascertain as it includes any closed cells and is not purely the density of the matrix polymer.

Structural factor. The original ideas of a structural factor were put forward by Zwikker and Kosten [86] pages 20-24. It is a number, usually between three and seven but always greater than one, that represents the effect that cellular structure has on the acoustic flow in a material. It is suggested (Beranek [6]) that for a material with few closed cells there is a relationship between porosity and the structural factor as shown in the graph below.



This is approximately linear and relates porosity to structural factor by: k=7.1528(1-Y) were k= structural factor and Y= the porosity.

Figure 32 Relationship between porosity and structural factor as suggested by Beranek.

Flow Resistance. This is normally a simple value to calculate but care must be taken in differentiating between measured flow resistance R and specific flow resistance R_1. Flow resistance is measured for a sample and by relating the measured R to the sample size a flow resistance per unit length, or specific flow resistance, can then be calculated.
K the volume coefficient of elasticity of air. For frequencies below 100 Hz where isothermal conditions prevail K is equal to $1x10^5$ N m^{-2}. Above 1000 Hz, it is mainly adiabatic conditions that prevail and K takes the value of ρc^2. Between 100 and 1000 Hz there will be a mixture of conditions and hence the value of K will vary between 1 and 1.4 $x10^5$ N m^{-2}.

As a simplification Beranek assumes that the bulk modulus of the matrix, Q, is much smaller than the bulk modulus of air K, and sets a limit K>20Q.

3.3.4 Discussion.

The model has been criticised by several authors; Mc Grath [54], Rosin [70], and Zarek [84]. Two major criticisms arise, first that it is over complicated in parts and approximations are used which are not stated in the paper. The second criticism is that the model ignores the interaction of the solid matrix with the fluid in the material. This would be the case when the matrix is solid and the porosity high. Beranek's model is reported to be suitable mainly for predicting the acoustic behaviour of rigid fibrous materials.

Rosin [70] uses a similar approach to Beranek [6] but corrects his shortcomings. These modifications are further added to by Bolton [10] who combines Rosin's basic theory with the complex density and elasticity of air and frequency dependent relationships for these two factors suggested by Attenbrough [4].

Parameter Variations

Table 10 Table of parameters used in demonstrating how changes in parameters effect absorption predicted using the Beranek model.

Parameter	Standard Value	Minimum	Maximum
Length /m	0.02	0.01	0.06
Air Flow Resistance /rayls m^{-1}	100000	50000	300000
Density /kg m^{-3}	30	20	40
Structural factor	5	4	9
Porosity	0.9	0.84	0.94

A set of values typical of acoustic grade polyurethane foams has been selected. To investigate how changes in these parameters affect the normal incidence acoustic absorption calculated using the Beranek model, each parameter will be varied individually and the results displayed graphically.

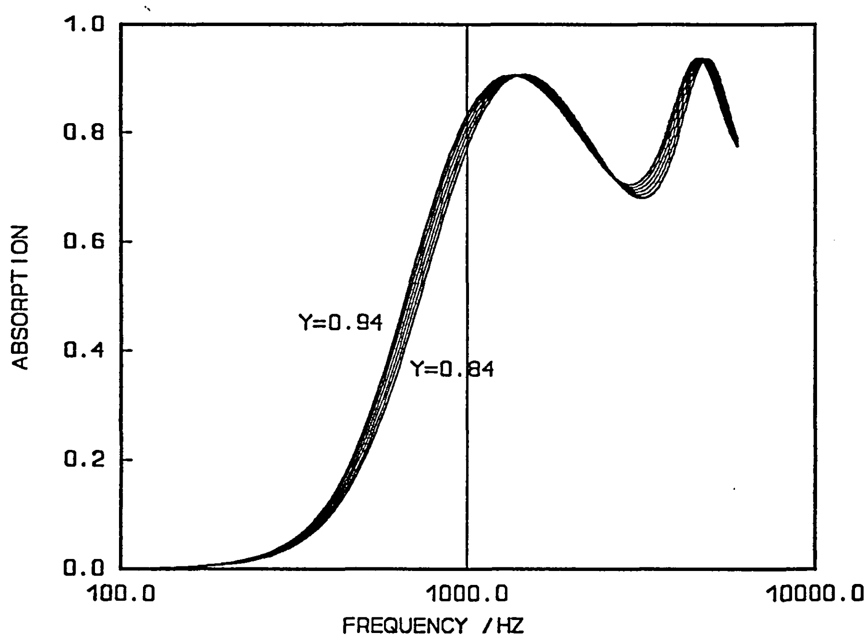


Figure 33 Graph of absorption, predicted using Beranek model, against frequency, at 6 different porosity.

Changes in porosity shift the absorption curve to a higher frequency. The changes are minimal.

A smoothing of the absorption curve accompanies increased structural factor. The increased absorption at higher frequencies has been at the cost of an overall reduction in the amplitude of the maxima.

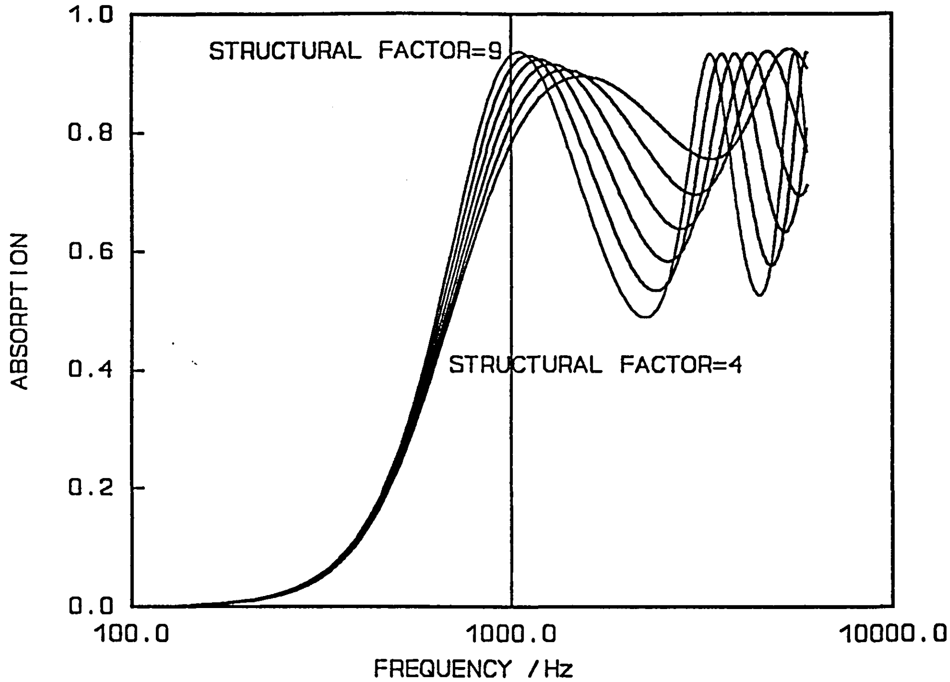


Figure 34 Graph of absorption, predicted using the Beranek model, against frequency, at 6 different structural factors.

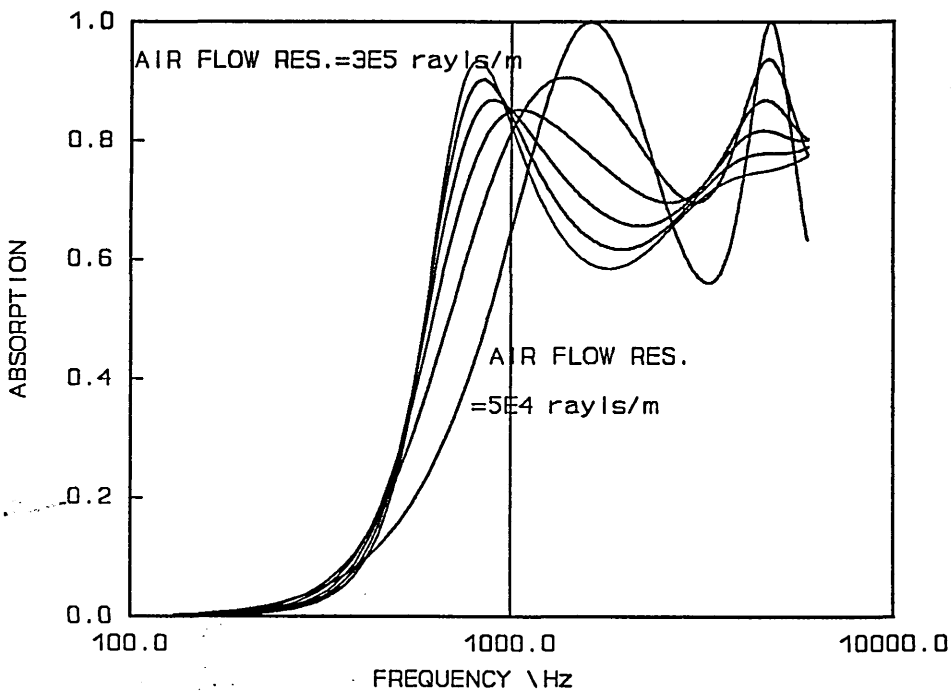


Figure 35 Graph of absorption, predicted using Beranek model, against frequency at 6 different levels of air flow resistance.

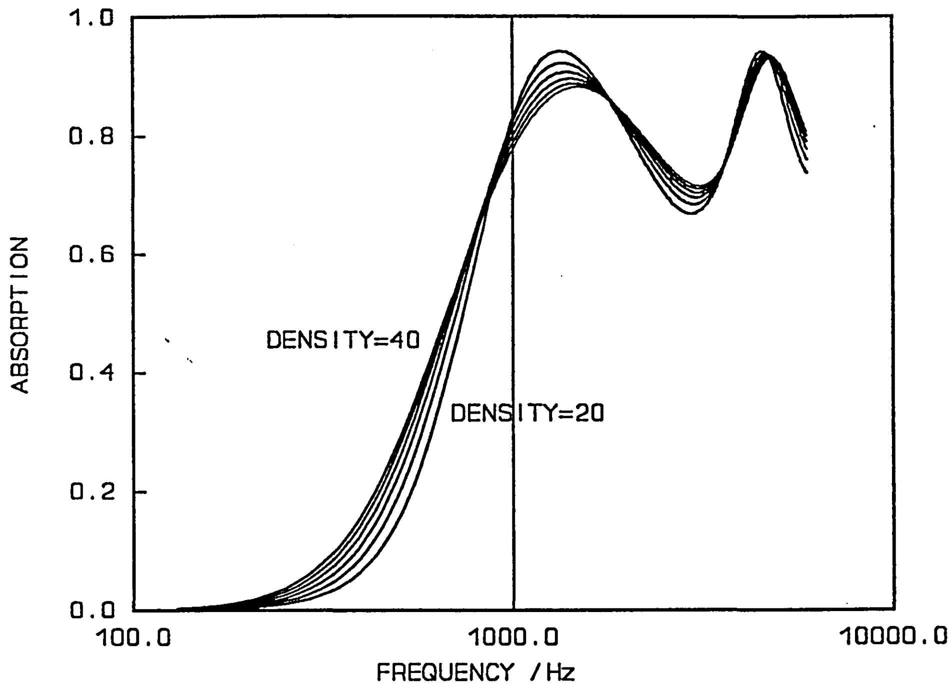


Figure 36 Graph of absorption, predicted using Beranek model, against frequency, at 6 levels of density.

When the specific air flow resistance is increased the first maximum will increase, peak and then reduce. Again, as with the structural factor, a smoothing of the curve is observed. An increase in the amplitude of the first minimum with increased specific air flow resistance. There is also an increase in the gradient of the curve as it approaches the first minimum, hence increasing absorption at lower frequencies.

Increased density increases the gradient of rise to the first maximum increasing absorption at lower frequencies.
This is accompanied by a smoothing of the remaining curve, increasing minima and decreasing maxima.
The usual effect of length is observed, that of increased gradient to the first maximum however a decrease in the magnitude of the first maximum is only partially observed. At a thickness of 35mm the first maximum starts to increase. The first minimum also starts to increase and then decreases with

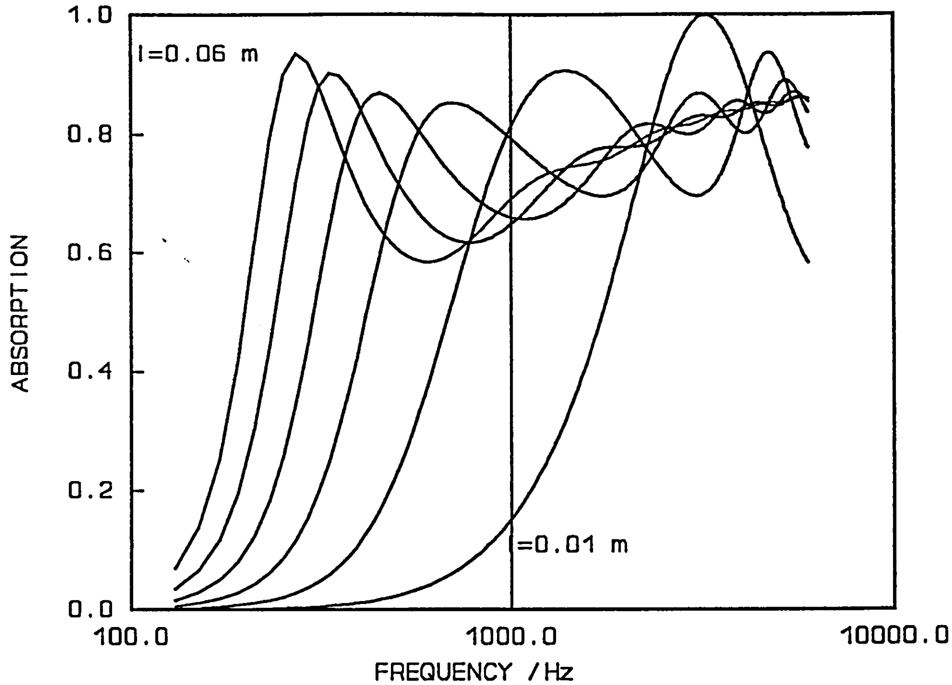


Figure 37 Graph of absorption, predicted using Beranek's model, against frequency, at 6 different lengths.

increased length.

3.4 Craggs' Model.

The model taken from [19] is based on the Rayleigh model. By using equations from Zwikker and Kosten [86] and Kuttruff [45], Craggs builds up his equations for the sound absorption of rigid porous materials as described below:

$$Z_o = \frac{\rho_o c_a^2}{\omega \Omega} \lambda$$
$$\lambda = \frac{\omega}{c_a} \Omega^{1/2} \left(K_s - j \frac{R}{\rho_o \omega} \right)^{1/2} \qquad (6)$$

Where Z_o=specific acoustic impedance

c_a=speed of propagation of sound

ρ_o=static value of gas density

Ω=porosity

R=specific air flow resistance

ω=angular velocity

K_s=structural factor

γ=propagation constant

Equation (2) is used to convert the specific acoustic impedance, length and propagation constant into normal incident acoustic absorption.

3.4.1 Discussion of parameters.

Air Flow Resistivity. The measurement technique is discussed in Section 4.3 below.

Porosity. Standard measurement, details have already been discussed in relation to the Beranek model (Section 3.3).

Structural Factor. Originally discussed by Zwikker and Kosten [86], and Craggs reports that it is greater than one and usually between three and seven.

Material density and sample length are straightforward measurements.

The density and speed of sound in air are known constants.

The reproduction of this model from the original paper [19] is difficult due to the large number of typographic errors. Although there are errors in the equation given in the paper careful reconstruction of the calculation show the above equations to be correct.

Table 11 Parameters used in the discussion of a model proposed by Craggs.

Parameter	Standard Value	Minimum	Maximum
Length /m	0.02	0.01	0.035
Air Flow Resistance /rayls m^{-1}	100000	5000	300000
Structural factor	5	4	9
Porosity	0.9	0.84	0.94

A set of four factors typical of those measured in polyurethane foams have been selected. Holding three of these factors constant and varying one a set of four graphs have been derived.

Increasing the structural factor shifts the absorption curve to higher frequencies, ie there is an increase in the frequency of the first and second maxima and also the first minima. An increase in the magnitude of the first minimum will smooth the curve. This, together with an increase in the second maximum, make increasing structural factor a method of improving higher frequency absorption at the cost of the lower frequencies.

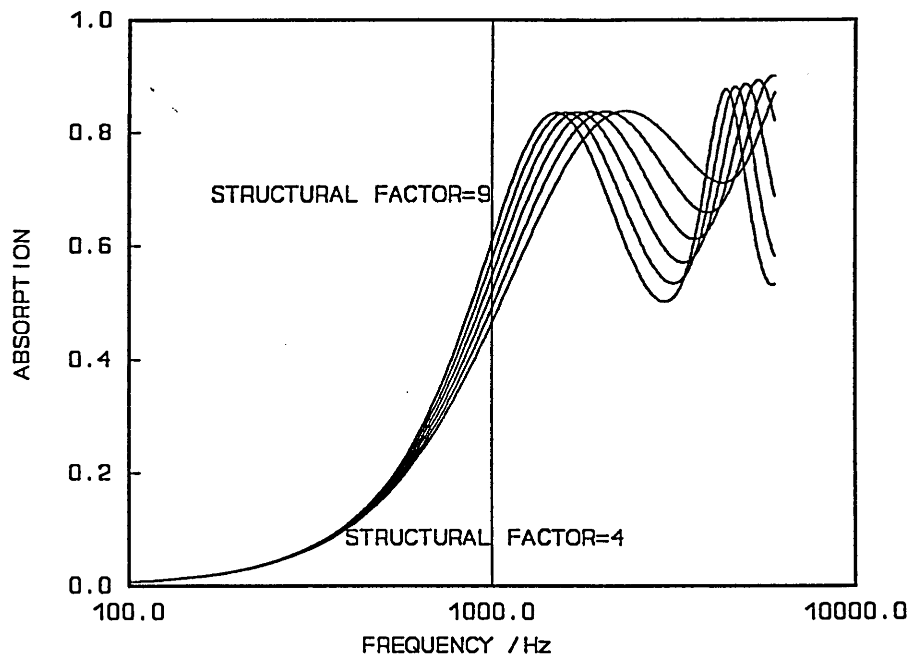


Figure 38 Graph of absorption, predicted using Craggs model, against frequency, at 6 different structural factors.

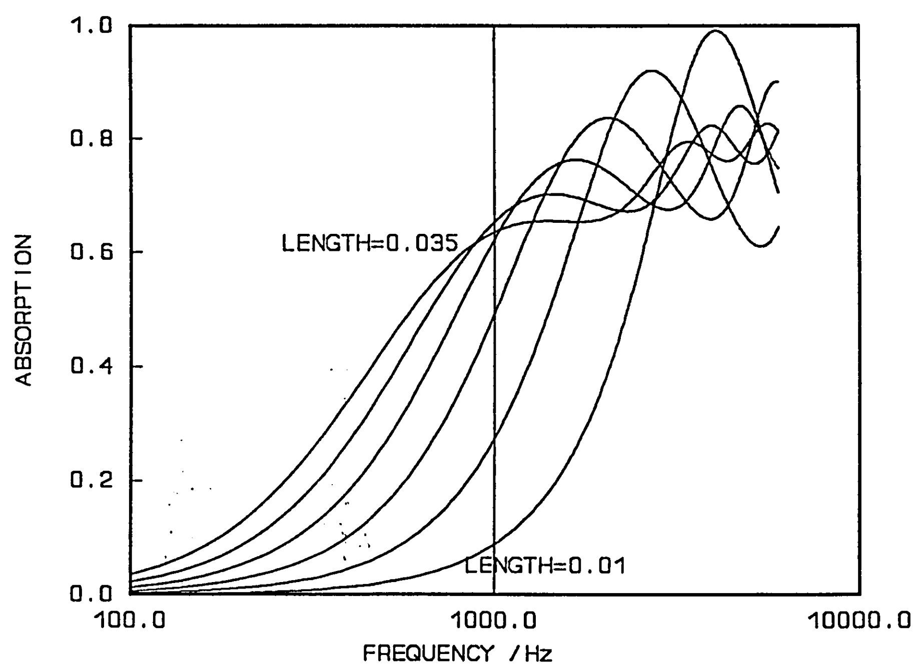


Figure 39 Graph of absorption, predicted using Craggs' model, against 6 different lengths.

Changes to the length of material will shift the position and amplitude of the peaks of the absorption curve. At increased thickness lower frequencies with larger wave lengths will be absorbed. This absorption will be at reduced amplitude.

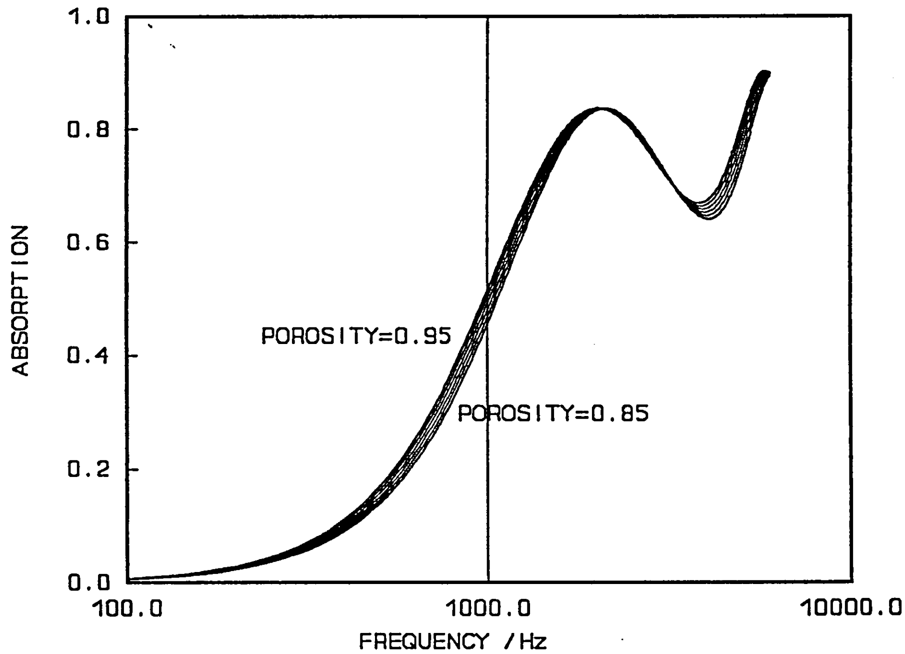


Figure 40 Graph of absorption, predicted using Craggs model, against frequency at 6 different porosity.

Porosity increases have minimal effect on the absorption curve for the chosen parameters. With a different set of base parameters the modifications caused by changes in porosity will have greater effect on the absorption curve.

Increases in the air flow resistance in a foam have little effect on the position of turning points in the absorption curve in relation to frequency. It does alter their amplitude, as can be seen in Figure 41. The first maximum increases while the fist minimum increases and then decreases. When the air flow resistance is increased beyond the range shown in Figure 41 the fist maximum will decrease. These changes are accompanied by an narrowing of the peaks.

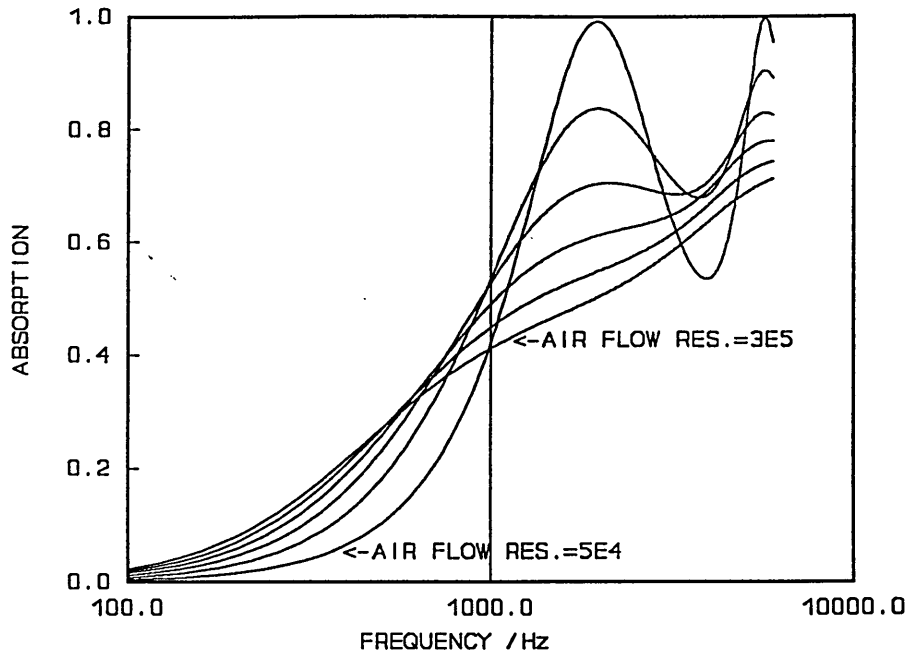


Figure 41 Graph of absorption, predicted using Craggs' model, against frequency at 6 different levels of air flow resistance.

3.5 Zarek's Model

King [41] considered the microstructure of a foam in terms of a lumped element model; this model was therefore unlike others discussed in this work. King's original ideas are the starting point for Zarek's analysis. She based her work on the material being formed from many lump masses with visco-elastic connections. These form a cubic lattice. By calculating the mechanics of one element, then reducing the element and adding other elements, finite difference approximations describing the equations of motion are obtained. The cubic lattice of mass elements with arbitrary shape will form an array of parallel pores or ducts that have a regularly varying cross section. As with previous work Zarek identifies the two longitudinal wave types.

From her work, Zarek formed several equations for the impedance of various combinations of films, foams and air gaps. The equation below is for the normal incidence acoustic impedance of a porous foam with a solid back.

$$Z_c=\frac{1}{(\rho c)_{air}(k_2^2-k_1^2)}\left[\left(\sqrt{2B-k_1^2}-j\sqrt{\frac{\varepsilon h}{e}(2B-k_2^2)}\right)^2\frac{ek_1}{j\omega h\tan(k_1 l)}\right.$$
$$\left.-\left(\sqrt{2B-k_2^2}-j\sqrt{\frac{\varepsilon h}{e}(2B-k_1^2)}\right)^2\frac{ek_2}{j\omega h\tan(k_2 l)}\right] \quad (7)$$

where

$$A=\left(\frac{h}{2gc_a^2}\right)\left[(1-h+g)-j\frac{W}{\omega}\right]\omega^2$$

$$B=\left(\frac{R}{2gc_f^2}\right)\left[(1-h)(1-g)+\left(\frac{g}{R}\right)-j\frac{W}{\omega}\right]\omega^2$$

$$C=\left(\frac{1}{g}\right)\sqrt{\left(\frac{hR}{c_a^2c_f^2}\right)}\left[(1-h)-j\left(\frac{W}{\omega}\right)\right]\omega^2$$

$$k^4-2(A+B)k^2+(4AB-C^2)=0$$

d=sample thickness (l)

h=Volume Porosity

g=Pore area per unit area

c_a=Speed of sound in fluid ($\sqrt{e/\rho}$)

c_f=Speed of sound in frame ($\sqrt{\varepsilon/\phi}$)

R=Density ratio of fluid to frame

W=Viscodynamic parameter

D=Ratio of fluid to air density

ω=angular velocity

ε=Young's modulus of frame (complex)

e=Young's modulus of fluid

ρ= density

3.5.1 Discussion of Parameters in Model

The volume porosity, h, is the difference between the volume of a chamber with and without a material of known volume (ie the volume of the solid matrix v). It follows that:

$$h=1-v/(\text{material volume}) .$$

By combining the above formula with a measured value of foam density (30 kg m^{-3} for Zarek) a figure for matrix density can be calculated. From Woods [83] the density of solid polyurethane is approximately 1220 kg m^{-3}. It would be expected that values of frame density in Zarek's paper would agree with the polymer density given in Woods or would be below this value. Calculation using data from Zarek's paper reveal that the frame density is well above that of solid polyurethane. With a density of 30 kg m^{-3} the maximum porosity will be approximately 0.97 .

For an isotropic material g the pore area per unit area of material is given by:

$$g= 1-(1-h)^{2/3}$$

The speed of sound in the fluid is c_a (the fluid is usually air). Zarek assumes isothermal fluctuations only and uses a value of c_a= 290 m s^{-1}; however this will only be the case at low frequencies or with very small structural factors.

The speed of sound in the frame c_f, could be calculated by measuring the modulus and density of the frame (from [84] page 233, $c_f=(e/\phi)^{1/2}$, e=Young's modulus, ϕ=foam density). There is ambiguity in that ϕ is labelled on page 234 as the frame density; Zarek, however, uses the value of the foam density in the calculation of the density ratio R.

The viscodynamic parameter, W, is highly dependent on the cell size. Zarek assumes that because of the high porosity the matrix will have only a small perturbation effect on overall fluid flow and hence the fluid flow can be approximated to flow around an array of small spheres. This approach has been used by other authors and the results are well known to a reasonable accuracy. Approximations of this type would not be appropriate for lower porosity or with smaller cells. The deduction of this parameter involves several approximations and assumptions. Because it cannot be measured there would be difficulty in using it in a predictive model.

The ratio, D, of impedance of the fluid in the pores to the impedance of air is in most cases unity.

As with Craggs' model, a set of values was to be used to evaluate how changes in parameters affect the normal incidence acoustic absorption coefficient (one parameter from a set being changed while the remainder are held constant). This process is repeated until all parameters have been changed. Graphical results of these changes are plotted here and discussed. For consistency, values chosen for the evaluation should be as those used in evaluation of other models. Unfortunately the parameters in Zarek's model are dissimilar to those in others models though they are related.
R (the density ratio) will vary with density of the frame material as will c_f the speed of sound in the frame, c_f will also be affected by the modulus of the frame material.

Table 12 Comparison of values suggested by Zarek and observed values.

Parameter	Standard Values	Zarek Values
Density /kg m^{-3}	30	30
Air Density /kg m^{-3}	1.2	1.2
Speed of Sound (c_a)	340	290
Porosity (h)	0.975	0.994-0.996
Length /m	0.05	0.05
Storage Modulus /N m^{-2}	1.5e5	30-3000
Viscodynamic Parameter	50000	9960-50000

3.5.2 Discussion of Model Performance.

Two sets of input characteristics have been put into the Zarek model. The first set of characteristics are typical of values given in Zarek's paper [85]. A second set represents measured characteristics. Both the sets are tabulated above Table 12). There are differences values used by Zarek's and standard values.

The data sets are used to calculate specific acoustic impedance Z_c from equation (7). Subsequently the value of Z_c is used to calculate normal incident acoustic absorption. Impedance and absorption values calculated from this model were too small to be realistic (of the order 10^{-10}). No obvious errors can be deduced from either references [85] or [84]. With such poor results further evaluation of this model will be inappropriate.

A brief investigation of the characteristic acoustic impedance Z_o (the equation on page 220 of reference [85]) has been made. This equation produces results in approximate agreement with the graphs produced later in the paper. Possible reasons for the unrealistic output from this model are: rounding errors, computational errors or programming error.

Rounding errors would occur because of the large differentials in the input parameters. If rounding errors were the problem, they should also affect the calculation of Z_o, a similar calculation.

Computational errors have been checked. There is agreement between Zarek's paper [85], her Phd thesis [84] and the calculations of Z_o. Many of the components in the in the calculation of Z_c are also used in calculation of Z_o which it is assumed is correct.

A similar argument can be used for the programming as used in the initial computations. As many similar components are used for calculations of Z_c and Z_o it is unlikely that errors would occur in the common parameters. All the subroutines used (for complex arithmetic etc.) have been used extensively in other programs. The calculations have been rechecked many times and no mistakes are apparent.

All possible errors have been investigated. It is suggested that future work could include a reassessment of this model.

3.6 Bolton - Lauriks Model.

The model developed by Bolton [10] brings together the concepts of several workers. The basis is the work of Zwikker and Kosten [86] with developments by Rosin [70] and additions of factors introduced by Attenbrough [4]. Lauriks et al [49] discuss the Bolton model in their paper.

In the reproduction of this model it is necessary to use information from both Lauriks et al [49] and Bolton [10]. However the models have fundamental differences which lead to difficulties in interpretation. For example in the equation for the complex density of air, Bolton uses j and Lauriks et al -j as the complex argument for the second term. In practice this has no effect on predicted behaviour. There are more significant inconsistencies.

The Bessel functions in the equation for the complex density and elasticity are given as J_o/J_1 in Lauriks (equations 20 and 21 page 148), J_1/J_o in Bolton (equation 6.14 page, and 173 equation, 6.26 page 185).

In the calculation of the parameter B (Lauriks <u>et al</u>, paper equation 23b (page 148), Bolton equation 6.31 page 187) the two authors have different expressions. The final term in the Lauriks equation (23b) is divided by the sample porosity h, whereas Bolton equation (6.31) is not divided by the porosity (note: $\rho_2=\rho_o h$ in Bolton).

Bolton has the square of the propagation constant in the expression for $a_{1,2}$ page 188. In Lauriks <u>et al</u> the term is not squared. Also in this expression the translation between using $-j$ or j is not consistent.

In the calculation of the propagation constants (Lauriks et al equation 22, page 148, Bolton equation 6.33 page 188) Bolton has an A squared term and Lauriks et al have none. The equation for calculating the acoustic impedance (Lauriks et al, equation 25, page 148, Bolton equation 6.48, page 197) Lauriks et al have a $-j$ included in the tanh argument, Bolton has none.

A further complication with Lauriks is the confusion between the complex modulus of air and that of the solid material in the foam. To conform with the notation given at the top of page 148, equation 21 should read E_p= whereas it reads E_s=. To make the Lauriks equations consistent with the Bolton equations it is necessary put the value of E_s in table 1 equal to E_p and let the equation 21 stand as stated.
The correct formulation for the calculating the values of $a_{1,2}$ on page 188 from Bolton has to be obtained from the original work of Rosin [70].

3.6.1 The Equation.

$$\frac{1}{j\omega Z}=\frac{\left(\frac{b_2}{\gamma_2}\right)\left[\frac{1}{E_2}-\frac{(1-h)\,b_1}{E_1}\right]\tanh(\gamma_2 l)-\left(\frac{b_1}{\gamma_1}\right)\left[\frac{1}{E_2}-\frac{(1-h)\,b_2}{E_1}\right]\tanh(\gamma_1 l)}{a_2-a_1} \quad (10)$$

where l= the sample thickness

The propagation constants, $\gamma_{1,2}$ are calculated from:

$$\gamma_{1,2}=\left[-\frac{A}{2}\pm\left(\frac{A^2}{4}-B\right)^{1/2}\right]^{1/2} \quad (11)$$

$$A=\frac{\omega^2\rho_1}{E_1}-j\frac{\omega s'}{hE_1}+\frac{\omega^2\rho_2}{hE_2}-j\frac{\omega s'}{hE_2} \quad (12)$$

$$B=\left(\frac{\omega^2\rho_1}{E_1}\right)\left(\frac{\omega^2\rho_2}{hE_2}\right)-j\left(\frac{\omega^2\rho_1}{E_1}\right)\left(\frac{\omega s'}{hE_2}\right)-j\left(\frac{\omega^2\rho_2}{hE_2}\right)\left(\frac{\omega s'}{E_1}\right) \quad (13)$$

$$a_{1,2}=1+j\frac{E_1\gamma_{1,2}^2+\omega^2\rho_1}{\omega s'} \quad (14)$$

$$b_{1,2}=h\,a_{1,2}+(1-h) \quad (15)$$

s' the coupling factor is calculated by;

$$s'=j\omega\rho_2(\mu'-1) \quad (16)$$

$$\mu'=\epsilon\left(\frac{\rho_{2e}}{\rho_2}\right)\quad,\quad \rho_2=\rho_c h\quad,\quad \rho_{2e}=h\rho_c^*$$

the dynamic stiffness (E_2) and dynamic modulus ρ_c^* of air are given by the following equations;

$$E_2=\frac{E_o}{1+\frac{2(\gamma-1)}{N_{pr}^{1/2}\lambda_c\sqrt{-j}}T_c\left[N_{pr}^{1/2}\lambda_c\sqrt{-j}\right]}$$

where;

J_x is a Bessel function of order x.

$$\rho_c^*=\frac{\rho_o}{1-\frac{2}{\lambda_c\sqrt{-j}}T_c[\lambda_c\sqrt{-j}]}$$

$$\lambda_c^2=\frac{8\omega\rho_o\epsilon}{h\sigma}$$

$$\textit{the function } T_c(x)=\frac{J_1(x)}{J_o(x)}$$

l=sample thickness

ω=angular velocity

ε=structural factor

h=sample porosity

ρ_o=density of air

ρ_1=the bulk density of the frame

$E_1=E_m(1+j\eta)$, E_m=dynamic bulk modulus, η= loss tangent of the foam

$E_o=\rho_o c^2$ c= the speed of sound in air

N_{pr}=Prandtl number (0.713 for air at 20°C)

γ=the ratio of specific heats (1.4 for air)

σ=the flow resistance through the foam

Equations of continuity and motion are developed in a similar way to those of Zwikker and Kosten [86] and Beranek [6]. Two waves are identified, one in the matrix and the other in the fluid. It is in the solution of the equations and the interpretation of the results in terms of phenomenological behaviour that Rosin greatly differs from the earlier authors. Bolton adds to Rosins work expressions for the frequency dependent complex properties of air, the density and bulk modulus. Justification for Bolton adding these terms is that Rosin's is original expression for complex density is only accurate at low frequencies. No explicit account is taken of inertial or dissipative reaction related to the frequency dependence of the oscillating flow in the pores. An expression for E_2, the complex bulk modulus, takes into consideration the changes to the modulus of air; low frequency isothermal and high frequency adiabatic.

3.6.3 Variables in the Model.

An exact value of the structural factor cannot be measured directly. Lauriks et al [49] has used heuristic methods to determine its value. Attenbrough [4] identifies it as the square of the tortuosity and, although this gives an indication of a value of structural factor, no specific method of determination it has been identified.

The complex value of frame stiffness at acoustic frequencies cannot be measured directly. Data presented in Appendix 6 below gives values of the complex stiffness of the foam at low frequencies (about 100 Hz). At higher frequencies, fluid flow processes will influence the measured value.

3.6.4 Influence of changes in the model parameters on the normal incident acoustic absorption.

As discussed in reference [69] it is incorrect to directly compare the efficiency of a sound absorber without knowledge of the type of sound that is to be absorbed. For example consider two materials the first with an absorption peak at 2000 Hz and the second a smaller peak at 1000 Hz. If frequency of the sound to be absorbed is predominantly at 1000 Hz the second material will be more appropriate. For a different sound source at predominantly 2000 Hz the first material would function better. Therefore discussion of changes in material parameters will be with reference to the shape of the curves and not improved efficiency. By understanding how parameters affect absorption it is possible to tune a material for a specific sound absorption application.

In the experimental part of this project a large number of polyurethane and other types of foam has been characterised. From the data obtained it was possible to establish a 'typical' range of property values for acoustic foams. These are used to investigate the predictions of the models.

Table 13 Property values used to investigate the model proposed by Bolton.

Parameters	Standard Values	Minimum	Maximum
Density /kg m^{-3}	30	15	40
Air Density /kg m^{-3}	1.2	-	-
Speed of Sound /m s^{-1}	340	-	-
Porosity	0.975	0.84	0.94
Structural Factor	5	3	8
Length /m	0.02	0.01	0.035
Air Flow Resistance /Rayls m^{-1}	100000	10000	210000
Storage Modulus /N m^{-2}	150000	50000	550000
Loss Tangent	0.2	0.1	0.6

Effects of changing the density can be seen in Figure 42. There is a general upward shift of the frequency at which the first absorption peak occurs with increasing density in this case the absorption peak has a maximum value between 25 and 30 kg m^{-3}. These peaks narrow as density increases. Changes can be explained in terms of increased mass (hence inertia) in the material frame of the porous material.

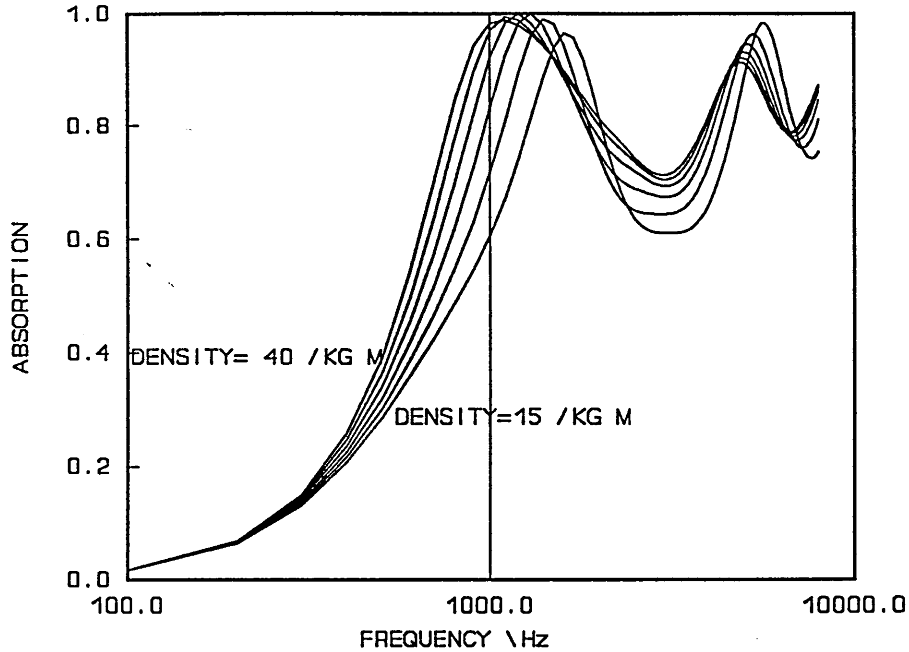


Figure 42 Effect of changes in density on the Bolton model.

Porosity. Changes in this factor, as can be seen in Figure 43, are predicted to alter the shape of the normal incident acoustic absorption curve only slightly. An increase in the peak absorption is apparent with an increase in porosity. Although with the chosen parameters changes in porosity there is little effect on the curve with a different set of parameters changes caused by varying porosity would be more noticeable.

A general smoothing out of the absorption curve can be seen with decreasing structural factor in Figure 44. It follows that when it is increased the overall absorption will increase. This can be seen as the dips in the absorption curve are filled.

