

**A study of standard
methods for measuring
the sound quality of
industrial products:
final report**

By Nicole D Porter and Bernard F Berry

January 1997

NPL REPORT CIRA(EXT)021

A study of standard methods for measuring the sound quality of industrial products: final report

Nicole D Porter and Bernard F Berry
National Physical Laboratory
Teddington
Middlesex
TW11 0LW

ABSTRACT

This report describes a project to investigate standard methods for measuring the sound quality of industrial products. The focus is on sound quality as a measure of an undesirable feature of the noise of a product, rather than of its desirable features.

The current EC and national requirements relating to the measurement of the acoustic output of industrial products are described. Any changes to methods of labelling to express sound quality information should be considered as an extension and not an alternative to the current framework. The concept of product sound quality is reviewed. It is shown that sound quality is not an absolute parameter but orientated towards a certain product and customer. The measurement of sound quality is a multi-dimensional problem requiring knowledge of auditory and non-auditory aspects of the sound and emotional and cognitive factors. The report discusses how the demand for extended noise information is increasing as more emphasis is placed on the sensory perception of products. For successful labelling, reliable and meaningful methods for delivering the information to the customer are required.

A number of candidate options currently used for describing the sound quality of products are described. These complementary measures can be divided into those that describe individual acoustic features of the sound and those that attempt to combine the features into an overall perceptual index. Since an overall evaluation is dependent on source type, it is concluded that it may be difficult ever to develop a global index that is independent of the actual source type. The feasibility of extending the current noise labelling system was investigated through consultations, case studies and a round table discussion. It is concluded that research is required in the short, medium and long term to explore the feasibility of introducing the 'quality stamp' approach (within 2 years), standardisation of loudness, tonality and impulsivity descriptors (5-10 years), and standardisation of other sound quality metrics (10-20 years).

© Crown Copyright 1997
Reproduced by permission of the Controller of HMSO
ISSN 1361-4053

National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW.

Extracts from this report may be reproduced provided the source is acknowledged.

Approved on behalf of Managing Director, NPL,
by A J Marks, Director, Centre for Ionising Radiation and Acoustics

CONTENTS

1	INTRODUCTION	1
2	REVIEW OF STANDARDS RELATED TO PRODUCT NOISE LABELLING	2
2.1	OLD APPROACH DIRECTIVES	2
2.2	NEW APPROACH DIRECTIVES	2
3	REVIEW OF SOUND QUALITY	5
3.1	BACKGROUND TO THE TERM "SOUND QUALITY"	5
3.2	THE SOUND QUALITY OF PRODUCTS	5
3.3	ASSIGNMENT OF SOUND QUALITY AS A MULTI-DIMENSIONAL TASK	6
3.4	CUSTOMER DEMANDS AND PRODUCT LABELLING	7
3.5	RESUMÉ	8
4	REVIEW OF EXISTING SOUND QUALITY MEASURES (CANDIDATE OPTIONS)	9
4.1	INTRODUCTION	9
4.2	STANDARD ANALYSES	9
4.2.1	Sound Level	9
4.2.2	Spectral Analysis	9
4.3	AUDITORY MODELS FOR SIGNAL REPRESENTATION	10
4.3.1	Sottek's model	10
4.3.2	Binaural models	10
4.3.3	Auditory streaming models	10
4.4	PSYCHOACOUSTIC INDICES	11
4.4.1	Loudness	11
4.4.2	Sharpness	12
4.4.3	Roughness	12
4.4.4	Fluctuation strength	13
4.4.5	Tonality	13
4.4.6	Impulsivity	14
4.4.7	Articulation index and speech interference level	16
4.5	GLOBAL EVALUATIVE COMBINED INDICES	16
4.5.1	Acoustic Quality, Q	17
4.5.2	Annoyance index	17
4.5.3	Weighted Sensation Level Function, WSLF	18
4.5.4	Sensory pleasantness	19
4.5.5	Unbiased annoyance (UBA)	19
5	FEASIBILITY STUDY	20
5.1	INTRODUCTION	20
5.2	PRELIMINARY CONSULTATIONS	20
5.3	CASE STUDIES	21
5.4	ROUND TABLE DISCUSSION	22
5.5	OVERALL FINDINGS	23
5.5.1	Existing situation on noise labelling	23
5.5.2	Complementary methods	23
5.5.3	Options for future noise labelling requirements	24
5.5.4	Research Needs	25

6	CONCLUSIONS	26
7	ACKNOWLEDGEMENTS	27
8	REFERENCES	28

TABLES AND FIGURES

APPENDICES

Appendix A:	Questionnaire
Appendix B:	Details of preliminary discussions
Appendix C:	Details of round table discussion meeting

1 INTRODUCTION

This study of standard methods for measuring the sound quality of industrial products was carried out for the DTI National Measurement System Policy Unit. The objectives of the project were:

- to investigate the use of standard methods of measuring the acoustic output of industrial products, and the concept of 'sound quality', to define types of industrial products or grade examples of the same type.
- to produce a study report which addresses the issue of how 'sound quality' of products should be defined, measured and integrated into the existing standards framework.

The study was not concerned with products whose function is to produce sound, nor directly with the manipulation by designers of product sound. The focus was on 'sound quality' as a measure of an undesirable feature of the product's noise rather than of its desirable features.

Two reports have been previously submitted in fulfilment of project milestones 1 and 2. Milestone 1 was *"to produce a preliminary report to identify candidate options"* and milestone 2 was *"to present the preliminary findings in sufficient detail to assess likely outcome, structure and topics to be addressed in the final report"*. This final report fulfils the last milestone *"to produce a study report of the outcome of the study"* and brings the information from the previous reports together.

Section 2 reviews the existing Directives and standards pertaining to the noise emission of industrial products. Section 3 reviews the concept of sound quality generally. Section 4 reviews candidate options for broader measures of sound quality of products. Section 5 describes the feasibility study examining how the various methods for quantifying and expressing sound quality could be applied to different types of product. The feasibility study consisted of preliminary consultations, case studies and a round table discussion. Section 6 presents the overall conclusions to the study and sets out the way forward to extend and introduce sound quality measures into the existing framework for noise labelling and declaration.

2 REVIEW OF STANDARDS RELATED TO PRODUCT NOISE LABELLING

There are various situations in which the need arises for the manufacturers and designers of industrial products to quantify the acoustic output of their products, and for those who specify or use such products to have an indication of the acoustic output. However, the key driving force behind the requirement to quantify the sound emitted by industrial products, and to declare the results of such quantification in various ways - including labelling of the product - is the existence of a range of EC Directives. These can conveniently be considered as being of two general types.

2.1 OLD APPROACH DIRECTIVES

These Directives, mostly published prior to 1985, each apply to a particular product such as motor vehicles¹, motorcycles², air compressors³, tower cranes⁴, welding generators⁵, power generators⁶, concrete breakers⁷, earth-moving machines⁸, lawnmowers⁹ and household appliances¹⁰. In each case the technical requirements for noise testing are an integral part of each Directive.

Such Directives typically contain a clause or "Article" requiring that, prior to being placed on the market, the products shall *"in a clear and durable fashion either directly or on a plate (such as a rivetted or self-adhesive plate) permanently attached to them bear marks identifying the manufacturer, describing the type and indicating the maximum sound power level expressed in dB(A)/1 pW"*.

Unlike the other products referred to above, household appliances are not subject to a requirement to meet an actual limiting level. Rather, the Directive (86/594/EEC) is concerned with ensuring that if noise information is provided it is given in terms of the A-weighted sound power level.

In 1992, a framework Directive¹¹ was published applying generally to labelling and product information on the consumption of energy and other resources by household appliances such as refrigerators, washing machines, dishwashers, ovens, water heaters, lighting sources, and air-conditioning appliances, with provision for further types of appliances to be added. This Directive states that the implementing Directives shall *"make provision for the inclusion on the label, or on the fiche, of information on airborne noise, where such information is provided pursuant to Directive 86/594/EEC."* The first such implementing or application Directive which related to refrigerators, freezers and their combinations, was adopted by the Commission on 21 January 1994. This was enforced in the UK on 1 January 1995 through the Energy Information (Refrigerators and Freezers) Regulations 1994. On 23 May 1995, the Commission adopted further application Directives relating to washing machines and tumble dryers. Relevant Energy Information Regulations came into force in the UK on 1 April 1996. An example of the energy label, which shows the provision for including noise labelling is given in figure 1.

Standardised procedures for determining the noise emitted by household appliances and for verifying declared noise emission values are given in a test code¹² published by the International Electrotechnical Commission (IEC). The fact that such a test code has been produced can be taken as an indication of how much the industry recognises the pressures from the domestic consumer for information on noise of products.