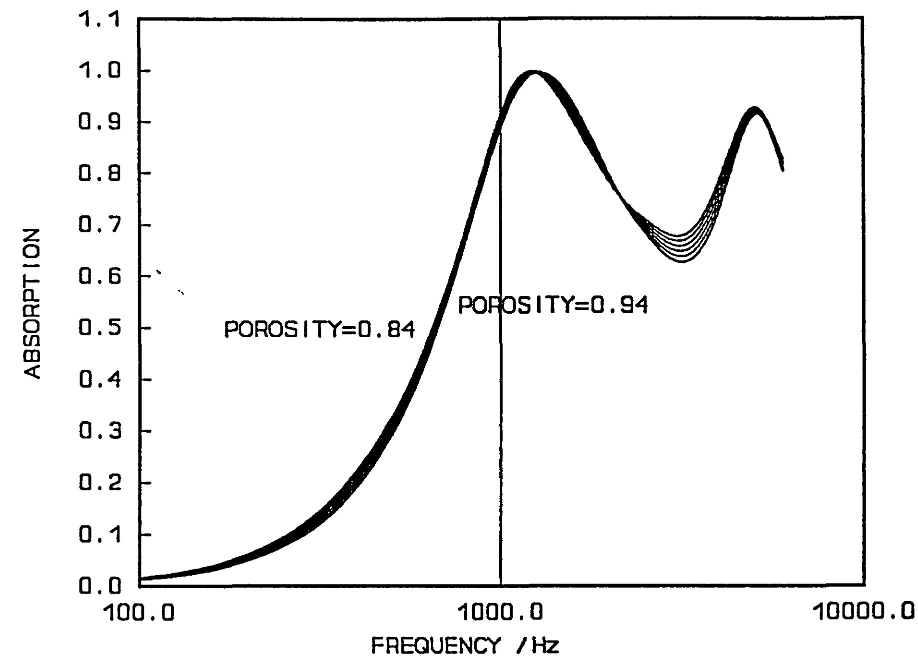


Figure 43 Effect of changes in porosity on the Bolton model.

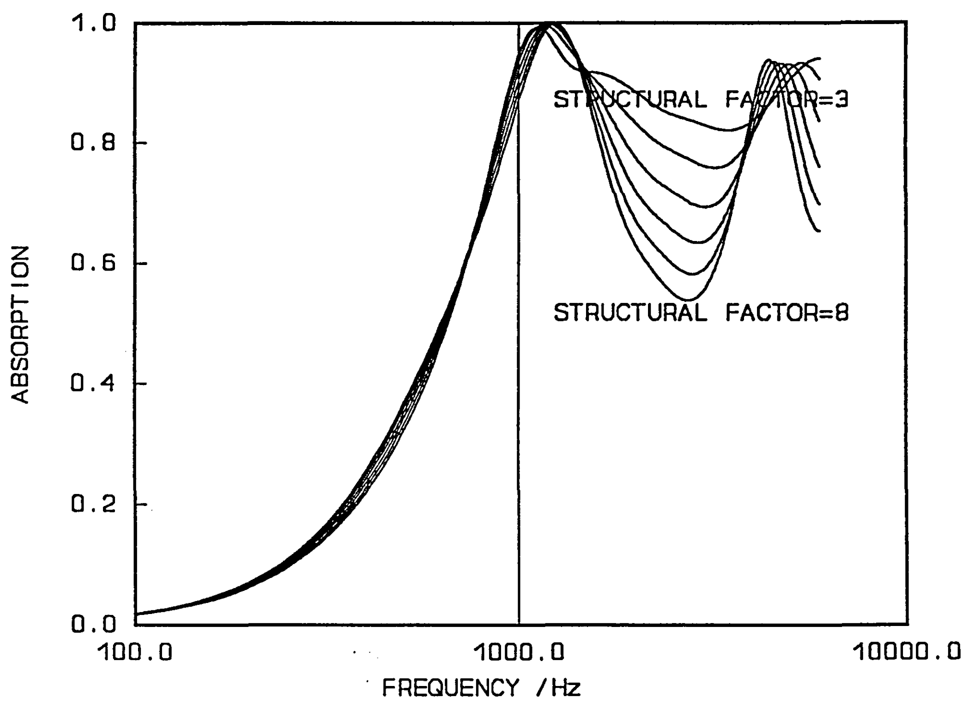


Figure 44 Effects that changes in structural factor will have on the predicted normal incident absorption using the Bolton model.

As with other models and as seen in the experimental data increases in length will decrease the frequency at which the first maximum occurs. With this increased absorption at lower frequencies comes a decrease in amplitude of the first maximum. These changes can be seen in Figure 45. It is therefore incorrect to assume that by increasing the thickness of an absorber its efficiency can be increased. Thickness is however a simple method of manufacturing a material to absorb noise in a specific narrow frequency band width (eg in the case of printers for computers).

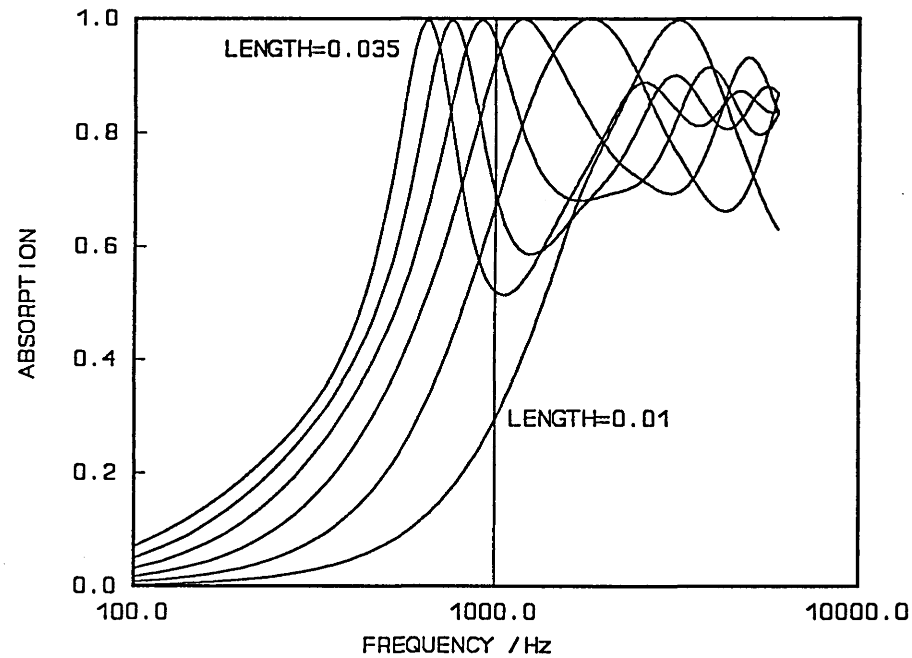


Figure 45 Effects of changes in length on predicted absorption using the Bolton model.

For a material to absorb sound energy it must first enter the material, hence a material with low resistance to air flow is required. When the material has entered the material high resistance is required to absorb the sound energy. These two requirements are a contradiction and hence a compromise is required. Figure 46 shows how changes in air flow resistance will first increase the peaks to a maximum with increase in R, then reduce as further air flow resistance is applied.

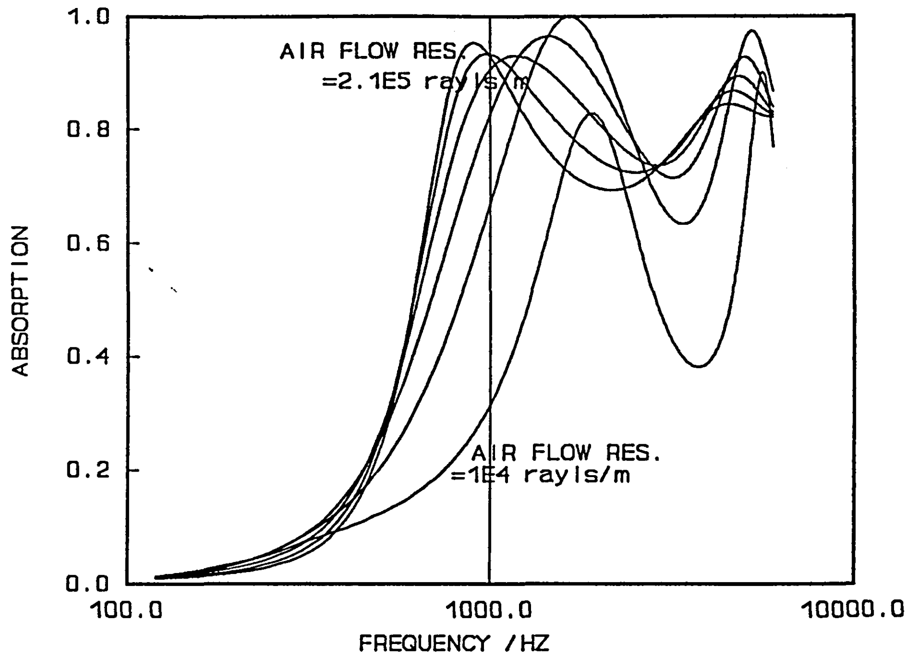


Figure 46 Effects on absorption predicted using the Bolton models when air flow resistance is varied.

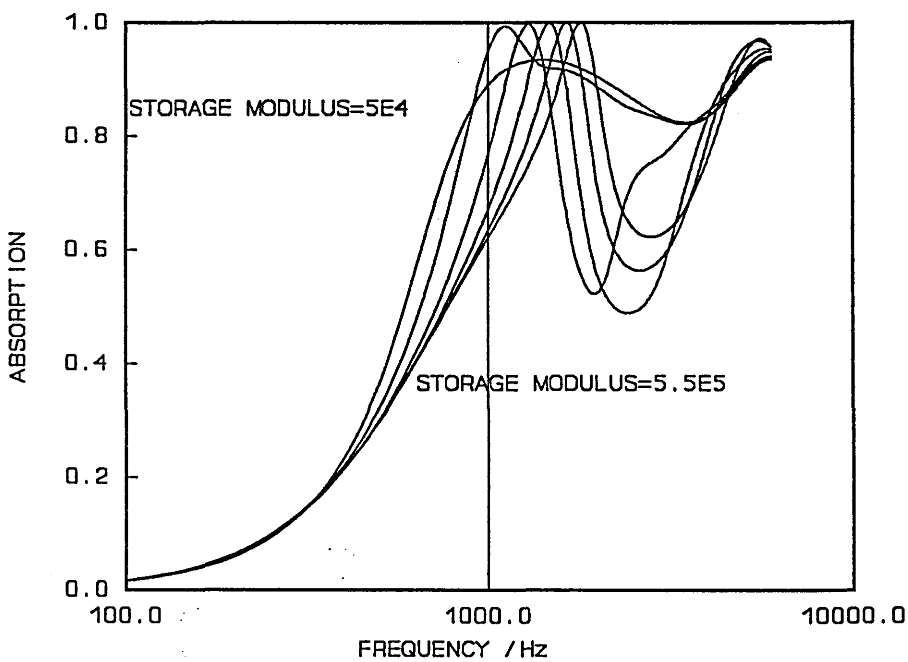


Figure 47 Effect of changing storage modulus on the normal incident absorption predicted using the Bolton model.

As the storage modulus is increased the frequency of the first peak decreases and broadens its width. The increase is slight using the selected parameters. Changes are shown in Figure 47 below:

A general shift of the normal incidence acoustic absorption curve is observed with an increase in loss tangent. The shift is towards the higher frequencies and is accompanied by a reduction in the magnitude of the first maximum as shown in Figure 48 below.

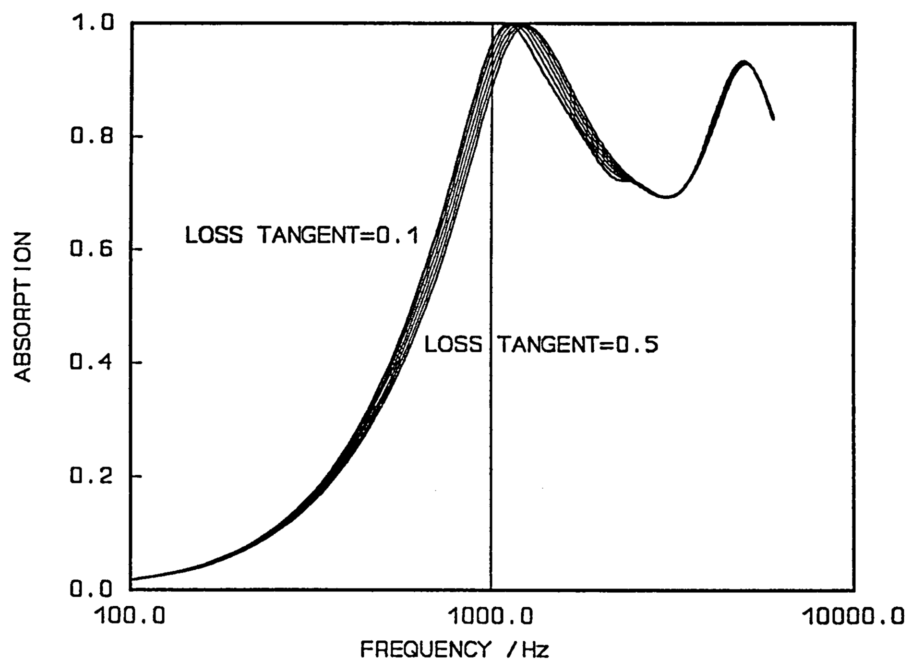


Figure 48 Effects of changes in loss tangent on the normal incident absorption predicted by the Bolton model.

The application of this model to porous elastic materials tested by making a detailed comparison between the predicted and measured acoustic behaviour of a range of flexible foams. The results of this study are presented in Chapter 5 below. Parameters in the model for which no specific values are available are adjusted until a 'best fit' is obtained. A range of air flow resistance values were achieved by subjecting a closed cell foam to different degrees of crushing which produced different levels of reticulation.

3.7 Lambert Model

3.7.1 Introduction

This is one of the most recent works on modelling the acoustic behaviour of cellular plastics. The original work by Lambert [47] has been subsequently developed further [54],[46]. The model was derived from a synthesis of two earlier models; Zwikker and Kosten [85] and Biot [8] a new model is derived. The basis of the model is a structure of prolate spheroids interconnected in a regular lattice structure as suggested by Zwikker and Kosten. Biot's theory of frequency dependant flow resistance and mass structural factor are then included. The inclusion of Biot's concepts requires the knowledge of size cell filaments (cell struts), the number of cells per unit length and the cell size.

3.7.2 Theory

From the decoupled mode theory of Zwikker and Kosten [86] he showed that;

$$\frac{Z_p}{\rho_0 c_0}=\left(\frac{\sqrt{k_p}}{\Omega}\right)\left(1-i\frac{1}{Q_p}\right)^{\frac{1}{2}}$$

$$\Gamma_p=\frac{\omega}{c_p}\left(1-i\frac{1}{Q_p}\right)^{\frac{1}{2}}$$

where Z_p=intrinsic acoustic impedance

Γ_p= propagation constant

ω = angular frequency of excitation

c_p= apparent speed of sound in the fluid of the pores

$=(\kappa_p \Omega \rho_p)^{-1/2}$

Q_p= dimensionless frequency parameter

$=\omega\rho_p/\Phi$

$k_p=k_s/\kappa_p P_o \gamma$

ρ_p=apparent density of fluid in the pores

$=\rho_o k_s/\Omega$

κ_p=inverse bulk modulus of the fluid in the pores

Ω=volume porosity

P_o=static pressure in the fluid

γ=ratio of the specific heats

k_s=dynamic structural factor of Zwikker& Kosten [86]

Φ=dynamic flow resistance per unit of volume

Lambert [46] investigates the influence of c_p, Q_p and k_p on the acoustic behaviour of open cell foams. Using Biot's classical treatment of elastic wave propagation in a fluid saturated granular material, together with refinements introduced by Sides et al [], expressions for the dynamic structural factor

(k_s) and dynamic flow resistance per unit volume (Φ) are derived,

$$k_s = 1 + \left(\frac{\eta}{\rho_0 \, \Omega \, \beta_0}\right) \frac{F_i(\kappa)}{\omega}$$

$$\phi = \left(\frac{\eta}{\Omega^2 \beta_0}\right) F_r(\kappa) = \phi_0 F_r(\kappa)$$

To account for deviation from Poiseuille flow a complex function $F(\kappa)$ ($F_r(\kappa)+iF_i(\kappa)$) is used. This function is dependent on frequency and pore geometry through the parameter κ where $\kappa=a_p(\omega/\nu)^{1/2}$). κ is referred to as the acoustical Reynold's number. Static flow resistance Φ_o ($=\eta/\Omega^2\beta_o$), is a function of the D'Arcy coefficient of permeability of the porous frame (β_o), bulk viscosity of the fluid in the pores ($\eta=\rho_o\nu$) and volume porosity (Ω).

The mean pore size parameter, a_p, is a frequency scaling factor used in expressions for the propagation constant and the acoustic impedance, and introduces the relationship between frequency and cell geometry. It has been shown by Sides [] that static flow resistance is related to a_p by;

$$\Phi_0 = \frac{8\eta}{\Omega \, a_p^2} .$$

Hence a prediction of a_p can be made from a measure of static flow resistance per unit volume and volume porosity . Alternatively, Lambert suggests an expression for a_p based on the topology of a prolate spheroidal open cell foam.

$$a_p = \frac{4}{N\pi} \frac{D\left[1-\left(\frac{N\pi}{6}\right)\left(\frac{d}{D}\right)^2\right]}{1+\frac{d}{D}\frac{\sin^{-1}e}{e}}$$

where the eccentricity e of the filament is e, $e=[1-(d/D)^2]^{1/2}$, where d is the minor axis and D the major axis and N is the average number of filaments per cell. The apparent speed of sound in the pores, c_p, is accounted for by deriving a relationship between c_p and the inverse bulk modulus κ_p using the equation;

$$\kappa_p = \frac{1}{P_0}\left[\frac{\frac{\omega_T}{\omega}+i}{\frac{\omega_T}{\omega}+i\gamma}\right]$$

where ω_T is the thermal relaxation frequency for fluids in the pores and is sometimes called the reciprocal time constant and $\omega_T=8\kappa_T/\rho_o c_p a_p^2 a_p^2$.

Lambert shows primarily from consideration of Biot's [] work, that these acoustic parameters are influenced by physical properties of the solid and gaseous phases and the cellular structure of the foam.

3.7.3 Discussion

An assumption that originates from Biot and is carried through in Lambert's work is that the cellular structure is uniform and that the bulk material is homogeneous and isotropic. Lambert further assumes that the foam is made from prolate spheroids interconnected in a lattice structure. Clearly this is not the case with real foams as illustrated in photomicrographs given in the following chapters, figures 51-54.

3.8 Empirical Models

Delany and Bazley [23] investigated samples of fibrous materials. Measurements of air flow resistance and specific acoustic impedance were made. Repeating the acoustic measurements with the use of different backing materials or with thicker samples enabled the propagation constant and characteristic impedance to be deduced.

To establish the empirical relationships, the real and imaginary parts of the propagation constant and normal incident acoustic impedance, were plotted against frequency divided by air flow resistance. The two components of the propagation constant were divided by the angular frequency and they were then plotted against frequency divided by air flow resistance. From the plotted data an approximate power-law relation is obtained. Values of calculated parameters in the relationships are given in Table 14.
The following relationships are used:

$$Z = Z_o Coth(\gamma l)$$
$$Z_o = R + jX \tag{27}$$
$$\gamma = \alpha + j\beta$$

Values required in the above equations are calculated by the following empirical relationship.

$$R = \rho c\left[1 + C_1\left(\frac{\rho f}{\sigma}\right)^{C_2}\right]$$
$$X = \rho c\left[C_3\left(\frac{\rho f}{\sigma}\right)^{C_4}\right]$$
$$\alpha = \frac{2\pi f}{c} C_5\left(\frac{\rho f}{\sigma}\right)^{C_6} \tag{28}$$
$$\beta = \frac{2\pi f}{c}\left[1 + C_7\left(\frac{\rho f}{\sigma}\right)^{C_8}\right]$$

Where: Z_o=characteristic acoustic impedance

Z=Specific acoustic impedance

γ=propagation constant

ρ=density of air

f=frequency

c=the speed of sound in air

σ=specific air flow resistance

It was found by Dunn and Davern [26] that constants in the Delany and Bazley model were inappropriate for reticulated polyurethane foams. By applying a technique similar to that described in reference [23] Dunn and Davern calculated a set of constants to fit the power-law relationship for a set of four reticulated polyurethane foams.

In Table 14 the constants of Delany and Bazley, Dunn and Davern, Qunli, and Cummings and Chang have been quoted. Cummings' and Chang's are for a polyether foam and represent yet another variation in the constants.

Table 14 Constants used by several authors in an empirical power law model.

	Source			
Constants	Ref.23	Ref.26	Ref.64	Ref.21
C_1	0.0571	0.114	0.196	0.209
C_2	-0.754	-0.369	-0.399	-0.548
C_3	-0.087	-0.0985	0.112	-0.105
C_4	-0.732	-0.758	-0.55	-0.607
C_5	0.189	0.168	0.157	0.163
C_6	-0.595	-0.715	-0.580	-0.592
C_7	0.0978	-0.136	0.185	0.188
C_8	-0.595	-0.491	-0.475	-0.554

3.8.1 Discussion of Empirical Model.

Fibrous materials have very different physical and mechanical properties from those of elastic porous material so it is not surprising that the coefficients have different values.

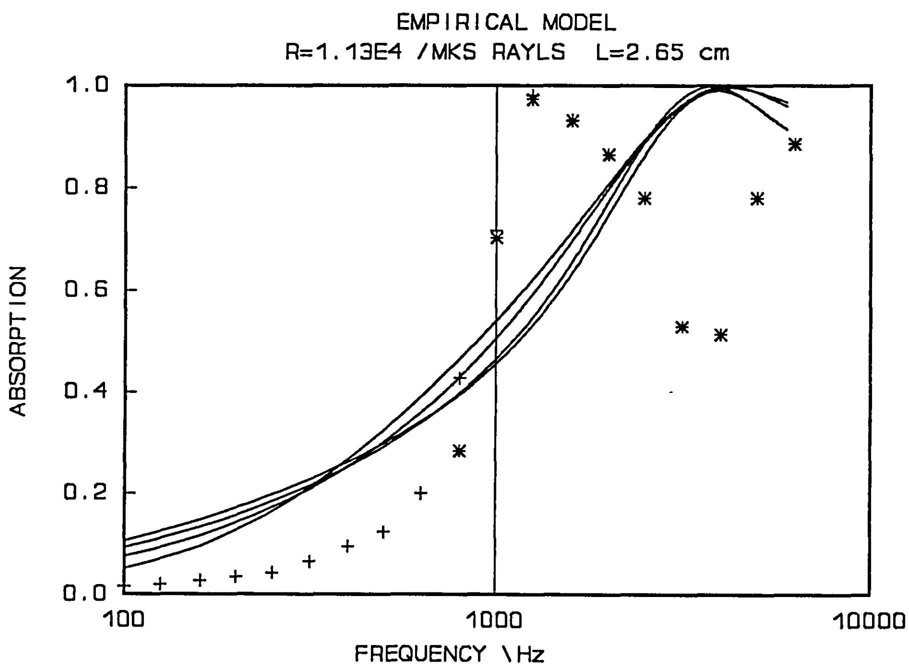


Figure 49 Comparison of acoustic absorption of VDK foam with that predicted by the empirical model.

This fact was noted in [26] and the study repeated with polyurethane foams. Dunn and Davern arrived at the coefficients of the power law model from measurements on four foams. Qunli [64] samples a larger selection of plastic porous open cell foams to refine the coefficients in the power law model. For data from fifteen different foams Qunli argues that "the empirical relationship established in this paper [64] are suitable for the calculation of acoustic properties of porous plastic open cell foams with medium flow resistance." As it has been shown in Chapter 5, this is also an exaggeration and although a material's air flow resistance is the primary factor in determining its acoustic properties, it is not the only factor. In principle the power law relation can be used to predict acoustic absorption behaviour. However there is much evidence, including experimental data obtained in the present investigation, to show that the power law coefficients must be determined for each category, or type, of foam.

Figure 49 shows the prediction of the empirical model with four sets of constants together with normal incidence acoustic absorption of VDK foam. The empirical model has the correct shape but the value of the calculated absorption is too large. No experimental data, when fitted to the empirical model, gave a good correlation between the two.

3.9 Relationship between Random and Normal Incidence Absorption.

The theory put forward by Zwikker and Kosten [86] shows how, in special cases, a relationship between normal incidence and random incidence absorption can be deduced. The following discussion examines the Zwikker and Kosten theory and how it relates to foams. Limitations of the theory are discussed.

The theory is applicable to materials that are locally reactive i.e. when a sound wave with oblique incidence the velocity component perpendicular to the material surface is dependent only on the pressure at that point, not on the angle of incidence. The impedance Z of a locally reactive material is independent of the angle of incidence.

By consideration of a plane wave impinging at an angle α on a locally reactive material an expression for the absorption at angle α is obtained:

$$a_\alpha = 1 - \left| \frac{Z\cos\alpha - W}{Z\cos\alpha + W} \right|^2 \qquad (29)$$

where Z= the complex impedance (R+jX)

α = the angle of incidence

a = the absorption at angle α

W =the acoustic impedance of air (420 Mks rayls)

From the above equation the formula for normal incidence sound absorption is obtained by setting α equal zero, ie

$$a_o = 1 - \left| \frac{Z-W}{Z+W} \right|^2 \qquad (30)$$

Now, by considering a small solid angle and integrating over the half space above the material one may obtain an expression for random incident absorption.

$$\bar{a} = \int_0^{2\pi} a_\alpha \sin 2\alpha \, d\alpha$$

The solution to the above expression, integrating and using equation (29), gives an equation for random incidence absorption in terms of the complex impedance of the material.

$$\bar{a} = \frac{8WR}{R^2+X^2} - 8\left(\frac{WR}{R^2+X^2}\right)^2 \ln\left(\frac{R^2+X^2}{W^2} + 2\frac{R}{W} + 1\right) + \frac{8R}{X}\left(\frac{WX}{R^2+X^2}\right)^2 \left(\frac{R^2}{X^2} - 1\right) \tan^{-1}\left(\frac{X}{R+W}\right)$$

Impedance is complex and expressed in terms of its real and imaginary parts, Z=R+jX. The normal incidence absorption expression (equation (30)) can also be expressed in terms of the material's complex impedance.

By the use of the parametric equations for the normal and random incident absorptions, both types of absorption can be calculated for a material when the impedance is known. By holding one part of complex impedance constant (either the real or the imaginary component) and varying the other impedance component, one may obtain a graph of normal against random incidence absorption, as demonstrated in Figure 50. Four constant values of the imaginary component of impedance were selected; 0, W_o, $2W_o$ and $3W_o$. The real component was then varied between 0.02 W_o and 12 W_o. Values of the real and imaginary components were selected as being typical of those expected in 30mm thick polyurethane foam. From Figure 50 it can be seen that there is no unique relationship between random and normal incidence absorption but a bounded region. Within this region the random incidence absorption can vary by over 10% for a given normal incident absorption coefficient. According to Zwikker and Kosten, porous media are generally not locally reactive, although they can be nearly so in certain cases.

It is concluded, therefore, that there is no unique relationship between random and normal incidence absorption coefficients that can be used with foams. First, because any normal incidence absorption can be made from an infinite number of real and imaginary components, these would all give different values for random incidence absorption. Secondly the theory is for locally reactive materials and foams are not strictly locally reactive.

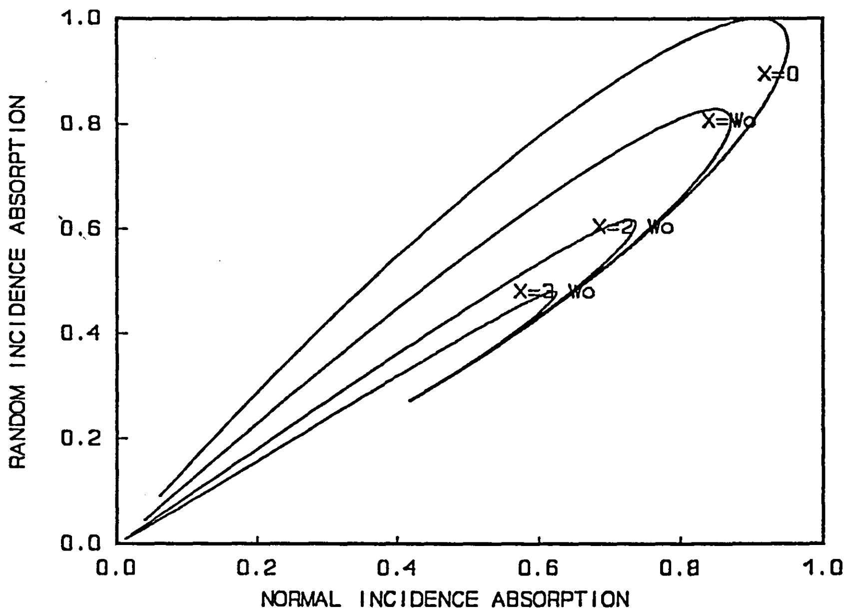


Figure 50 Graph of normal incident absorption against random incident absorption predicted using a relationship suggested by Kosten and Zwikker.

One of the reasons for discussing the Zwikker and Kosten relationship is that it is often quoted in literature as a method of relating the two types of absorption eg [75]. This is incorrect assumption and the relationship will not give accurate results. At best the graph will give only an indication of the relationship between the two coefficients.

CHAPTER 4

EXPERIMENTAL

4.1 Material Characteristics and Acoustic Performance.

Chapter 3 described several models that could be used to predict the acoustic absorption behaviour of plastic foams. In this chapter, methods of measuring the values of parameters used in the models are described. To evaluate the models a set of experiments were devised. This chapter deals with objectives, experimental technique and the theoretical basis of these measurements.

Several material characteristics were measured: acoustic absorption, acoustic impedance, static air flow resistance and dynamic mechanical properties. Photographic studies of the structure were made by the use of electron microscopy.

4.2 Structural Studies Cellular structures were studied by using a scanning electron microscope. The initial studies with optical devices were unsatisfactory due to poor depth of field. Although the magnifications were small (typically 100x) the scanning electron microscope gave the most satisfactory results. Due to the non conductive nature of the samples a thin coating of gold was splattered onto the samples while they where under vacuum. From the micrographs a study of the types of cells was made. In Appendix 7 the theoretical cell formation is discussed. Most of the samples photographed exhibited the expected pentagonal dodecahedron shape. Examples of the windows can be seen in Figure 51 (micrograph of VDK); some of the ruptured windows will have been caused by the vacuum necessary in conducting electron microscopy. Other interesting structures are the post treatment (impregnation) shown in Figure 52 (micrograph of VAF-H). The post treatment of the foam is primarily flame retardant, however the coarse surface will have effects on the passage of air through the foam. In the theoretical treatment of sound absorption, the several models included factors related to cell size. Figure 53 (Barasond) shows a good all round sound absorber. Because the Barasond is made from scrap foam bonded with the original polymer there are few complete cells left to measure. Another cell structure in which factors like cell size are difficult to ascertain is the densified foam. A different type of production process from that used for PUR foams is used in the production of Polyimide. The cell structure is similar, however, due to expansion and there is an elongation in the direction of foam rise. The Polyimide is less inclined to reticulate, inducing a large number of windows with fine dividing struts. An assumption of symmetrical cells used in many models is not always applicable as can be seen in Figure 54 (a micrograph of a polyimide foam).

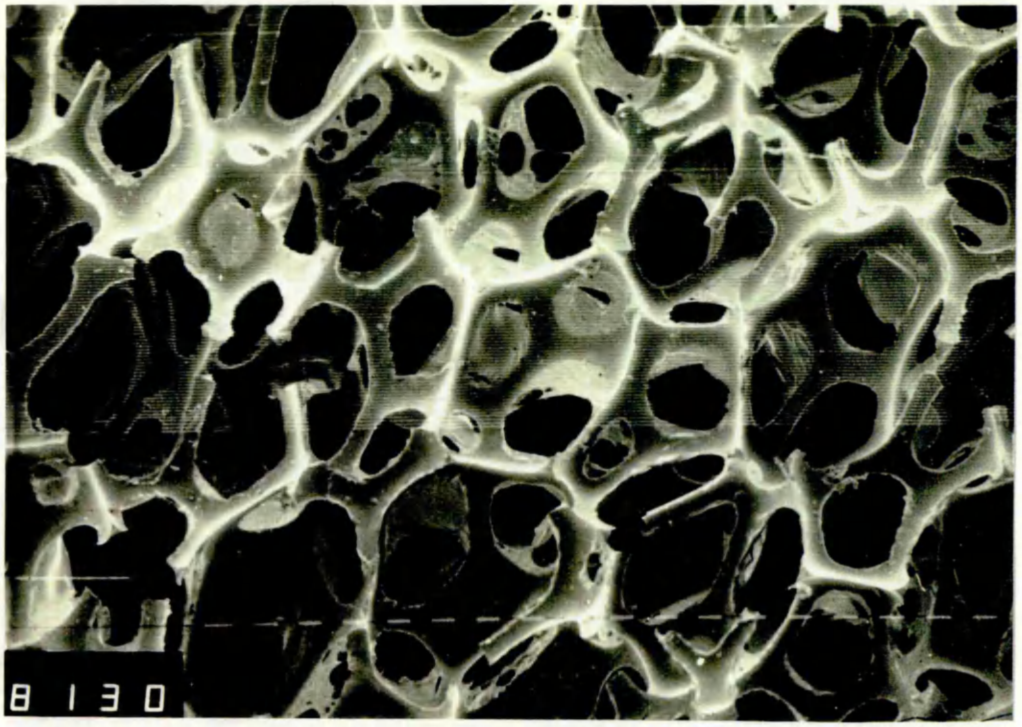


Figure 51 Micrograph of a PUR acoustic foam, VDK.

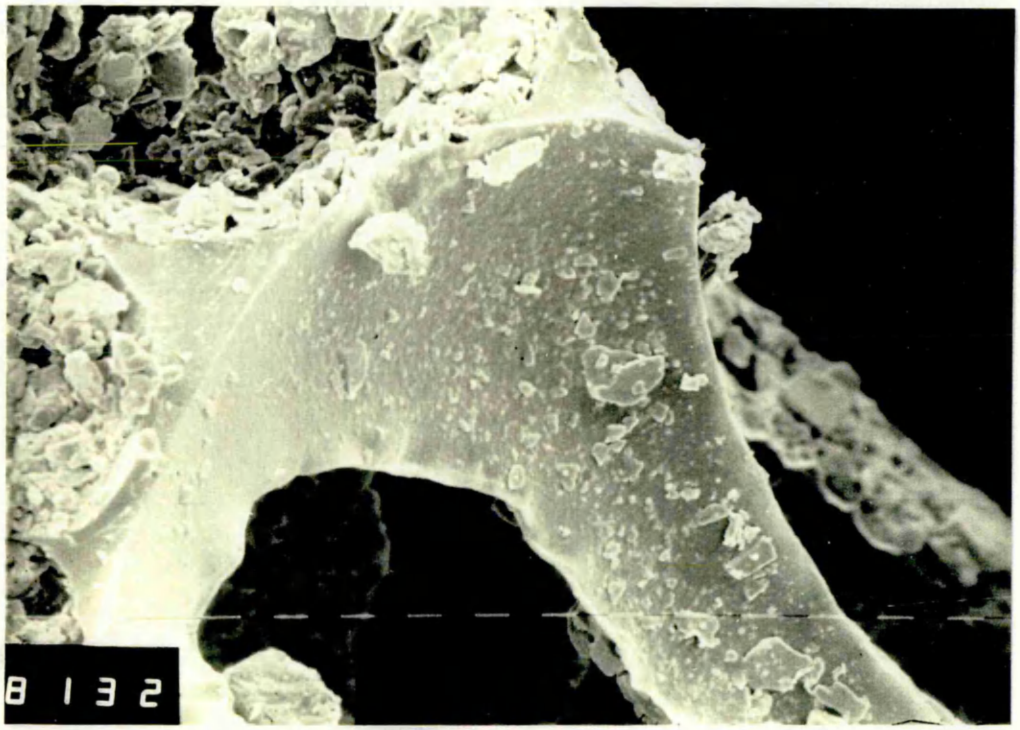


Figure 52 Micrograph of post treated PUR foam, VAF-H.

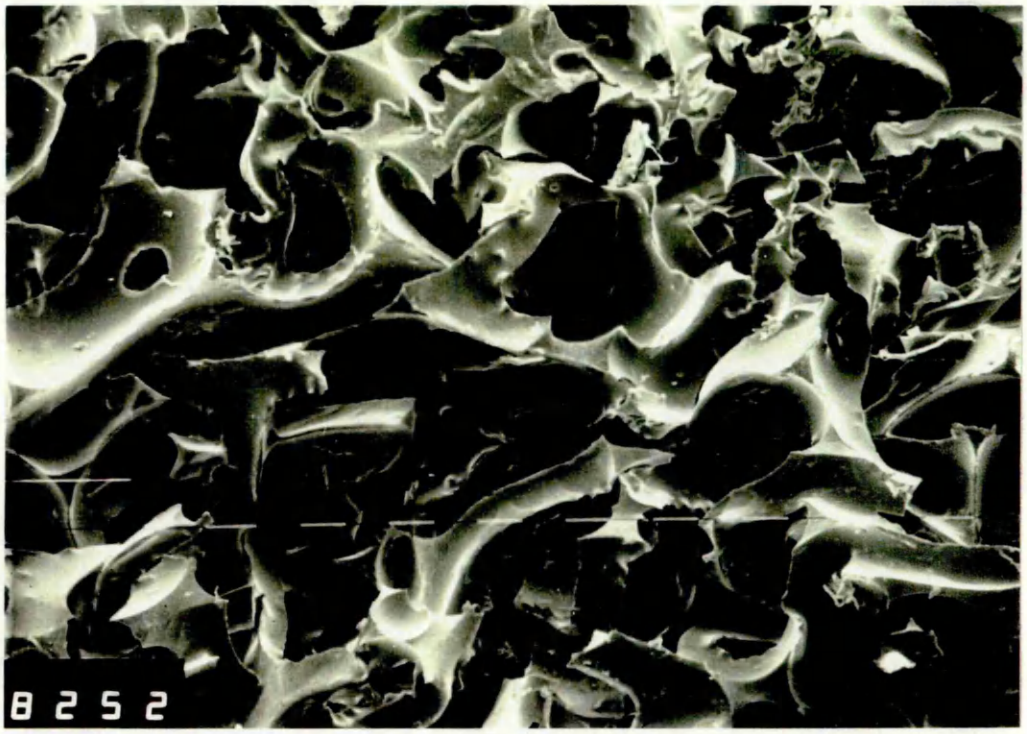


Figure 53 Micrograph of a bonded PUR chip foam, Barasond.

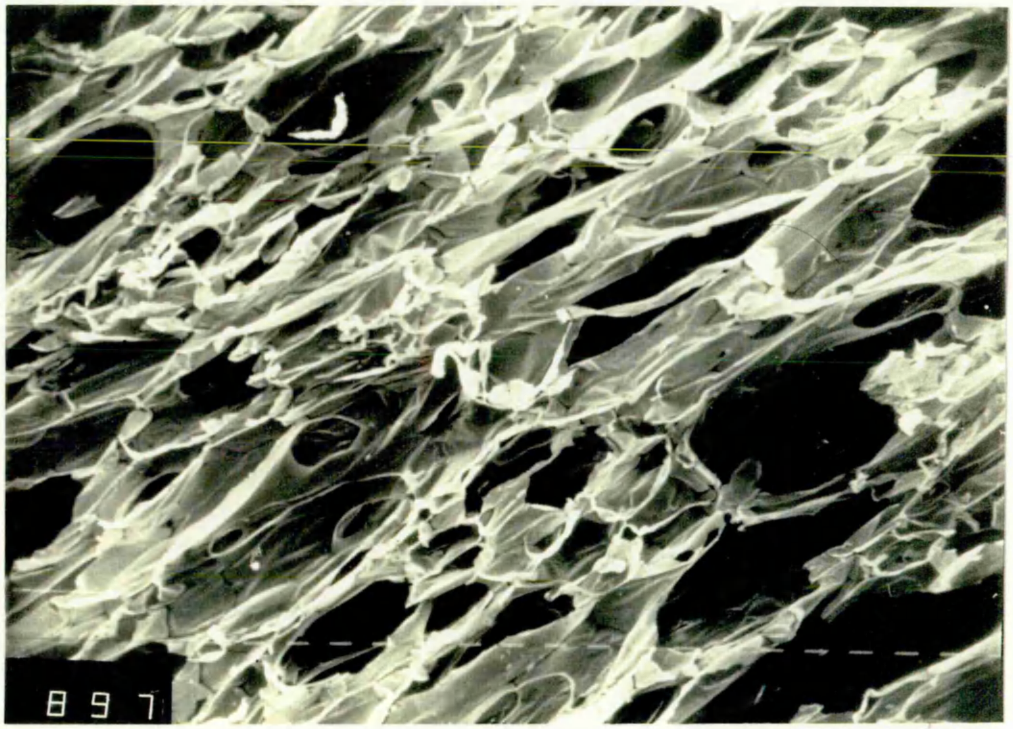


Figure 54 Micrograph of a polyimide foam, TA301.

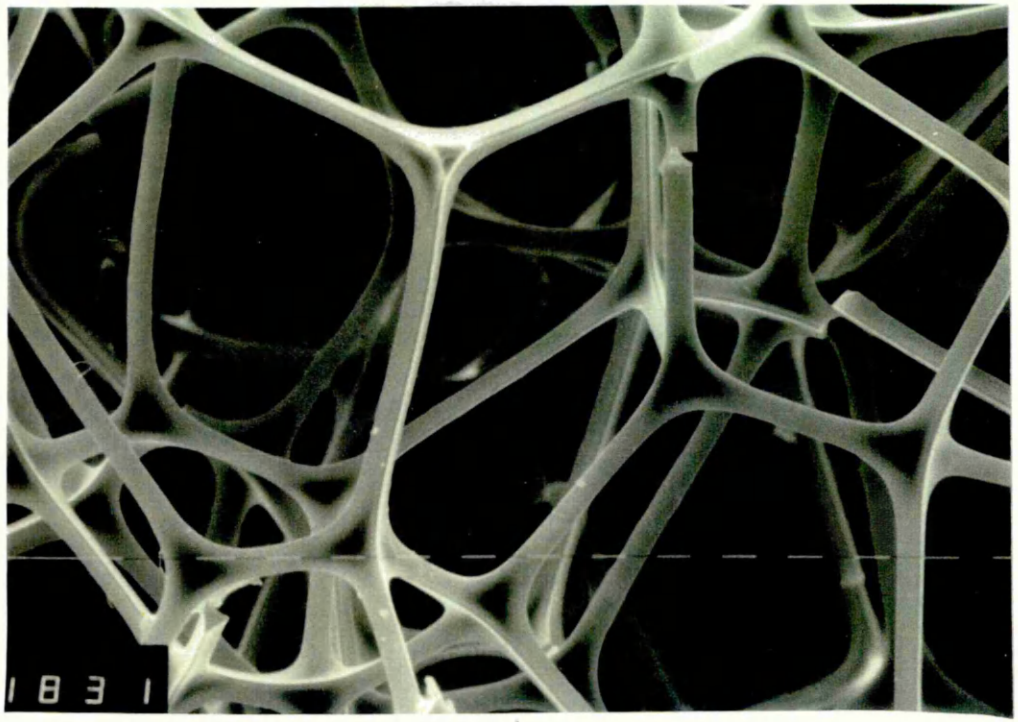


Figure 55 Micrograph of melamine foam Basotec.