2.2 NEW APPROACH DIRECTIVES

In May 1985, a resolution on a "New Approach to Technical Harmonisation and Standards" was adopted by the Council of Ministers. The resolution emphasised *"the importance and desirability of the new*

approach which provides for reference to standards - primarily European Standards - ..for the purposes of defining the technical characteristics of products..”

The four fundamental principles on which the New Approach is based are as follows:

- EC Directives contain the essential requirements with which products must conform,
- the task of preparing technical specifications in the form of harmonised standards is entrusted to the European Committee for Standardisation (CEN),
- the technical specifications are not mandatory and are to be considered voluntary standards, but
- products complying with the provisions of harmonised standards are presumed to comply with the essential requirements established by the Directives.

The essential components of the framework within which the standards related to noise have been developed are therefore:

- CEN and its Technical Committee TC211 “Acoustics”,
- the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), to whom CEN look, whenever possible, in order to transform International standards into European standards,
- the relevant Technical Committee, Sub-committees and Working Groups of ISO and IEC, in particular ISO/TC43/SC1/WG 28 “Standards for sound power measurement”, and
- the associated Technical Committees of BSI.

Each New Approach Directive published after 1985 prescribes the essential requirements for a broad product category, and defines the procedure for obtaining the declaration of conformity or CE mark. This mark shows compliance with the essential requirements of the Directive, one route to which is compliance with CEN standards. In future, products without the mark may not be offered for sale within the European Union.

The most wide-ranging of these Directives affecting industrial products is the so-called Machinery Directive¹³. This Directive applies to all machinery, defined as an “assembly of components, at least one of which moves, for a specific application, in particular for the processing, treatment, moving or packaging of material”. The Directive is principally concerned with the safety of machines, including the need to control excessive sound emission. The Directive sets out two essential safety requirements:

- The machinery must be so designed and constructed that the risks resulting from the emission of airborne noise are reduced to the lowest level taking account of technical progress and the availability of means of reducing noise, in particular at source.
- Specified quantitative information on airborne noise emitted by machinery under defined operating conditions must be made available by the manufacturer.

The Directive gives detailed instructions regarding the nature of the information to be provided, and the form in which it is to be presented. The acoustical quantities to be measured are the overall sound power level (in dB(A) re 1 pW) and the emission sound pressure level (in dB(A) re 20 μ Pa) at the workstation (operator position). The decision on which of these two parameters is included in the information provided by the manufacturer, is made by comparing the emission sound pressure level at the workstation to thresholds defined in the Directive. If the emission sound pressure level exceeds 85 dB(A), then both quantities must be declared.

Noise information must be given in the instruction handbook of the product and also in any technical documentation describing the product. This latter requirement is important because it ensures that the information on noise is made available not only after the product has been bought but also before purchase. Noise is thus considered part of the product performance, allowing a potential buyer to consider the noise issue before purchase.

To comply with the Directive, manufacturers can refer to harmonised European standards giving methods of test and CEN and ISO are working closely together to produce suitable standard specifications for noise measurement. The standards of interest are all Type B standards within the CEN hierarchy, that is they apply in principle to the noise of a wide variety of machinery. Type C standards giving detailed machinery-specific methods will be based upon these, and they will select and refer to individual Type B standards for the appropriate method of noise measurement. The most relevant Type B standards are those in the ISO 3740 series, which describe methods of determining sound power levels from measurements of sound pressure level around the machinery¹⁴⁻²². The various parts are designed for different acoustic environments and achieve different levels of accuracy. The ISO 9614 series of standards describes methods of determining sound power level by sound intensity level measurement²³⁻²⁴.

Detailed requirements for the declaration of noise emission information are dealt with in the ISO 7574²⁵ series published in 1985 and ISO 4871²⁶ published in 1984. ISO 4871, having completed the final stages of revision and ISO voting procedures, now awaits actual publication. It is intended that it will be a key document in the implementation of the Machinery Directive. Of particular importance in the present context is the fact that the standard will provide two options for the treatment of measurement uncertainties in noise labelling. Users will be able either to add together the measured value and the uncertainty to give a single figure or to state separately the measured value and the uncertainty.

Also in the process of being formulated is a new directive on "Noise requirements for machinery used outdoors". It should be noted that this proposed directive will not replace the Machinery Directive. For those machines to which the new directive applies, some will be required to have noise labels which are very similar to those discussed above, whilst others will also have to meet a noise limit. There is at present intense discussion on all aspects of this directive, including the question of which machines will have to meet limits.

3 REVIEW OF SOUND QUALITY

3.1 BACKGROUND TO THE TERM "SOUND QUALITY"

Those involved with designing or legislating for quieter products have been principally concerned with reducing the energy emitted by the products. The rationale for these efforts, in terms of noise levels, appears to be "the lower the noise level the better". This seems a sensible approach for many products that emit high energy levels that are potentially hazardous to health. However many products now only emit "safe" amounts of energy.

More recent work has developed a multi-layered approach to noise design and control. This is not only based on reducing the total energy emitted, but evaluating and controlling the impact of noise characteristics contained in the time structure and frequency spectrum. This is in line with the recently evolving methods to deal with environmental noise assessment, based on the analysis of individual acoustic features ²⁷.

The adoption of the term "sound quality" in the mid-eighties recognised that acoustic emissions have more features than level alone. Furthermore, the auditory events associated with the features have other characteristics apart from loudness. Identification and measurement of the features led to the separation of various physical and psychophysical quantities. Sets of these quantities were then used to describe the "sound quality" of a sound.

The term "sound quality" has evolved further in the past few years and at the same time the concept of product quality has been introduced. A variety of standards have introduced quality in the context of industrial products e.g. ISO 8204:1994²⁸. These have related quality to *'the suitability of a product with respect to specific present demands'*.

Blauert²⁹ defined sound quality as:

'the adequacy of a sound in the context of a specific technical goal or task'.

Depending on one's expectations of a sound, the word "adequacy" may suggest either an essential quality of the sound related to sufficiency to a task, or an incidental quality of the sound related to detraction from a task. As explained in Section 1, the emphasis in this study has been on the concept of sound quality as applied to the incidental and generally undesirable noise emitted by a product. In any event, it is important to note that the concept of sound quality implicitly involves subjective judgement.

3.2 THE SOUND QUALITY OF PRODUCTS

The sound quality of a product has been defined by a number of researchers. Their definitions show considerable commonality in their approach to the topic. Blauert, in his work to develop and define "product-sound quality", limits his definition of "sound" to the auditory event attached to perceiving a sound rather than the actual physical event (acoustic signal). He associates "product" with specific examples of a product as well as a class of product. Using this, Jekosch and Blauert³⁰ defined "product-sound quality" as:

"A descriptor of the adequacy of a sound attached to a product. It results from judgements upon the totality of auditory characteristics of the said sound - the judgements being performed with reference to a set of

those desired features of the product which are apparent in the users actual cognitive and emotional state".

Richard Lyon³¹ has defined sound quality as:

"A perceptual reaction to the sound of a product that reflects the listener's reaction to how acceptable the sound of that product is."

Genuit³² defines acoustic quality as:

"The degree to which the totality of the individual requirements made on an auditory event are met".

He associates negative acoustic quality with a sound that produces an auditory event perceived as unpleasant, annoying or disturbing, or negative associations or incompatibility with the product. Positive quality is associated with a sound that is no longer perceived as an auditory event (or at least not a disturbing one), that is perceived as pleasant, or creates positive associations in relation to the product.

All the definitions quoted above show a consistency in that quality is related to a perception, dependent on the judgment of the totality of auditory characteristics against specific requirements. Thus the acoustic emission from the product, leads to the perception of an auditory event, upon which the hearer makes a judgement of the quality of the sound³³.

emission ➡ perception ➡ quality judgment
--

The hearer judges by reference to a set of *desired features of the product*. In particular, the hearer judges with reference to the desired features which are apparent at the time of the judgements, and this depends on their cognitive and emotional state at that time. The hearer may have prior knowledge of the individual product sample or class of products and can compare the auditory attributes with a desired set they already have in mind. As a result, they assign a given sound quality to the product. Emotions are involved if a judgement is affected also by the emotional state of the hearer. An example of the dual involvement of cognition and emotion is given by the judgment of the noise of a chain saw being used by another person to cut down trees which the hearer feels should remain.

3.3 ASSIGNMENT OF SOUND QUALITY AS A MULTI-DIMENSIONAL TASK

Evaluating product sound quality depends on three main areas of knowledge and experience³⁴:

- (i) *acoustics*, especially related to mechanical engineering and physics,
- (ii) *psychoacoustics*, i.e. basic relationships between the acoustic input and the perception of the sound,
- (iii) *psychologic effects and rules* which govern the judgement process by which sound quality is assessed.