4.3 Air Flow Resistance.

4.3.1 Theoretical Basis

Sound waves are oscillatory in nature, creating a dynamic movement of air. Hence any measure of resistance to air flow should include this dynamic effect. Dynamic air flow resistance can be measured [73] but this is complicated and involves using bulk materials. A simpler method of assessing a foam's effect on the passage of air through it is static air flow resistance. Craggs [19] suggests the following relationship between angular frequency (ω), dynamic airflow resistance(R_e) and static airflow resistance (R_s):

$$R_e = R_s\left(0.6 + 0.55\left(\frac{\omega}{R_s}\right)^{1/2}\right) \qquad (33)$$

The method of measuring static air flow resistance is to determine the pressure differential required to maintain a given flow rate across a sample of known thickness (details of the apparatus used for such measurements are given in BS 4443 Pt. 6, 1980). By measuring the pressure at several different flow rates two factors can be calculated. First a component related to the permeability (which is usually denoted K), the second component B, is related to the tortuous route by which the fluid must travel to pass through a foam (the inertial flow resistance). To calculate K and B a relationship first suggested by Forcheimer [32] for air flow in sand, and later used by Gent and Rush for open cell foams, is used. The Forchheimer model is:

$$\frac{\Delta P}{l}=\frac{\eta_o V}{K}+\frac{\rho_o V^2}{B} \tag{34}$$

where η_o and ρ_o are respectively the viscosity and density of air while v is the linear flow velocity across a sample. Hilyard and Collier [38], in a later paper, relate the two constants K and B to structural characteristics of foam.

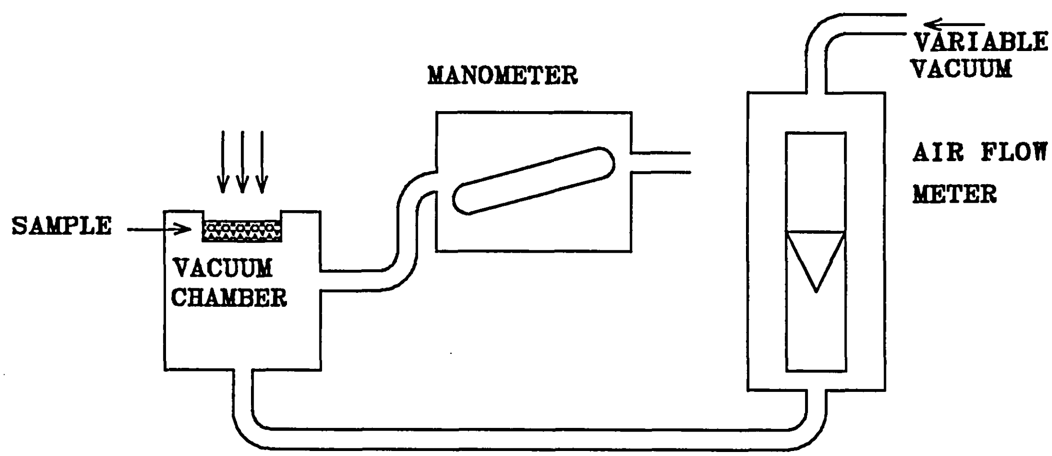


Figure 56 Schematic representation of equipment used to measure static air flow resistance.

The equipment used to measure static air flow resistance is shown schematically in Figure 56 with a photograph of the equipment in Figure 58. The two types of sample holder used

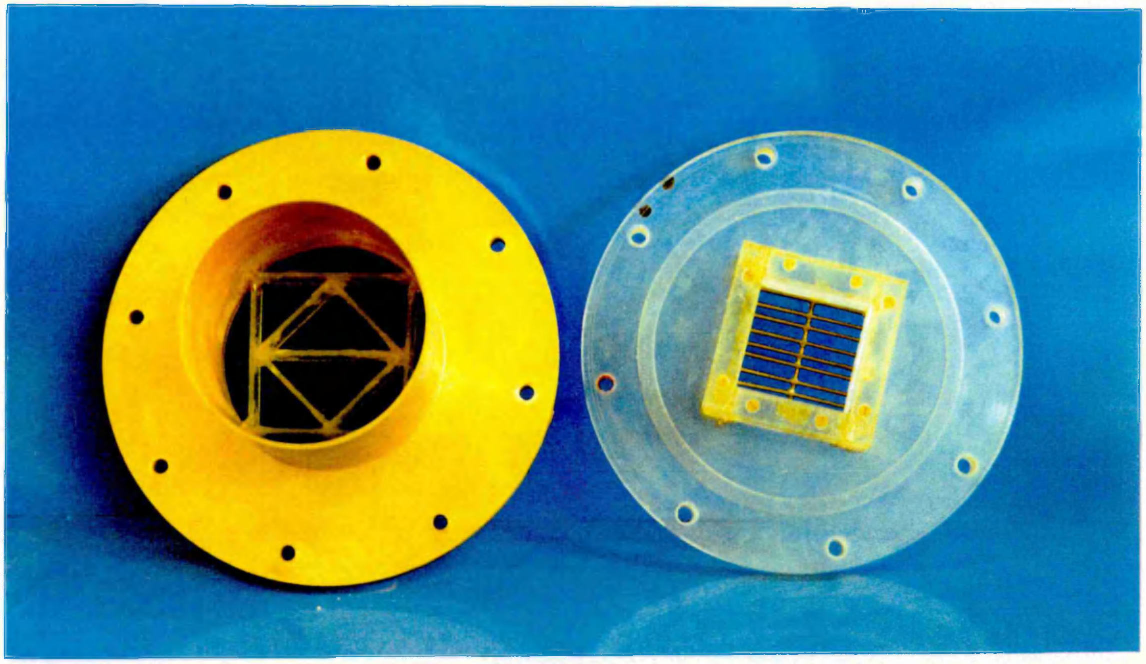


Figure 57 Two types of sample holder used in measurement of static air flow resistance.

are shown in Figure 57. The circular sample holder does not conform to BS 4443 Pt. 6 but does have the advantage that the same sample can be used for both the static air flow resistance and the normal incident absorption measurements. Details of the calculation of K and B are shown in Appendix 4.

4.3.2 Procedure.

Standard 50x50mm samples were cut by using a band saw. For circular samples a special rotary blade was made. Care had to be taken that the vertical sides of the sample remained upright. All samples are cut approximately 2% oversize to create a good seal with the sample holder. When the sample was placed in the holder distortion could occur. Therefore visual inspection of both sides of the sample after its insertion into the holder was made.

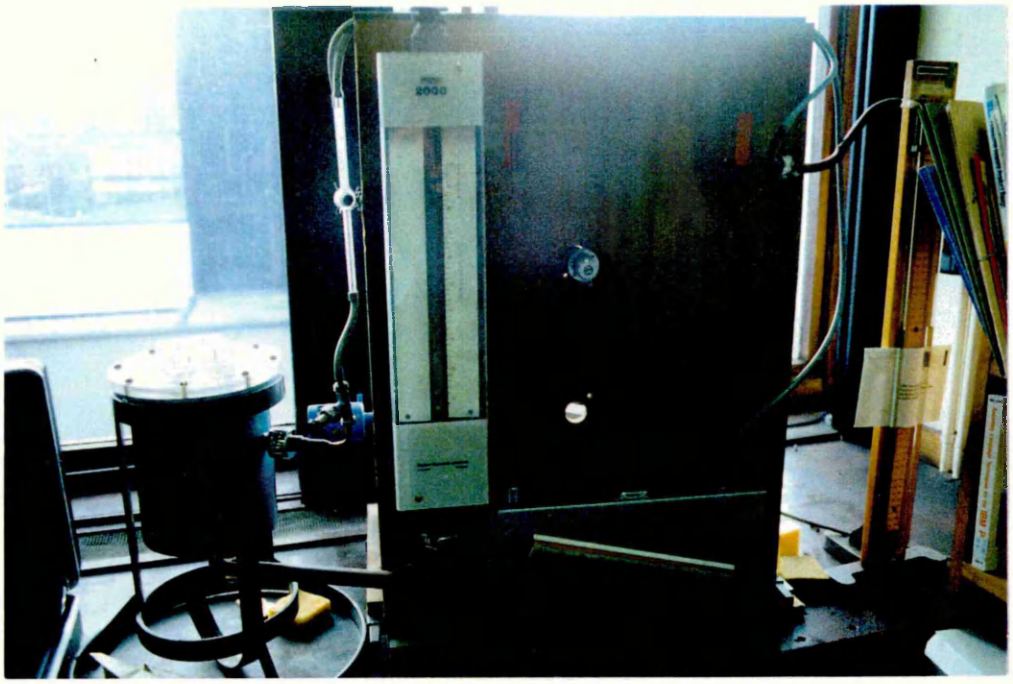


Figure 58 Photograph of the equipment used to measure static air flow resistance.

A constant air flow was then maintained across the sample. This created a pressure drop in the vacuum chamber. Measurements were made of the pressure drop at several maintained air flows. The results were then plotted and calculation performed as described in Appendix 4.

4.4 Dynamic Mechanical Properties

4.4.1 Background

Sound waves impinging on an elastic porous material transfer a portion of their dynamic energy to the matrix. The degree of interaction (ie coupling) between the matrix and air wave depends on the dynamic stiffness and damping of the matrix. Cellular materials are highly non linear at strains greater than about 3 % but it is unlikely that such high deformations will be experienced in the current situation, and therefore the small-strain dynamic mechanical properties will be used in the model evaluation of the acoustic performance of a foam. The small strain dynamic properties depend on two main factors, foam characteristics and external environment. The foam characteristics are the type of matrix polymer, matrix structure, foam density and resistance to air flow. External factors include rate of excitation, temperature and humidity.

Foams under dynamic excitation exhibit a phase difference between the applied stress and the resultant strain (ie visco-elastic behaviour). The dynamic stress-strain relationship is therefore expressed in complex notation as

$\sigma(\omega) = E^*(\omega)\,\varepsilon(\omega)$ Where σ is the stress

ε the strain

ω the angular frequency;

$E^*(\omega)$ is the complex Young's modulus which can be written

$E^*(\omega) = E'(\omega) + j\,E''(\omega)$ E' being the storage modulus

and E'' the loss modulus

The storage modulus E' is associated with elastic processes whereas E'', the loss modulus, is associated with the energy loss process. The complex modulus is often written in terms of the loss tangent $\delta(\omega)$ (or loss factor), which is the ratio of the dissipated energy to the stored energy. The expression for the complex modulus therefore becomes

$$E^*(\omega)=E'(\omega)\{1+j\delta(\omega)\}, \qquad where\ \delta(\omega)=\frac{E''(\omega)}{E'(\omega)} \qquad (35)$$

Further details on the visco-elastic behaviour of foams can be found in Hilyard et al [36] and general visco-elasticity theory is found in Ferry [31].

Several methods of evaluating dynamic properties are available. Three have been used, and their relative merits together with basic measurement techniques are discussed below.

4.4.2 BMW Test Method.

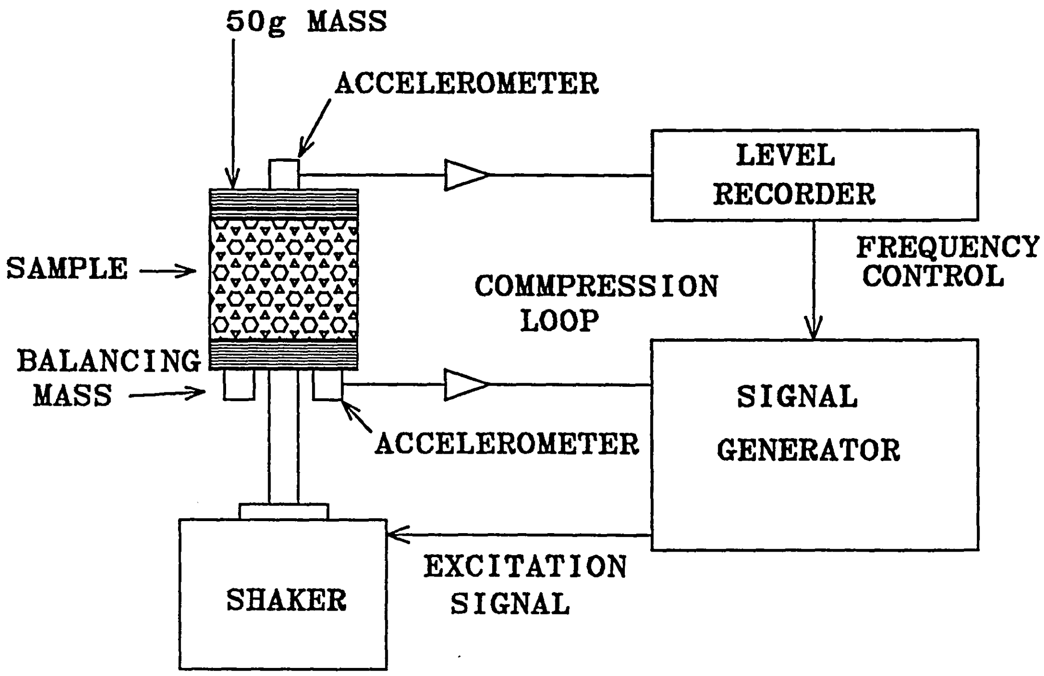


Figure 59 Schematic representation of equipment used in the BMW test method.

The simplest dynamic test is based on a resonance method called the "BMW" test. This test procedure was set down by Bayerische Motereu Werke AG [9] which has been adopted as a 'semi-standard' by industrial organisations. The arrangement is illustrated in Figure 59, and a photograph of the apparatus used is shown in Figure 60.

Figure 60 Photograph of BMW testing equipment.

The test piece, with loaded area $A=2.5\times10^{-3}$ m^2 supports a mass of 50 g. The piece is attached to the mass and driving plate by double sided adhesive tape. The compression loop holds the excitation acceleration constant as the sine sweep is carried out. The acceleration of the suspended mass is displayed on a level recorder and the resonance frequency f_o and 3 dB band width (Δf) determined from an optically magnified trace. The storage modulus is calculated from the value of the first resonance frequency f_o using the expression

$$E=\frac{4\pi^2 f_o^2 Mh}{A}, \qquad (36)$$

where h is the specimen height, and η the loss tangent,

$$\eta=\frac{\Delta f}{f_o} \qquad (37)$$

The advantages of the BMW test are that it is simple to carry out and relatively small samples are required. As a method of comparative evaluation it has its greatest advantage in that it is widely used as a standard in the automotive industry. The disadvantage of the method that it only determines loss tangent and storage modulus at one frequency, f_o. However this can be varied by changing the mass loading on the sample up to a limit of around 200 Hz. Only small shifts in the resonant peak about 100 Hz are usually possible from changes in the mass so the property values determined in this way apply only to low acoustic frequencies.

Because of the simplicity of the method and data analysis the BMW method is widely used for elastic porous materials but has proved unsuitable for rigid porous materials e.g. polyimide, closed cell foams and highly filled PU foams.

4.4.3 Dynamic Mechanical Spectroscopy

The second method used to measure small strain dynamic properties was the Dynamic Mechanical Spectrometer (DMS). The DMS is fully described in [15]. Larger samples than those used in the BMW test are placed between metal plates. Each sample is subjected to a compression cycle, these cycles being at a fixed frequency and amplitude. The storage and loss modulus were calculated from the in phase and 90 degrees out of phase components of the stress-strain ratio. Measurement and control of the DMS are by micro computer, as are the manipulation and presentation of the results. Temperature and relative humidity were noted. The disadvantages of this test method are that it is complicated, time consuming (a typical data collection run taking approximately one hour), the equipment is expensive, it uses larger samples than the simple BMW test method (above) and it only measures a limited frequency range (0.7-70 Hz). This frequency range is ideal for the vibration analysis of automotive seating but not for acoustics, where most of the frequencies of interest are much higher. Advantages of the DMS are that materials can be compared over the same frequency range and measurements can be made at low frequencies.

4.4.4 Dynamic Mechanical Thermal Analysis

The third method of dynamic measurement is DMTA: Dynamic Mechanical Thermal Analysis. A small sample is put through dynamic excitation at a single frequency (usually one Hertz). Force and displacement readings are taken and the loss tangent and storage modulus calculated. The temperature is then increased and the measuring process repeated. From the results, a temperature-loss tangent and temperature-storage modulus curve can be plotted. These plots have the same shape as frequency-loss tangent and frequency-storage modulus curves and can be related using master curves [31]. The translation between temperature and frequency is possible. Other useful information is obtained from the DMTA measurements, eg glass transition temperature (Tg).

The advantages of this method are that a large amount of peripheral information is obtained as well as dynamic properties over a large temperature range. The disadvantages are that the test pieces are small and the master curves are difficult to obtain.

It was found that generally there is good correlation between the three measuring techniques when frequency and temperature are taken into account. Problems arise with highly damped foams which have unusual properties, for instance where the glass transition close to or just above ambient. It is with this type of interesting foam that correlation between dynamic mechanical measurement techniques is difficult.

4.5 Acoustic Performance

4.5.1 Acoustic Absorption

Two types of acoustic absorption coefficient can be measured: random incidence absorption (α) and normal incidence absorption (α_o). Random incidence absorption describes the energy absorbed when sound impinges on, and is reflected from, a material at all possible angles (each angle having equal probability of occurring).

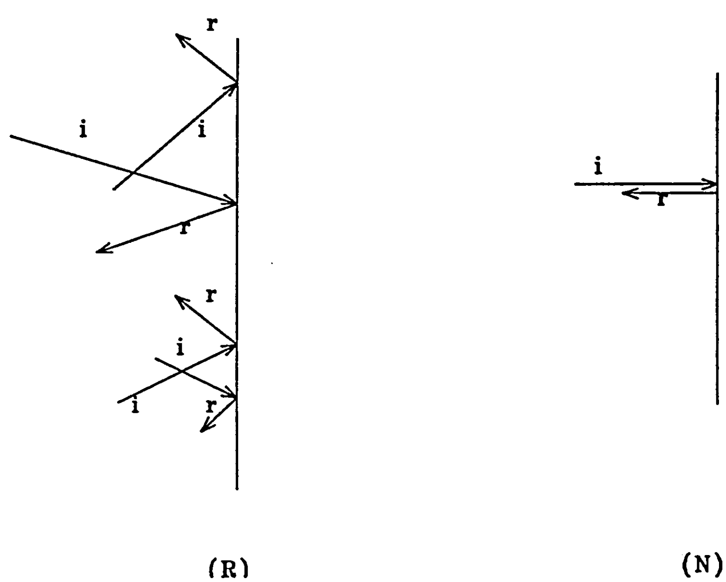


Figure 61 Schematic representation of random (R) and normal (N) incident sound absorption.

Normal incidence absorption describes the loss in energy when sound impinges and is reflected, normal to a material surface.

The two type of absorption have been related [86]. A discussion of the relationship proposed by Zwikker and Kostens is given in Section 3.6. Generally the two absorptions will be of similar magnitude to the random incidence absorption, usually being greater than the normal incidence absorption. There are many methods of measuring the two types of absorption coefficient [56][1]. The most widely used method for normal incident absorption is the standing wave tube method (details are given in ASTM C384 "IMPEDANCE AND ABSORPTION OF ACOUSTICAL MATERIAL BY IMPEDANCE TUBE METHOD" [3].) For random incident absorption measurements the reverberant room method is usually used (BS 3638 "METHODS FOR THE MEASUREMENT OF SOUND ABSORPTION COEFFICIENT (ISO) IN A REVERBERANT ROOM" [12]). There are advantages and disadvantages to both methods. Random incidence absorption is more realistic as noise is multi-directional and is rarely normal to a surface. The major problems with random incidence absorption are the sample size required, the size and type of room needed to undertake the measurements and the reproducibility of the results. For the measurement of the random incident absorption coefficient by reverberant room, a material sample of size 10 m^2 is needed. In Section 5.2 the variability of physical properties across sheets of foam is investigated and it is shown that these variations are large. Therefore when one measures property values to be used in a predictive model, it is appropriate that these measurements are on the same sample or samples obtained in close proximity on the same sheet. As the reverberant room requires test samples many times larger than those used for the other measurements, point specific anomalies may occur when comparing the averaged absorption of a whole sheet. Another problem is that once smaller measurement samples have been cut from a sheet on which acoustic measurements have been made it is unsuitable for further acoustic work. With normal incidence absorption the same sample can be used for many tests. The size of the sheet does have advantages in that for general material evaluation the averaging of anomalies over the sheet is advantageous.

A reverberating room has to be 150 m^3 but ideally 200 m^3 [12] with non-parallel sides, to create the required free field. Unless a specifically designed room is used then there is a large degree of variation in measurements. The standing wave tube, when used carefully can produce accurate and reproducible results. A discussion of the techniques and theories needed for accurate standing wave measurements are given in the following sections. From consideration of the other types of measurements to be made, the normal incidence absorption measured by the standing wave tube was selected as the measure of acoustic performance of the foams.

4.5.2 Standing wave tube theory:

The acoustic pressure of a sound wave can be expressed as follows:

$$P = A\cos 2\pi ft \tag{38}$$

where A is the amplitude, f the frequency and t the time. If one considers a plane wave travelling down a tube, impinging on a material, and being reflected back then the incident pressure (P_i) wave may be expressed as;

$$P_i = A\cos 2\pi ft \tag{39}$$

and the reflected pressure wave (P_r) as;

$$P_r = B\cos 2\pi f(t-2y/c) \qquad (40)$$

where B is the amplitude of the reflected pressure wave, y the distance from the plane at which the reflection takes place and c is the speed of sound in the tube. It follows that at a given distance y from the sample at time t the total pressure will be:

$$P_i + P_r = P_t = A\cos(2\pi ft) + B\cos\left(2\pi f\left[t-2\frac{y}{c}\right]\right) \qquad (41)$$

Which can be rearranged to form:

$$P_t = A\cos(2\pi ft) + B\cos(2\pi ft)\cos\left(\frac{4\pi y}{\lambda}\right) + B\sin(2\pi ft)\sin\left(\frac{4\pi y}{\lambda}\right)$$
(42)

where λ is the wavelength c/f. By probing this sound field, i.e. varying y, it can be seen from equation (42) that a maximum pressure is expected when

$$\cos\left(\frac{4\pi y}{\lambda}\right) = 1 \;\Rightarrow\; P_t = (A+B)\ \cos(2\pi ft)\ ; \qquad (43)$$

$\cos(4\pi y/\lambda)$ will equal unity when $4\pi y/\lambda = 2\pi n$ $\quad n=1,2,3,,,,,$

ie $y = n\lambda/2$.

Similarly from equation (42) a minimum pressure occur when

$$\cos\left(\frac{4\pi y}{\lambda}\right) = -1 \;\Rightarrow\; P_t = (A-B)\cos(2\pi ft)\ ; \qquad (44)$$

$\cos(4\pi y/\lambda)$ will equal minus unity when $4\pi y/\lambda = (2n-1)\pi$

ie $y = (2n-1)\lambda/4$ $\qquad n=1,2,3,,,,,,$

Therefore by probing the tube that contains a standing wave two pressure amplitudes of A+B and A−B can be measured at maximum and minimum amplitudes. Also the wave length λ can be calculated from the positions of the maximum and minimum amplitudes in the tube.

A sample's absorption coefficient is defined as the ratio of absorbed energy to incident energy. This is proportional to pressure squared and is given by;

$$\alpha_o = 1 - \left(\frac{A}{B}\right)^2 \tag{45}$$

Using the expressions for the maximum and minimum sound pressure in a tube (equations (43) ,(44)) the ratio n is given by:

$$n = \frac{(A+B)\cos(2\pi ft)}{(A-B)\cos(2\pi ft)} = \frac{A+B}{A-B} \tag{46}$$

which can be rearranged to give

$$\frac{A}{B} = \frac{(n-1)}{(n+1)} \tag{47}$$

Therefore by substituting the value for A/B above into equation (45) an expression for the normal incident absorption is obtained in terms of the maxima and minima measured in the standing wave tube.

$$\alpha_o = \frac{4n}{n^2+2n+1} \tag{48}$$

4.5.3 Acoustic Impedance

When sound energy impinges on a material it is not reflected from the surface but appears to be reflected from a hypothetical plane within the sample. Using the phase shift in the reflected wave relative to the incident wave together with the acoustic absorption coefficient it is possible to calculate the acoustic impedance of the test piece.

The general theory for the calculation of normal acoustic impedance can be found in Reference [3]. To increase the accuracy of the calculated impedance the theories of Scott [74] and Ando [2] are used. Scott suggests that when the tube attenuation is taken into consideration the real and imaginary components of the impedance can be calculated with an accuracy of 1%. The Ando paper helps make adjustment for the end effect of the probe microphone.

Scott's equation relating the standing wave ratio to γ, wave length and wave position is:

$$\frac{P_{max}}{P_{min}}=\left[\frac{2\cosh^2(\alpha D_m+\gamma)-\frac{\alpha^2}{\beta^2}\sinh^2 2(\alpha D_m+\gamma)}{2\sinh^2(\alpha d_n+\gamma)+\frac{\alpha^2}{\beta_2}\sinh^2 2(\alpha d_n+\gamma)}\right]^{\frac{1}{2}}; \tag{49}$$

here, α the attenuation constant is calculated from the relationship given by Kinsler and Frey [42],

$\alpha=2.78\times10^{-5} \times f^{1/2}/a$, (a is the tube radius)

The wave constant β is equivalent to $2\pi/\gamma$. If the wave-length is over twice the length of the tube, the position of the second minimum is calculated by using the standard relationship:

$$\gamma=c'/f,$$

where f is the frequency, c' is the speed of sound in the tube, which can be calculated from the formula found in Reference [42]

$$c'=c\left(1-\frac{1}{2r}\sqrt{\frac{v'}{\pi f}}\right) \tag{50}$$

where r is the tube radius, c is the free space velocity of sound and v' a function of the kinematic viscosity and diffusivity of air.

To calculate γ a initial estimate of the function inverse hyperbolic tangent of the Standing Wave Ratio ($\tanh^{-1}$ SWR) is put into equation (49) and several iterations of the Newton-Raphson method performed until a stable solution is reached. When γ has been calculated the resistance (R) and reactance (X) can be calculated using the equations from Scott [74]:

$$\frac{R}{\rho c}=\frac{2r}{1+r^2+(1-r^2)\cos\left(\frac{4\pi d_1}{\lambda}\right)} \tag{51}$$

$$\frac{X}{\rho c}=\frac{-(1-r^2)\sin\left(\frac{4\pi d_1}{\lambda}\right)}{1+r^2+(1-r^2)\cos\left(\frac{4\pi d_1}{\lambda}\right)} \tag{52}$$

$$\textit{where } r=\tanh\gamma=\frac{|p_{min}|}{|p_{max}|}$$

It has been shown by Ando [2] that the true length of the acoustic probe, taking into consideration the end effect (l_a) is greater that the physical length, and hence this end effect is also included in the calculations; l_a is dependent upon the cross section of the probe tube orifice (tube thickness and diameter).

The additional accuracy obtained from the inclusion of tube attenuation and the end effect has a minimal affect on the normal incidence acoustic absorption. Calculations using data from a range of samples showed that when tube attenuation is included the normal incidence absorbtion at lower frequencies (100-350 Hz) increased by a maximum of 2%. At higher frequencies the increase is less than 1%.

4.5.4 Standing Wave Tube Procedure

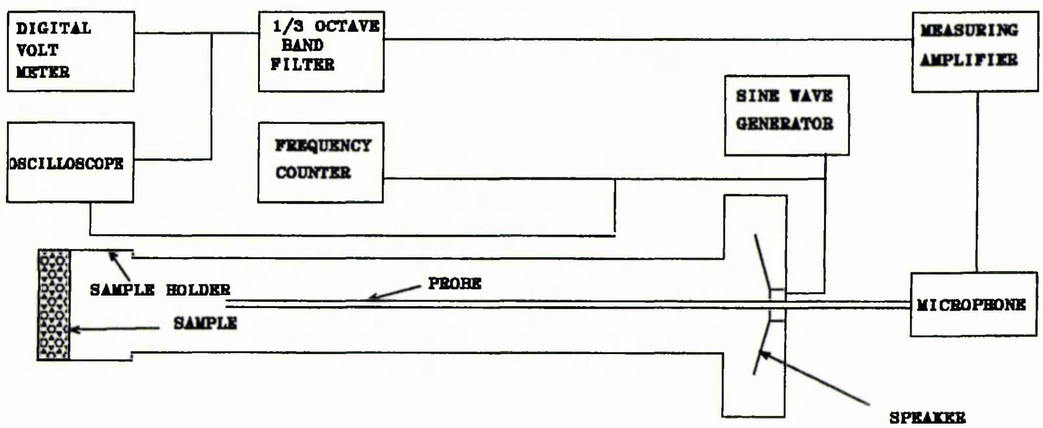


Figure 62 Schematic representation of the apparatus used to measure normal incidence acoustic absorption.

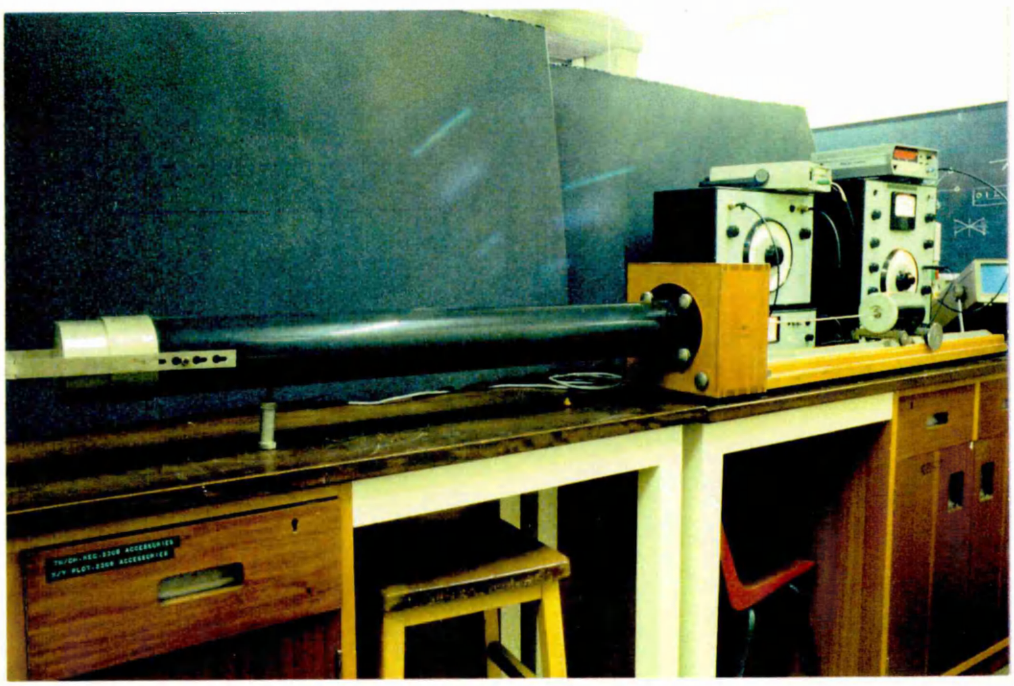


Figure 63 photograph of apparatus used to measure normal incident acoustic absorption.

A schematic representation of the equipment is shown in Figure 62 and a photograph in Figure 63. The basic measurement technique is given in Reference [3], the manufacturer's instruction literature. It was found that for practical repeatable measurements several additions to the manufacturer's recommended equipment configuration were required. With these modifications the results were found to be repeatable within one percent. This repeatability was also possible between different experienced operators.

The basis for the measurement instrumentation is a B&K 4002 standing wave tube. An oscilloscope is added to check by inspection the purity of the input sinusoid. When the input signal is too large input clipping occurs. This is not apparent unless an oscilloscope is used to monitor the signal. Additionally the oscilloscope is used to inspect the output signal from the measuring amplifier. Any unwanted noise can be seen, as can any distortion in the signal produced by the measuring amplifier. A frequency counter is used for accurate setting of the frequency. An additional check of frequency is made through calculation of the wave length in the tube and also from the oscilloscope. The suggested method of using the meter on the B&K 2606 measuring amplifier for direct absorption measurements is replaced by a digital volt meter. Details of the calculations required when a voltage reading, proportional to the pressure in the tube, is used are is given in most literature on the standing wave tube. A digital reading is more accurate than the analogue meter with a small scale and few graduations. Readings are still taken from the meter for later comparison with the calculated readings. Modifications to the manufacturers procedures check most aspects of the system at least twice. Computational checks are also made when the measurements are converted into the required format.

4.5.5 Cepstral Analysis.

This type of technique is becoming more popular with the wider availability of suitable digital data acquisition computers. The principle of the technique is that a signal of finite length is generated from a speaker and this impinges on a sample; hence a portion is absorbed, the remainder being reflected. The input and reflected levels are measured by a microphone close to the test sample. The speaker and microphone are on the same axis. By using digital signal processing techniques input, output and external noise can be separated. From the separated signals acoustic impedance and hence absorption can then be calculated.

The main advantages of this technique is its speed. By having short bursts of sound a complete spectrum can be collected and calculated in minutes. Because the system necessarily includes a computer, the control and calculations are easily automated. Disadvantages are the complexity and cost of setting up such a system. Results compare favourably with the standing wave tube, though unresolved noise is often present. Improvements have been made using twin phase matched microphones and intensity type measurements. It is this type of equipment that is used by Paul Hanscombe (see appendix 1)

CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

5.1 Design of Test Programmes.

To study material methods of optimising the acoustic performance of a foam for a particular noise control application it is necessary to be able to vary any important parameter e.g. the air flow resistance, the stiffness, or the loss tangent, while all other parameters remain constant. Current knowledge of PU foam technology does not allow us to do this. Previous studies [84][64][2] have not been able to completely verify model predictions using independently measured values of material properties.

The objective of the experimental studies was to investigate the set of physical characteristics that can be used to optimise the sound absorption of cellular materials. The measurable characteristics (e.g. flow resistance) must then be related to the physical parameters of the foam (e.g. cell size and reticulation) which can be controlled during production. The experimental investigation included (i) systematic studies of the important variables and (ii) the detailed examination and analysis of particular foam comparing performance with model predictions.

5.2 Variability in Properties and Performance of Cut Slabstock.

5.2.1 Sampling Procedure

A sheet of polyurethane foam (62.0 x 54.0 x 2.6 cm) was chosen at random from normal production stock, the type of foam selected being described by the manufacturer as suitable for acoustic use. From this sheet 12 samples were cut and labelled as shown in Figure 64. The air flow resistivity of each sample was measured. A contour map of constant air flow resistivity was then drawn Figure 65), each contour representing a constant airflow resistivity. Assumptions made to create the contour map were that the airflow acted through the centre of the sample and that variation vertically or horizontally between two adjacent centres could be described linearly. Full normal incident acoustic absorption data were obtained for samples A1, A4, B2, B3, C1 & C4 and is shown graphically in Figure 66. These were chosen after evaluation of flow resistance data (data are given in Table 15). The samples chosen represent pairs of maximum, minimum and median flow resistance. To ascertain whether flow resistance and acoustic absorption are the only material characteristic that vary across the sheet, electron micrographs where taken eg Figure 67 and Figure 68 and the density and dynamic mechanical properties measured at specific points on the sheet.

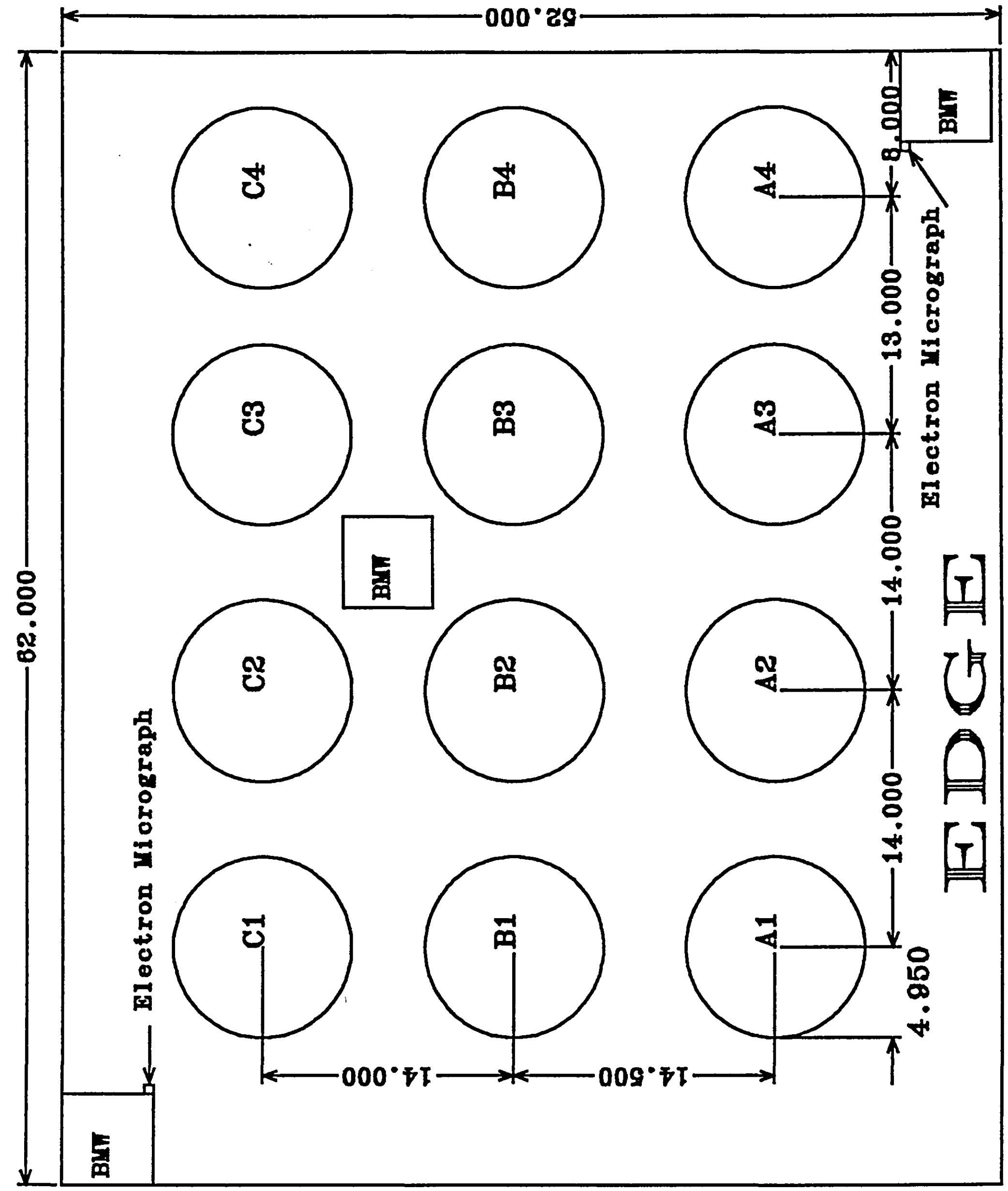


Figure 64 Diagram of where test samples were cut from a standard sheet of foam. (dimensions in cm)

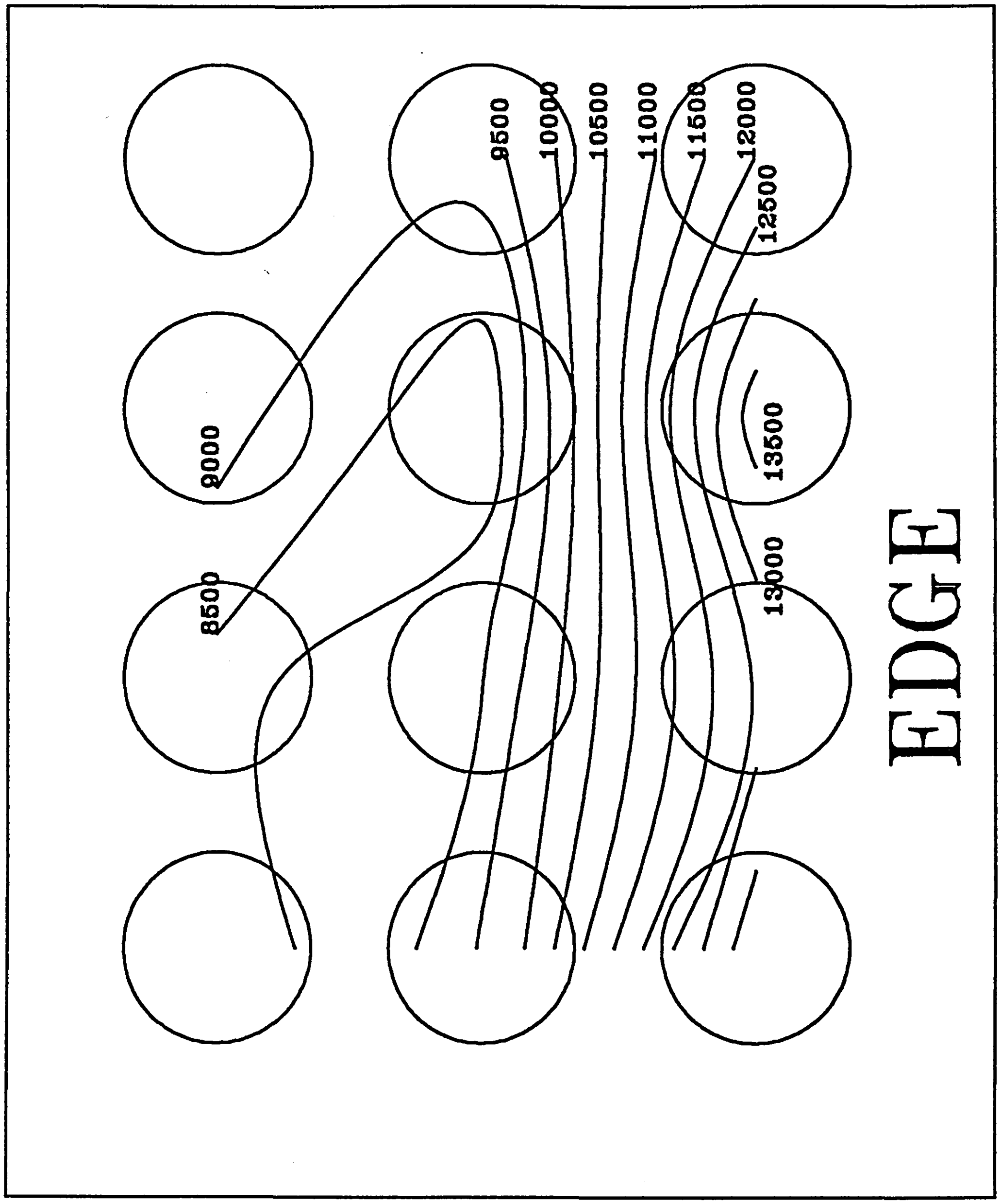


Figure 65 Contour map of air flow resistance variation as measured across a sheet of standard foam. (all contours in mks rayls m^{-1})

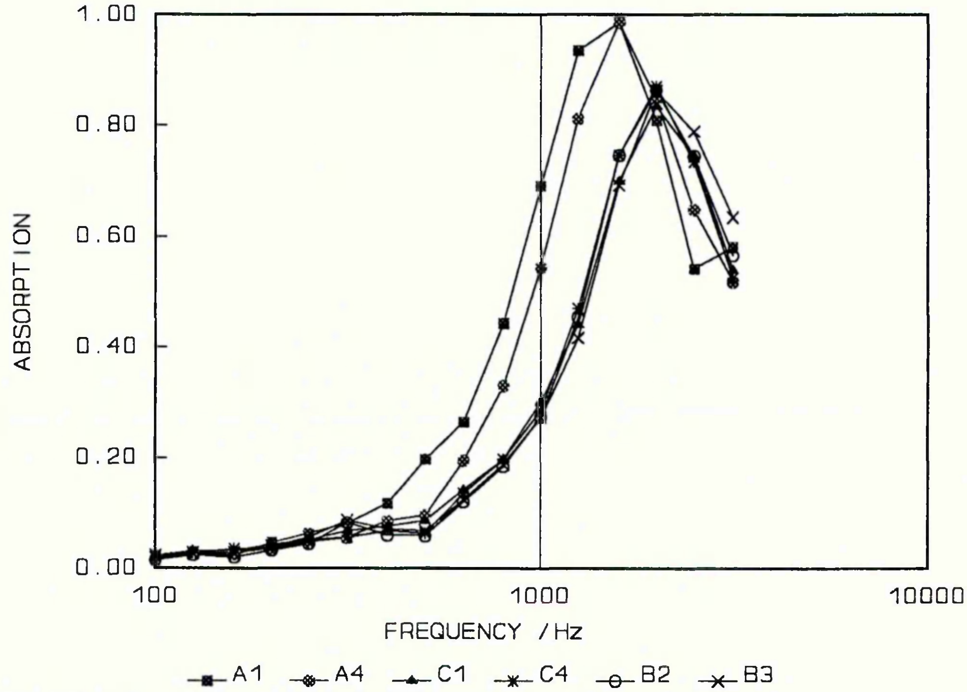


Figure 66 Graph of measured acoustic absorption at set frequencies for samples cut from a typical foam sheet.