There is a continuing debate as to whether quality can be assigned to an auditory event, disregarding the product itself and essentially without the involvement of cognition and emotion, i.e. whether it can be

assigned in an "unbiased" manner. If we assume that listeners, at least in the laboratory, are able to assess some characteristics of the auditory event in such a way that the effects of cognition and emotion are carefully monitored and can thereby be discounted, then a number of basic attributes can be used to assign quality statements to auditory events, such as loudness, pitch, pitch strength, sharpness, roughness, fluctuation strength and tonality. These are termed *psychoacoustic quantities*.

Outside the laboratory, assignment of sound quality is not limited to the use of basic psychoacoustic quantities, though these may suffice to establish a quality statement. Product sound is an important factor for customer satisfaction, but customers are not only interested in the product sound *per se*, the product sound is a carrier of information for them, e.g. it provides information about the functioning of a product and its class. Quality is judged by reference to a set of desirable auditory features as well as many kinds of desirable non-auditory ones. Assigning good sound quality therefore demands positive associations with the product. And positive and negative associations require memory, emotions and cognition, i.e. non acoustic factors and meanings. Genuit et al³⁵ have stated that

'sounds should sound pleasant, raise positive associations to the products, and not disturb otherwise'.

Sound quality is not an absolute parameter but orientated towards a certain product and customer. Assignment of a given sound quality has been described as a multi-dimensional problem requiring knowledge of auditory and non-auditory aspects of the sound and emotional and cognitive factors. Basic psychoacoustic measures cannot take into account meaning, and they are of only limited use for sound quality evaluation. Nevertheless, it may be possible to utilise some of these basic measures in constructing more useful measures of sound quality.

3.4 CUSTOMER DEMANDS AND PRODUCT LABELLING

Lyon³¹ suggests that sound quality, especially in home appliances, is becoming more important to consumers and companies as an element of the total quality concept, because consumers are ready to pay more for appliances which sound less annoying and more pleasant. In fact factors contributing to the selection of electrical home appliances were investigated by Kuwano et al³⁶ and the noise level was ranked third following efficiency and price. This leads to the conclusion that sound quality is one of the most important product features of home appliances.

At present, where products are labelled by manufacturers with their noise output, either by regulation or voluntarily, the purpose is principally to reduce the environmental and health effects of noise. Sound quality evaluation and the extension of labelling to noise levels below those which may be hazardous would help meet the requirement from users and customers for more noise information. The significance of this extension is illustrated by consideration of a hair dryer. A hair dryer may not produce so much noise that it disturbs your neighbour or puts at risk your hearing, but the noise may nevertheless have a "roughness" characteristic because of the coincidence of a resonance and a blade passing frequency which the user perceives as irritating and unpleasant and indicative of a malfunction or poor product quality.

Labelling is principally concerned with the end product, but it is worth considering how the output is designed (or not) and tested with respect to the design target. The sound quality of products can be designed and tailored at various stages through a product cycle:

- (1) Design specification stage.
At the product design stage, a target sound can be considered. This may be based on existing, older, comparable products or possibly on sound simulations.
- (2) Testing of targets
Expert opinion, management opinion and customer opinions are all important when deciding on the target sound of the product. This can be done through jury experiments, sound simulations etc and leads to a final product design specification.
- (3) Building of a prototype
Once a prototype of a new product exists, a new stage of sound quality evaluation can begin since the actual operating noise of the components are available for analysis and test. The prototype can also be tested against the target sound. Based on detailed knowledge of the origins of the sources of sound, design changes can be developed. This can be done by obtaining judgments on the sounds or by adopting signal manipulation techniques to amplify or reduce contributions from different noise sources.

More information on sound quality evaluation in the product cycle can be found in ref³⁷.

It is likely to be cheaper to design a product correctly than to retrofit or re-design at a later stage. Therefore, since customers are placing more importance on the sensory perception of products, designers should include this in design. Manufacturers should also learn to sell their product by labelling it in a way that will encourage the customer to buy it, based on both its functionality and its sensory qualities. However, for successful product labelling, there needs to be agreement on reliable methods of delivering this information to the customer.

3.5 RESUMÉ

Sound quality is not an absolute parameter but orientated towards a certain product and customer. Assignment of a given sound quality has been expressed as a multi-dimensional problem requiring knowledge of auditory and non-auditory aspects of the sound and emotional and cognitive factors. Basic psychoacoustic measures cannot take into account meaning, so they are of only limited use for sound quality evaluation. More sophisticated measures can be developed, but it may not be prudent to try to adopt a global index for all circumstances. The demand for extended noise labelling is increasing as more emphasis is placed on the sensory perception of products. For successful labelling, reliable and meaningful methods are required for delivering the information to the customer.

4 REVIEW OF EXISTING SOUND QUALITY MEASURES (CANDIDATE OPTIONS)

4.1 INTRODUCTION

There are a number of problems which hinder the development of a general method for evaluating sound quality, including cognitive influences and the fact that the evaluation is a multi-dimensional task (physical, psychoacoustical and psychological). It is possible to quantify specific dimensions and to cope with some cognitive factors, but it is almost impossible to set up a general rule about which dimensions are selected and how they are combined to derive a global index³⁸. It is therefore imperative that the users of any indices for sound quality evaluations do not ignore the restrictions. As a prerequisite, the user must be aware of the background, the restrictions and the applicability of the methods.

Methods used to describe aspects of sound quality were divided into four groups by Bodden³⁸:

- basic or standard analyses (often considered as a first step to building further indices)
- auditory models (to represent the auditory system capabilities)
- indices to predict psychoacoustic quantities
- indices to predict global evaluative measures (combined indices).

These will be discussed in turn. All the measures described can be considered as candidate options for quantifying sound quality as set out in the objectives of this project. A number of analysis packages are available to calculate a variety of indices (see Bodden³⁸).

4.2 STANDARD ANALYSES

Traditional analyses are limited to the analysis of signals in a purely physical manner. They can only give a general indication of the auditory attributes of the sound. For example, sound pressure level can give a rough impression of perceived loudness and spectral analysis can give information about a variety of perceptual attributes e.g. tonality, pitch.

4.2.1 Sound Level

The sound level can be measured over various time intervals and can be expressed in a number of ways. This may include filtering to obtain A-weighted (or B, C or D-weighted) levels which attempt to simulate the sensitivity of the ear to different frequencies.

4.2.2 Spectral Analysis

Spectral analysis gives an indication of how the energy of the stimulus is distributed across the frequency spectrum. A basic choice is made between constant absolute bandwidth analysis and constant percentage bandwidth analysis. Octave and third-octave band analysis are examples of the latter and are widely used.

The mathematical basis of frequency analysis is the Fourier transform which takes different forms depending on the type of signal being analyzed. Fourier demonstrated that a complex waveform can be analysed into a series of sinusoidal components at various frequencies, each having a given amplitude and

phase. In principle the analysis requires an integration over infinite time which is impossible practically and not in line with how the ear works. A process called windowing is therefore applied in which a sample of the waveform is observed within a time window and is assumed to have a value of zero outside the time limits of the sample.

The Fast Fourier Transform (FFT) is a calculation procedure for obtaining Discrete Fourier Transforms (DFT). This reduces the number of arithmetic operations compared with direct evaluation. FFT analysis operates on whole blocks of data at a time and is not a continuous process. The FFT can be used to give spectrograms representing both the temporal and spectral characteristics of the sound. The major drawback of FFT is the fixed frequency resolution whereby the signals are represented by frequency channels of constant absolute bandwidth. The frequency resolution capabilities of the human auditory system are unlike this in that the bandwidth is narrow at low frequencies and wider at higher frequencies. Hence constant percentage bandwidth analysis is often used, of which octave and third-octave band analysis are examples.

4.3 AUDITORY MODELS FOR SIGNAL REPRESENTATION

To overcome the problem that FFTs do not emulate the non-constant bandwidth frequency resolving characteristics of the ear, models have been developed to follow more closely the capabilities of the auditory system. Some models incorporate head transfer functions to take into account diffraction and reflections caused by the outer geometry of the ear. In future these models may enable the separation of a complex sound into its basic components so that they can then be assessed individually. The models are not as yet suitable for sound quality assessment but could offer possibilities for the future.

4.3.1 Sottek's model

This model is based on the monaural signal processing abilities of the human auditory system based on anatomy and physiology, particularly of the basilar membrane. It takes into account the non-linear properties of the ear. The model can be used to calculate a number of psychoacoustic indices and could form a basis on which to evaluate sound quality. The model is described in detail in reference³⁹.