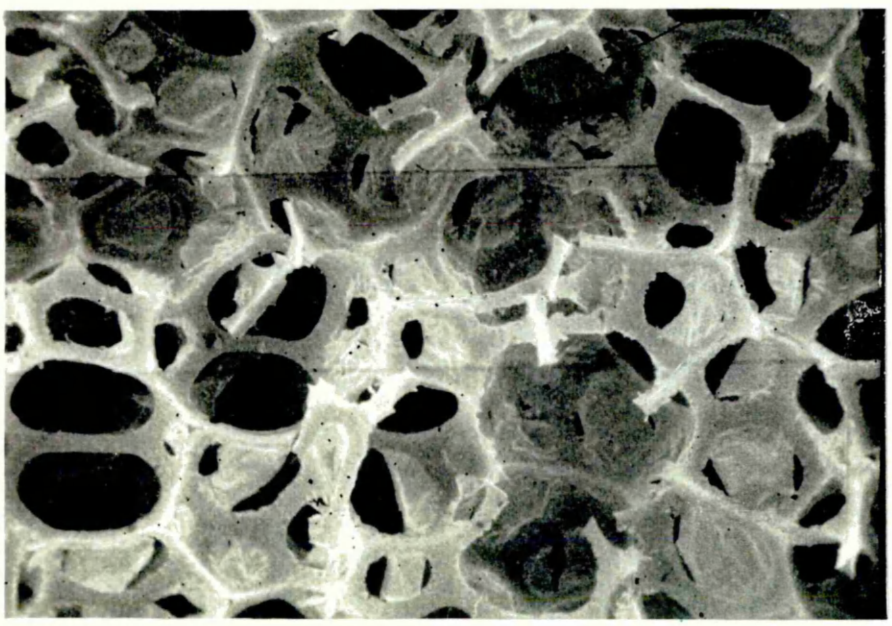


Figure 67 First of two micrographs used to compare structure across a foam sheet.

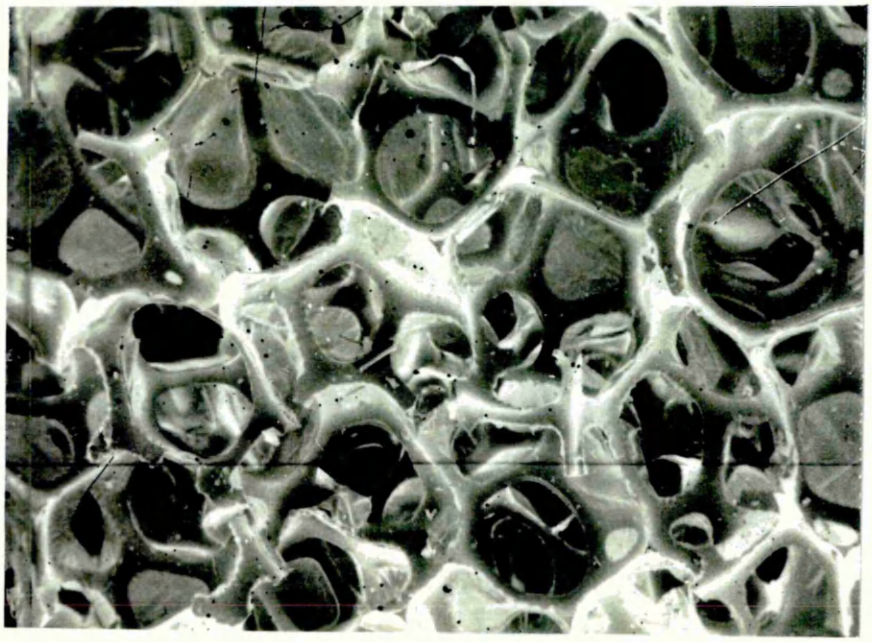


Figure 68 Second of two micrographs used to compare structure across a foam sheet.

5.2.2 Flow Resistivity Contours and Acoustic Absorption.

In addition to the normal incident acoustic absorption and air flow resistance all twelve circular samples were weighed and the density was calculated. The maximum variation in either the horizontal or vertical direction was 1%. Changes in density were attributed to measuring and cutting error. Three samples were taken at different positions in the sheet (top left, centre and bottom right as shown in Figure 64) and dynamic mechanical measurements made. All three measurements gave the same values for the loss tangent (tan δ=0.21) and a storage modulus of $4.35x10^5$ Pa. Electron micrographs were taken at the positions shown in Figure 64. The objective of these micrographs were to ascertain visually if there were any large variations in the cell size or general cell structure. No appreciable differences were noted. From the measurements taken it was concluded that the changes in all of the other factors were minimal. The changes in acoustic absorption were due to variation in airflow resistance brought about through changes in the levels of reticulation. With these foams the degree of reticulation was controlled chemically during the expansion process.

A contour map of static air flow resistance is given in Figure 65. Table 15 gives the values of air flow resistivity obtained from the samples taken from the sheet.

Table 15 Air flow resistance on PUR foam sheet.

Specific Air Flow Resistance in rayls m^{-1}				
	1	2	3	4
A	13900	12600	138000	12000
B	9300	9000	9100	9300
C	8200	8400	9300	9300

Full acoustic data on these samples is given in Appendix 5.

5.2.3 Discussion.

It can be seen that the static air flow resistance and normal incidence acoustic absorption of the commercial foam were point specific but other material properties (E' and tan δ) were constant. An increase in the first maximum normal incident absorption coefficient was observed as the flow resistance of the 26mm thick test pieces increased from 221 Mks rayls to 338 Mks rayls. A frequency shift was also noted, the frequency of the first maximum also increasing. Although this experiment gave useful results, the range of flow resistances available did not allow an investigation of behaviour in the region close to the suggested optimum flow resistance ($3\rho_o c$). However it did show that the properties and hence performance of this acoustic grade foam were variable and less than optimum.

5.3 Influence of Air Flow Resistivity.

5.3.1 Sample Preparation

A highly non-reticulated (closed cell), and hence high air flow resistance, foam was selected for study. The foam was subject to several crushings under controlled nip pressure. After each crushing some of the cell windows were broken and hence the air flow resistance decreased. Between each crushing measurements of airflow, mass and normal incidence absorption were taken. The effects of crushing on other material properties (i.e. dynamic modulus and damping) were also investigated. After each crushing the foam recovered in a warm oven (50° C) for at least 48 hours. It required this time period for full dimensional recovery. To assess dimensional recovery height was measured and general shape judged visually with the sample placed in the standing wave tube sample holder.

Originally, the samples were crushed using a 'Mayes' crushing machine, normally used for ascertaining mechanical properties of concrete. These initial investigations showed that linear compression technique were unsuitable. After recovering from a compressive stress of approximately 3.2×10^6 Pa, there was little change in the air flow resistance. A pinch compression between two steel rollers did produce a marked change in air flow resistance. The number of times the sample passed through the pinch rollers and the distance between the rollers gave an indication of the degree of cell window removal, and hence the expected change in air flow resistance.

This technique did not lend itself to accurate measurements of the forces involved, hence the degree to which the foams would be reticulated between each pass was not accurately predictable. With experience the changes in reticulation brought about on each pass could be judged within the required limits. Thus the degree of reticulation and hence the air flow resistance could be varied in a semi-controlled fashion.

5.3.2 Results.

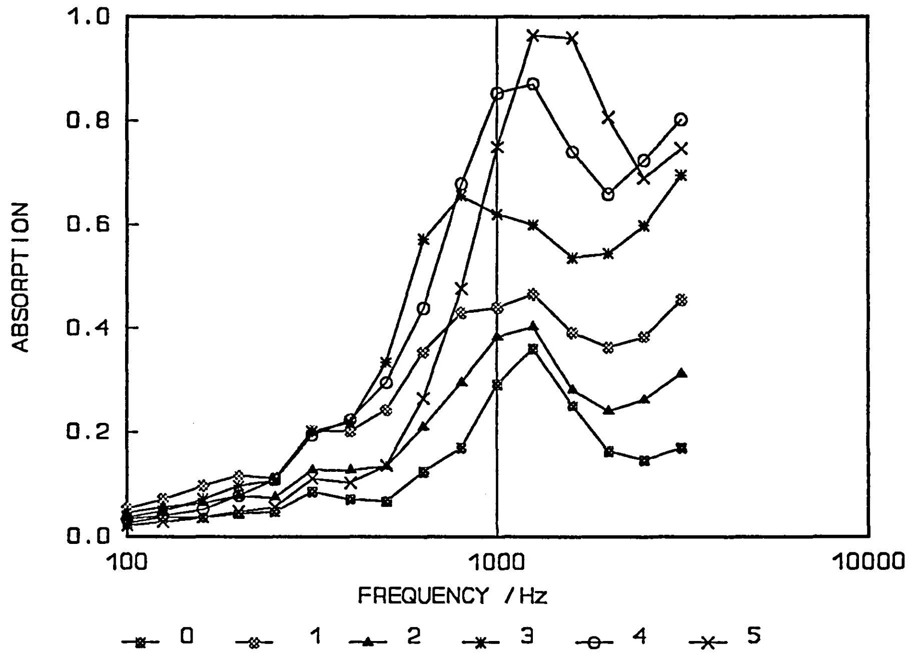


Figure 69 Graph of the absorption against of a highly unreticulated foam after air flow resistivity has been increased by five crushings (0-5).

The normal incidence absorption coefficients on a sample PUR foam after five levels of crushing are shown in Figure 69. The corresponding changes in static air flow resistivity are given in Table 15. As anticipated, the resistance to air flow falls as the amount of crushing increases.

Table 16 Air flow resistance measurements on highly unreticulated foam test pieces as a function of the number of crushings.

No of Crushings	Specific air flow resistance /mks rayls
0	to large to measure
1	5948
2	2208
3	1760
4	1088
5	416

Density measurements were made on each sample after each crushing to ascertain if any other physical characteristics changed. No change in the mass of the test sample could be detected. Density remained constant at 30 ± 1 kg m^3.

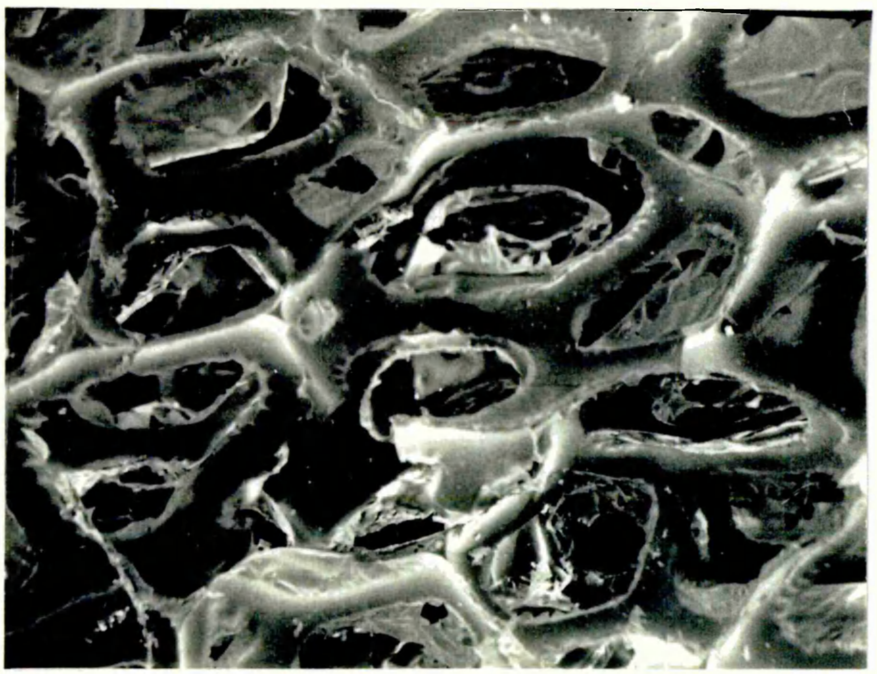


Figure 70 Micrograph of a highly unreticulated foam after six levels of crushing.

Mechanical properties and an inspection of electron micrograph were also conducted. Because of the measuring techniques these tests were conducted on samples taken very close in the foam sheet to the acoustic samples.

The micrographs Figure 70, show the destruction of cell windows after crushing. Cell struts and general cell structure are unaltered by the crushings. Table 17 shows the changes in loss tangent and storage modulus brought about by varying degrees of crushing. Different samples were used to measure acoustic and dynamic mechanical properties. Because of the lack in precision when crushing, the degree of cell window removal is not identical in each test set. The degree of crushing is proportional to changes in air flow resistance, hence by simple interpolation the dynamic mechanical properties can be calculated for the measured acoustic absorption curves.

Table 17 Dynamic properties and flow resistance of foam test pieces after several crushings.

No of Crushings	R_1 /mks rayls	Loss Tangent δ	Storage Modulus /10^7 Pa
0	∞	0.51	2.08
1	1016	0.51	1.81
2	887	0.59	1.40
3	700	0.52	1.68
4	436	-	-

5.3.3 Discussion

This study provided a wider range of flow resistances than in the investigation described in Section 5.2 above (about 390 to 5800 Mks rayls). Although the loss tangent of the foam remained approximately constant the storage modulus showed a small decrease, as a result of the reticulation process. This change in modulus should have only a small influence on the acoustic absorption properties of the foam. The data shows that the first maximum in the normal incidence acoustic absorption curve increased with decreasing resistance to air flow. The frequency of first maximum decreased and then increased.

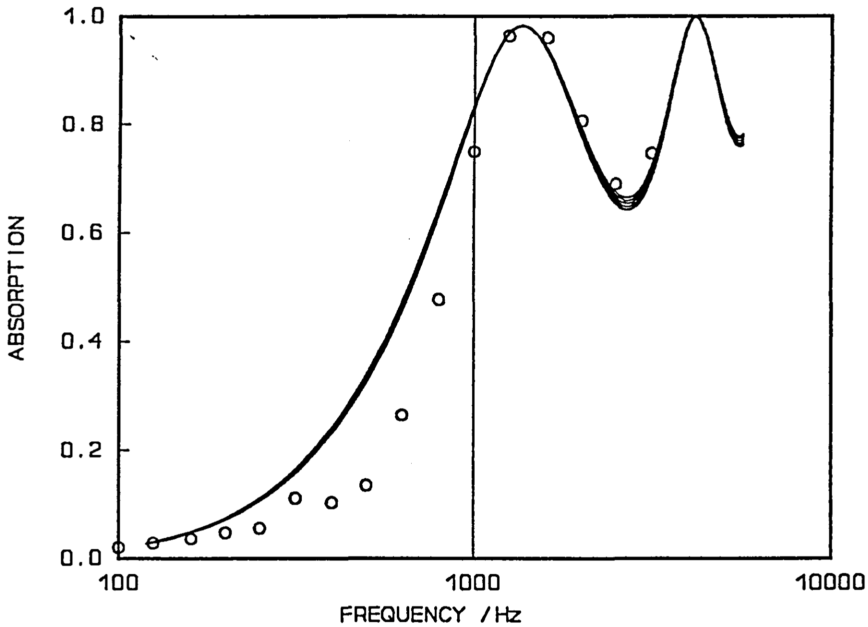


Figure 71 Graph of frequency against absorption, measured data from a crushed foam, predicted data using Bolton model with varying porosity.

From the data obtained an investigation of the theoretical predictions of the model suggested by Bolton (Section 3.3) is undertaken. There are two parameters used in the model that have not been measured in the five crushed foams; structural factor and porosity. It has been shown in Section 3.5 that porosity has minimal effect on the frequency absorption curve. Figure 71 (the Bolton model with parameters of the foam after five levels of crushings, varying porosity and with structural factor set to 3) shows this assumption is also true of the sample under consideration.

Both Lauriks et al [49] and Bolton [10] use heuristic methods to derive a value for structural factor. Lauriks refers to

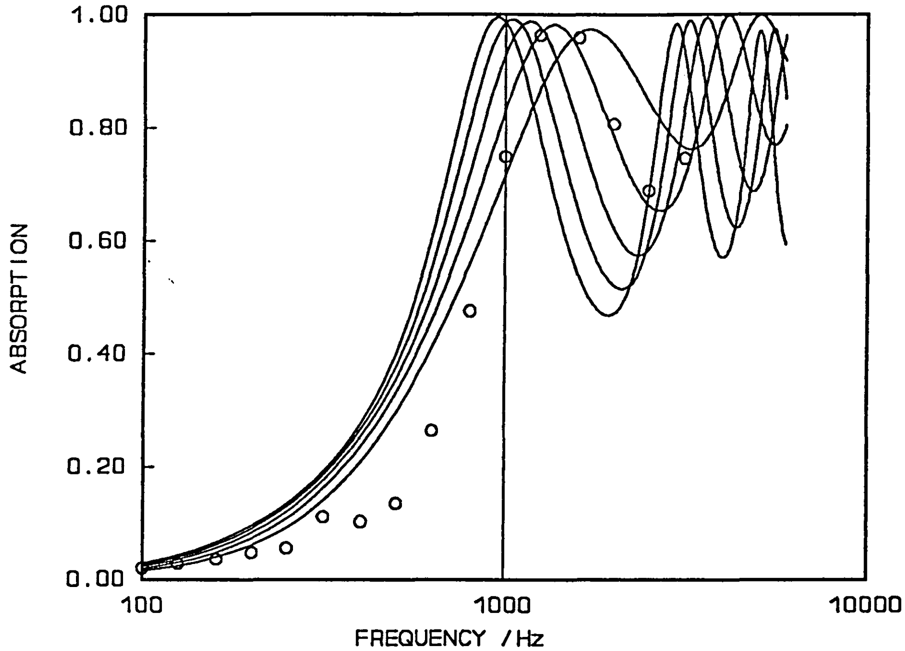


Figure 72 Graph of frequency against absorption, measured data from a crushed foam, predicted data using Bolton model varying structural factor from 1 to 5 (5 right-1 left).

work by Allard et al [1] which details a conductivity method for determining structural factor. Of the two values of structural factor used by Lauriks et al only one agrees with inferences given by experimental results of Allard et al.

A variation of five different structural factors (1 to 5) is shown in Figure 72. All other parameters have been measured except porosity which has been set at 0.94. From inspection the most suitable value for structural factor is seen to be about 3. When the model is fitted to the other samples with higher levels of air flow resistance, as shown in Section 3.5 above, there is decreasing correlation between measured and theoretical levels of acoustic absorption. Trends in the curves shapes are seen between the theoretical and measured data, the predicted values remaining larger than measured.

As more cells are destroyed, there will be changes in the

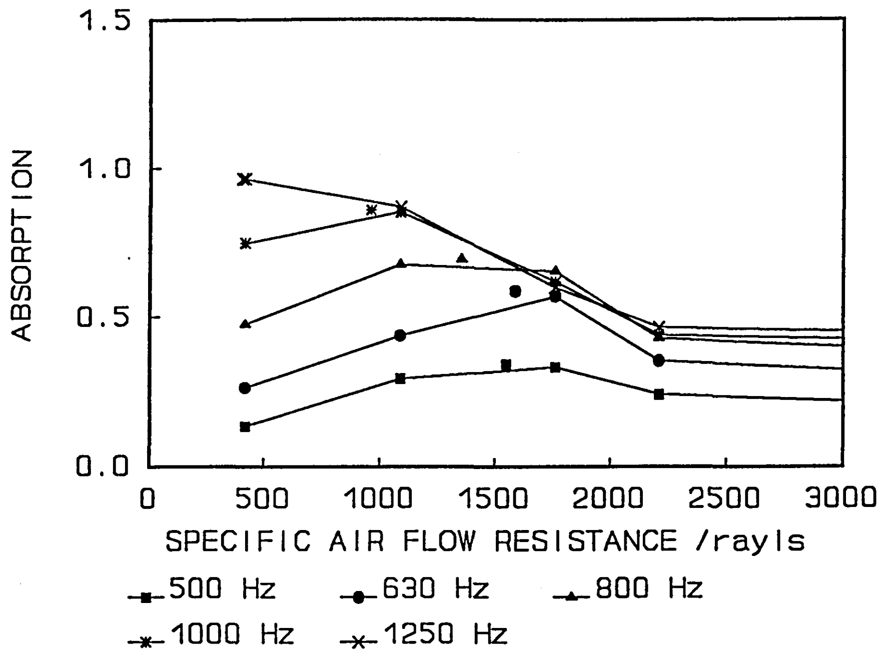


Figure 73 Graph of acoustic absorption against specific air flow resistance. Data are taken for measurements at specific frequencies.

tortuosity of the air path through the foam, hence slight changes to structural factor. Investigation has shown that changing the structural factor for the theoretical curves of materials with higher air flow resistance will not increase the correlation with measured absorption, in this example.

Table 18 Normal incidence absorption and air flow resistance data obtained from a foam after five levels of crushing.

Frequency /Hz	No crushings & Specific air flow resistance /rayls					
	0	1 5984	2 2208	3 1760	4 1088	5 416
500	0.08	0.13	0.24	0.33	0.30	0.13
630	0.12	0.21	0.35	0.57	0.44	0.26
800	0.17	0.30	0.43	0.65	0.67	0.48
1000	0.29	0.38	0.44	0.62	0.85	0.75
1250	0.36	0.40	0.46	0.60	0.87	0.96

Figure 69, a graph of the normal incidence absorption coefficient measured after five different levels of crushing, shows that the acoustic absorption at a given frequency maximises with increased air flow resistance. For increased clarity a graph (Figure 73) of normal incidence absorption against flow resistance at specific frequencies has been drawn. At each frequency there is a maximum which can clearly be seen. We will call this maximum R_{max}. Due to lack of data points the exact position of R_{max} is unclear. By quadratic interpolation between the three largest absorptions on each curve a more accurate estimate of the true maximum is obtained. In Figure 73 calculated maxima are not joined to other points whereas measured data points are. The frequency/air flow resistance relationship of these maxima are shown in Figure 74. Similar maxima to those measured can also be predicted by using the Bolton model. In the graph continuous lines are predicted data from the Bolton model (input parameters are the measured data for the crushed foams). Flow resistance and normal incidence acoustic absorption at five different frequencies have been calculated. Using a simple computer routine the air flow resistance at which maximum absorption at a given frequency (R_{max}) is found (the seeking program and program details are given in Appendix 3 - program Bolt6). A plot of the value of air flow resistance against the values of maximum acoustic absorption shows a fair correlation between R_{max} theoretical and measured. However when the air flow resistance (measured in mks rayls m^{-1}) for the maxima is plotted against the frequency for R_{max} (Figure 74) the theoretical plot is a different shape from the measured values although of a similar order of magnitude. Also included in the graph are the results of the felting experiment discussed below.

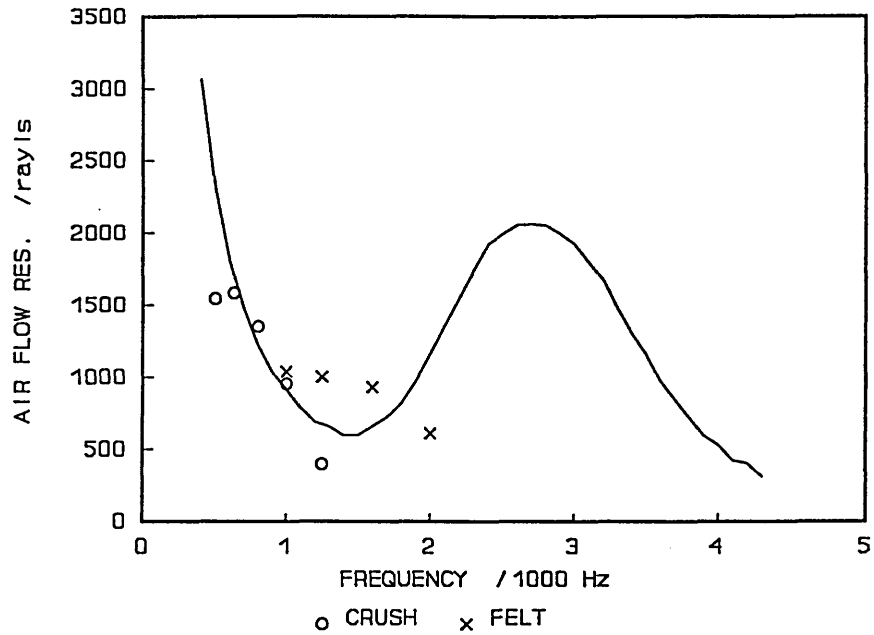


Figure 74 Graph of specific air flow resistance against frequency for the calculated maxima of data from the crush and felting experiment.

5.4. Influence of Static Compression (Felting).

5.4.1. Experimental Procedure.

To change its air flow resistance, the foam was compressed in the two dimensions perpendicular to the direction in which the air resistance and the incident acoustic absorption were measured. Two samples of the same material underwent similar compression conditions, then measurements of air flow resistance and acoustic absorption were made. It was expected that from these measurements a relationship between acoustic absorption and air flow resistance could be established. Unfortunately other characteristics of the foam also change. Collier [15] has shown that substantial changes in storage modulus and loss tangent can be expected when a foam is under pre- compressive strain. An obvious increase in density occurs with compression. Results of the experiment were however useful as they demonstrate the effects of "Felting" on acoustic absorption. Felting (ie compressing a foam then thermo setting the compression) is a process that is becoming more and more common in the foam manufacturing industry.

Four compressions were selected (1:1,1.37:1,1.72:1,2.1:1). For the acoustic measurements the smaller 29mm sample holder of the B&K type 4002 standing wave tube was used. At the higher compressions when the larger 99mm sample holder was used the foam buckled away from the back wall of the holder. It was also found by inspection that there was difficulty obtaining a uniform compression over the sample. Air flow resistance measurements used the 50x50 mm sample holder as specified in BS 4443 Pt. 6, method 16. All samples were cut from a small region of a sheet, as close together as possible to minimise the effect of variations in properties that can occur across a sheet. These types of variation are demonstrated in Section 5.2.3. above.

5.4.2 Results.

The air flow resistance at four different levels of compression are given in Table 19.

Table 19 Results of air flow resistance component to felting experiment.

Compression ratio	Air Flow Resistance /mks rayls
1:1	253
1.37:1	453
1.72:1	755
2.1:1	1133

The effects that these changes in air flow resistance had on acoustic absorption are shown in Figure 75. There is a shift in the magnitude of maximum absorption coefficient and a change in frequency of this maximum. The experiment clearly demonstrates quantitatively the effects that mechanical compression (felting) has on the acoustic absorption properties of a slab stock foam.

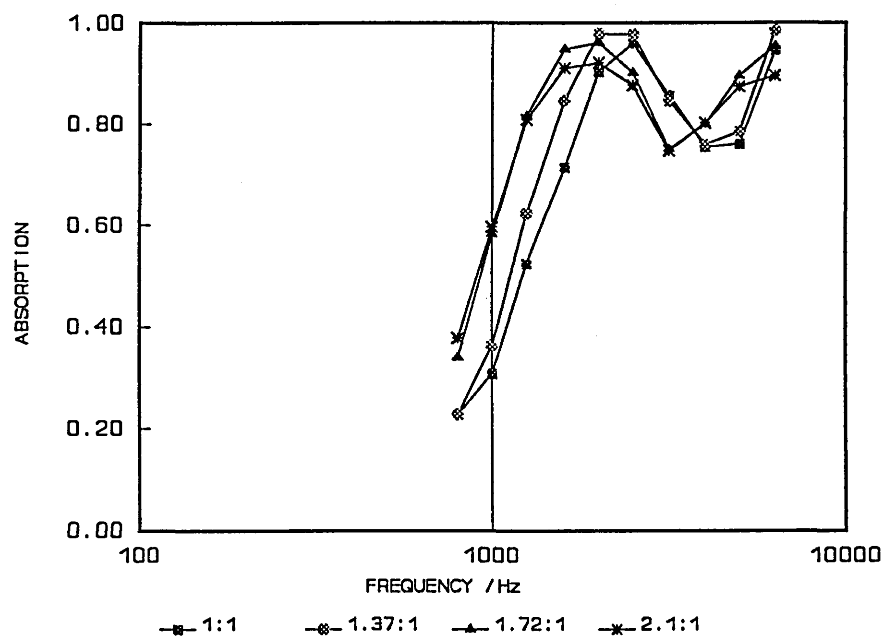


Figure 75 Graph of normal incident absorption measured on felted foam.

5.4.3 Discussion

Densification is a popular method of processing foams specifically with speciality foams like Basotec (details of which are given in Appendix 7.3). It is a method of increasing density and air flow resistance without having the reduced flexibility that would be incurred if at production, foam expansion was limited.

Figure 75 shows a graph generated from the data above. Four frequencies have been selected and the normal incidence absorption against specific air flow resistance plotted. The graph demonstrates a maximum at each frequency (R_{max}). This maximum is not constant for each frequency. At higher frequencies the maximum normal incidence absorption occurs at higher air flow resistances.

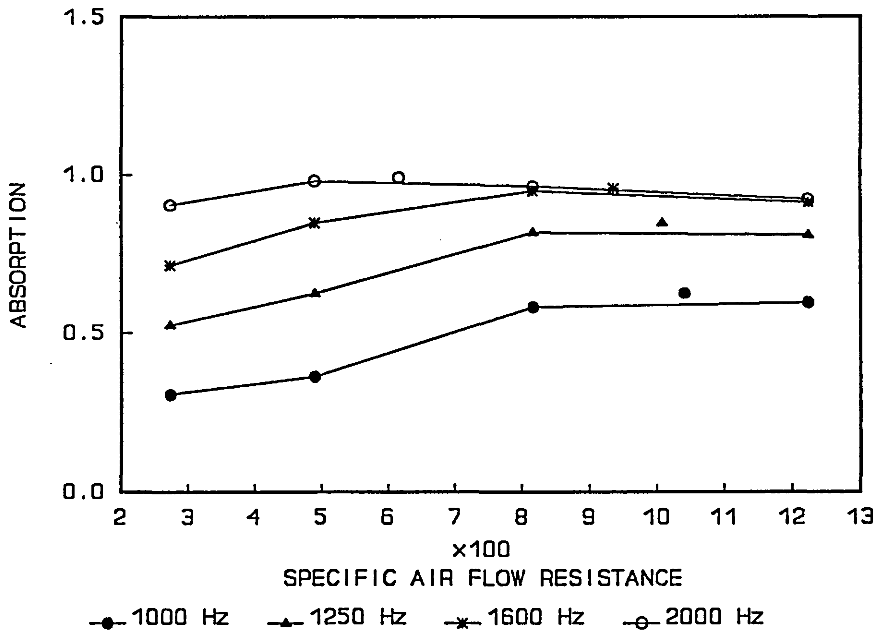


Figure 76 Graph of air flow resistance against absorption taken from four frequencies of the felting experiment data.

A similar exercise to that conducted in Section 5.3.3 above is instigated on this data set. Plotting the absorptions at different air flow resistance, with frequency held constant (Figure 76) shows that a maximum occurs at each frequency. Using quadratic interpolation of the three highest points a more accurate estimate for values of absorption and air flow resistance where these maxima occur is made. As with the results of Section 5.3 above the trends are as predicted from theory.

5.5 Influence of Foam Mechanical Properties

5.5.1. Materials

The purpose of this study was to investigate how changes in the dynamic mechanical properties affect the normal incident acoustic absorption coefficient of a foam. As it is difficult to alter the dynamic properties of a foam physically it was thought easier to select foams with different chemical compositions. After consultation with foam manufacturers, arrangements were made to have four sheets of foam specially made. Samples from these four foams were then measured for air flow resistance, DMTA, BMW test method,DMS, and acoustic absorption. From the results it can be seen that the ideal situation, with all factors constant except loss tangent and storage modulus, between foams, did not occur.

5.5.2. Results and Discussion.

By changing the type of block co-polymer used in the foam matrix, variations in the loss tangent and storage modulus were obtained. Property values are given in Table 20.

Table 20 Table of measured data on four specially formulated foams. The loss tangent and storage modulus were measured at 10 Hertz.

Foam	Tan δ	E' /10^7 Pa	Specific Air Flow Resistance 10^{-3} /rayls m^{-1}	Density /kg m^{-3}
1	0.20	0.58	0.8	86
2	0.26	0.33	0.3	84
3	0.42	0.67	1.1	84
4	0.55	1.03	3.0	78

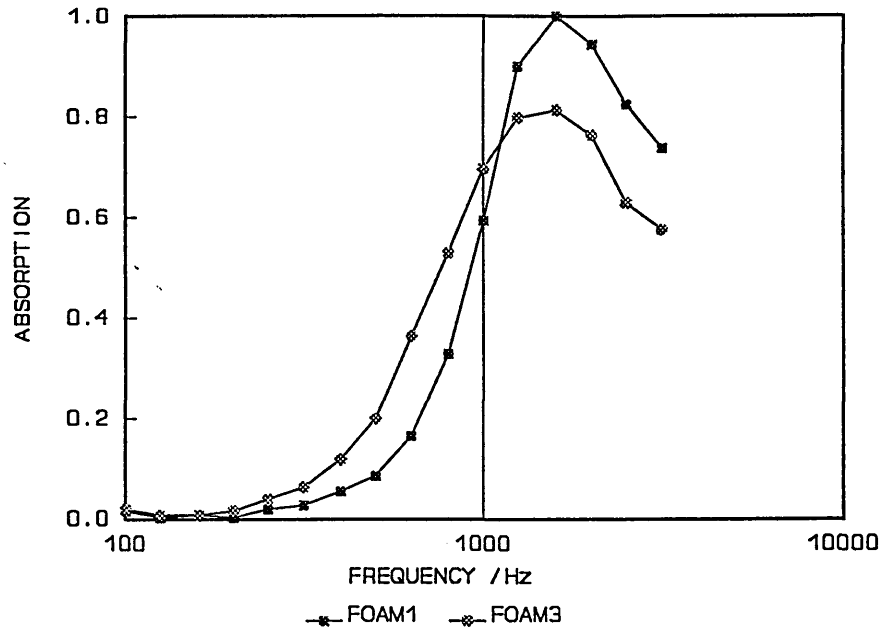


Figure 77 Normal incident absorption curves of foams with different mechanical properties.

From Table 20 it can be seen that there are variations in the measured characteristics. By considering materials 1 and 3 the most similar, changes to the shape of the normal incident absorption curve can be compared with predicted changes. In Section 3.5.4 (Bolton model) increases in storage modulus are predicted to decrease the frequency of the first absorption peak while decreasing the amplitude and broadening this peak. As a consequence the lower frequency absorption would increase. Predicted changes are seen in the absorption curves of foams 1 and 3 (Figure 77). Due to the variability of the data from this experiment the results can only be used for inferences. According to manufacturers it is not realistic to reduce further the variability in foam characteristic by means of control of the chemical formulation.

5.6 Comparison of Experimental Data with Model Predictions.

From inspection of Figure 78 to Figure 82 given below a fair fit to measured data is seen in the low and moderate flow resistance foam test pieces. However measured values for normal incidence absorption are less than the predicted values, the greater the air flow resistance the greater the discrepancy. The two parameters that have not been measured are the structural factor and the porosity. From Figure 43 it can be seen that changes due to the variation in the porosity are predicted to be small. However variation of the structural factor is predicted to make significant changes in the absorption curve and this parameter can be optimized to give the 'best fit'. The best value of structural factor was between 2 and 3. Further refinements to the model gave a better fit measured and predicted behaviour in a particular frequency range but a poorer fit at other frequencies.
The application of the Bolton model has been studied further by comparing the predicted and measured behaviour of Calmphalt, (an asphalt-impregnated polyurethane), VDK (a flame retardant polyurethane) and FF201 a (a polyimide foam). These foams had very different characteristics modulus, damping, flow resistivity. The results of this comparison are given in Figure 83–Figure 85 where predicted values are calculated for structural factors between 1 and 5. As with the results for the crushed foams it can be seen that the discrepancy between measured and predicted behaviour is largest for the high flow resistance foam (Calmphalt). The agreement for VDK foam was quite good.

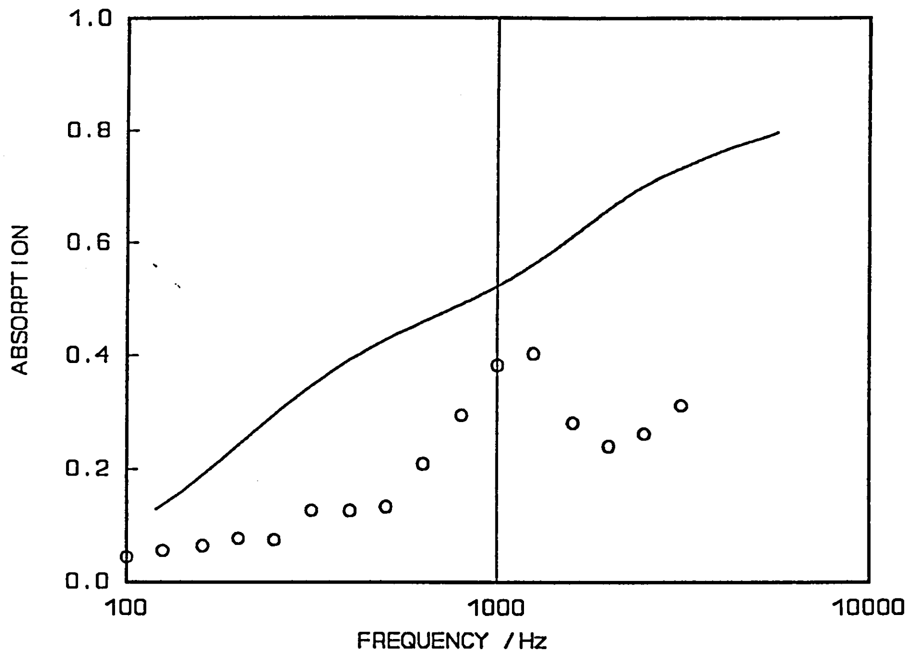


Figure 78 Graph of acoustic absorption against frequency for a PUR foam after one level of crushing. Curve predicted using the Bolton model.

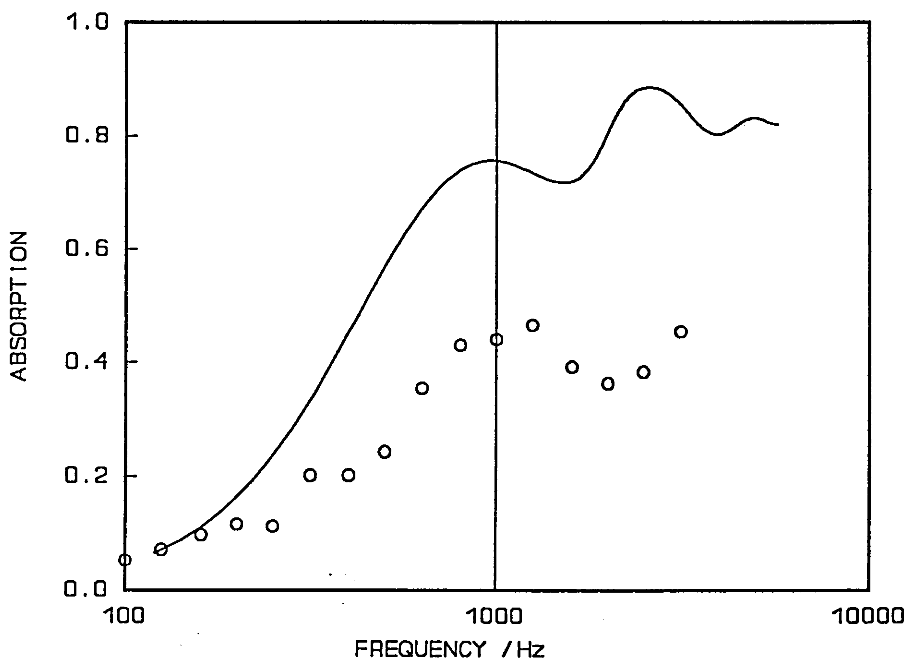


Figure 79 Graph of absorption against frequency for a PUR foam after two levels of crushing. Curve predicted using the Bolton model.