4.3.2 Binaural models

Although the auditory system comprises two ears, most current measurement indices use monaural sound recordings and analysis techniques. Binaural processing using information relating to the differences of the signals at the two ears, can improve our ability to detect and analyse signals in noisy backgrounds, suppress room echoes, and locate sound sources in reverberant rooms. Binaural recordings (using dummy heads) and analysis techniques can therefore offer additional information, above that of the monaural system, relating to spatial discrimination, directionality, selectivity, suppression and pattern recognition. Furthermore, these systems can have considerable benefits when emulating simultaneous, pre- and postmasking effects. This information facilitates the extraction of sounds from a mixture of signals and can have an effect on perceived sound quality. More information on binaural systems is given in reference⁴⁰.

4.3.3 Auditory streaming models

When we listen to a rapid sequence of sounds, the sounds may be perceived as a single perceptual stream, or they may be split into a number of perceptual streams, a process known as primary auditory streaming segregation or fission. Fission is more likely to occur if the elements making up the sequence differ significantly in frequency, amplitude, location or spectrum. Such elements of a sound would normally

emanate from more than one sound source. The general principles which govern the perceptual organisation of the auditory world correspond well to those described by Gestalt psychologists. Under the principle of similarity, sounds are grouped into a single perceptual stream if they are similar in pitch, timbre, loudness or subjective location. Usually we attend to one perceptual stream at a time which stands out from the background formed by other streams. Stream formation may also depend on information not directly available in the acoustic waveform. Using streaming models, the auditory scene is analysed and the individual acoustic objects are formed.

4.4 PSYCHOACOUSTIC INDICES

The link between auditory attributes and objective measures is psychoacoustics. As a result of psychoacoustic research, psychoacoustic quantities have been developed. These quantities and their relation to the physical parameters of the acoustic signal are the basis of the calculation of psychoacoustic indices. The indices therefore represent instrumental measures to predict psychoacoustic quantities. The development of the indices has been based on psychoacoustic investigations which have in some instances been carried out only on a number of specific signals and are therefore of limited use. The indices are mainly defined for monaural listening only.

The descriptions below give an overview of the currently available psychoacoustical indices. These are loudness, sharpness, roughness, fluctuation strength, tonality, impulsivity, articulation index and speech interference level. They have been incorporated into a number of commercially available acoustical analysis systems. Apart from loudness, these indices are not as yet standardized.

4.4.1 Loudness

Loudness belongs to a category of intensity sensations. It is assumed that sound is analysed in the hearing system by a bank of filters. The bandwidth of these filters corresponds to equal subdivisions of the critical band rate scale or critical bands. These in turn correspond to equal subdivisions of the basilar membrane in the human inner ear, where the frequency-place transformation takes place.

The critical bandwidth is about 100 Hz at lower frequencies (< 500 Hz) and grows logarithmically at higher frequencies. Above 300 Hz, critical bandwidths are comparable with the third-octave band filter width (around 23% of centre frequency). The ear can build critical bands with values which are not integer values of the critical band rate scale since the ear can be regarded as a set of continuously overlapping filters.

The concept of loudness was developed to project human perception of loudness over a linear scale. A pure tone of 1 kHz and a sound pressure of 40 dB is defined as having a loudness of *1 sone*. Signals perceived as being twice as loud have a loudness of *2 sone*. For sinusoidal signals an increase in sound pressure level of 10 dB leads to a multiplication of loudness by two.

The *loudness level* of a sound, measured in *phon*, is numerically equal to the sound pressure level of a pure tone at 1 kHz, which produces the same sensation of loudness as the sound in question. The dependence of the loudness of narrow band sounds on frequency can be represented as a set of equal loudness level contours. Such a representation shows that the hearing system is most sensitive for frequencies around 4 kHz, and has reduced sensitivity at higher and lower frequencies. Furthermore, particularly at low frequencies, the contours are not parallel but are level dependent. A-weighting is based on the 20 phon contour which represents a fairly low-level sound. In fact for everyday sounds, A-weighting

underestimates the loudness of low frequency components.

That our ear adds intensities that fall into the width of one critical band to give a total level has been shown by Zwicker and Fastl⁴¹. Consequently the loudness of a band of noise measured as a function of the width of the band does not increase up to a certain bandwidth (about the same size as the critical bandwidth) for a constant overall sound level of the test signal. Beyond this bandwidth, there is an increase in loudness. When the bandwidth of a sound is sufficient to occupy more than one critical band, the loudness in adjacent, but non overlapping, bands is summed to give the total loudness.