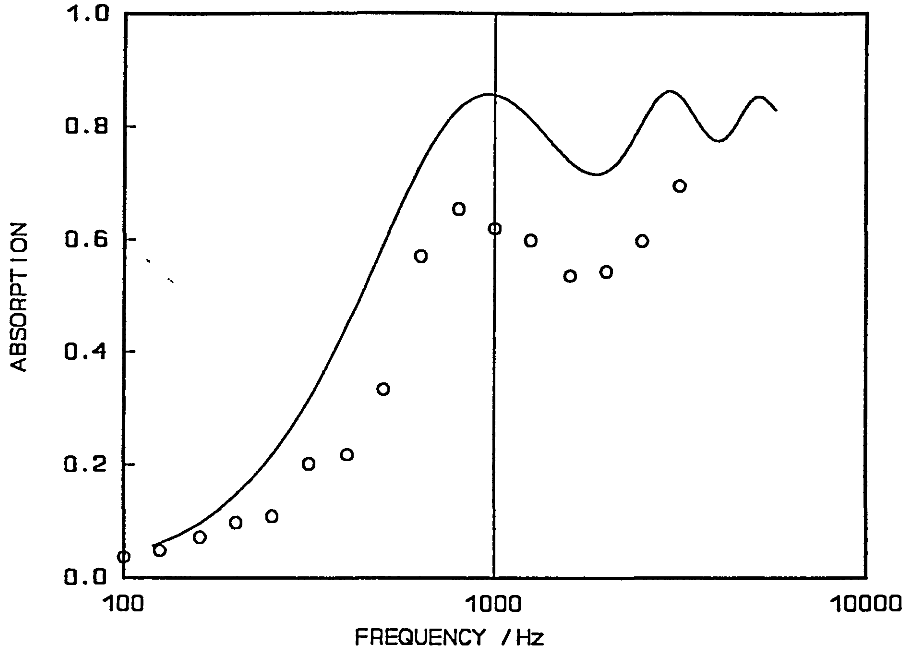


Figure 80 Graph of absorption against frequency for a PUR foam after three levels of crushing. Curve predicted using the Bolton model.

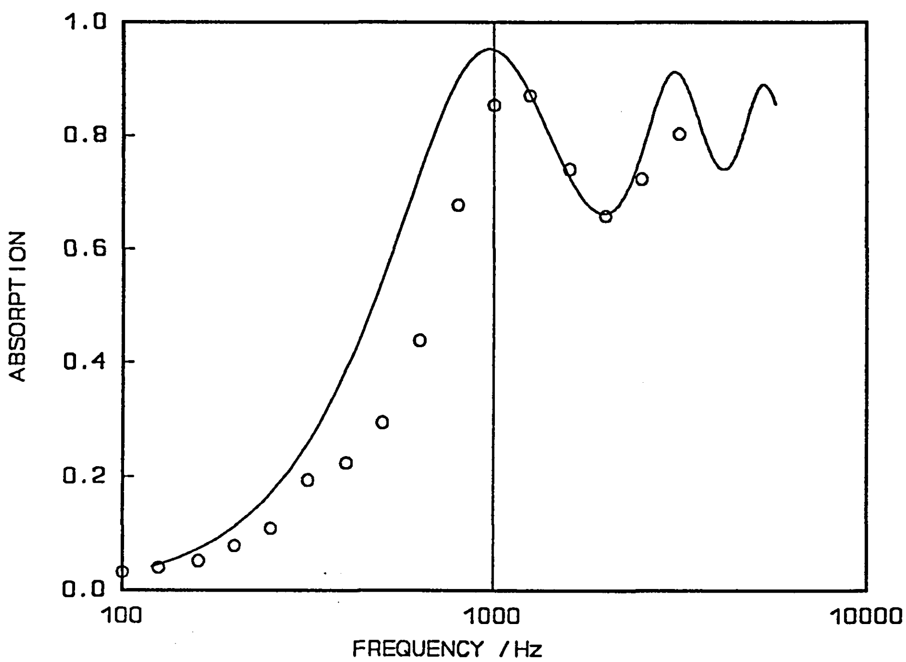


Figure 81 Graph of absorption against frequency for a PUR foam after four levels of crushing. Curve predicted using the Bolton model.

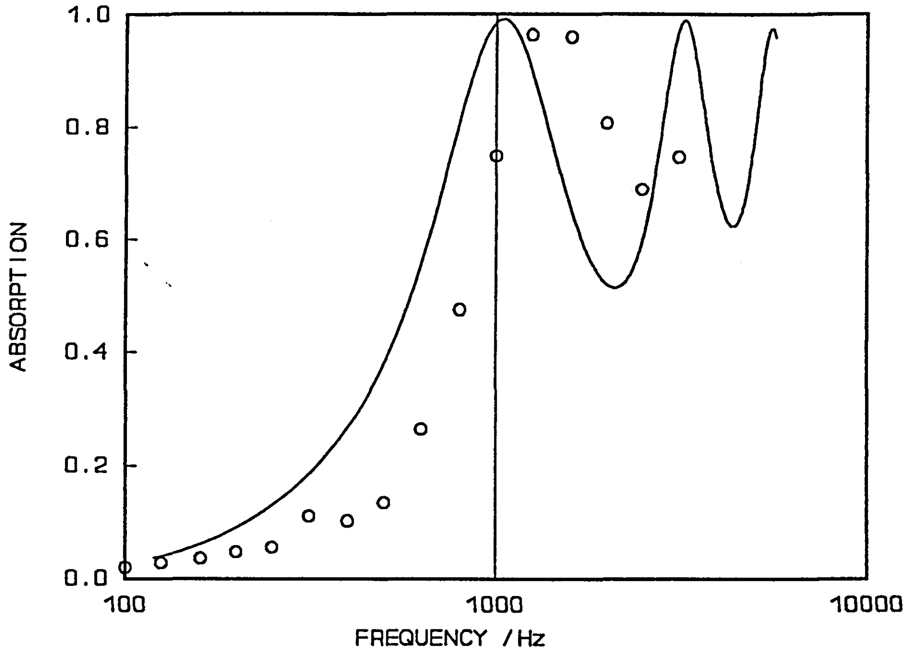


Figure 82 Graph of absorption against frequency for a PUR foam after five levels of crushing. Curve predicted using the Bolton model.

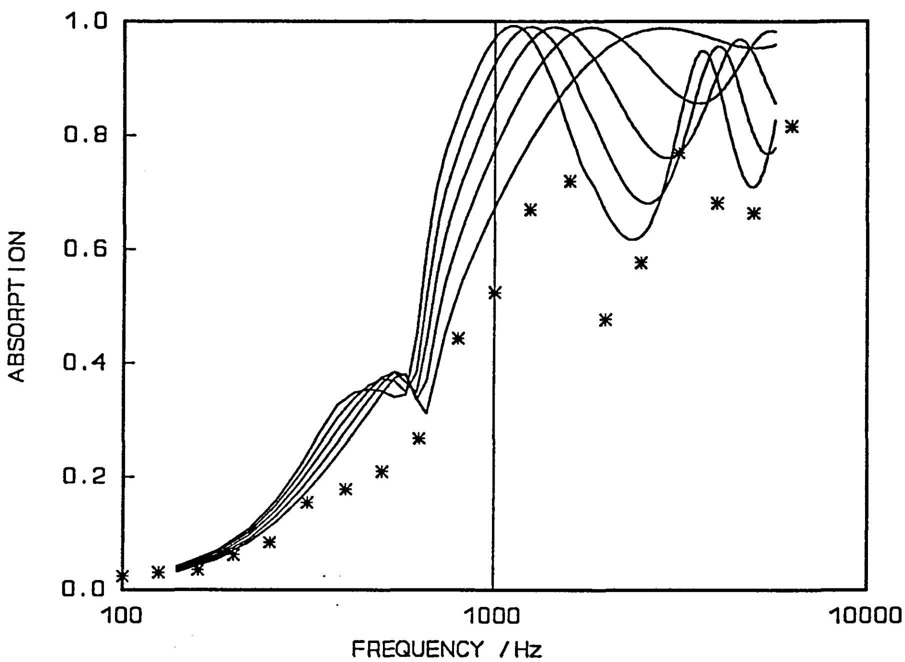


Figure 83 Comparison of the measured acoustic absorption behaviour of FF201 with that predicted by the Bolton model.

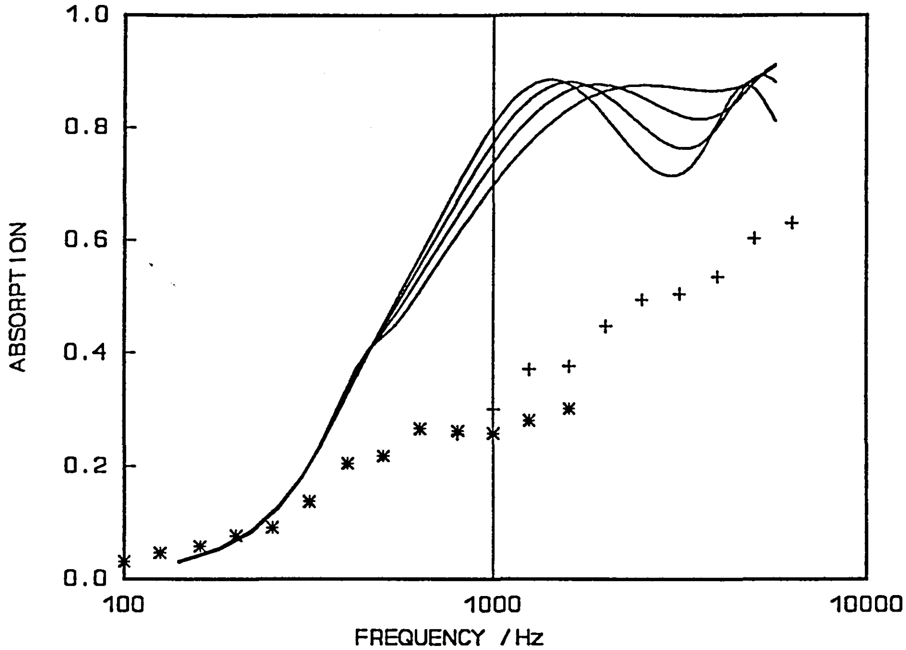


Figure 84 Comparison of the measured acoustic absorption behaviour of Calmphalt with that predicted by the Bolton model.

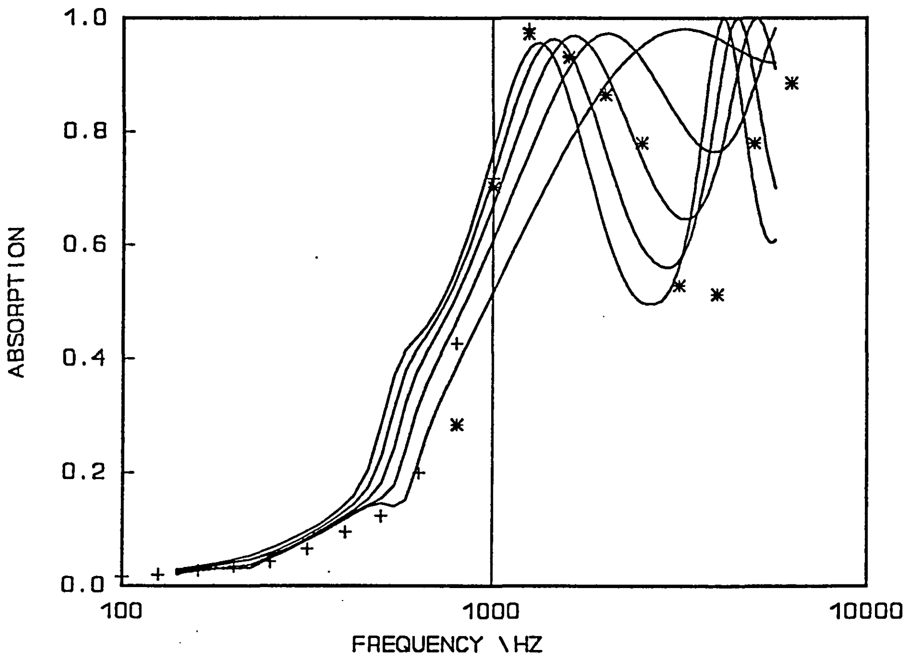


Figure 85 Comparison of the measured acoustic absorption behaviour of VDK with that predicted by the Bolton model.

5.7 Conclusions

In Sections 5.3 and 5.4 above, the value of air flow resistance for maximum acoustic absorption coefficient at a particular frequency, R_{max}, has been determined from measured data. The absorption coefficient at maximum was also determined. It has been suggested by White and Walker [82] and implied by the empirical relationship of Delany and Bazley [23] that the normal incidence absorption is only dependent upon air flow resistance. If this is correct the relationship between R_{max} amplitude (ie the absorption coefficient at maximum) as a function of frequency given by the two sets of measurements, Section 5.3 and 5.4, should be identical. Because the samples used in Section 5.4 than those in 5.3, had a smaller thickness it would be expected that data plotted would have a similar relationship but extend to higher frequencies.

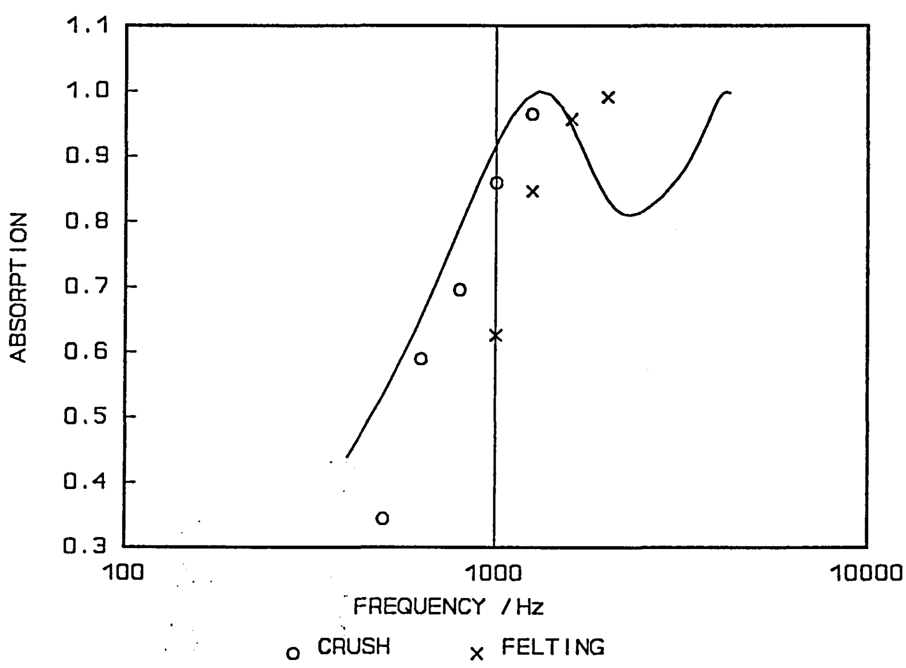


Figure 86 Comparison of the absorption coefficient at maximum (R_{max} amplitude) against the frequency of maximum absorption, with behaviour predicted by the Bolton model using 'typical' values of foam physical parameters.

From Figure 86, a graph of the frequency of R_{max} against the amplitude of R_{max}, it can be seen that the two data sets do not have an identical relationship. However because of the strong dependence of acoustic absorption on air flow resistance the data sets are of a similar order.

To determine if the trend of poor agreement between theoretical prediction of the model with increased air flow resistance apply to other materials the behaviour of three additional foams has been compared with values given by the Bolton model. Graphs of the absorption measurements on the materials and how they fit their theoretical absorption are given in Section 5.6 The materials were selected to provide a range of physical characteristics. The measured data for Calmphalt, with high air flow resistance, is not reproduced by the theoretical model. However, FF201 with a lower air flow resistance has a better fit and VDK with low air flow resistance shows a very good fit. These observations agree with these discussed previously for the crushed PUR foam.

CHAPTER 6

CONCLUSIONS

6.1 Acoustic Absorption Behaviour of Polyurethane Foam.

Polyurethane foam is the most widely used of all cellular plastic for noise control applications. High performance foams are employed in some specialist applications e.g. where non-flammability is of paramount importance. In the majority of cases, constraints imposed by the manufacturing process mean that commercial foams have less than optimum acoustic properties. The purpose of the technical part of this study was to identify the physical and mechanical parameters which control the acoustic absorption behaviour of foams and establish values of these parameters which optimise performance.

6.1.1 Optimisation of Performance.

It has been stated in the literature (White and Walker [82]) that optimum acoustic absorption is obtained when the air flow resistance of an absorber is $R_1 l=3\rho_o c$, which is approximately 1200 Mks rayls. When considering the optimisation of sound absorption it is important to establish what is meant by "optimum". Because a material's sound absorbing properties are frequency dependent it follows that a sound absorbing material that is optimal for one noise source (e.g. predominantly high frequency sound) will not necessarily be optimal for a different noise source (e.g. predominantly low frequency sound). Consequently to optimise a material, it is necessary to identify the frequency components of the sound that it is required to absorb. Several methods of ranking sound absorption characteristics have been devised,(e.g. NRC [12]) which rank materials according to a single parameter (single value index). Only one of these methods [69] includes in its ranking a consideration of the frequency content of the noise to be absorbed.

Five theoretical models for the bulk acoustic properties of foam have been investigated in the present work. In Chapter 3, the influence of changes to the parameters on the normal incident absorption have been discussed. To design a material for optimum sound absorption, several additional factors require review: the availability of the changes in the material, how changes in one parameter affect other parameters and the characteristics of the noise to be absorbed. A further set of considerations that will be discussed later are commercial criteria, eg how much is the customer person prepared to pay for acoustic comfort?

In Chapter 5, an experimental investigation of how changes in several material parameters affected acoustic absorption was described. To bring about changes to parameters, for example dynamic stiffness, at the manufacturing stage requires the expensive manufacture of small sample batches. In general, unless extremely large quantities of a product are required this type of specialist manufacture would not be practical. The large scale use of material is seen in the automotive industry. Usually the materials available for sound absorption would be standard foams or simply modified (e.g. densified) standard foams. Modifications to foams, such as densification, not only increase the density but also change other characteristics e.g. air flow resistance. An alternative to modification is selection. A wide range of foam is produced. By the identification of critical parameter values, a foam suitable for a specific acoustic application can be selected from standard production.

In any acoustic absorption application, the noise to be absorbed can be broken into its individual frequency components. An acoustic absorbing material that is to be used for this noise application must be selected with a knowledge of the frequency components of the source noise. A single value (SV) method of evaluating acoustic absorption materials for specific noise spectra is suggested in reference [69].

Optimisation can be achieved by applying the acoustic absorption characteristics of material available together with the spectra of the sound to be absorbed into the evaluation formula, reference [69]. The single figure output is then used to rank the materials and the optimum chosen. Other non-acoustic factors will also have to be taken into consideration such as material characteristics (such as price or flammability) and the physical environment where the material is to be used. To use optimisation with a theoretical model a given noise spectrum, a given set of parameters and the single value technique is required. Each parameter is varied, the remainder being held constant, until optimum sound absorption is obtained. The other parameters in their turn will then be varied till a new optimum is obtained. Each time an optimum is found the value of the varying parameter replaces the previous value of that parameter. A schematic chart of this technique is shown in below. The results will give a local optimum. It should not be concluded that results from this technique will always give the absolute optimum. By changing the order in which the variables are selected a different optimum can be attained. Alternatively if the process is repeated and the parameters selected in a different order it is possible that a different local optimum could be obtained. Although there are problems with this method of optimisation, within the possible variation of the parameters available, spurious local maximum optimisation will be obvious.

6.1.2 Theoretical Modelling.

Of the models discussed in Chapter 3 only those of Zarek and Bolton can realistically be related to foams. Other models have been used as stepping stones without which more advanced theoretical predictions could not have been evaluated.

Zarek's model is promising. The concept is attractive in that it is based on a clearly perceived mechanical model. However there are parameters in the model that are loosely defined. Furthermore it is difficult to reconcile values of material parameters given in [85] with those of practical foams. Above all other problems with the model is that when numerical calculations based on this model were attempted here, the results were quite unrealistic. The reasons for this apparent failure of the model have not been found.

The Bolton model has been shown to give good correlation with the behaviour of low air flow resistance foams. At higher air flow resistance the correlation breaks down. The fit of Bolton's model has been shown for several foams with a variety of characteristics. Because the fit is good for a range of material it is concluded that the model should be used for materials with a low air flow resistance.

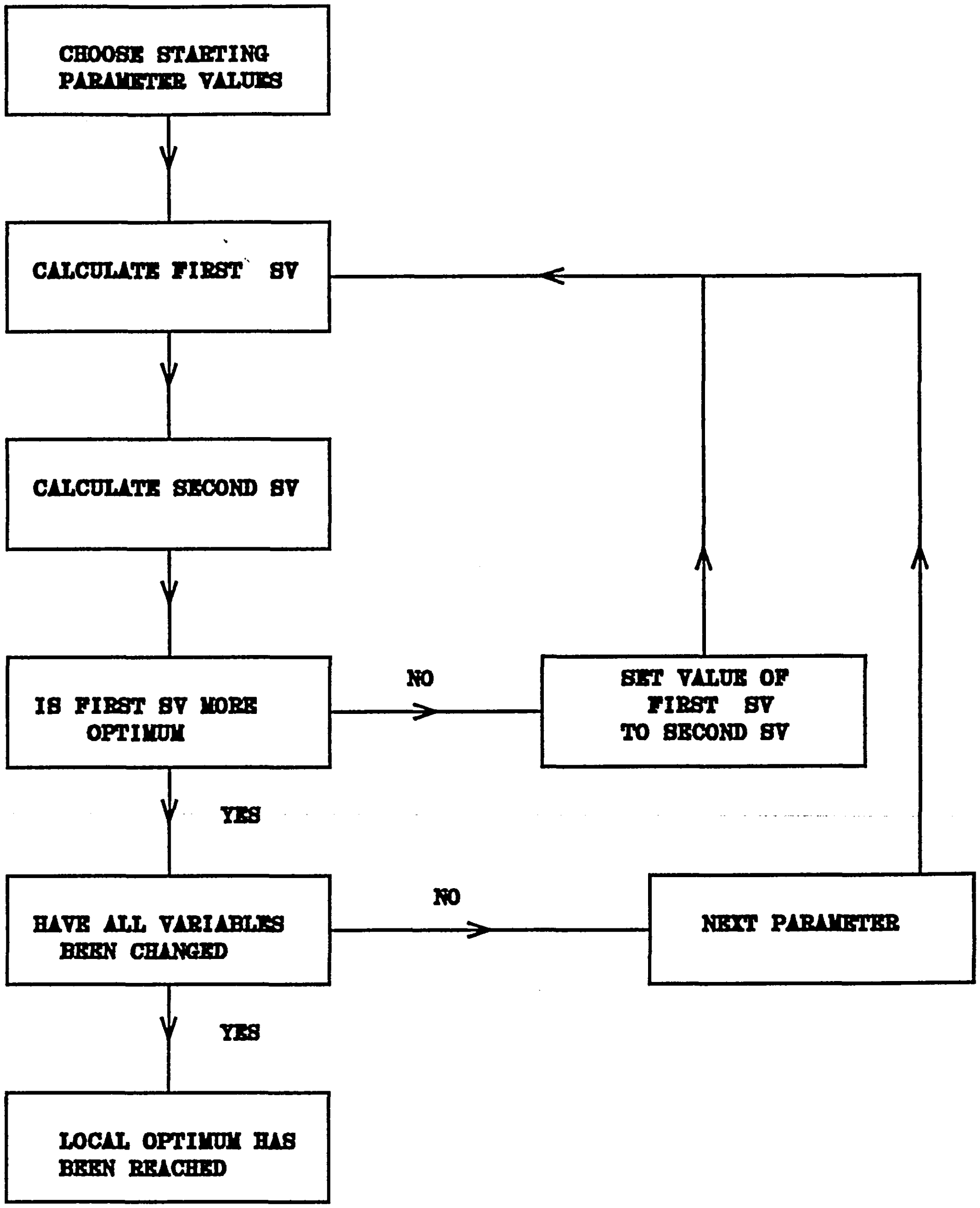


Figure 87 Optimisation method for foam selection.

Lamberts model and its limitations are discussed in Chapter 3. This model includes many factors not included in other works; for example in the measurements of air flow resistance (section 4.3) two constants are measured. The first related to permeability (K) the second to inertial flow resistance (B). In other models information from the second factor is not used.

6.2 Commercial Considerations.

In Chapter 2 a case for an increase in the demand for acoustic absorbing material has been presented. The predicted increase in demand could be fulfilled by alternative materials. Many of the foam producing companies have too little knowledge of or expertise in acoustics. There are technical service acoustic engineers only in a few companies. To exploit fully the potential increase in demand for acoustic material requires the education of personnel at all levels. A typical example of the lack of information getting to a customer is in the case study in Section 2.6. It was by chance that Mr Belcher came across a person with a knowledge of high performance foams. Until this time Rockwool, a commonly used acoustic absorbent, would have been used. After the flame retardant properties of the foam had been demonstrated, the material was viewed by R. Belcher as a suitable alternative. Had the new material not been used the proposed marketing strategy could not have been implemented and an overall loss for R. Belcher and the foam industry would have been the inevitable consequence. Although, in this example a large turnover of material would not be expected it is typical of the problems facing the foam industry. The problem is to educate existing users of acoustic absorbing materials to the advances that have been made in foams. A further problem is the identification of new acoustic foam users.

In Section 2.2.2 a case for the increase in demand due to the introduction of new legislation has been made. There are two major areas that legislation will affect: automotive and industrial. Automotive manufacturers are already cooperating with foam suppliers. Industrial legislation will require companies unaware of acoustics to reduce noise output either in their manufacturing or in the machines they produce. It is in these companies, inexperienced in acoustics, that a large potential will develop. It will be the material supplier with the best sales and technical backup that will capture these customers.

A review of the sale, support and general expertise for acoustic materials shows that foam manufacturers could improve their commercial activities. It was found by telephone conversation and requesting literature that mineral wool and felt suppliers were better equipped to deal with acoustic enquiries, was despite the fact that enquiries were for research related to a competitive product. As discussed in Section 2.1.1 there are two companies that deal extensively in acoustic foams. They have small departments dealing with a large and expanding acoustics market.

A major outlet for acoustic materials is in the companies who deal in all noise control materials e.g. The Noise Control Centre in Melton Mowbray. These companies are primarily converters. Foam is sold by these companies in sheet form and as composites. A problem for the advancement of the acoustic foam industry through this type of 'acoustic expert' is that their loyalties are divided. In addition to stocking foam acoustic material they also stock all other competing acoustic material.

The acoustic absorbing materials that are commercially available are very different, and foam is one of the more expensive. Foam has had other disadvantages, most of which have been eliminated with the introduction of higher performance materials. It is a challenge for any supplier to sell the advantages of more expensive material. In the current circumstances a large portion of the increase in demand for acoustic materials will be taken by alternatives. Slowly, under the present ideas, there will be a change in usage to foams which in most circumstances is a superior material.

The proposition of a company producing only acoustic grade slabstock foam is not viable. When manufacturing foam a large variety is produced. Although technology has many of the variables under control, variations do, in practice, occur. It has been found that due to the large volume of foam that must be produced for economic reasons, a large customer base is required. By diversifying this customer base any slack periods in one sphere of operation will have minimal effect on turnover. Due to high storage cost of foam a quick through put of product is important.

An area in which new companies might be viable is in the smaller acoustic converters and suppliers of expertise and acoustic products. With minimal initial outlay a small business can be set up. Initial requirements will include sound measurement equipment, tools for simple conversions (it is possible to specify to a larger company and the required product sizes) and small premises. By only buying goods as required the problems in cash flow are reduced (it has already been noted in Section 2.3 that through-put by the foamers is of a few days).

6.3 Delany and Bazley Empirical coefficients.

Results from the use of these coefficients have been shown not to give accurate correlation between theoretical and measured results. There has been a wide spread of coefficients measured by several authors, giving a variety of predicted absorptions. By the nature of the ideas behind the coefficients they will work for a set of materials from which they are deduced. For practical predictions, unless work has already been undertaken for a foam batch it is unlikely that the empirical model will be of practical use for the prediction of sound absorbing properties of foams.

6.4 High Performance Foam.

In general the high performance foam does not have the acoustic performance of more well-established sound absorbers. It is only in areas where the material's other properties are of greater importance that they will be of serious commercial use. The demand has been predicted for acoustic materials and soon the high performance foams will be adapted to improve their acoustic performance. Already in the case of Basotec (with low air flow resistance) the manufacturers (BASF) are investigating the effects of densification (hence increased air flow resistance) on acoustic absorption. Many of the other materials are of the closed cell type and would require a lowering of the air flow resistance. Difficulties would arise but if the demand is high enough and recognised by the foam industry, these will be overcome. In most foam companies acoustical products represents a small proportion of their turn over and it is as a consequence that their reaction to demand will be slow.

6.5 Future work.

Of the theoretical models investigated the Bolton, Zarek and Lambert models are worth further study. In the case of the Bolton model investigation into the reasons why the model makes poor predictions at high air flow resistance should be undertaken. The model could also be improved by including further information on measured parameters, for example using both the constants K and B in the air flow resistance equation in a similar way to Lambert.

Zarek's ideas are interesting but the due to the unrealistic suggested input parameters and the poor results it is not possible to evaluate the model's performance. Further investigation would be justified in both these aspects of the model.

The Lambert model is has many interesting features and is worth further investigation. For use in high performance alternatives for the measurements on cell dimensions are required.

Commercially an increase in demand for acoustic materials is obvious. The suitability of foams to fulfil the demand is also obvious. Future work in relating these facts to foam manufacturers and acoustic end users is essential if foams are to be competitive in this expanding market.

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APPENDIX 1

INDUSTRIAL LINKS

Primary Industrial Contacts.

Company: BASF(UK).
Earl Road,
Cheadle Hulme,
Cheadle,
Cheshire SK8 6QG. Tel 061-485 6222

Contacts:	R Cousins	Marketing Development U.K.
	P Shrimpton	
	Dr D. Scherzer	Foam product development U.K.
	R. Schulze	Foam Product Development
	Dr W. Frank	Germany

BASF is a major European chemical and plastics supplier.

Company: Hyman PLC

Draka Foams
Dinting Lodge Industrial Estate,
Glossop,
Derbyshire, SK13 9LE. Tel 04574 61141

Contact: Tony Griffiths - Technical Director.

Stephen Duffy - Development Manager.

Hyman is one of the largest producers of slabstock foam in the U.K.

Company: Pritex Ltd.
Station Mills,
Wellington,
Somerset TA21 8NN. Tel 0823 664271

Contact: Paul Hanscombe - Acoustic Engineer

Pritex is a relatively small company, part of the Relyon group. At Pritex in Somerset they have one slabstock producing machine (Max Foam type).

Company: Ranwal

Chaul End Lane,
Luton. LU4 8HB Tel 0582 595151

Contact: Roger Rodwell - Acoustic Engineer

Ranwell is a foam processing company.

Company: T.Matt Engineering

Weldon Road,
Loughbrough,
Leicestershire LE11 0RN. Tel 0509 217171

Contact: Clive Thompson - Managing Director

T.Matt is a sound insulation company which originally manufactured sound insulation for large generating and compressor units. Now it is involved in all aspects of sound absorption.

Company: John Cotton

Spring Garden Mill,
Colne,
Lancs., BB8 8EL Tel 0282 863550

Contact: Brian Sigsworth.

A felt manufacturer in direct competition with foam manufacturers for many acoustic applications.

Company: Rockwool

Pencoed,
Bridge End,
Mid Glamorgan. CF35 6NY. Tel 0656 862621

Contact: Mrs C.M.Perkins

Rockwool is a fibre based product which competes with foams.

Company: Manrose Ltd.,

Bedford Ave,
Slough. Tel 0753 691399

Contact: R. Belcher. Managing Director

Manrose is a manufacturer and designer of high quality fans. Additional contacts were made with many other companies within the acoustic absorption market. Above only the major companies together with the main contacts have been described.

Interview with R. Belcher MD of Manrose Ltd.

The interview was instigated by a mutual acquaintance of R. Belcher and the author. An acoustics related product produced by Manrose required revitalisation within the market. It was suggested to R. Belcher that the author had experience in the acoustic field and could assist in re-designing the product.

The Product:

An acoustic ventilator system for use in homes that have a sealed double glazing system. It is primarily a fan that circulates fresh air into a building without admitting noise. The air flow is fan assisted as shown in Section 3.6. By passing over the layers of Rockwool sound energy admitted into the ventilator will be absorbed bringing transmitted sound level below the levels required by the Board of Agreement.

Marketing policy:

There are two major types of purchasers for such ventilators: the first are contractors building near noise sources. When such buildings are constructed it is required by the local council that sound levels in domiciles are below specified levels. This is achieved with double glazing and generally sealing against the ingress of noise. Unfortunately the insulation will also prevent adequate air circulation, hence the inclusion of appropriate ventilators. The second major customer group is authorities that wish to create or expand a noise producing installation within a built up area, although permission to build noise creating establishments within residential areas is not normally permitted. In special cases such as essential transport (air, rail or road), exceptions are made. Again it is required by the local council that all domiciles affected by an increase in noise are fitted with suitable double glazing and appropriate ventilators. Generally authorities or consultants involved are required by the local council to apply for a list of approved ventilators and the relevant supplier. A tender is then sent to all suppliers on the list. It is from this tender that all purchasing decisions are made. As all units by virtue of their conformation with the Board of Agreement requirements will fulfil the required function the purchasing decision is made primarily on cost. R. Belcher states that strict controls are enforced on such expenditure and considerable benefits have to be exhibited for non-purchase of the least expensive ventilators. Therefore any major marketing expense involved the sales of the product is unjustifiable with the exception of obtaining relevant approval. On the basis of this information the discussion between R. Belcher and the author was how to reduce the cost per unit of the ventilator without reducing the air flow or acoustic performance.

A major factor considered in the original units design was flammability.

A suggested solution:
Use Basotec melamine foam for the acoustic absorbing material and re-design the interior of the unit. Section 3.6 indicates

the modifications and where the Basotec will be used. Three major design changes are instigated to reduce cost. Metal work cost is reduced by not including a centre panel. This would not be possible if the material was not rigid. Assembly time costs are reduced by inserting pre-cut foam sections into the cover box. The foam will be slightly over size, fitting tightly into the cover box and eliminating gluing. Because the central foam panels will not support the fan and electrical components they will be attached to the back plate. Additional cost savings are devised e.g. putting a fused terminal block in the unit rather than having an external fuse, these modifications are not relevant to discussions on acoustics and foams. A general reduction in the overall cost of the unit is achieved, making it a highly marketable product.

APPENDIX 2

MAJOR COMPANIES WITHIN THE FOAM INDUSTRY

In this appendix a list of major companies within the foam industry is given. As described in Section 3.1.1 these companies fall into three major categories; Suppliers, Foamers, and Converters. The list is not exclusive and only head offices have been given where several subsidiaries are all in the industry.

1.Chemical Suppliers

Dow Chemicals Co Ltd.,
Stana Place,
Fair Bank Ave.,
Staines,
Middlesex.

Bayer U.K. Ltd.,
Bayer House,
Strawberry Hill,
Newberry,
Berks.

BP Chemicals Ltd.,
Belgrave House,
76 Buckingham Palace Road,
London SW1.

ICI Chemicals Ltd.,
PO Box 13,
The Heath,
Runcorn,
Cheshire, WA7 4QF.

2.Foam Manufactures

Woodville Polymers Engineering,
Alton Lane,
Ross on Wye,
Hereford shire, HR9 5NF.

Kay Metzler Ltd.,
Manor Farm Road,
Alperton,
Wembley,
Middlesex, HAO 1YE.

Raylon Ltd.,
Station Mills,
Wellington,
Somerset TA21 8NN.

Harrison & Jones Ltd.,
Swan Mill-Foxden Lane
Middleton Junction,
Manchester, M24 1QR.

Dunlopillo Ltd.,
Hirwaun Industrial Estate,
Aberdare,
Mid Glamorgan,CF44 9UR.

Elastogran U.K. Ltd.,
Wimsey Way,
Alfreton Trading Estate,
Alfreton,
Derby DE55 4NL.

WR Grace Ltd.,
Northdale House,
North Circular Road,
London NW10 7UH.

Bridgetown Industries Ltd.,
Green Lane,
Bridgetown,
Cannock,
Staffordshire, WS11 3JW.

Beaver Foams Ltd.,
Blue Bell Close,
Clover Hook Industrial Park,
Alfreton,
Derby, DE55 4RD.

Ferguson & Timpson Ltd.,
5 Athol Ave.,
Hillington,
Glasgow, G52 4UA.

Guthrie Corporation PLC,
6th Floor,
6 Devonshire Square,
London EC2M 4LA.

Dow Corning STI Ltd.,
Unit 3&4,
Holloway Drive,
Wardley Industrial Estate,
Worsley,
Manchester, M28 4LA.

Draka Foams
Dinting Lodge Industrial Estate,
Glossop,
Derbyshire, SK13 9LE.

3.Converters (Companies who manufacture components from ready formed foam blocks).

Custom Foams Ltd.,
Unit 2&17
Deans Road,
Old Wolverton,
Milton Keynes, MK12 5PU.

Caligen Foams Ltd.,
Broad Oak,
Accrington,
Lancs., BB5 2BS.

Bestobell Services Co. Ltd.,
Marshgate Estate,
Taplow Road,
Taplow,
Maidenhead,
Berks., SL6 0ND.

Marley Foam Ltd.,
Dickley Lane,
Lenham,
Maidstone,
Kent, ME17 2DE.

Bestobell Protection,
Saxby Road,
Melton Mowbury,
Leicester LE13 1BP.

Noise Control Foams,
Charles House,
Toutley Road,
Berks. RG11 5QN.

APPENDIX 3
LISTING OF COMPUTER PROGRAMS

Notes on the computer programs written:
All programs where written in Fortran then compiled and run on an IBM PC or compatible.

Because most of the data from these programs has been used to draw graphs via a spreadsheet the input and output of data was via files.

When using complex notation, because the IBM compiler does not support complex arithmetic a set of subroutines were used. These use standard complex methods:

For multiplication.

```
      SUBROUTINE MULT(A1,B1,A2,B2,ANR,ANI)
C***********************************************************CT
HIS SUBROUTINE MULTIPLIES TOGETHER THE TWO COMPLEX No'S
C        A1+iB1 AND A2+iB2 AND RETURNS THE ANSWER AS
C                   ANR+iANI
C**********************************************************
  IMPLICIT REAL*8 (A-H,O-Z)
      ANR=A1*A2-B1*B2
      ANI=A1*B2+A2*B1
      END
```

For division:

```
      SUBROUTINE DIV(A1,B1,A2,B2,ANR,ANI)
C**********************************************************C
     THIS SUBROUTINE DIVIDES THE TWO COMPLEX No
C        A1+iB1 BY A2+iB2 AND RETURNS THE ANSWER AS
C                   ANR+iANI
C**********************************************************
  IMPLICIT REAL*8 (A-H,O-Z)
      T1=A2*A2+B2*B2
      T2=-B2
      CALL MULT(A1,B1,A2,T2,T3,T4)
      ANI=T4/T1
      ANR=T3/T1
      END
```

To raise a complex number to a power:

```
        SUBROUTINE POWE(A1,B1,POW,ANR,ANI)
C************************************************************
C            THIS SUBROUTINE RAISES THE TWO COMPLEX No
C         A1+iB1 TO THE POWER POW AND RETURNS THE ANSWER AS
C                            ANR+iANI
C************************************************************
       IMPLICIT REAL*8 (A-H,O-Z)
       POW1=POW
       T1=(A1*A1+B1*B1)**(POW1/2.0D0)
       IF (A1.GT.(-1.0D-10).AND.A1.LT.(1.0D-10)
      +.AND.B1.GT.0.0D0)THEN
       T2=DATAN(1.0D0)*2.0D0
       ELSEIF (A1.GT.(-1.0D-10).AND.A1.LT.(1.0D-10)
      +.AND.B1.LT.0.0D0)THEN
        T2=-DATAN(1.0D0)*2.0D0
       ELSE
       T2=DABS(DATAN(B1/A1))
       ENDIF
       PYE=DATAN(1.0D0)*4.0D0
       CALL TCHEQ (PYE,T2)
       IF (A1.LT.0.0D0.AND.B1.GT.0.0D0)THEN
        T2=-T2+PYE
        ELSEIF(A1.LT.0.0D0.AND.B1.LT.0.0D0.OR.B1.EQ.0.0D0)THEN
        T2=T2+PYE
        ELSEIF(A1.GT.0.0D0.AND.B1.LT.0.0D0)THEN
        T2=2.0D0*PYE-T2
       ENDIF
       TEE1=T2*POW1
       ANI=T1*DSIN(TEE1)
       ANR=T1*DCOS(TEE1)
       END
```

In the power routine to reduce an angle to within 0 and 2π radians.

```
       SUBROUTINE TCHEQ(PYE,B1)
       IMPLICIT REAL*8 (A-H,O-Z)
       IX=B1/(2.0D0*PYE)
       B1=B1-2.0D0*PYE*IX
       END
```

To calculate the factorial of a number:

```
      SUBROUTINE FACT(NUM,FAC)
C*********************************************************C
        THIS SUBROUTINE CALCULATES THE FACTORIAL OF  NUM
C                AND RETURNS THE ANSWER AS
C                        FAC
C*********************************************************
  IMPLICIT REAL*8 (A-H,O-Z)
      IF(NUM.LT.0.1D-9.AND.NUM.GT.-0.1D-9)THEN
       FAC=1
      ELSE
        FAC=1.0D0
        DO 20,J=1,NUM
         FAC=FAC*J
 20     CONTINUE
      ENDIF
      END
```

Calculation of a complex Bessel function using an expansion:

```
      SUBROUTINE BESSL(X,Y,N,AJNR,AJNI)
      IMPLICIT REAL*8 (A-H,O-Z)
C*********************************************************C
THIS SUBROUTINE WILL CALCULATE THE  N th  ORDER BESSEL
C                FUNCTION
C     OF THE COMPLEX No X+iY RETURNING THE ANSWER AS
AJNR+iAJNI
C*********************************************************
  ITT=10
      AJNR=0.0D0
      AJNI=0.0D0
      DO 10,K=0,ITT
       POW=2.0D0*K+N
       SINE=(-1.0D0)**(K)
       CALL POWE(X,Y,POW,ANR,ANI)
       IT2=K+N
       CALL FACT(IT2,T2FAC)
       CALL FACT(K,AKFAC)
       BOT=2.0D0**POW*AKFAC*T2FAC
       T3R=ANR*SINE/BOT
       T3I=ANI*SINE/BOT
       AJNR=AJNR+T3R
       AJNI=AJNI+T3I
 10   CONTINUE
      END
```

A subroutine to calculate the tangent of a complex number.

```
SUBROUTINE TANI(A1,B1,ANSR,ANSI)
IMPLICIT REAL*8 (A-H,O-Z)
TA=DTAN(A1)
THB=DTANH(B1)
T1=-TA*THB
T2=1.0
CALL DIV(TA,THB,T2,T1,ANSR,ANSI)
END
```

A subroutine to calculate the hyperbolic tangent of a complex number.

```
SUBROUTINE TANHI(A1,B1,ANSR,ANSI)
IMPLICIT REAL*8 (A-H,O-Z)
IF(A1.GT.100.0D0)THEN
THA=1.0D0
ELSEIF(A1.LT.-100.0D0)THEN
THA=-1.0D0
ELSE
THA=DTANH(A1)
ENDIF
TEMP=B1
PYE=DATAN(1.0D0)*4.0D0
CALL TCHEQ(PYE,B1)
TB=DTAN(B1)
B1=TEMP
T1=THA*TB
T2=1.0D0
CALL DIV(THA,TB,T2,T1,ANSR,ANSI)
END
```

A subroutine the calculates the specific acoustic impedance from the characteristic acoustic impedance, length and propagation constant.

```
SUBROUTINE CONV (ZR,ZI,ALPR,ALPI,AL,ZAR,ZAI)
 IMPLICIT REAL*8 (A-H,O-Z)
 TR2=AL*ALPR
 TI2=AL*ALPI
 TI1=DTANH(TR2)*DTAN(TI2)
 CALL DIV(1.0D0,TI1,DTANH(TR2),DTAN(TI2),TAR,TAI)
 CALL MULT(ZR,ZI,TAR,TAI,ZAR,ZAI)
 END
```

From the specific acoustic impedance of air and of a sample normal incident absorption is calculated.

```
      SUBROUTINE ACON (ZR,ZI,ANO)
      IMPLICIT REAL*8 (A-H,O-Z)
      WO=420.0
      ANO= 1.0D0-((ZR*ZR-WO*WO+ZI*ZI)**2+(2*WO*ZI)**2)/
     1 (((ZR+WO)**2+ZI*ZI)**2)
      END
```

The program takes account of tube attenuation when converting data measured on the standing wave tube into normal incident acoustic absorption (Section 5.5.3).

```
      PROGRAM IMP
      IMPLICIT REAL*8 (A-H,O-Z)

       OPEN (1,FILE='A1.PRN',STATUS='OLD')
       OPEN (2,FILE='A2.PRN',STATUS='OLD')
       OPEN (3,FILE='A3.PRN',STATUS='OLD')
       OPEN (4,FILE='A4.PRN',STATUS='OLD')
       OPEN (5,FILE='A5.PRN',STATUS='NEW')

      PI=DATAN(1.0D0)*4.0D0
      ACC=0.0000001D0
      WRITE (*,*) 'PLEASE INPUT NO OF DATA POINTS'
      READ (*,*) IK
      DO 40,I=1,IK
       READ (1,*) FRE
       WRITE(*,*) FRE
       READ (2,*) VM1
       WRITE(*,*) VM1
       READ (3,*) VM2
       WRITE(*,*) VM2
       READ (4,*) Y1
       WRITE(*,*) Y1
       IF (VM1.GT.1.0D-9.OR.VM1.LT.-1.0D-9)THEN
       VD=2.74D-5
       CO=339.7
       CD=CO*(1.0D0-1.0D0/(2.0D0*PI)*DSQRT(VD/(PI*FRE)))
        WRITE(*,*) CD
       Y1=Y1-.0018D0
       T4=CD/FRE*0.5D0
       BETA=PI/(T4)

       ALPH=2.78D-5*(FRE**0.5D0)/0.0495D0
      T7=VM1/VM2
      CALL CHECK1(Y1,T4)
      GAM1=0.5D0*DLOG((T7+1)/(T7-1))-ALPH*Y1

 CALL IMPED(FRE,BD1,Y1,T7,ACC,GAM2,PI,T4,GAM1,BETA,ALPH)
       DEL=PI-ALPH*DSINH(2.0D0*(ALPH*Y1+GAM2))/
     +  (2.0D0*BETA)-Y1*BETA
      CALL TANHI(GAM2,DEL,TA1R,TA1I)
      XT=-ALPH/BETA
      CALL DIV(TA1R,TA1I,1.0D0,XT,ANR,ANI)
       CALL ACON (ANR,ANI,ABSORB)
       WRITE (5,*) FRE,ABSORB
       ENDIF
40    CONTINUE
      END
     SUBROUTINE IMPED (FRE,BD1,XLDN,T7,ACC,GAM2,
    +  PI,T4,GAM1,BETA,ALPH)
      IMPLICIT REAL*8 (A-H,O-Z)
      RP=T7
      A1=ALPH*ALPH*0.5D0/(BETA*BETA)
      DO 20,I=1,10000
       WRITE (*,*) I,GAM1
       TE1=DSINH(ALPH*XLDN+GAM1)
       TE2=DSINH(2.0D0*(ALPH*XLDN+GAM1))
```

```
      TE5=2.0D0*TE1*TE1+A1*TE2*TE2
      TE3=DCOSH(ALPH*BD1+GAM1)
      TE4=DSINH(2.0D0*(ALPH*BD1+GAM1))
      FX=(2.0D0*TE3*TE3-A1*TE4*TE4)/TE5-RP*RP
      TE6=DSINH(4.0D0*(ALPH*BD1+GAM1))
      TE7=DSINH(4.0D0*(ALPH*XLDN+GAM1))
      XT1=2.0D0*(TE4-A1*TE6)/TE5
      XT2= (2.0D0*TE3*TE3-A1*TE4*TE4)
     + *2.0D0*(TE2+A1*TE7)/(TE5*TE5)
      FXD=XT1-XT2
      GAM2=GAM1-FX/FXD

      IF (DABS(GAM1-GAM2).LT.ACC) THEN
      WRITE (*,*)'No OF ITERATIONS=',I
       RETURN
       ELSE
        GAM1=GAM2
      ENDIF
20    CONTINUE
      WRITE (*,*)'NON CONVERGENCE OF N/R'
      CALL EXIT
      END


      SUBROUTINE CHECK1  (A1,T4)
      IMPLICIT REAL*8 (A-H,O-Z)
       DO 30,I=1,3
        T5=-T4+A1
        IF (T5.GT.0.0D0)THEN
        A2=A1
        A1=A1-T4
        ELSE
        RETURN
        ENDIF
30     CONTINUE
       WRITE (*,*)'SOMETHING IS WRONG ERROR 1'
       CALL EXIT
       END
```

Program used to calculate normal incident acoustic absorption from the model suggested by Zwikker and Kosten (Section 4.1).

```
      PROGRAM KOSZWIK
      IMPLICIT REAL*8 (A-H,N-Z)
      REAL *8 A(4)
       OPEN (2, FILE='I1.PRN',STATUS='OLD')
       OPEN (3, FILE='T1.PRN',STATUS='NEW')
       OPEN (4, FILE='T2.PRN',STATUS='NEW')
      DO 90,J=1,4
       READ (2,*) A(J)
 90   CONTINUE
       C=DSQRT(A(4)/A(2))
       DO 10 I=1,2000,10
       AOM=8.0D0*DATAN(1.0D0)*I
       THET=AOM*A(1)/C
       FI=A(3)*AOM*0.5*A(1)/C
       topr=dcosh(fi)*dcos(thet)
       topi=dsinh(fi)*dsin(thet)
       botr=dsinh(fi)*dcos(thet)
       boti=dcosh(fi)*dsin(thet)
       call div(topr,topi,botr,boti,tobr,tobi)
       dot=a(3)/2.0d0
       call mult(tobr,tobi,1.0d0,dot,anr,ani)
       zr=a(2)*c*anr
       zi=a(2)*c*ani

BOT1=(DCOSH(FI)*DCOSH(FI)-DCOS(THET)*DCOS(THET))*4.0/(A(2)*C)
       ZR1=(2.0*DSINH(2.0*FI)+A(3)*DSIN(2.0*THET))/BOT1
       ZI1=(A(3)*DSINH(2.0*FI)-2.0*DSIN(2.0*THET))/BOT1
       CALL ACON (ZI,ZR,ANO)
       write (*,*) zr-zr1,zi-zi1
       WRITE(3,*) I,ANO
       WRITE(4,*) ZR/420.0d0,ZI/420.0d0
  10   CONTINUE
      END
```

Program used to calculate normal incident acoustic absorption using a model suggested by Beranek (Section 4.2)

```
      PROGRAM BT1
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL *8 A(9)
      OPEN (1, FILE='t1.prn',STATUS='NEW')
      OPEN (2, FILE='T2.PRN',STATUS='NEW')
      OPEN (3, FILE='t3.prn',STATUS='NEW')
      OPEN (4, FILE='T4.PRN',STATUS='NEW')
      OPEN (5, FILE='T5.PRN',STATUS='NEW')
      OPEN (6, FILE='t6.prn',STATUS='NEW')
      OPEN (7, FILE='T7.PRN',STATUS='NEW')

      OPEN (8, FILE='D1.PRN',STATUS='OLD')
      X=0.0D0
      PYE=DATAN(1.0D0)*4.0D0
      DO 30,K=1,9
      READ (8,*)  A(K)
 30   CONTINUE
      IL=A(8)
      A(IL)=A(IL)-A(9)
      DO 20,J=1,6
      A(IL)=A(IL)+A(9)
      AL=A(1)
      XR1= A(2)
      ROM=A(3)
      RO=A(4)
      AK1=A(5)
      AK2=A(6)
      Y1 =A(7)
      DO 60,K=1,6
       WRITE (J,*) A(K)
 60   CONTINUE
       DO 10 I=10,6000,20
        F1=1.0D0*I
      CALL BERA (F1,ZI,ZR,AL,XR1,ROM,RO,Y1,AK1,AK2,J,
     + XLBR,XLBI)
      CALL CONV (ZR,ZI,XLBR,XLBI,AL,ZAR,ZAI)
      CALL ACON (ZAR,ZAI,ANO)

        WRITE(J,*) I,ANO
        WRITE(*,*)J,I,ANO
 10    CONTINUE
       CLOSE (J)
 20    CONTINUE
      END
```

```
      SUBROUTINE BERA (F1,ZI,ZR,AL,XR1,ROM,RO,Y1,AK1,AK2,J,
     + XLBR,XLBI)
      IMPLICIT REAL*8 (A-H,O-Z)
       W=8.0D0*DATAN(1.0D0)*F1
      SW=W*W
      T1=DSQRT(Y1/AK2)
      T2D=XR1/(RO*AK1)
      T3=RO*(AK1-1)/ROM
      T4=(1+T3)*(1+T3)
      T7=(1+Y1*T3)
      T5=XR1*((1+RO*(Y1*AK1-1.0D0)/
     + ROM)+RO*RO*(AK1*AK1-1)*
     + Y1/ROM/ROM)
     + /T4
      T8=(XR1*XR1*(Y1/AK1+ROM/(RO*AK1)))/(T4*ROM*ROM)
      T6=1.0D0+XR1*XR1/(T4*ROM*ROM*SW)

      T11=XR1*XR1/(ROM*ROM*SW*T4)
      SR1=T5/T6
      SRO1=RO*AK1*((T8/SW+T7)/(1+T11))
C     SR1=<R1>  SR01=<p1>
C
      XR3= SRO1
      XI3= -SR1/W
      CALL POWE(XR3,XI3,0.5D0,XR2,XI2)
      XLBT=T1*W
      XLBR=-XLBT*XI2
      XLBI=XLBT*XR2
      ZR=AK2*XLBI/(W*Y1)
      ZI=-XLBR*AK2/(W*Y1)
      RETURN
      END
```

Program used to calculate normal incident acoustic absorption using a model suggested by Craggs (Section 4.3).

```
      PROGRAM CRAGGS
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL *8 A(9)
      OPEN (1, FILE='t1.prn',STATUS='NEW')
      OPEN (2, FILE='T2.PRN',STATUS='NEW')
      OPEN (3, FILE='t3.prn',STATUS='NEW')
      OPEN (4, FILE='T4.PRN',STATUS='NEW')
      OPEN (5, FILE='T5.PRN',STATUS='NEW')
      OPEN (6, FILE='t6.prn',STATUS='NEW')
      OPEN (7, FILE='T7.PRN',STATUS='NEW')

      OPEN (8, FILE='C1.PRN',STATUS='OLD')
      PYE=DATAN(1.0D0)*4.0D0
      DO 30,K=1,6
       READ (8,*)  A(K)
       WRITE (*,*) K,A(K)
30    CONTINUE
      IL=A(5)
      A(IL)=A(IL)-A(6)
      DO 40,J=1,6
       A(IL)=A(IL)+A(6)
       DO 60,L=1,4
        WRITE (J,*) A(L)
60     CONTINUE
       ROM=1.29
       C=334.0
       DO 10 I=100,6000,20
        ANG=2.0D0*PYE*I
        CALL CR1 (A(4),ROM,ANG,A(3),A(1),C,A(2),ZAR,ZAI)
        CALL ACON (ZAR,ZAI,ANO)
        WRITE (J,*) I,ANO
10     CONTINUE
       CLOSE(J)
40    CONTINUE
      END

      SUBROUTINE CR1 (R,ROM,ANG,OM,AL,C,XKS,ZAR,ZAI)
      IMPLICIT REAL*8 (A-H,O-Z)
      B1=-R/(ROM*ANG)
      CALL POWE(XKS,B1,0.5D0,T1R,T1I)
      GAMR=ANG*DSQRT(OM)/C*T1R
      GAMI=ANG*DSQRT(OM)/C*T1I
      ZOR=GAMR*ROM*C*C/OM/ANG
      ZOI=GAMI*ROM*C*C/OM/ANG
      CALL CONV(ZOR,ZOI,-GAMI,GAMR,AL,ZAR,ZAI)
      END
```

Program used to calculate the normal incident acoustic absorption using a model suggested by Zarek (Section 4.4).

```
      PROGRAM ZARAC1
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL *8 A(12)
      OPEN (1, FILE='t1.prn',STATUS='NEW')
      OPEN (2, FILE='T2.PRN',STATUS='NEW')
      OPEN (8, FILE='ZD1.PRN',STATUS='OLD')
      DO 30,K=1,12
       READ (8,*)  A(K)
       WRITE (*,*) K,A(K)
  30  CONTINUE
      DENS=1.18D0/A(6)
      ETA=A(4)*A(4)*DENS
      IL=A(12)
      A(IL)=A(IL)-A(11)
       A(3)=1.0D0-(1.0D0-A(2))**(2.0D0/3.0D0)
        A(4)=DSQRT(ETA/DENS)
          A(6)=1.18D0/DENS
       DO 60,L=1,10
        WRITE (1,*) A(L)
        WRITE (2,*) A(L)
  60   CONTINUE

        CF2=A(4)*A(4)
        RGCF= A(6)/(2.0*A(3)*CF2)
        CA2=A(5)*A(5)

        CA2G2=2.0*A(3)*CA2
        GH1=(1-A(2)+A(3))/CA2G2
        GARSCACF=(1/A(3))*DSQRT(A(2)*A(6)/(CA2*CF2))

      DO 10,I=100,6000,50
       OM=8.0*ATAN(1.0)*I
       OM2=OM*OM
       AR=A(2)*OM2*GH1
       AI=-A(2)*OM/(CA2G2)*A(7)
       BR=RGCF*OM2*((1.0-A(2))*(1.0-A(3))+A(3)/A(6))
       BI=-RGCF*OM*A(7)
       CR=(1-A(2))*OM2*GARSCACF
       CI=-GARSCACF*(A(7))*OM
C***********************************************************
C        CALCULATION OF THE FOUR ROOTS OF K
C***********************************************************
       T10=AI-BI
       T11=AR-BR
       CALL MULT(T11,T10,T11,T10,T13,T12)
       CALL MULT(CR,CI,CR,CI,T15,T14)
       T16=T14+T12
       T17=T13+T15
       POW=0.5D0
       CALL POWE(T17,T16,POW,T19,T18)
       XK1I=+AI+BI+T18
       XK1R=+AR+BR+T19
       XK2I=+AI+BI-T18
       XK2R=+AR+BR-T19
       CALL POWE(XK1R,XK1I,POW,XXK1R,XXK1I)
       CALL POWE(XK2R,XK2I,POW,XXK2R,XXK2I)
```

```
C***********************************************************
   CALL ZC(XXK1R,XXK1I,XXK2R,XXK2I,BR,BI,A(1),OM,A(2),
     +  A(9),A(10),ZCR,ZCI)
      CALL ACON (ZCR,ZCI,ANO)
      WRITE (1,*) I,ANO
      WRITE (2,*) I,ZCR,ZCI
      WRITE (*,*) I,ANO
 10   CONTINUE
      END

      SUBROUTINE ZC(XK1R,XK1I,XK2R,XK2I,BR,BI,AL,OM,AH,
     +  EM,XLT,ZCR,ZCI)
      IMPLICIT REAL*8 (A-H,O-Z)
      XLE=1.1D5
      ETR=EM
      ETI=XLT*EM
C     XLE=YOUNGS MODULUS OF AIR
C     ET=YOUNGS MODULUS OF MATERIAL

      CALL MULT(XK1R,XK1I,XK1R,XK1I,X2K1R,X2K1I)
      CALL MULT(XK2R,XK2I,XK2R,XK2I,X2K2R,X2K2I)
      T1R1=X2K2R-X2K1R
      T1I1=X2K2I-X2K1I
      CALL DIV(1.0D0,0.0D0,T1R1,T1I1,T1R,T1I)
      T2R=2.0D0*BR-X2K1R
      T2I=2.0D0*BI-X2K1I
      T3R=2.0D0*BR-X2K2R
      T3I=2.0D0*BI-X2K2I
      T4R1=XK1R*XLE
      T4I1=XK1I*XLE
      T4R=T4I1*(AH*OM)
      T4I=-T4R1*(AH*OM)
      T14R1=XK2R*XLE
      T14I1=XK2I*XLE
      T14R=T14I1*(AH*OM)
      T14I=-T14R1*(AH*OM)
      T5R=ETR*AH/XLE
      T5I=ETI*AH/XLE
      T6R1=XK1R*AL
      T6I1=XK1I*AL
      CALL TANI(T6R1,T6I1,T6R,T6I)
      T7R1=XK2R*AL
      T7I1=XK2I*AL

      CALL TANI(T7R1,T7I1,T7R,T7I)
      CALL POWE(T2R,T2I,0.5D0,ST2R,ST2I)
      CALL POWE(T3R,T3I,0.5D0,ST3R,ST3I)
      CALL MULT(T5R,T5I,T3R,T3I,T53R,T53I)
      CALL POWE(T53R,T53I,0.5D0,ST53R,ST53I)
      CALL MULT(T5R,T5I,T2R,T2I,T52R,T52I)
      CALL POWE(T52R,T52I,0.5D0,ST52R,ST52I)
      CALL DIV(T14R,T14I,T7R,T7I,T147R,T147I)
      CALL DIV(T4R,T4I,T6R,T6I,T46R,T46I)

      T12R=ST2R+ST53I
      T12I=ST2I-ST53R
      CALL MULT(T12R,T12I,T12R,T12I,ST12R,ST12I)
      T11R=ST3R+ST52I
      T11I=ST3I-ST52R
      CALL MULT(T11R,T11I,T11R,T11I,ST11R,ST11I)
      CALL MULT(ST12R,ST12I,T46R,T46I,T21R,T21I)
```

```
CALL MULT(ST11R,ST11I,T147R,T147I,T22R,T22I)
T31R=T21R-T22R
T31I=T21I-T22I

CALL MULT(T31R,T31I,T1R,T1I,ZCR,ZCI)
ZCR=ZCR*420.0D0
ZCI=ZCI*420.0D0
END
```

Program used to calculate the normal incident acoustic absorption using a model suggested by Bolton (Section 4.5).

```
      PROGRAM BOLT2
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 A(11)
      OPEN (1, FILE='T1.PRN',STATUS='NEW')
      OPEN (2, FILE='T2.PRN',STATUS='NEW')
      OPEN (3, FILE='T3.PRN',STATUS='NEW')
      OPEN (4, FILE='T4.PRN',STATUS='NEW')
      OPEN (5, FILE='T5.PRN',STATUS='NEW')
      OPEN (6, FILE='T6.PRN',STATUS='NEW')
      OPEN (7, FILE='T7.PRN',STATUS='NEW')

      OPEN (8, FILE='D1.PRN',STATUS='OLD')
      PYE=DATAN(1.0D0)*4.0D0
      DO 60,K=1,11
       READ (8,*) A(K)
60    CONTINUE
      I1=A(10)
      A(I1)=A(I1)-A(11)

      DO 70,K=1,6
      A(I1)=A(I1)+A(11)
      ARO1=A(1)
      ARO0=A(2)
      AC=A(3)
      AH=A(4)
      AE=A(5)
      AL=A(6)
      ASIG=A(7)
      AE1R=A(8)
      ALT=A(9)
      ANPR=.713D0
      AE1I=AE1R*ALT
       DO 50,L=1,9
        WRITE(K,*) A(L)
50     CONTINUE
      DO 30,I=100,6000,20
       OM=PYE*2.0D0*I

       CALL BOLT (I,OM,ARO0,AC,AH,ANPR,AE,AL,ASIG,ARO1,
     +  AE1R,AE1I,K)
30    CONTINUE
70    CONTINUE
      CALL EXIT
      END
```

```
      SUBROUTINE BOLT (I,OM,ARO0,AC,AH,ANPR,AE,AL,ASIG,ARO1,
     + AE1R,AE1I,K)
C*****************************************************
C      PARAMETERS PASSED TO THIS SUBROUTINE ARE
C     e=THE  STRUCTURAL FACTOR = AE
C     c=THE SPEED OF SOUND IN AIR=AC
C       THE ANGULAR VELOCITY LITTLE OMEGA=OM
C     h= THE POROSITY=AH
      IMPLICIT REAL*8 (A-H,O-Z)
      AE0=ARO0*AC*AC
      GAM=1.4D0
      ALAMC2=(8.0D0*OM*ARO0*AE/(AH*ASIG))
      CALL POWE (0.0D0,-1.0D0,0.5D0,RMJR,RMJI)
C*******************************************************
C  RMJR+jRMJI ARE THE COMPLEX SQUARE ROOTS OF -j
C*******************************************************
      ALAMC=DSQRT(ALAMC2)
      ANPRR=DSQRT(ANPR)
      TTC1=ANPRR*ALAMC
      TTC1R=TTC1*RMJR
      TTC1I=TTC1*RMJI
      CALL BESSL(TTC1R,TTC1I,1,TTC2R,TTC2I)
      CALL BESSL(TTC1R,TTC1I,0,TTC3R,TTC3I)
      CALL DIV (TTC2R,TTC2I,TTC3R,TTC3I,TCR,TCI)
      TTE21R=2.0D0*(GAM-1.0D0)
      CALL DIV (TTE21R,0.0D0,TTC1R,TTC1I,TE22R,TE22I)
      CALL MULT (TE22R,TE22I,TCR,TCI,TE211R,TE21I)
      TE21R=1.0D0+TE211R
      CALL DIV(AE0,0.0D0,TE21R,TE21I,AE2R,AE2I)
C       CALCULATION OF COMPLEX DENSITY
       ROT1R=ALAMC*RMJR
       ROT1I=ALAMC*RMJI
       CALL BESSL(ROT1R,ROT1I,1,ROT2R,ROT2I)
       CALL BESSL(ROT1R,ROT1I,0,ROT3R,ROT3I)
       CALL DIV (ROT2R,ROT2I,ROT3R,ROT3I,ROT4R,ROT4I)
       CALL DIV (-2.0D0,0.0D0,ROT1R,ROT1I,ROT5R,ROT5I)
       CALL MULT(ROT5R,ROT5I,ROT4R,ROT4I,RROT5R,ROT6I)
       ROT6R=RROT5R+1
       CALL DIV (ARO0,0.0D0,ROT6R,ROT6I,AROCR,AROCI)
       ARO2ER=AH*AROCR
       ARO2EI=AH*AROCI
       ARO2=ARO0*AH
       AUDR=ARO2ER*AE/ARO2
       AUDI=ARO2EI*AE/ARO2
       ASDR=-AUDI*OM*ARO2
       ASDI=(AUDR-1.0D0)*ARO2*OM
       CALL DIV(1.0D0,0.0D0,AE1R,AE1I,TABR1,TABI1)
       CALL DIV(1.0D0,0.0D0,AE2R,AE2I,TABR2,TABI2)
       CALL MULT(ASDR,ASDI,TABR1,TABI1,TABR3,TABI3)
       CALL MULT(ASDR,ASDI,TABR2,TABI2,TABR4,TABI4)
       T1R=OM*OM*TABR1*ARO1
       T2R=TABI3*OM/AH
       T3R=OM*OM*ARO2/AH*TABR2
       T4R=TABI4*OM/AH
       T1I=OM*OM*TABI1*ARO1
       T2I=-TABR3*OM/AH
       T3I=OM*OM*ARO2/AH*TABI2
       T4I=-TABR4*OM/AH
       AAI=T1I+T2I+T3I+T4I
       AAR=T1R+T2R+T3R+T4R
C-----------------------------------------------
```

```
      CALL MULT(TABR1,TABI1,TABR2,TABI2,CG2R,CG2I)
      OM3=OM*OM*OM
      OM4=OM*OM3
      TB1R=CG2R*OM4*ARO2*ARO1/AH
      TB1I=CG2I*OM4*ARO2*ARO1/AH
      CALL MULT(CG2R,CG2I,ASDR,ASDI,CG3R,CG3I)
      TB2R=OM3*ARO1/AH*(-CG3I)
      TB2I=OM3*ARO1/AH*CG3R
      TB3R=OM3*ARO2/AH*(-CG3I)
      TB3I=OM3*ARO2/AH*CG3R
C-------------------------------------------------
      ABR=TB1R-TB2R-TB3R
      ABI=TB1I-TB2I-TB3I
      CALL MULT(AAR,AAI,AAR,AAI,TG1R1,TG1I1)
      TG1R2=TG1R1-4.0D0*ABR
      TG1I2=TG1I1-4.0D0*ABI
      CALL POWE(TG1R2,TG1I2,0.5D0,TG1R3,TG1I3)
      TG1R4=(-AAR+TG1R3)/2.0D0
      TG1R5=(-AAR-TG1R3)/2.0D0
      TG1I4=(-AAI+TG1I3)/2.0D0
      TG1I5=(-AAI-TG1I3)/2.0D0
      CALL POWE(TG1R5,TG1I5,0.5D0,AGAM1R,AGAM1I)
      CALL POWE(TG1R4,TG1I4,0.5D0,AGAM2R,AGAM2I)
      AGAM1R=DABS(AGAM1R)
      AGAM1I=DABS(AGAM1I)
      AGAM2R=DABS(AGAM2R)
      AGAM2I=DABS(AGAM2I)
      CALL MULT(AGAM1R,AGAM1I,AGAM1R,AGAM1I,TLA1R,TLA1I)
      CALL MULT(TLA1R,TLA1I,AE1R,AE1I,TLA1R1,TLA1I1)
      TLA1R2=TLA1R1+OM*OM*ARO1
      TLA1R3=-OM*ASDI
      TLA1I3=OM*ASDR
      CALL DIV(TLA1R2,TLA1I1,TLA1R3,TLA1I3,TLA1R4,ALA1I)
      ALA1R=1-TLA1R4
      CALL MULT(AGAM2R,AGAM2I,AGAM2R,AGAM2I,TLA2R,TLA2I)
      CALL MULT(TLA2R,TLA2I,AE1R,AE1I,TLA2R1,TLA2I1)
      TLA2R2=TLA2R1+OM*OM*ARO1
      TLA2R3=-OM*ASDI
      TLA2I3=OM*ASDR
      CALL DIV(TLA2R2,TLA2I1,TLA2R3,TLA2I3,TLA2R4,ALA2I)
      ALA2R=1-TLA2R4
      ALB1R=AH*ALA1R+1.0D0-AH
      ALB1I=AH*ALA1I
      ALB2R=AH*ALA2R+1.0D0-AH
      ALB2I=AH*ALA2I


C*********************************************************
C     CALCULATION OF IMPEDANCE
C*********************************************************
      TZ1R=ALA2R-ALA1R
      TZ1I=ALA2I-ALA1I
      CALL DIV(1.0D0,0.0D0,TZ1R,TZ1I,TZ2R,TZ2I)
      CALL DIV(ALB2R,ALB2I,AGAM2R,AGAM2I,TZ3R,TZ3I)
      TZ4R=TABR2
      TZ4I=TABI2
      CALL DIV (ALB1R,ALB1I,AE1R,AE1I,TZ5R,TZ5I)
      TZ6R=TZ5R*(1.0D0-AH)/AH
      TZ6I=TZ5I*(1.0D0-AH)/AH
      TZ7R=AGAM2R*AL
      TZ7I=AGAM2I*AL
```

```
CALL TANHI (TZ7R,TZ7I,TZ8R,TZ8I)
CALL DIV(ALB1R,ALB1I,AGAM1R,AGAM1I,TZ9R,TZ9I)
CALL DIV(ALB2R,ALB2I,AE1R,AE1I,TZ10R,TZ10I)
TZ11R=TZ10R*(1.0D0-AH)/AH
TZ11I=TZ10I*(1.0D0-AH)/AH
TZ12R=AGAM1R*AL
TZ12I=AGAM1I*AL
CALL TANHI (TZ12R,TZ12I,TZ13R,TZ13I)
TZ14R=TZ4R-TZ6R
TZ14I=TZ4I-TZ6I
TZ15R=TZ4R-TZ11R
TZ15I=TZ4I-TZ11I
CALL MULT (TZ14R,TZ14I,TZ3R,TZ3I,TZ16R,TZ16I)
CALL MULT (TZ16R,TZ16I,TZ8R,TZ8I,TZ17R,TZ17I)
CALL MULT (TZ9R,TZ9I,TZ15R,TZ15I,TZ18R,TZ18I)
CALL MULT (TZ18R,TZ18I,TZ13R,TZ13I,TZ19R,TZ19I)
TZ20R=TZ17R-TZ19R
TZ20I=TZ17I-TZ19I
CALL MULT(TZ20R,TZ20I,TZ2R,TZ2I,TZ21R,TZ21I)
TZ22R=-TZ21I*OM
TZ22I=TZ21R*OM
CALL DIV (1.0D0,0.0D0,TZ22R,TZ22I,ZR,ZI)
ZR=ZR/420.0D0
ZI=ZI/420.0D0
ABSORP=4.0D0*ZR/((ZR+1.0D0)**2.0D0+ZI*ZI)
WRITE(K,*) I,ABSORP
WRITE(*,*) I,ABSORP
RETURN
END
```

Modification of the Bolton program to find the maximum normal incident acoustic absorption that can be attained at a single frequency by varying the air flow resistance. Additional modifications have been made to the program to increase its speed.

```
      PROGRAM BOLT3
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 A(11)
      OPEN (1, FILE='T1.PRN',STATUS='NEW')

      OPEN (8, FILE='D1.PRN',STATUS='OLD')

C THIS PROGRAM CALCULATES THE POSITION OF THE FIRST
C   MAXIMUM ABSORPTION
C  AT VARYING LEVELS OF AIR FLOW RESISTANCE

      PYE=DATAN(1.0D0)*4.0D0
      HZ=300

      DO 60,K=1,11
       READ (8,*) A(K)
 60   CONTINUE
      PERM=A(7)
      DO 50,K=1,50
       A(7)=PERM
       HZ=HZ+100
       CALL PROG(A,K,HZ,ABS)
       WRITE (1,*) A(7),HZ,ABS
 50   CONTINUE
      END

      SUBROUTINE  PROG(A,K,HZ,ABS)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 A(11)
      ACC=.00001
      PYE=DATAN(1.0D0)*4.0D0
      ANPR=.713D0
      AE1I=A(8)*A(9)
      OM=PYE*2.0D0*HZ
      CALL BOLT (OM,A,ANPR,ABS1)
      STEP=4000
      A(7)=A(7)+STEP
      CALL BOLT (OM,A,ANPR,ABS2)
      IF(ABS1.GT.ABS2)THEN
       STEP=-STEP
       A(7)=A(7)+STEP
       ELSE
       A(7)=A(7)-STEP
      ENDIF

      DO 10,I=1,1000
       A(7)=A(7)+STEP
       CALL BOLT (OM,A,ANPR,ABS2)
       R1=A(7)*A(6)
       WRITE (*,*) HZ,R1,ABS2
       IF(DABS(ABS1-ABS2).LT.ACC)THEN
        ABS=(ABS1+ABS2)/2.0D0
        RETURN
        ELSEIF(ABS1.LT.ABS2)THEN
         ABS1=ABS2
```

```
         ELSE
         A(7)=A(7)-STEP
         STEP=STEP/2.0D0
        ENDIF
 10    CONTINUE
       END

       SUBROUTINE BOLT (OM,A,ANPR,ABS)
C*******************************************************
C      PARAMETERS PASSED TO THIS SUBROUTINE ARE
C     e=THE  STRUCTURAL FACTOR = A(5)
C     c=THE SPEED OF SOUND IN AIR=A(3)
C       THE ANGULAR VELOCITY LITTLE OMEGA=OM
C     h= THE POROSITY=A(4)
       IMPLICIT REAL*8 (A-H,O-Z)
       REAL*8 A(11)
       AE0=A(2)*A(3)*A(3)
       GAM=1.4D0
       ALAMC2=(8.0D0*OM*A(2)*A(5)/(A(4)*A(7)))
       CALL POWE (0.0D0,-1.0D0,0.5D0,RMJR,RMJI)
C*********************************************************
C  RMJR+jRMJI ARE THE COMPLEX SQUARE ROOTS OF -j
C*********************************************************
       ALAMC=DSQRT(ALAMC2)
       ANPRR=DSQRT(ANPR)
       TTC1=ANPRR*ALAMC
       TTC1R=TTC1*RMJR
       TTC1I=TTC1*RMJI
       CALL BESSL(TTC1R,TTC1I,1,TTC2R,TTC2I)
       CALL BESSL(TTC1R,TTC1I,0,TTC3R,TTC3I)
       CALL DIV (TTC2R,TTC2I,TTC3R,TTC3I,TCR,TCI)
       TTE21R=2.0D0*(GAM-1.0D0)
       CALL DIV (TTE21R,0.0D0,TTC1R,TTC1I,TE22R,TE22I)
       CALL MULT (TE22R,TE22I,TCR,TCI,TE211R,TE21I)
       TE21R=1.0D0+TE211R
       CALL DIV(AE0,0.0D0,TE21R,TE21I,AE2R,AE2I)

C        CALCULATION OF COMPLEX DENSITY

        ROT1R=ALAMC*RMJR
        ROT1I=ALAMC*RMJI
        CALL BESSL(ROT1R,ROT1I,1,ROT2R,ROT2I)
        CALL BESSL(ROT1R,ROT1I,0,ROT3R,ROT3I)
        CALL DIV (ROT2R,ROT2I,ROT3R,ROT3I,ROT4R,ROT4I)

        CALL DIV (-2.0D0,0.0D0,ROT1R,ROT1I,ROT5R,ROT5I)
        CALL MULT(ROT5R,ROT5I,ROT4R,ROT4I,RROT5R,ROT6I)

        ROT6R=RROT5R+1.0D0
        CALL DIV (A(2),0.0D0,ROT6R,ROT6I,AROCR,AROCI)
        ARO2ER=A(4)*AROCR
        ARO2EI=A(4)*AROCI
        ARO2=A(2)*A(4)
        AUDR=ARO2ER*A(5)/ARO2
        AUDI=ARO2EI*A(5)/ARO2
        ASDR=-AUDI*OM*ARO2
        ASDI=(AUDR-1.0D0)*ARO2*OM
        CALL DIV(1.0D0,0.0D0,A(8),AE1I,TABR1,TABI1)
        CALL DIV(1.0D0,0.0D0,AE2R,AE2I,TABR2,TABI2)
        CALL MULT(ASDR,ASDI,TABR1,TABI1,TABR3,TABI3)
        CALL MULT(ASDR,ASDI,TABR2,TABI2,TABR4,TABI4)
```

```
      T1R=OM*OM*TABR1*A(1)
      T2R=TABI3*OM/A(4)
      T3R=OM*OM*ARO2/A(4)*TABR2
      T4R=TABI4*OM/A(4)
      T1I=OM*OM*TABI1*A(1)
      T2I=-TABR3*OM/A(4)
      T3I=OM*OM*ARO2/A(4)*TABI2
      T4I=-TABR4*OM/A(4)
      AAI=T1I+T2I+T3I+T4I
      AAR=T1R+T2R+T3R+T4R

C-----------------------------------------------
      CALL MULT(TABR1,TABI1,TABR2,TABI2,CG2R,CG2I)
      OM3=OM*OM*OM
      OM4=OM*OM3
      TB1R=CG2R*OM4*ARO2*A(1)/A(4)
      TB1I=CG2I*OM4*ARO2*A(1)/A(4)
      CALL MULT(CG2R,CG2I,ASDR,ASDI,CG3R,CG3I)
      TB2R=OM3*A(1)/A(4)*(-CG3I)
      TB2I=OM3*A(1)/A(4)*CG3R
      TB3R=OM3*ARO2/A(4)*(-CG3I)
      TB3I=OM3*ARO2/A(4)*CG3R
C-----------------------------------------------
      ABR=TB1R-TB2R-TB3R
      ABI=TB1I-TB2I-TB3I
      CALL MULT(AAR,AAI,AAR,AAI,TG1R1,TG1I1)
      TG1R2=TG1R1-4.0D0*ABR
      TG1I2=TG1I1-4.0D0*ABI
      CALL POWE(TG1R2,TG1I2,0.5D0,TG1R3,TG1I3)

      TG1R4=(-AAR+TG1R3)/2.0D0
      TG1R5=(-AAR-TG1R3)/2.0D0
      TG1I4=(-AAI+TG1I3)/2.0D0
      TG1I5=(-AAI-TG1I3)/2.0D0
      CALL POWE(TG1R5,TG1I5,0.5D0,AGAM1R,AGAM1I)
      CALL POWE(TG1R4,TG1I4,0.5D0,AGAM2R,AGAM2I)

      AGAM1R=DABS(AGAM1R)
      AGAM1I=DABS(AGAM1I)
      AGAM2R=DABS(AGAM2R)
      AGAM2I=DABS(AGAM2I)

      CALL MULT(AGAM1R,AGAM1I,AGAM1R,AGAM1I,TLA1R,TLA1I)
      CALL MULT(TLA1R,TLA1I,A(8),AE1I,TLA1R1,TLA1I1)
      TLA1R2=TLA1R1+OM*OM*A(1)
      TLA1R3=-OM*ASDI
      TLA1I3=OM*ASDR
      CALL DIV(TLA1R2,TLA1I1,TLA1R3,TLA1I3,TLA1R4,ALA1I)
      ALA1R=1-TLA1R4

      CALL MULT(AGAM2R,AGAM2I,AGAM2R,AGAM2I,TLA2R,TLA2I)
      CALL MULT(TLA2R,TLA2I,A(8),AE1I,TLA2R1,TLA2I1)
      TLA2R2=TLA2R1+OM*OM*A(1)
      TLA2R3=-OM*ASDI
      TLA2I3=OM*ASDR
      CALL DIV(TLA2R2,TLA2I1,TLA2R3,TLA2I3,TLA2R4,ALA2I)
      ALA2R=1-TLA2R4

      ALB1R=A(4)*ALA1R+1.0D0-A(4)
      ALB1I=A(4)*ALA1I
      ALB2R=A(4)*ALA2R+1.0D0-A(4)
```

```
      ALB2I=A(4)*ALA2I
C***********************************************************
C     CALCULATION OF IMPEDANCE
C***********************************************************
      TZ1R=ALA2R-ALA1R
      TZ1I=ALA2I-ALA1I
      CALL DIV(1.0D0,0.0D0,TZ1R,TZ1I,TZ2R,TZ2I)
      CALL DIV(ALB2R,ALB2I,AGAM2R,AGAM2I,TZ3R,TZ3I)

      TZ4R=TABR2
      TZ4I=TABI2
      CALL DIV (ALB1R,ALB1I,A(8),AE1I,TZ5R,TZ5I)
      TZ6R=TZ5R*(1.0D0-A(4))/A(4)
      TZ6I=TZ5I*(1.0D0-A(4))/A(4)
      TZ7R=AGAM2R*A(6)
      TZ7I=AGAM2I*A(6)
      CALL TANHI (TZ7R,TZ7I,TZ8R,TZ8I)

      CALL DIV(ALB1R,ALB1I,AGAM1R,AGAM1I,TZ9R,TZ9I)

      CALL DIV(ALB2R,ALB2I,A(8),AE1I,TZ10R,TZ10I)
      TZ11R=TZ10R*(1.0D0-A(4))/A(4)
      TZ11I=TZ10I*(1.0D0-A(4))/A(4)
      TZ12R=AGAM1R*A(6)
      TZ12I=AGAM1I*A(6)
      CALL TANHI (TZ12R,TZ12I,TZ13R,TZ13I)
      TZ14R=TZ4R-TZ6R
      TZ14I=TZ4I-TZ6I
      TZ15R=TZ4R-TZ11R
      TZ15I=TZ4I-TZ11I
      CALL MULT (TZ14R,TZ14I,TZ3R,TZ3I,TZ16R,TZ16I)
      CALL MULT (TZ16R,TZ16I,TZ8R,TZ8I,TZ17R,TZ17I)
      CALL MULT (TZ9R,TZ9I,TZ15R,TZ15I,TZ18R,TZ18I)
      CALL MULT (TZ18R,TZ18I,TZ13R,TZ13I,TZ19R,TZ19I)
      TZ20R=TZ17R-TZ19R
      TZ20I=TZ17I-TZ19I
      CALL MULT(TZ20R,TZ20I,TZ2R,TZ2I,TZ21R,TZ21I)
      TZ22R=-TZ21I*OM
      TZ22I=TZ21R*OM
      CALL DIV (1.0D0,0.0D0,TZ22R,TZ22I,ZR,ZI)
      ZR=ZR/420.0D0
      ZI=ZI/420.0D0
      ABS=4.0D0*ZR/((ZR+1.0D0)**2.0D0+ZI*ZI)

      RETURN
      END
```

Computer program used to calculate the empirical model discussed in Section 4.6.

```
       PROGRAM IMPERICAL
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL *8 C(8)
      OPEN (1, FILE='E1.PRN',STATUS='OLD')
      OPEN (2, FILE='E2.PRN',STATUS='OLD')
      OPEN (3, FILE='E3.PRN',STATUS='OLD')
      OPEN (4, FILE='E4.PRN',STATUS='OLD')
      OPEN (5, FILE='E5.PRN',STATUS='NEW')
      OPEN (6, FILE='E6.PRN',STATUS='NEW')
      OPEN (7, FILE='E7.PRN',STATUS='NEW')
      OPEN (8, FILE='E8.PRN',STATUS='NEW')
      WRITE (*,*) 'INPUT SIGMA'
      READ (*,*) SIG
      wRITE (*,*) 'SAMPLE LENGTH'
      READ (*,*) AL
      RO=1.2D0
      CA= 344.0D0
      TWOPI=DATAN(1.0D0)*8.0D0
      DO 10,I=1,4
       DO 20,J=1,8
        READ (I,*) C(J)
 20    CONTINUE
       IO=I+4
       WRITE (IO,*) SIG,AL
       DO 30,K=100,6000,20
        T1=RO*K/SIG
        T2=TWOPI*K/CA
        ZR=1.0D0+C(1)*(T1)**C(2)
        ZI=C(3)*(T1)**C(4)
        ALPH= T2*C(5)*(T1)**C(6)
        BETA= T2*(1.0D0+C(7)*(T1))**C(8)

        CALL CONV(ZR,ZI,ALPH,BETA,AL,ZAR,ZAI)
        CALL ACON(ZAR,ZAI,ANO)

        WRITE (IO,*) K,ANO
 30   CONTINUE
 10   CONTINUE
      END
```

Program used to calculate normal incident and random incident acoustic absorption as discussed in Section 4.7

```
      program koswik
c     the program is calculated normal and random incident
c     absorption from given impedance
      IMPLICIT REAL*8 (A-H,O-Z)
      CHARACTER*10 fname,ANS
      WRITE (*,'(A)') ' PLEASE TYPE IN FILE NAME WITH A
     +.PRN EXTENSION'
      READ (*,'(A)') fname
      OPEN (3,FILE=fname,STATUS='NEW')
      WRITE (*,*) 'INPUT VALUE OF X'
      READ (*,*) X
      DO 10,I=1,500
      R=10.0*I
      WO=420.0D0
      CALL NORM(X,R,WO,ABSN)
      CALL RANDO(X,R,WO,ABSR)
      WRITE (3,*) R,ABSN,ABSR
 10   CONTINUE
      END

      SUBROUTINE NORM(X,R,WO,ABSN)
      IMPLICIT REAL*8 (A-H,O-Z)
      T1R=R-WO
      T2R=R+WO
      CALL DIV (T1R,X,T2R,X,T3R,T3I)
      ABSN=1.0D0-(T3R*T3R+T3I*T3I)
      END

      SUBROUTINE RANDO(X,R,WO,ABSR)
      IMPLICIT REAL*8 (A-H,O-Z)
      Z2=R*R+X*X
      BR=Z2/(WO*WO)+2.0D0*R/WO+1.0D0
      TTAN=DATAN(X/(R+WO))
      T1=8.0D0*WO*R/Z2-8.0D0*(WO*R/Z2)**2.0D0*DLOG(BR)
      T2=8.0D0*R/X*(WO*X/Z2)**2.0D0*(R*R/X/X-1.0D0)*TTAN
      ABSR=T1+T2
      END
```

APPENDIX 4
CALCULATION OF AIR FLOW RESISTANCE

The basic relationship put forward by Reference [38] is:

$$\frac{dP}{dx}=\eta\frac{V}{K}+\rho\frac{V^2}{B} \tag{54}$$

Where, K and B are constants
η viscosity of air
ρ density of air
V the velocity of air through the material
P pressure
x distance

if f is the volume flow rate through the material V can be expressed as follows:

$$V=\frac{flow\ rate}{area}=\frac{f}{A}$$

equation (54) can then be written as:

$$\frac{dP}{f}=\frac{\eta\,dx}{A\,K}+\frac{\rho\,f\,dx}{A^2\,B}$$

when a graph is plotted of dP/f against f expressions for the gradient G and intercept I can be calculated or read off. Expressions for G and I are deduced as:

$$I=\frac{\eta dx}{AK} \quad and \quad G=\frac{\rho dx}{A^2B}$$

It follows that after the expression for I and G can be rearranged to give solutions for K and B;

$$K=\frac{\eta dx}{AI} \quad \& \quad B=\frac{\rho\ dx}{A^2G}$$

where dx is the thickness of the given testpiece
Rearranging (54) gives

$$\frac{dP}{dxV}=\frac{\eta}{K}+\frac{\rho V}{B} \tag{59}$$

$$From\ Beranek\ R_1=\frac{dP}{dxV} \quad when V=0$$

When V=0 from (54) dP/dx will also =0 however taking limits as V tends to 0 the expression for R_1 becomes:

$$R_1=\frac{\eta}{K}$$

COSTS

CHEMICAL	COST	MIX RATIO
ISOCYANATE	2100	450
POLYOL	1700	250
OTHER	6000	10
COST PER TONNE		2014
POWER		3
RATES		8.7

LABOUR RATE/HOUR	
MANUAL	4.20
TECHNICAL	6.24
STORAGE	278 meters cubed

FOAM	
DENSITY	30 KG/METRE CUBED
SELL PRICE	110 PER CUBIC METRE

MACHINE	COST	No OF MEN PER MACHINE MANUAL	TECHNICAL	LABOUR COST P.A.	MACHINE HOUSING	RATES P.A.	MACHINE SCRAP %	FOAM SCRAP %
MAXFOAM	590000	4	2	60902.4	3000000	33400	10	5
VERTIFOAM	430000	3	1	39187.2	2300000	24700	10	2
MINIFLEX	300000	2	1	30451.2	1900000	18500	10	2

	INITIAL	PER ANNUM
LABORATORY	170000	65000
ADMINISTRATION	250000	100000

QUANTITY= 1000 TONNES PER ANNUM

DAILY PRODUCTION (VOL) 278

CALCULATIONS VERTIFOAM

		T0	T1	T2	T3	T4	T5	T6
BUILDINGS		(2,720,000)	3,250	3,250	3,250	3,250	3,250	3,250
MACHINES		(430,000)						
WORKING CAPITAL		(900,000)						
SCRAP								
TOTAL REVENUE			3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	3,593,333
TOTAL COSTS			(2,248,972)	(2,248,972)	(2,248,972)	(2,248,972)	(2,248,972)	(2,248,972)
BEFORE TAX		(4,050,000)	1,347,612	1,347,612	1,347,612	1,347,612	1,347,612	1,347,612
TAXABLE ALLOWANCE								
25	%		107,500	80,625	60,469	45,352	34,014	25,510
TAXABLE			1,240,112	1,266,987	1,287,143	1,302,260	1,313,598	1,322,101
CORP TAX	35			(434,039)	(443,445)	(450,500)	(455,791)	(459,759)
		(4,050,000)	1,347,612	913,573	904,166	897,112	891,821	887,852
NPV FACTOR	20	1	0.8333	0.6944	0.5787	0.4823	0.4019	0.3349
NPV		(4,050,000)	1,123,010	634,425	523,244	432,635	358,403	297,340
		-4050000	-2926990.311	-2292564.925	-1769320.534	-1336685.686	-978282.9875	-680943.0345
GROSS NPV=		124378.03916						

	T7	T8	T9	T10	T11
BUILDINGS	3,250	3,250	3,250	3,250	
MACHINES					
WORKING CAPITAL				900,000	
SCRAP					(43,000)
TOTAL REVENUE	3,593,333	3,593,333	3,593,333	3,593,333	
TOTAL COSTS	(2,248,972)	(2,248,972)	(2,248,972)	(2,248,972)	
BEFORE TAX	1,347,612	1,347,612	1,347,612	2,247,612	(43,000)
TAXABLE ALLOWANCE					
25	19,133	14,350	10,762	139,786	
TAXABLE	1,328,479	1,333,262	1,336,849	2,107,825	
CORP TAX	(462,735)	(464,968)	(466,642)	(467,897)	(737,739)
	884,876	882,644	880,970	1,779,714	(780,739)
NPV FACTOR	0.2791	0.2326	0.1938	0.1615	0.1346
NPV	246,953	205,275	170,738	287,434	(105,078)
	-433990.3421	-228715.5578	-57977.69143	229456.10486	124378.03916

COSTS .

	CHEMICAL			LABOUR RATE/HOUR		FOAM	
	COST	MIX RATIO					
ISOCYANATE	2100.00	450.00		MANUAL	4.20	DENSITY	30.00 KG/METRE CUBED
POLYOL	1700.00	250.00		TECHNICAL	6.24	SELL PRICE	110.00 PER CUBIC METRE
OTHER	6000.00	10.00					
COST PER TONNE		2014					
	POWER	3.00		STORAGE	278	meters cubed	
	RATES	8.70					

MACHINE	COST	No OF MEN PER MACHINE MANUAL	TECHNICAL	LABOUR COST P.A.	MACHINE HOUSING	RATES P.A.	MACHINE SCRAP %	FOAM SCRAP %
MAXFOAM	590000.00	4.00	2.00	60902.40	3000000.00	33400.00	10.00	5.00
VERTIFOAM	430000.00	3.00	1.00	39187.20	2300000.00	24700.00	10.00	2.00
MINIFLEX	300000.00	2.00	1.00	30451.20	1900000.00	18500.00	10.00	2.00

	INITIAL	PER ANNUM
LABORATORY	170000.00	65000.00
ADMINISTRATION	250000.00	100000.00

QUANTITY= 1000.00 TONNES PER ANNUM

DAILY PRODUCTION (VOL) 278

CALCULATIONS MAXFOAM

		T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
BUILDINGS		(3,420,000)	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	
MACHINES		(590,000)											
WORKING CAPITAL		(900,000)										900,000	
SCRAP													(59,000)
TOTAL REVENUE			3,483,333	3,483,333	3,483,333	3,483,333	3,483,333	3,483,333	3,483,333	3,483,333	3,483,333	3,483,333	
TOTAL COSTS			(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	(2,279,387)	
BEFORE TAX		(4,910,000)	1,207,196	1,207,196	1,207,196	1,207,196	1,207,196	1,207,196	1,207,196	1,207,196	1,207,196	2,107,196	(59,000)
TAXABLE ALLOWANCE													
25.00	%		147,500	110,625	82,969	62,227	46,670	35,002	26,252	19,689	14,767	191,800	
TAXABLE			1,059,696	1,096,571	1,124,228	1,144,970	1,160,527	1,172,194	1,180,945	1,187,508	1,192,430	1,915,396	
CORP TAX	35.00			(370,894)	(383,800)	(393,480)	(400,739)	(406,184)	(410,268)	(413,331)	(415,628)	(417,350)	(670,389)
		(4,910,000)	1,207,196	836,303	823,396	813,717	806,457	801,012	796,929	793,866	791,569	1,689,846	(729,389)
NPV FACTOR	20.00	1	0.8333	0.6944	0.5787	0.4823	0.4019	0.3349	0.2791	0.2326	0.1938	0.1615	0.1346
NPV		(4,910,000)	1,005,997	580,766	476,503	392,417	324,097	268,257	222,408	184,628	153,411	272,920	(98,167)
		-4910000.00	-3904002.98	-3323237.23	-2846734.67	-2454317.26	-2130220.29	-1861962.94	-1639554.81	-1454927.00	-1301515.66	-1028596.10	-1126763.06
GROSS NPV=		-1126763.06											

COSTS

CHEMICAL	COST	MIX RATIO
ISOCYANATE	2100.00	450.00
POLYOL	1700.00	250.00
OTHER	6000.00	10.00
COST PER TONNE		2014

POWER	3.00
RATES	8.70

LABOUR RATE/HOUR	
MANUAL	4.20
TECHNICAL	6.24
STORAGE	278 meters cubed

FOAM		
DENSITY	30.00	KG/METRE CUBED
SELL PRICE	110.00	PER CUBIC METRE

MACHINE	COST	No OF MEN PER MACHINE MANUAL	TECHNICAL	LABOUR COST P.A.	MACHINE HOUSING	RATES P.A.	MACHINE SCRAP %	FOAM SCRAP %
MAXFOAM	590000.00	4.00	2.00	60902.40	3000000.00	33400.00	10.00	5.00
VERTIFOAM	430000.00	3.00	1.00	39187.20	2300000.00	24700.00	10.00	2.00
MINIFLEX	300000.00	2.00	1.00	30451.20	1900000.00	18500.00	10.00	2.00

	INITIAL	PER ANNUM
LABORATORY	170000.00	65000.00
ADMINISTRATION	250000.00	100000.00

QUANTITY= 1000.00 TONNES PER ANNUM

DAILY PRODUCTION (VOL) 278

CALCULATIONS MINIFLEX

		T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
BUILDINGS		(2,320,000)	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	
MACHINES		(300,000)											
WORKING CAPITAL		(900,000)										900,000	
SCRAP													(30,000)
TOTAL REVENUE			3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	3,593,333	
TOTAL COSTS			(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	(2,234,036)	
BEFORE TAX		(3,520,000)	1,362,548	1,362,548	1,362,548	1,362,548	1,362,548	1,362,548	1,362,548	1,362,548	1,362,548	2,262,548	(30,000)
TAXABLE ALLOWANCE													
25.00	%		75,000	56,250	42,188	31,641	23,730	17,798	13,348	10,011	7,508	97,525	
TAXABLE			1,287,548	1,306,298	1,320,360	1,330,907	1,338,817	1,344,750	1,349,199	1,352,536	1,355,039	2,165,022	
CORP TAX	35.00			(450,642)	(457,204)	(462,126)	(465,817)	(468,586)	(470,662)	(472,220)	(473,388)	(474,264)	(757,758)
		(3,520,000)	1,362,548	911,906	905,343	900,422	896,730	893,962	891,885	890,328	889,160	1,788,284	(787,758)
NPV FACTOR	20.00	1	0.8333	0.6944	0.5787	0.4823	0.4019	0.3349	0.2791	0.2326	0.1938	0.1615	0.1346
NPV		(3,520,000)	1,135,456	633,268	523,926	434,231	360,376	299,386	248,909	207,062	172,325	288,818	(106,023)
		-3520000.00	-2384543.64	-1751275.62	-1227350.01	-793118.92	-432743.17	-133357.24	115551.56	322613.37	494938.52	783756.35	677733.62
GROSS NPV=		677733.62											

APPENDIX 6
TABLE OF MATERIAL CHARACTERISTICS

Material	ρ/Kg m^{-3}	l /m 10^{-3}	R_1 /MKS Rayls 10^4	E /N m^{-2} 10^5	η
Calmphalt	100	20	9.43	1.28	0.67
VDK	34	26.5	1.81	1.25	0.12
VAF-H	122	27	-	-	-
FF201	10.7	27.5	26.62	4.81	0.12
CC306	6.2	27.5	26.62	1.02	0.10
TA301	6.6	28	5.49	0.85	0.08
Barasond	166	25	2.16	1.08	0.14
Barafire	76.9	27.5	0.28	0.3	0.04
Barafoam	34	25	0.42	-	-
8/1706/3	78	27.5	0.302	1.03	0.55
5/1706/3	84	28	0.111	0.67	0.42
2/3005/10	86	28	0.08	0.33	0.20
3/3105/5	84	28	0.03	0.32	0.42
Crush0	30	31.5	-	20.8	0.51
Crush1	30	31.5	18.6	16.3	0.52
Crush2	30	31.5	6.9	15.2	0.53
Crush3	30	31.5	5.5	14.7	0.53
Crush4	30	31.5	3.4	14.0	0.54
Crush5	30	31.5	1.3	-	0.56
Map A1	30	26	1.3	4.35	0.21
A4	30	26	1.2	4.35	0.21
C1	30	26	0.82	4.35	0.21
C4	30	26	0.93	4.35	0.21
B2	30	26	0.90	4.35	0.21

Material	ρ/Kg m^{-3}	l /m 10^{-3}	R_1 /MKS Rayls 10^4	E /N m^{-2} 10^5	η
B3	30	26	0.91	4.35	0.21
Basotec	11	25	1.06	3.87	0.01
Fire seal	90	25	0.36	-	-
VTR400 1:1	38	25	1.01	5.03	0.30
1.37:1	38	25	1.81	4.20	0.20
1.72:1	38	25	3.02	2.84	0.15
2.1:1	38	25	4.53	4.01	0.12

Normal Incident Absorption of Selected Materials

Material	100	125	160	200	250	315	400	Frequency /Hz 500	630	800	1000	1250	1600	2000	2500	3150			
Barafire	0.01	0.02	0.03	0.04	0.04	0.05	0.07	0.06	0.11	0.14	0.16	0.22	0.28						
Basotec		0.00	-0.01	0.00	0.02	0.02	0.04	0.05	0.12	0.12	0.19	0.30	0.38						
Calmphalt	0.01	0.03	0.04	0.06	0.08	0.13	0.20	0.21	0.26	0.26	0.25	0.28	0.30						
CC306	0.02	0.02	0.06	0.06	0.07	0.14	0.14	0.17	0.24	0.27	0.35	0.45	0.62	0.00	0.00				
Con mod med	0.00	-0.01	-0.00	0.00	-0.01	0.00	-0.00	-0.00	0.03	0.05	0.08	0.10	0.13	0.26	0.41	0.49			
2/3005/10	-0.01	-0.00	-0.00	0.00	0.02	0.04	0.08	0.13	0.33	0.62	0.80	0.81	0.70	0.00	0.00	0.00			
3/3105/2	0.01	0.00	0.01	0.02	0.03	0.04	0.06	0.07	0.13	0.20	0.30	0.54	0.78	0.00	0.00	0.00			
5/2406/8	0.01	0.02	0.04	0.06	0.08	0.15	0.18	0.23	0.36	0.59	0.65	0.63	0.54	0.00	0.00	0.00			
8/1706/3	0.00	0.02	0.03	0.06	0.09	0.16	0.21	0.27	0.39	0.54	0.62	0.69	0.60	0.00	0.00	0.00			
6523	-0.01	-0.00	-0.00	0.02	0.03	0.03	0.11	0.18	0.28	0.30	0.35	0.41	0.36	0.31	0.38	0.28			
6532 ABB	-0.01	-0.01	-0.01	-0.01	-0.00	0.00	0.03	0.04	0.13	0.23	0.37	0.59	0.80	0.91	0.91	0.79			
CHMR THICK	-0.00	0.01	0.01	0.02	0.04	0.08	0.05	0.05	0.12	0.18	0.27	0.45	0.75	0.86	0.74	0.56			
FF201	0.02	0.02	0.03	0.07	0.07	0.14	0.18	0.21	0.27	0.49	0.67	0.91	1.00	0.00	0.00	0.00			
FIRE SEAL	-0.01	-0.01	0.00	-0.00	-0.01	0.07	0.04	0.05	0.09	0.11	0.16	0.24	0.41	0.57	0.69	0.61			
TA301	-0.00	0.01	0.01	0.03	0.04	0.06	0.07	0.08	0.21	0.37	0.39	0.65	0.82						
VAF-H	0.01	0.02	0.03	0.04	0.04	0.06	0.08	0.08	0.15	0.21	0.29	0.53	0.66	0.00	0.00	0.00			
VDK	-0.00	0.00	0.01	0.02	0.03	0.06	0.09	0.12	0.20	0.43	0.72	0.98	0.93	0.00	0.00	0.00			
CRUSH 0	0.01	0.02	0.02	0.03	0.03	0.07	0.06	0.05	0.13	0.19	0.32	0.37	0.24	0.15	0.17	0.19			
CRUSH 1	0.01	0.02	0.02	0.03	0.04	0.08	0.06	0.06	0.12	0.16	0.29	0.36	0.25	0.16	0.14	0.17			
CRUSH 2	0.03	0.04	0.05	0.07	0.06	0.12	0.12	0.13	0.20	0.29	0.38	0.40	0.28	0.24	0.26	0.31			
CRUSH 3	0.04	0.06	0.08	0.11	0.10	0.19	0.20	0.24	0.35	0.43	0.44	0.46	0.39	0.36	0.38	0.45	0.00	0.00	0.00
CRUSH 4	0.02	0.03	0.06	0.09	0.10	0.19	0.21	0.33	0.57	0.65	0.62	0.60	0.53	0.54	0.60	0.69	0.00	0.00	0.00
CRUSH 5	0.02	0.03	0.04	0.07	0.10	0.19	0.22	0.29	0.44	0.68	0.85	0.87	0.74	0.66	0.72	0.80	0.00	0.00	0.00
CRUSH 6	0.00	0.01	0.02	0.04	0.05	0.10	0.10	0.13	0.26	0.48	0.75	0.96	0.96	0.81	0.69	0.75	0.00	0.00	0.00
A1	0.00	0.01	0.01	0.04	0.05	0.07	0.11	0.19	0.26	0.44	0.69	0.94	0.99	0.81	0.54	0.58	0.00	0.00	0.00
A2	-0.00	0.01	0.02	0.03	0.05	0.06	0.09	0.12	0.24	0.35	0.61	0.88	0.99	0.77	0.57	0.50			
A4	-0.00	0.01	0.02	0.03	0.04	0.05	0.08	0.09	0.19	0.33	0.54	0.81	0.99	0.85	0.65	0.52			
B3	0.01	0.01	0.02	0.03	0.05	0.08	0.07	0.06	0.12	0.19	0.00	0.42	0.69	0.86	0.79	0.63			
B2	-0.00	0.01	0.01	0.02	0.04	0.08	0.05	0.05	0.12	0.18	0.27	0.45	0.75	0.86	0.74	0.56			
C1	0.00752	0.018407	0.02	0.03	0.04	0.06	0.07	0.08	0.14	0.20	0.30	0.44	0.70	0.83	0.74	0.54			
C4	0.003774	0.014057	0.02	0.03	0.04	0.05	0.06	0.06	0.13	0.20	0.29	0.47	0.74	0.87	0.73	0.53			
BARASOND										0.33	0.52	0.77	0.93	0.98	0.93	0.79	0.76	0.84	0.96

APPENDIX 7

PLASTIC FOAMS AND THEIR MANUFACTURE

General Considerations

A foam is a low density cellular solid created by the solidification of a liquid mixture or polymer melt containing many bubbles. It is important when considering foams to realise the many types exist and new types of foam are becoming available on a regular basis. As a material used in technical applications foams have many advantages over conventional products, in particular unique properties associated with their structure and multi-phase nature. A foam will retain some of the qualities of the constituent phases and, due to structural factors, will exhibit additional properties. Another important characteristic of foams is that they make efficient use of the base polymers, which in addition to being a cost saving also makes efficient use of a raw material that could in the not so distant future be in short supply.

Although materials such as wood, bone and honeycomb are technically cellular materials the following discussion is limited to the consideration of synthetic cellular polymers. Most polymers can be foamed but only a few have been exploited on a commercial basis. With new needs being created in many applications there is an increasing demand for foams with different properties and base polymers. Only a relatively small number of the possible materials has been investigated in the current work. The most widely used polymer system for foam manufacture is polyurethane. For this reason most of the following discussion on plastic foams and their manufacture will concentrate on polyurethane foams. Other cellular polymers have been investigated in our laboratories including polyethylene, polyimide, melamine etc. It is important to realise that foams come in a variety of forms and are being used in many diverse applications and their further possible applications are considerable.

Polyurethane Foams

Polyurethane foams are available in many different forms with different characteristics and different applications. They range from rigid (typically used for appliance housing) through semi-rigid (typically used for energy absorbing bumper liners) to flexible (typically used for comfort cushions). Densities range from about 15 $kg.m^{-3}$ to 500 $kg.m^{-3}$.

Polyurethane foams are manufactured by mixing together chemical ingredients which react to form either a linear polymer or a polymer network which expands and sets (details are given below). The reaction mixture of the polyurethane foam can be injected into a closed mould to form unit mouldings (e.g. vehicle cushions) or the mixture can be placed on a conveyer with containing side walls for continuous block production. This type of foam is commonly known as slabstock. Other manufacturing methods include pouring the reaction mixture onto a sheet and letting a "bun" form. Buns are an extremely inefficient method of foam production. The injection moulded foam or RIM (Reaction Injection Moulded) have many uses including acoustic applications. It has been argued by Speciality Composites, Delaware USA, (in their data sheet) that the properties of cast RIM foams are more controllable hence the foam will be more suitable for acoustic application.

There are justifications for this argument but the overriding factor is cost. Slab stock is less expensive than RIM foams. Other types of moulded foams are RRIM Reinforced Reaction Injection Moulding. A reinforcing filler is added to the foam reaction mixture which increase the stiffness and strength of the finished product. Typical strengthening materials could be a glass fibre mat placed in the mould before the reaction mixture is injected. RIM and RRIM are becoming very popular methods of making products, particularly components for energy management applications.

Chemistry of PUR Foams.

To discuss physical properties of foams adequately it is necessary to have to have an appreciation of their production chemistry. Of all the foams made polyurethane slabstock is produced in the largest quantity. Techniques used for its production will be similar to some of the other foams. The chemistry when studied in detail is complicated and small modifications to a production formulation can produce large changes in foam performance characteristics. Therefore only a brief description of the basic production chemistry of polyurethane foam is given below.

The first polyurethane foams were produced in about 1953 using a high pressure technique developed by Otto Bayer and his associates [83]. Development of the chemistry and production technology has advanced rapidly since then. Polyurethanes are unusual as industrial polymers in that the polymerisation reaction takes place during the forming process. The basic building block from which polyurethane foam is constructed is a urethane.

$$R'\text{-}NH\text{-}\underset{\underset{O}{|}}{C}\text{-}OR$$

R and R′ are simple hydrocarbon groups (for example $(CH_2)_n$). To create a polymer the urethane groups have to be joined in a repeating polymer chain. This polymerisation of urethane to form polyurethane is obtained by reacting an isocyanate with a polyalcohol (or polyol).

$$\underset{\textit{Polyol}}{n(HO\text{-}R\text{-}OH\text{-})} + \underset{\textit{diisocyanate}}{n(OCN\text{-}R'\text{-}NCO)} \rightarrow \underset{\textit{Polyurethane}}{\text{-}(R\text{-}\underset{\underset{O}{|}}{O}\text{-}C\text{-}NH\text{-}R'\text{-}\underset{\underset{O}{|}}{NH}\text{-}C\text{-}O)\,n\text{-}}$$

Polyurethane is a solid polymer and to obtain a foam some type of blowing or foaming is undertaken just before the completion of polymerisation. Three basic methods of blowing are used: (i) mechanical frothing, high speed stirrer or gas injector are used to incorporate air or some other gas, typically a relatively inert gas such as nitrogen injected into the polymer melt or reacting mixture (ii) physical blowing, low boiling point liquids are mixed with the reaction mixture or polymer melt under pressure. The volatile liquid will form a gas either when heated by the exothermic polymerisation reaction or when the polymer melt is depressurised. (iii) chemical part of the polymerisation reaction will generate gas. When the liquid-gas mixture is allowed to solidify the foam is formed. Typical liquids used in physical blowing are chlorofluorocarbons CFCs and water, these are discussed further in Section 2.3.2.

When manufacturing polyurethane foams the chemical reaction used to create a blowing gas is between the isocyanate and water which creates carbon dioxide gas. An example of the type of reaction is given below.

$$\underset{\text{water}}{2H_2O}+\underset{\text{Diisocyanate}}{ONC-R'-NCO} \rightarrow \underset{\text{Diamine}}{H_2N-R'-NH_2}+\underset{\text{Carbondioxide (gas)}}{CO_2\ (g)}$$

$$\underset{\text{Diamine}}{H_2N-R'-NH_2}+\underset{\text{Diisocyanate}}{2\,(ONC-R'-NCO)} \rightarrow \underset{\text{Diisocyanatopolyurea}}{ONC-R'-\underset{H}{\underset{|}{N}}-\underset{O}{\underset{\|}{C}}-\underset{H}{\underset{|}{N}}-R'-NCO}$$

The diisocyanatopolyurea can, as an isocyanate then react with polyol to form polyurethane. Polyurethanes can be divided into two family types depending upon the initial polyol. These two families are polyether and polyester. A diagrammatic representation of the chemical structure of the two families is given below.

$$\left[R-O-(\underset{CH_3}{\underset{|}{CH}}-CH_2-O)_x-(CH_2-CH_2-O)_y-H\right]_n$$

Polyether

$$\left[R-O-(\underset{O}{\underset{\|}{C}}-(CH_2)_4-\underset{O}{\underset{\|}{C}}-O-CH_2-CH_2-O)_x-H\right]_n$$

Polyester

Polyethers are the more common of the two polyurethane types and the oldest. Both families can be modified to give different physical characteristics. The main differences between the two families is that of cost, control- regularity of cell structure, chemical resistance and oxidation rate.

Polyesters are more expensive than polyethers and although polyesters have many advantages over polyethers it is because of the cost factor that polyethers are produced in larger quantities. There is greater control over cell, structure and general cell size uniformity in polyester. By control of air flow resistance (through cell size control) acoustic absorption can be controlled (see Chapter 3). It is the increased control and uniformity of polyester foams that makes them more popular for specialist technical applications. Organic resistance to solvents and detergents is better in polyester however the resistance to water and heat is not as good. Another important chemical reaction at which polyester have better resistance is oxidation.

Many variations in the type of polyol and isocyanate are available and these will create foams with different properties. Some foaming reactions require modifications to produce the required characteristics hence further additions to the reaction mixture are required. A typical formulation for a polyether and polyester foam are given below. The formulation is followed by a brief description of some of the commonly used additives and their function within foam production or how they modify foam properties.

Table 21 A typical formulation for PU foam. (producing a 30 Kg m^{-3} medium hardness material, possibily used for acoustic application)

Typical Formulation	
Ingredients	Parts By Weight
Polyol	100
Iscocyanate	40
Water	5
Amine (Catalyst)	0.06
Silicone (Surfactant)	1.25
Blowing Agent	2.0
Stannous Ocoate (Catalyst)	0.22

<u>Catalysts</u> are used to control the rate of polymerisation of the reaction mixture. Without a catalyst the time taken to initiate the polymerisation reaction would be excessive, creating several problems. A major consideration in any production process is speed. The longer the product takes to be produced the more expensive it will be. If however the polymerisation is too quick the gases will be unable to expand and a very dense foam produced. It is therefore important that some control on the rate at which polymerisation takes place.

<u>Blowing Agents</u> In polyurethane foam there are two main additives used in the formation of cells or bubbles, first the water that reacts with isocyanate (as detailed earlier in this section) blowing the foam with carbon dioxide, and secondly adding a volatile solvent that will gas at low temperatures. There is usually a combination of both these methods used in foam production. Ideally only the water-isocyanate reaction would be used because of cost and the environmental problems

associated with low boiling point solvents (see section 2.2 CFCs). The water reaction is highly exothermic causing an increased fire hazard at the production and post production storage stages. The addition of water, by promoting cross linking, also produces a harder foam. Figure 88 shows the typical effect of the addition of water on the hardness and density of a PUR foam (data from reference [81]). Limiting the amount of water controls the degree to which heat affects the foam.

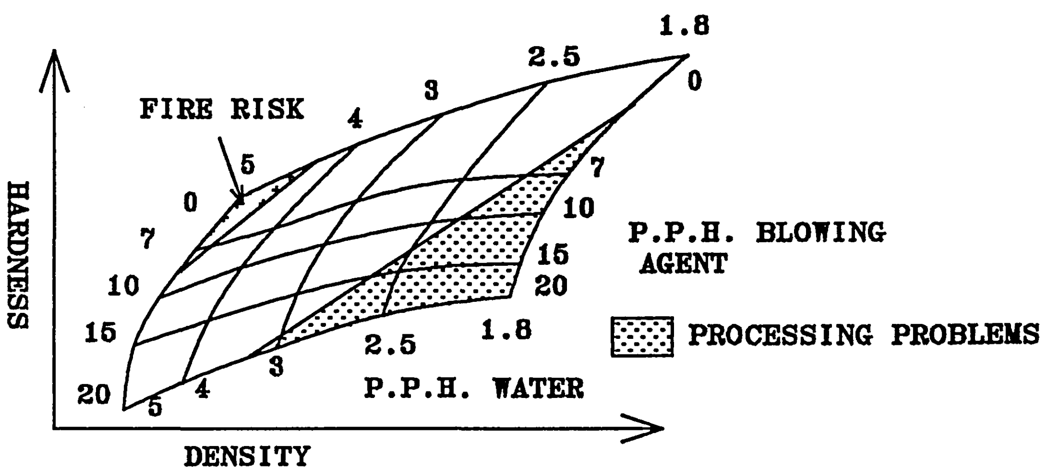

Figure 88 Influences of blowing agent on the hardness and density of TDI foam.

Colour There are obvious reasons for colouring foams, particularly the appearance. As foams are not often not seen (coated or used as part of a composite for example) then the aesthetic aspects are only of limited importance. Colour is more often used as a method of identification of foam type. The colour can also give some protection to the foam from the effects of ultra violet light degradation.

Flame retardants - Smoke suppressants In section 2.3.2 the problems with flammability is discussed in detail. To improve a foam's performance in a fire additives can be incorporated at the production stage. Several different additives for different functions e.g. ignition, smoke generation, burning etc. are available. Care has to be taken as chemicals added can affect the performance characteristics of the foam. Modifications to the general formulation are made to compensate for the effects of flame retardant additives.

Fillers There are several reasons for incorporating fillers, primarily strength and cost. For example the addition of reinforcing fibres enhances the strength and stiffness of the polymer matrix and hence the foam. If a cheap bulking filler such as talc is added the cost of the foam is reduced. However there are limitations to the amount of bulking filler that can be used. Too much filler would greatly reduce the strength of the material. Fillers have also been used recently as a method of increasing the visco elastic properties of a material (ie damping). As an example see the micrograph of 'Calmphalt', shown in Figure 89'Calmphalt' manufactured by Bridgestone is an asphalt filled polyurethane foam.

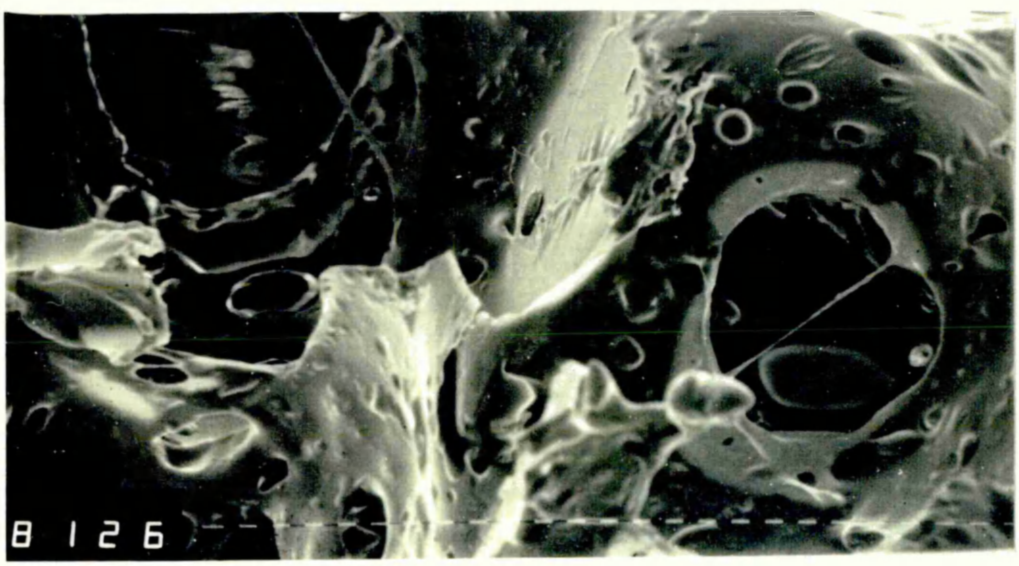

Figure 89 Micrograph of Calmphalt, impregnated PUR foam.

Surfactants are often underestimated in there contribution to foam creation, they play a very important multi- functional roll. They are surface active ingredients that aid in the mixing of incompatible components. The amount of open or closed cells can be controlled by surfactants. Additionally, surfactants help stabilise the small gas bubbles formed at the earlier stages of foam formation and at a later stage in the expansion process with larger bubbles surfactants reduce stress concentrations in the thinning cell windows.
Chain extenders and Cross linkers are two of the possible additives that will change the chemical bonding in the polymer matrix. The changes to chemistry will affect properties like strength, visco elasticity etc. These additives also affect the curing rate of the polymer.

Other additives are available for various applications. In the above section an indication of the most popular types of additive used has been given. For further details on the specification of additives and the range of their effects see [81] [70] [11].

The basic technology and chemistry of polyurethane foam manufacture has been described. Changes to foam properties can be achieved by modifying either aspects. One possible modification to the chemical structure of a foam matrix will now be discussed. Changes to the chemical structure will bring about modifications to the matrix polymer and hence the foam's performance characteristics. Although one possible chemical modification will be discussed many others are available e.g. cross linking of the polymer chains. Each change will create new characteristics in a foam matrix.

Rather that use a linear polyurethane a polyurethane elastomer can be considered. The differences between the linear and elastomeric polyurethane are as follows; the linear polyurethane is rheologically simple because of its simple geometry. Linear polymers are the repetition of the same monomer. The elastomer is not rheologically simple because it is a multi block co-polymer. Multi block copolymers are a sequence of different polymer segments as shown in Figure 90. The blocks in an elastomer will have different levels of hardness and when hard and soft blocks are alternated the hard blocks try, by distorting the softer segments, to form semi crystalline domains (see Figure 92). The length and quantity of soft segments will govern the size and degree of orientation within the domains. Stresses induced while the polymer is still in its liquid phase will determine the degree of orientation of the domains. Changes in orientation both within and external to the domains will affect the physical and hence the acoustic properties of a material. It is the intermolecular bonds between the polymer chains that give rise to the elastomeric properties within a material. An increase in orientation leads to an increase in the intermolecular bonding and hence elasticity. Figure 92 shows slight branching which will result in slight stiffening of the polymer. When there are many cross links as depicted in Figure 93 a rigid stiff material is created. Chapter 3 shows how changes in elastic properties affect the acoustic absorption of a foam. Other characteristics besides the material properties of the matrix polymer will also affect the end performance of a foam, e.g. cell structure.

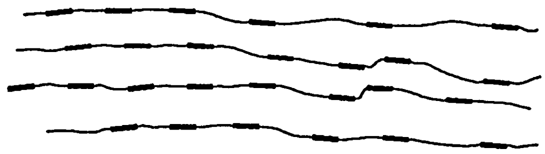

Figure 90 Diagrammatic representation of linear multi-block co-polymer.

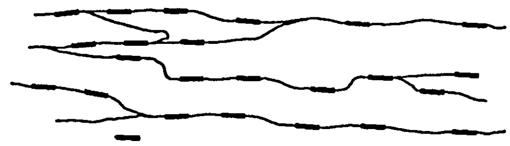

Figure 91 Diagrammatic representation of branched multi-block co-polymer.

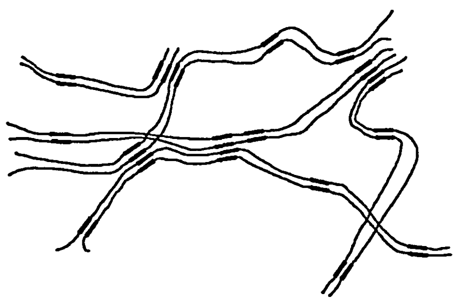

Figure 92 Diagrammatic representation of polymer with a segregated domain structure in block co-polymer.

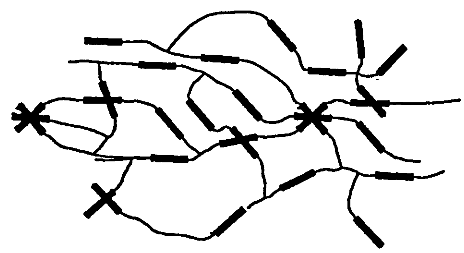

Figure 93 Diagrammatic representation of rigid highly crossed linked block co-polymer.

The segments are polyether or polyester and-polyurethane. Physical properties can be controlled by varying the size and proportion of soft segments also the rate at which the polymer is formed. These effects are not always obvious, and (for example) adding soft segments does not necessarily make a softer material. The addition of soft segments allow the hard segments to form small, near crystalline, domains creating a harder material. There will be little orientations of the domains unless critical stresses are applied at the time of polymer formation. By increasing or decreasing the degree of orientation a different set of properties is obtained. One of the most important properties that is orientation dependent is the viscoelastic behaviour.

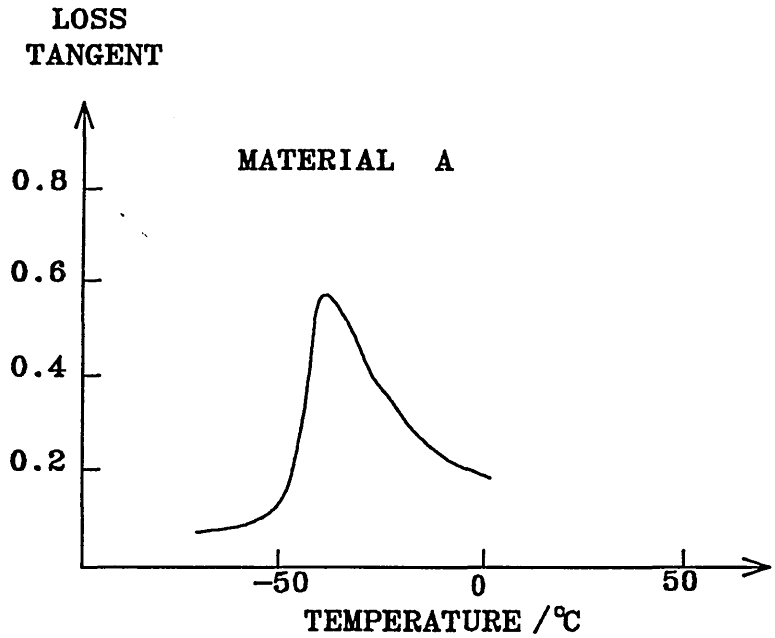

Figure 94 Graph of loss tangent (@1 Hz) against temperature for material A.

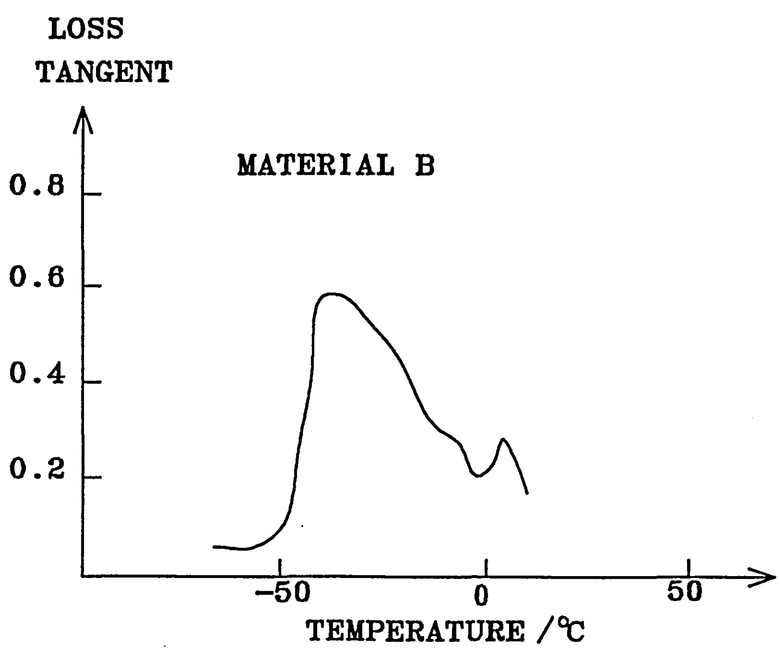

Figure 95 Graph of loss tangent (@1 Hz) against temperature for material B.

When Dynamic Mechanical Thermal Analysis, DMTA, (see Section 4.4.4) is undertaken the effects of the hard and soft phases can be detected. Material A has a smooth tan δ with a narrow peak indicating a rheologically simple linear polymer. Comparing material A with material B, we see that B exhibits a broad undulating curve. The undulations can be explained as the addition of two or more tan δ peaks from the two or more phases. As described in Reference [31], changes to temperature (at constant frequency) in the DMTA are analogous to changes in frequency (at constant temperature). Hence changes in the tan δ measured using DMTA give an indication of the changes in frequency dependent properties to be expected.

PUR foam manufacture

There are two commonly used methods of slab stock production, the horizontal and Vertifoam processes. These are shown in the Figure 96 and Figure 97 and are typical of slabstock production. However each manufacturer incorporates specific modifications. The horizontal foam machine in this case a Max-foam manufactured by Viking engineering in Stockport, places the reaction mixture onto a moving paper conveyer belt. As the foam expands the paper drops away to maintain a flat top.

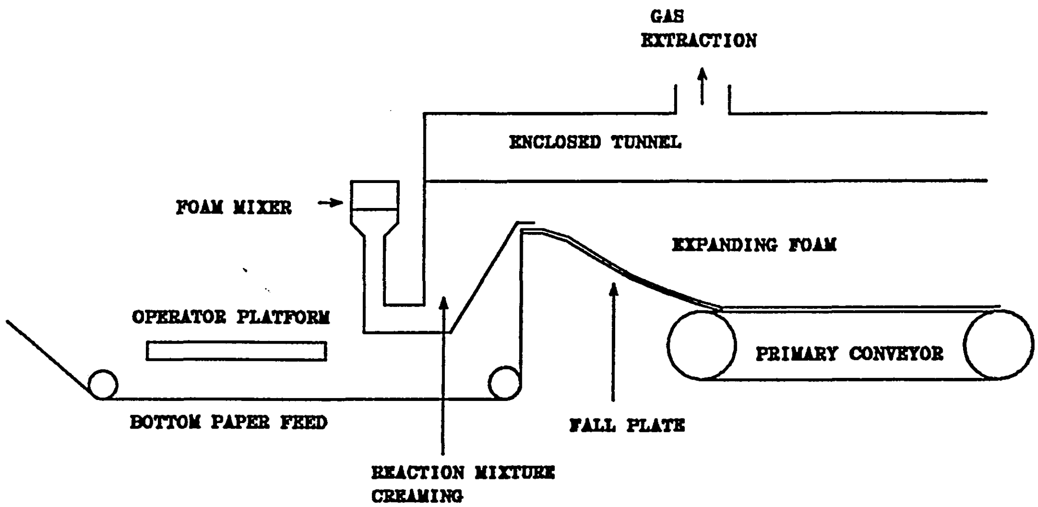

Figure 96 The Maxfoam method of manufacturing slabstock foam.

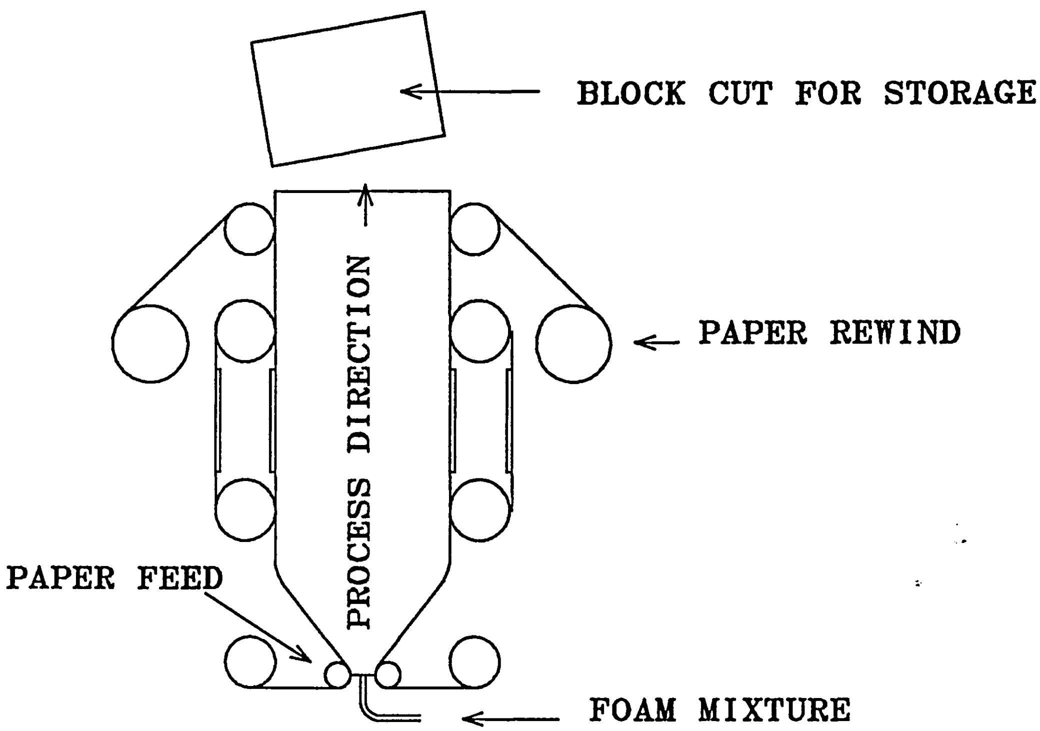

Figure 97 The Vertifoam method of manufacturing slabstock foam. This technique reduces top wastage and minimises cell distortion due to foam rise.

The vertifoam machine places the reaction mixture at the bottom of a tall column. Moving paper at the sides of the column assists in the foam rise. When enough of the set foam protrudes from the top of the column it is cut into blocks and sent for storage.

After production both slab stock manufacturing methods require that the soft foam be given at least 24 hours to set (the exception is a new development by Hyman Ltd., hypa-cure that sets within a few hours). Care has to be taken as polyurethane foams when manufactured emit toxic isocyanate vapour and a large amount of heat. If the heat reaches a significant level then the foams will ignite (even with flame inhibitors). It is important therefore that foams have a large open area away from the main production area to be allowed to cool off and set.

Cell structure of PUR foams.
The structure of the foam can easily be seen microscopically at low magnification. Although several different cell shapes are present the predominant shape is pentagonal dodecahedron. There is also an elongation of the cells in the direction of foam rise. The degree of elongation is related to the production techniques and in some foams appears to be negligible. However the effects of foam rise and heat gradients across a foam on cell structure cannot be ignored. Measurements of material properties have shown significant directional dependence [66]. One of the main reasons for anisotropy across a foam block is the thermal gradient caused by the exothermic reaction and heat retention in the centre of the foam due to the thermal insulation properties of the foam.

The polymerisation reaction that forms foam is exothermic and in the heat of formation is used to expand gases trapped in the chemical mixture thus creating the bubbles. When the bubbles are large enough they contact each other, distorting the shape of the bubble from spherical to dodecahedral. Where the bubbles contact, pentagonal windows are created. With further expansion the windows can be made to break leaving just the outer struts shared by three pentagons (see Figure 98). The degree of burst windows in a foam is called the amount of reticulation and can be controlled in manufacture. A large amount of windows form a highly un-reticulated foam.

An idealised two dimensional model show of the stages that a foam passes through in its expansion is given in Figure 98. By changing the formulation the foam can be made to set at any stage in its expansion.

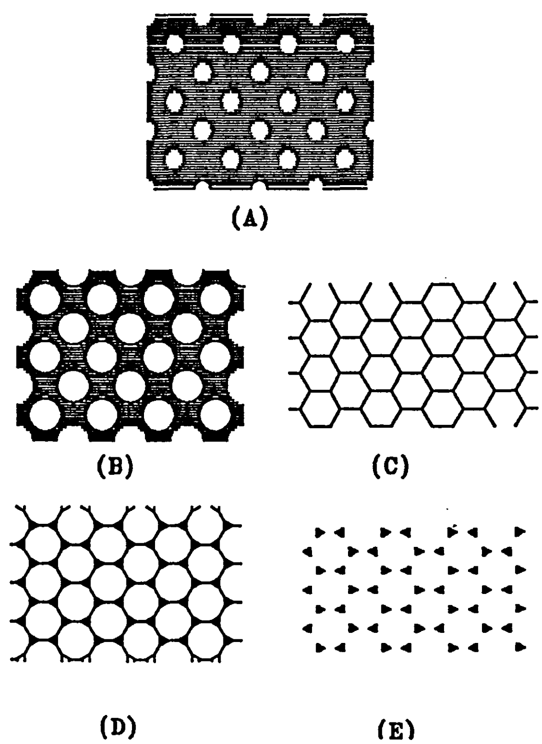

Figure 98 Schematic representation of cell formation in PUR foam.

In (A) the bubbles are just forming. Foam set at this stage has high density and retain many characteristics of the matrix material but will be lighter and less expensive than the solid counterpart.

When the bubbles grow there is no longer the room for them to remain circular and hence they distort into flat sides as can be seen in (C). Each of the flat surfaces where two bubbles contact are called windows. With further expansion the windows get thinner (D) untill eventually they burst (E). If expansion continues there is no longer sufficient strength in the foam's struts and the foam will collapse. As mentioned earlier, by changing the reaction mixture the foam can be made to set at any stage. Within a foam there is a degree of non-uniformity where different parts of the material have reached different expansion at the time of set. The most critical change in properties occurs with bursting of the window (the cell opening process, which governs reticulation). Cell windows affect the way air can flow through the material. Also completely closed cells act as small cushions.

By examination of the cell structure under the microscope it is possible to visualise what happens when a foam test piece is compressed. Small compressive strains will initially flex the struts and the behaviour is linear. If the strain continues the struts buckle and eventually the material will collapse and has the compressive characteristics of the matrix polymer. In acoustic fields the deformation of cell elements will be small, in general confined to the initial linear part of the stress strain response. The degree of reticulation (ie number of windows) influences these mechanical characteristics. A cell window will connect struts giving the foam additional stiffness. When struts are connected movement or collapse of one strut will have an affect other surrounding struts. Compression of a foam will force air from the material. Flow through the foam will be affected by windows, restricting the air travelling through the matrix by it having to travel through the small cells and by tortuous routes. These restrictions to air flow together with the frictional forces created when air travels over the matrix surface, considerably affect the dynamic proprieties of the foam. Acoustic properties will depend on the small strain dynamic mechanical properties and to a greater extent on the air flow resistance characteristics.

Post treatment of PUR foams.

After a polyurethane foam has been produced it is rarely in a form that can be easily used hence some form of post treatment has to be undertaken. Many types of post treatments are used on slab-stock and RIM polyurethane foam. Some post treatments are aimed at changing the cellular structure and others are intended just to make the foam a practical size and shape. The post treatment to convert foam into a saleable product is an important cost factor in foam production.

Figure 99 is a simplification of the possible routes that slabstock foam can take after it has been produced. The blocks produced by the slab-stock technique are a cube with approximately 2 metres sides (some variation will occur dependent upon the type of machine being used). Blocks of this size are easily moved but inconvenient in other respects. The first operation therefore is a reduction of the block foam into manageable sizes.

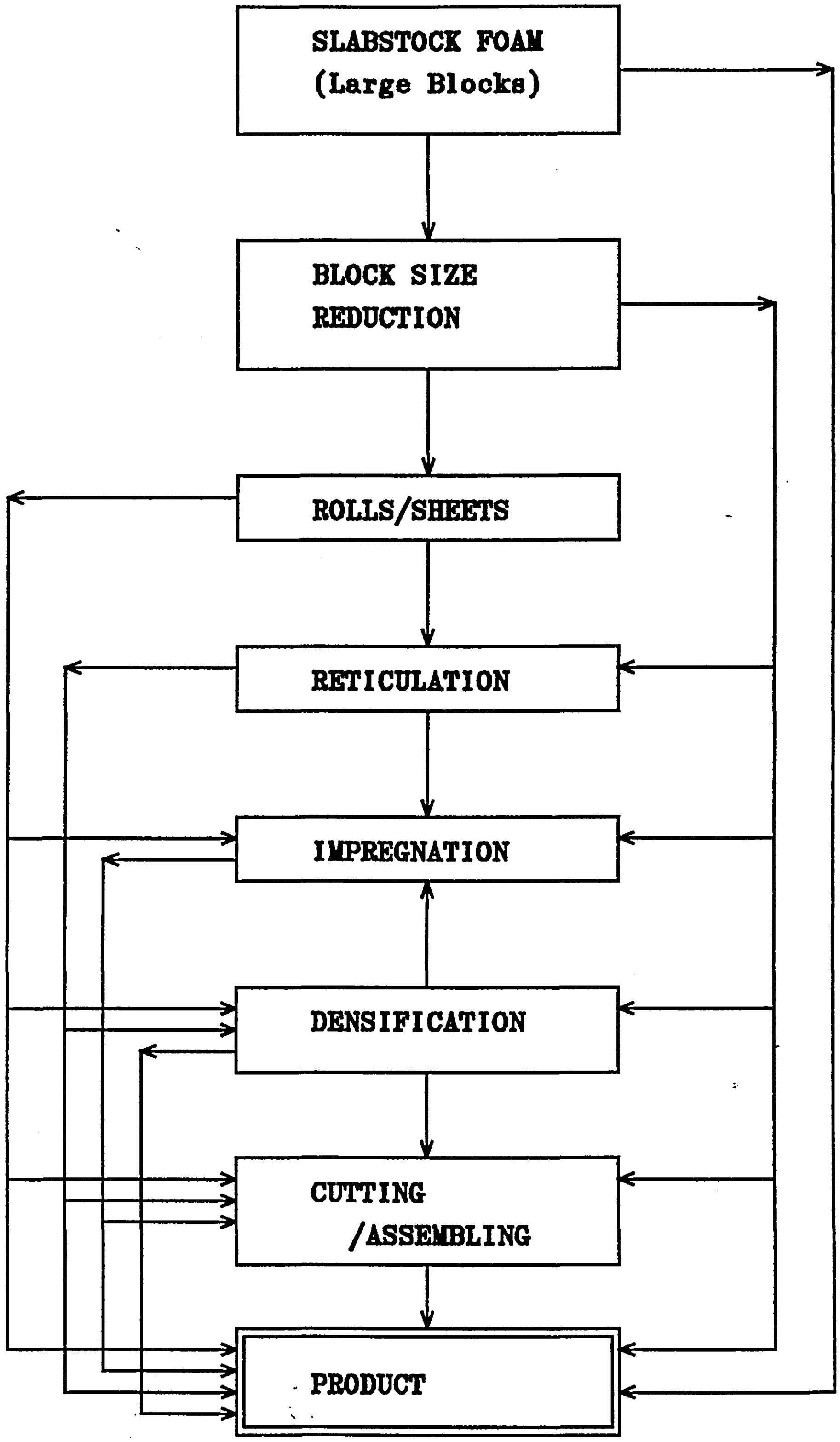

Figure 99 Schematic representation of the route taken in post treatment of slabstock foam.

Several popular cutting techniques are shown in the following figures. Figure 100, splitting a block if sheets of material are required. Figure 101 shows contour cutting, in which a continuous wire cutting forms complex shapes. In die cutting (Figure 103) a cutting die is placed over the foam and the sandwich compressed. This process is used for components produced in large quantities that are cut from sheets, e.g. shaped acoustic panels for the inside of computer printers. Boring (Figure 102) is used in the formation of circular components. Continuous deformation cutting (Figure 104) creates an uneven surface. This unevenness has several functions and the primary acoustic application is to act in the diffusion of the incident sound field. Peeling (Figure 105) is another method of obtaining sheet material. This technique is used to produce thinner continuous sheets than the fixed size thicker sheets produced by splitting. In Figure 100 to Figure 105 some of the many cutting techniques have briefly been described. Other post treatments that can be undertaken, before or after cutting, are reticulation (Figure 106) densification (Figure 108) and impregnation (Figure 107), all of which are used in acoustic foams.

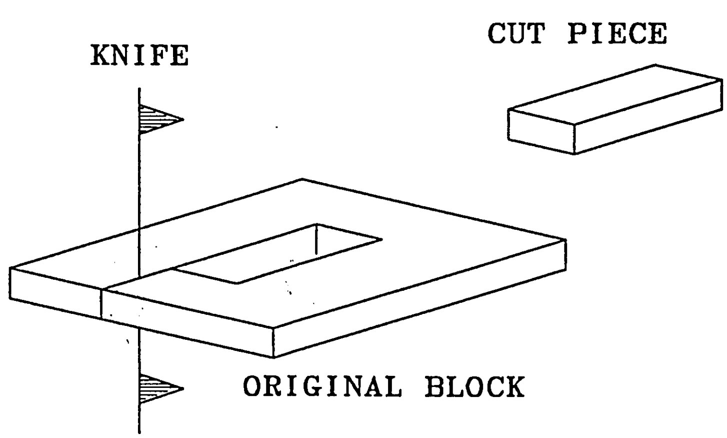

Figure 101 Contour cutting of slabstock foam.

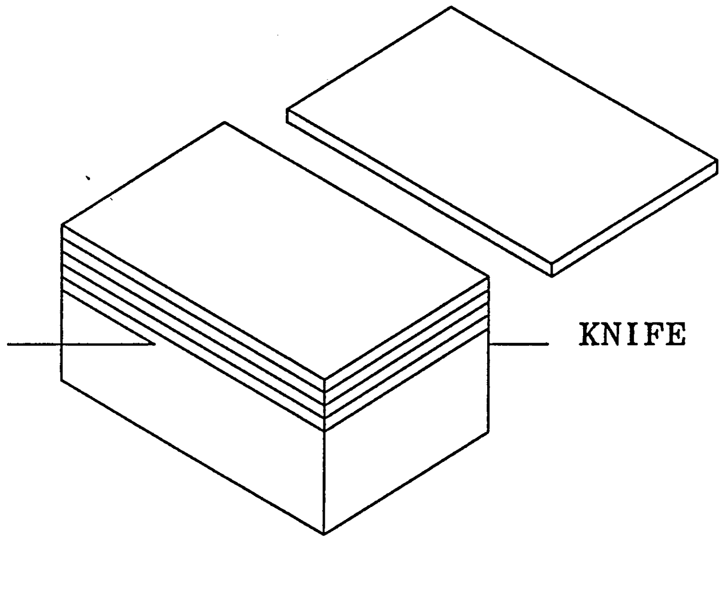

Figure 100 Horizontal splitting of slabstock foam.

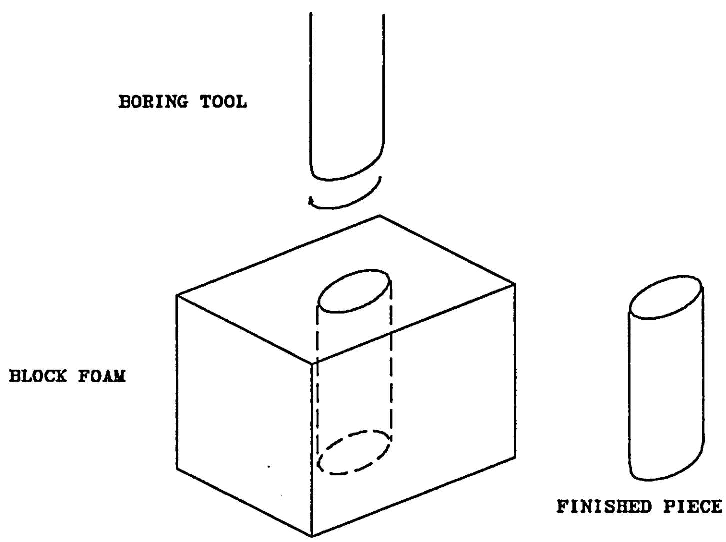

Figure 102 Boring slabstock foam.

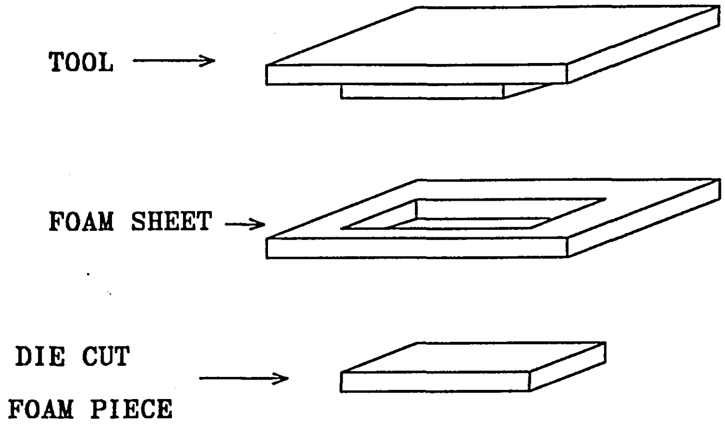

Figure 103 Die cut slabstock foam.

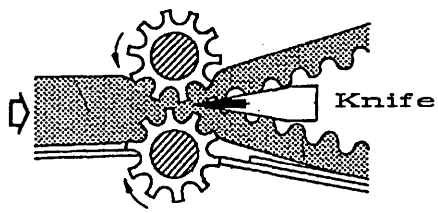

Figure 104 Continuous deformation cutting of slabstock.

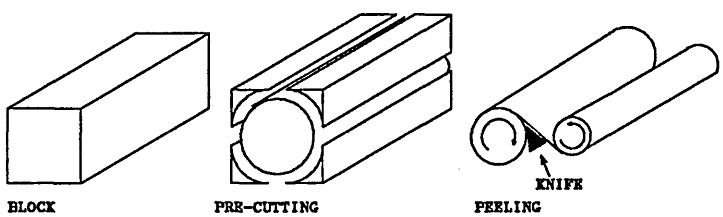

Figure 105 Peeling slabstock foam.

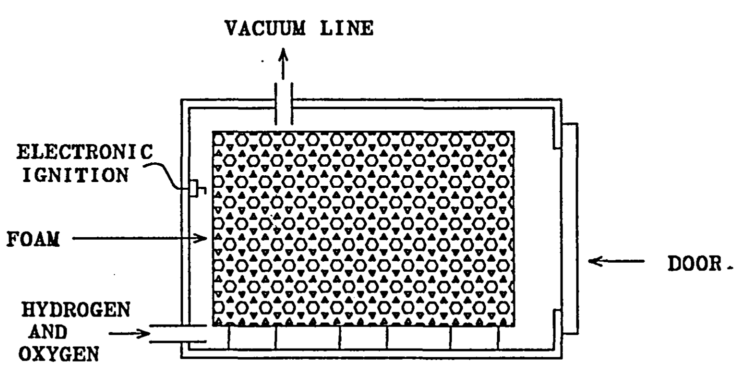

Figure 106 Reticulation chamber, used to reduce the number of cell windows in a foam.

Reticulation is the reduction of the amount of cell windows within the foam. Methods of reticulation include chemical erosion or mechanical destruction. Figure 106 demonstrates the explosive mechanical technique. An oxygen-hydrogen mixture is put into a closed reaction chamber. Ignition of the mixture is then remotely carried out. The ensuing explosion destroys the cell windows. Changes to the amount of reticulation in a foam will affect the acoustic absorption of the material [68].

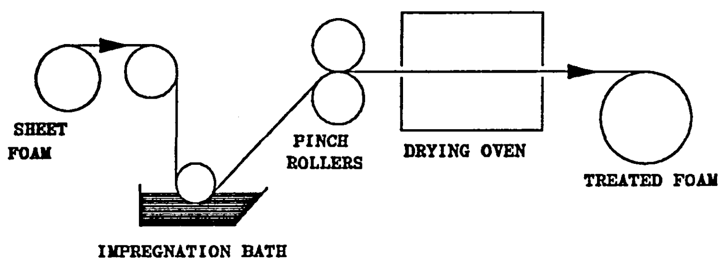

Figure 107 Diagram of the method used to impregnate sheet PUR foam.

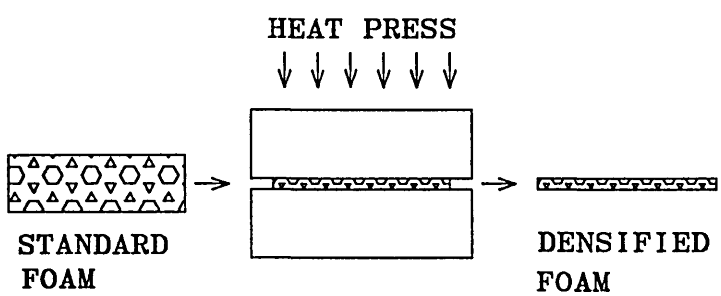

Figure 108 Diagrammatic representation of a method used to increase the density of slabstock foam (Densification).

Impregnation as shown in Figure 107 is a method of coating the polymer matrix to confer new properties onto the foam: flame resistance, high frequency welding or additional strength to become self supporting. An example of impregnated PUR foam can be seen in the micrograph (Figure 110) of a post production impregnated foam (British Vita's VAF-H).

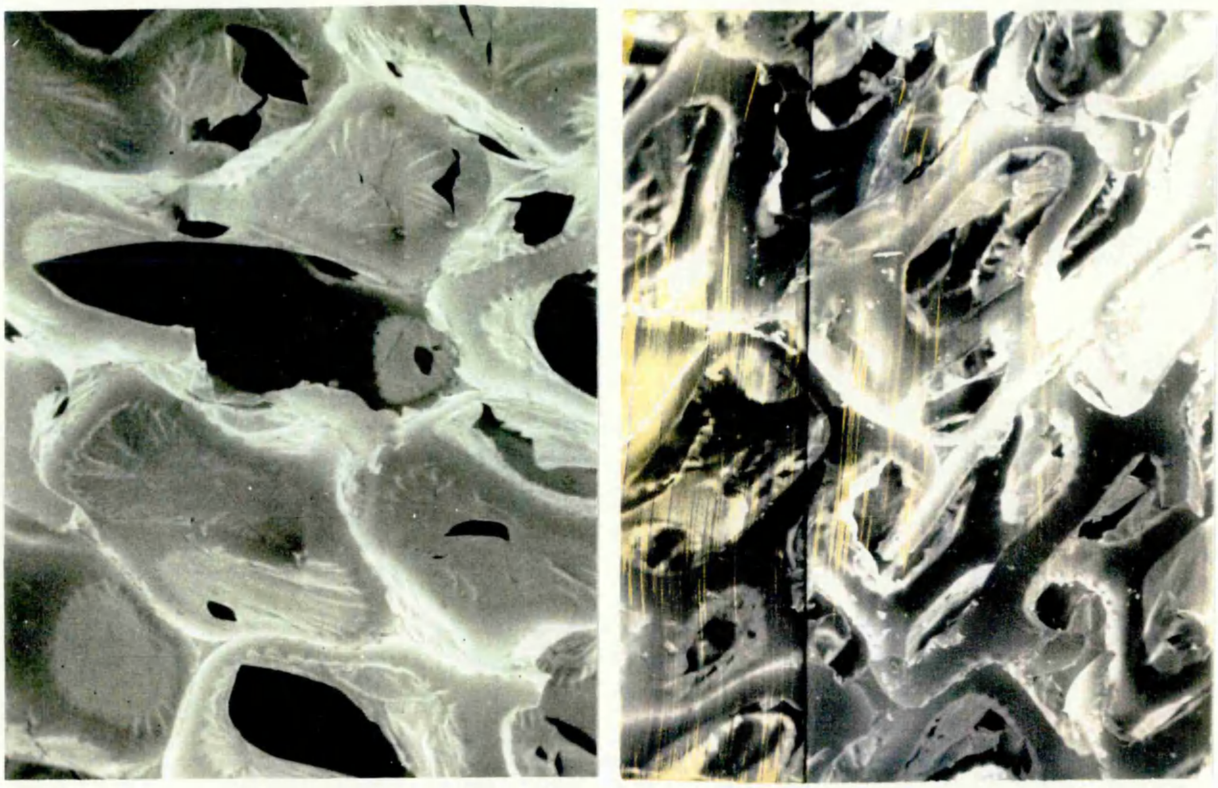

Figure 109 Electron micrograph of foam before and after reticulation.

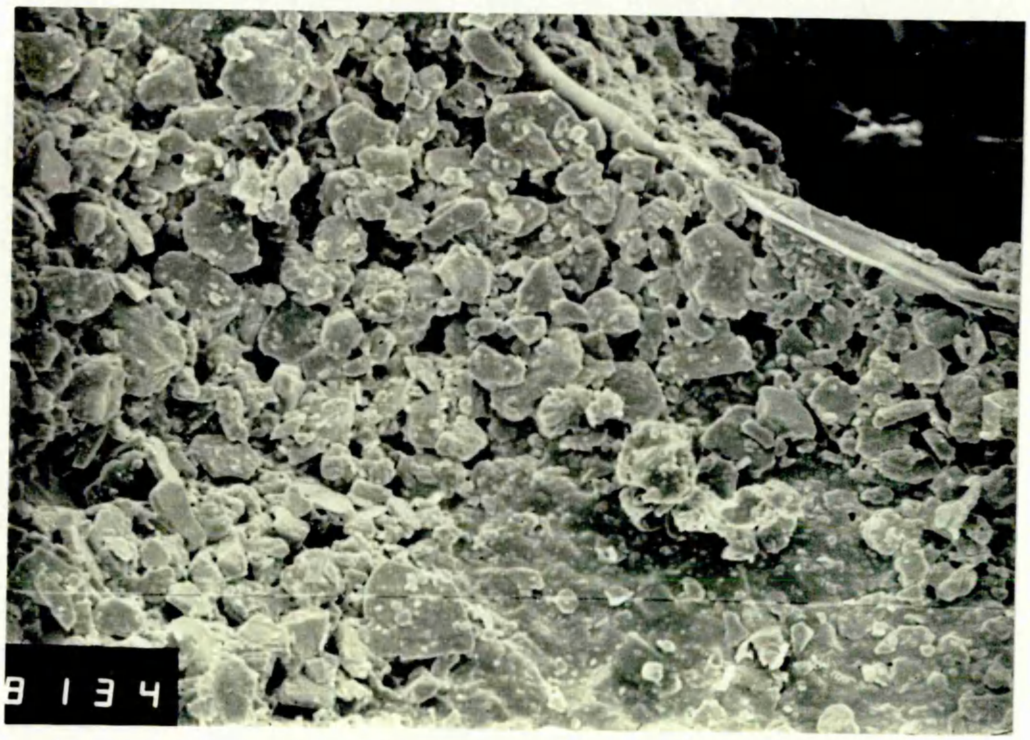

Figure 110 Micrograph of VAF-H (manufactured by British Vita).

Densification as shown in Figure 108 is becoming a more popular method of post treating foams, especially foams with newly developed matrix materials (e.g. melamine foam). By heating compressed foam and retaining the compression while the foam cools a proportion of the compression sustained by the foam will remain, forming a higher density material. The densified foam will have distorted cells creating non standard properties within the foam.

All the post treatments mentioned and the many other possible treatments can modify the size, shape and performance characteristics of a foam. All foams that are sold will have to undergo some degree of modification before being suitable for the end user. A final post treatment that is commonly used is the construction of composite materials, that is when other materials are bonded to foam. The choice of bonding material is wide: metals, rubber plastics, other foams and many others can be bonded to the foam, creating new specialised materials. Composites are a subject area in themselves (for further examples see [26] [33]).

High performance Foams

Introduction

Before describing several examples of High Performance Foams, we will discuss the primary factors influencing their development. The original standard polyurethane foam has been used for many years, with slight modifications to polymer chemistry and production techniques offering some fulfilment of changes in market demand. To satisfy the requirements of the new market fully, more radical changes in the performance of foams were required. Market forces influencing cellular polymers are discussed in Section 2.3.4. Changes in foam performance have been brought about primarily by the introduction of new matrix polymers and the associated production techniques, additives, and post treatment.

Major requirements of these new foams are flammability, weight, cost reduction, durability, and of course acoustic absorption. It is with these factors in mind that a description of a few of the most prominent High Performance Foams, that are available, will be given.

Three approaches have been used in material development: first the use of materials not normally associated with cellular polymers, e.g. melamine, secondly the development of new polymers such as polyphasphazene and finally modifications of standard polyurethane foams by the use of additives or modification of the polymer chemistry.

The methods used for the creation of High Performance Foams are obtained from, and are widely used in, other fields of material production.

Materials

1. Melamine

Melamine is used in the form of a powder as a fire retardant additive in polyurethane foam. It was a logical progression therefore, when BASF developed Basotec, a foam wholly based on melamine. Bulk melamine is a solid brittle material, although when melamine fibres have a thin cross section (typically a length to width ratio of 10 and a width of between 7 and 15 microns) the material becomes flexible. Figure 111 shows a micrograph of melamine foam. As the dimensions of the struts in the foam will be largely dependent upon the cell size it follows that the brittleness of Basotec will be dependent upon the expansion of the foam.

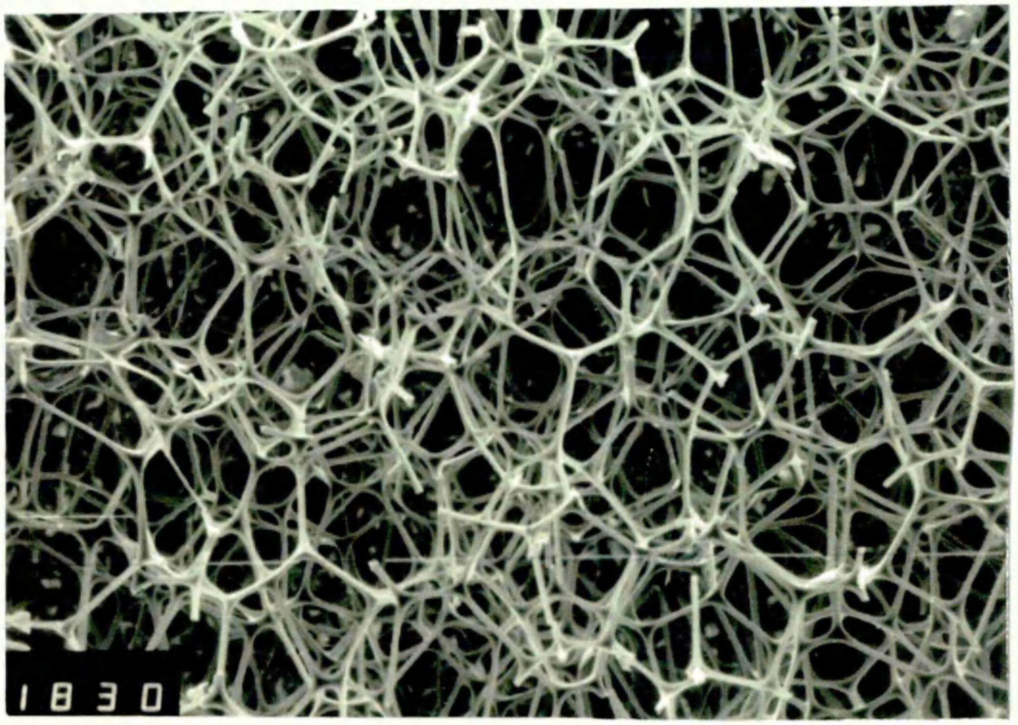

Figure 111 Micrograph of melamine foam (Basotec, manufactured by BASF).

Basotec is manufactured by emulsification of a liquid blowing agent with a melamine formaldehyde precondensate to reduce an open cell foam. By variation in the degree of expansion, materials are created with varying mechanical properties, from the very flexible (almost elastomeric) to the extremely brittle qualities of the rigid thermosetting polymer precursor. Further modifications to the morphology and hence the mechanical properties are possible by thermo- mechanical post treatment. When the material is heated to a suitable temperature and compressed the filaments will distort. If, when the material is re-cooled, the compression is maintained, the filaments sustain most of their distortion. The retained distortion will increase the apparent density of the foam and changes the general appearance of the material: it becomes woolly in texture. Typical density is between 11 and 25 $kg.m^{-3}$ and can be increased to the order of 100 $kg.m^{-3}$ by the thermo mechanical post treatment. When lower density virgin foams are treated the thinner filaments will remain, hence the foam will retain flexibility, but the filaments will be distorted. It is possible therefore to increase the density of the material and still retain most of the flexibility of the low density foam. A degree of flexibility is lost due to interlocking of the distorted filaments.

The positive characteristics of Basotec are that it is an easily machineable material, it is possible to cut or mill accurately, its elastic resilience make it possible to press mould cut from Basotec.

The original objective of utilising the fire retardant properties of melamine in a foam has also been achieved, with Basotec reaching the highest possible flammability rating obtainable for an organic material. Thermal decomposition will take place when the material is exposed to temperatures of higher than 220° C for prolonged periods.

Acoustically Basotec has, overall, reasonable sound absorption qualities. The manufacturers have designated 11 $kg.m^{-3}$ material as their acoustic grade. The lightness of this material relative to polyurethane (acoustic grade polyurethane is typically 28- 60 $kg.m^{-3}$), together with its high resistance to flammability, makes Basotec highly suitable for any aerospace application. Other known acoustic applications include noise control in domestic and commercial premises (primarily in Europe). In the U.K. it is being used as a part of a composite panel for acoustic related automotive application. The composite is easily shaped and moulded using Basotec thermoforming qualities.

The performance of Basotec as a thermal insulator is comparable to that of other insulating materials. These thermal properties, together with an ease in processing, explain why, at present, the major application for the material is in thermal insulation.

One of the main areas in which foams constitute a serious fire hazard is seating. The lightness and fire resistance of Basotec would make it an ideal substitute for standard polyurethane foams, but unfortunately the SAG factor (2.5) of the elastified grades do not make it an ideal substitute for standard foams. The SAG factor is however close to the values required by the automotive manufacture (typically 3) and with current work being undertaken in Germany it is possible that Basotec could be developed for seating in the foreseeable future.

There are also problems with Basotec, in its affinity to absorb water. When it is used for any building applications some type of sealing or post treatment (ie hydrophobing) is often required. This modification to Basotec will have an effect on the properties, particularly the acoustic performance. Another problem, for which solutions are currently being sought, is that of mechanical strength. It requires little effort to break or tear a 40mm sheet (density 11 $kg.m^{-3}$) by hand. Also the material is easily damaged by surface abrasion. BASF is aware of the areas in which development is required and extensive research is being undertaken at their laboratories in Germany.

Polyphosphazene

To call Polyphosphazenes a new material is untrue. Its first preparation was reported in 1897 [78]. Due to early production problems of safety and stability in the constituent chemicals and the finished material, it was not possible to produce polyphosphazene commercially on any reasonable scale until 1965 [57]. The potential of polyphosphazene was originally seen by The Firestone Tyre and Rubber Co., which marketed two grades of elastomer under the trade names PNF and APN polyphosphazenes. In 1983 the Ethyl corporation obtained the exclusive world wide rights to Firestone's polyphosphazene technology. By 1985 the Ethyl group was commercially producing polyphosphazene. Several types of material are available, from a soft gum type rubber to a foam. Applications range from vibration, electrical and thermal insulation to seals and hoses. Although there is a highly interesting and diverse range of products only polyphosphazene foam will be discussed here.

Polyphosphazene polymer can be processed using standard rubber compounding equipment. Standard additives such as blowing agents, plasticizer, fillers and curatives can similarly be used in typical formulations. This interchangeability between equipment and chemicals used in polyphosphazene and other foamable elastomeric material production will reduce research and set-up costs making polyphosphazene an attractive commercial prospect.

Criteria for the selection of functional ligands in the foamable polyphosphazene polymer are processability, non use of halogenated organic groups and high flame resistance. The polymer that has been selected by the Ethyl Corporation for its polyphosphazene is an Aryloxypolyphosphazene elastomer, trade name EYPEL $_{TM}$-A. Material characteristics make polyphosphazene foam easily processed, particularly in extrusion. One of the main uses for the polyphosphazene foam has been in extruded section, for thermal and acoustic insulation of structural components e.g. pressure hulls of submarines.

The basic morphology of the cells within the foam is regular closed cells; these cells tend to be substantially enlarged towards the surface of the material. Closed cells have many advantages in terms of resistance to liquid ingress, but closed cells will lead to poor air flow qualities and hence reduced acoustic absorption.

Of all the commercially exploitable characteristics attributed to polyphosphazene foam, flame resistance is the most prominent. In comparing polyphosphazene to other materials (a table of characteristics is given in Appendix 6), it can be seen that its flame resistance is greatly improved on standard foams and a slight improvement compared to that of other high performance cellular polymers. Being nitrogen filled, closed celled polyphosphazene is a very good thermal insulator with poor sound absorbing characteristics.

Polyimide

Again, this is a relatively new polymer to be foamed. It was produced originally by the Imi-Tech corporation of America in about 1982, under the trade name Solimide. Polyimide foam came to the U.K. about two years later and has been distributed by several companies. Initially polyimide production was hampered by processing problems these have been overcome with a novel foaming technique. Powdered polyimide prepolymer is mixed with a blowing agent. To polymerise, cross link and expand the mixture microwave heating is employed. It is the high thermal insulation of polyimide foam that prohibits the use of conventional heating techniques.

The ability of polyimide to char rather than burn means that little smoke will be created. Generally the material will be stable up to 260°C and will function down to -180°C. Originally unsuitable for seating because of its high compression set, the manufacturers brought out a cushion grade of solimide in 1986. The material can be made at several different densities with varying cell sizes and a variety of properties. All the grades are very light compared with polyurethane foams (typical densities are between 7 and 12 $Kg.m^{-3}$) and all retain excellent flame retardant properties.

Acoustically Solimide has a fair performance, though obviously the different grades have different sound absorbing characteristics. This reasonable acoustic absorption is related to the air flow resistance of the material. From an inspection of micro graphs the cell look closed. There is, however, a degree of air flow through all grades and this is probably due to the rupturing of cell windows during manufacture. Also from the micro-graphs and from inspection of the material there is elongation of the cells. Elongation will be associated with the anisotropy of the characteristics of the foam.

Silicone Foam

First made commercially in the early sixties, the original foams were unstable at elevated temperature. Several modifications have been made to the formulation, primarily the use of platinum catalysts. Many other developments of silicones used in foams have been made and are well documented in References [50][65][51]. A large variation in the physical characteristics is shown to be possible without the detraction of low toxicity and the recently achieved stability at high temperatures. In the literature a great deal of data has been presented on how changes in chemistry will affect properties such as strength, density and flame retardancy with little data on acoustic absorption. Lee and Spells [51] present results on acoustic measurements and discuss the effect of changes in absorption brought about by changes in formulation also the effects of additives.

Other Foams

There are many other materials that could be included in this discussion on new high performance foams e.g. Viton. Viton is fluoroelastomer (a polymer containing fluorine) manufactured by Du Pont, and is the trade name of a family of chemical and heat resistant foams. However due to its relatively high cost, closed cell nature and processing characteristics it is not used for acoustic applications.