Loudness can be judged for sounds in the quiet or for partially masked sounds, with the effects of partially masked loudness being both spectral and temporal. Masking represents one of the most basic effects in psychoacoustics. It is important to the judgement of a number of features of sound in noise, including loudness. Masking is the amount (or the process) by which the threshold of audibility for one sound is raised by the presence of another (masking) sound. A masking pattern can be thought of as a graph of the amount of masking (in dB) produced by a given sound as a function of the frequency of the masked sound. Further details can be obtained from reference⁴¹.

Zwicker has developed a calculation procedure for loudness which has been adopted in ISO 532B⁴² which uses masking patterns. The spectral effects of loudness can be assessed using multi-channel analysis. The fundamental assumption of the loudness model is that loudness is not produced from spectral lines or from spectral distribution of the sound directly but that total loudness is the sum of the specific loudnesses that are produced at different critical band rates.

4.4.2 Sharpness

There has been a tendency to transfer any aspect of a steady sound not related to loudness or pitch to a sensation called timbre. Often, important sensations are extracted from timbre. The sensation of *sharpness* is one of these. The hearing sensation of sharpness represents an attribute for the evaluation of tone colour. The most important parameters influencing sharpness are the spectral content, the centre frequency of narrow band sounds and their bandwidth. The sensation of sharpness is produced by high-frequency components in acoustic signals. Like loudness, sharpness is defined as a linear sensation. A narrow band noise around 1 kHz with a bandwidth lower than 150 Hz (the critical bandwidth) and a sound pressure level of 60 dB, is said to have a sharpness of 1 *acum*.

Although the calculation of sharpness has not been standardised, most algorithms use an equation derived by Aures⁴³ to determine sharpness from specific loudness.

4.4.3 Roughness

The sensation of *roughness* results from amplitude modulations of a sound at frequencies between around 15 Hz to 300 Hz^{41,44}. The maximum roughness sensation is at around 70 Hz. At lower frequencies, noises are not perceived as rough, with the sensation being described as *fluctuation strength*. At higher modulation frequencies, the components of an amplitude modulated signal become audible as separate tones.

Roughness is produced not only by amplitude modulated tones, but also by frequency modulations and amplitude modulated noise. The unit of roughness is the *asper*. A pure tone of 1 kHz and 60 dB, whose amplitude is modulated at a frequency of 70 Hz and a degree of modulation of 1, is said to have a roughness of 1 asper. Roughness is only very slightly dependent on the sound pressure level of the signal.

Roughness has not been standardised. One analysis suite (HEAD BAS system) adopts a calculation based on partial roughness from degrees of modulation of band signals and adds them to get a total roughness value⁴⁵.

4.4.4 Fluctuation strength

Fluctuation strength is the sensation associated with amplitude modulation at very low modulation frequencies (usually < 15 Hz). It depends on a number of parameters including modulating frequency, modulation depth, centre frequency and frequency deviation. The sensation reaches its maximum at modulation frequencies of about 4 Hz. Like roughness, fluctuation strength is not greatly dependent on the sound pressure level of the signal. The corresponding unit, *vacil*, is determined by the same method as for roughness, but in this case with a modulation frequency of 4 Hz rather than 70 Hz.

4.4.5 Tonality

The problem of quantifying, in an objective way, the tonality of noise has received considerable attention, primarily in research on the assessment of environmental noise. The findings are however generally applicable in the context of product sound quality. The presence of tonal features has often been judged subjectively where the noise is considered to contain a whine, hiss, screech etc. For objective identification, we need to look more carefully at the auditory system and associated signal detection mechanisms.

It is now generally accepted that the ear can be modelled as a bank of parallel bandpass filters having overlapping centre frequencies. The basilar membrane provided the basis for this model. Each location on the basilar membrane responds to a different range of frequencies, so that each different point corresponds to a filter with a different centre frequency. The width of each auditory filter is the critical band.

When trying to detect a tone in background noise the listener is assumed to make use of a filter with a centre frequency close to that of the tonal signal. This filter will pass the signal but will remove a great deal of the noise. Only the components in the noise which pass through the filter will have any effect in masking the signal i.e. the masking effects of a broadband noise on a pure tone do not extend beyond the limits of the bandwidth of the auditory filter (critical band) surrounding the tone. It is generally assumed that the threshold for a signal (tone) is determined by the amount of noise passing through the auditory filter; specifically, threshold is assumed to correspond to a certain signal-to-noise ratio at the output of the filter.

In general the masked threshold of a pure tone in wide band noise occurs where the sound pressure level of the tone is of the order of 4 to 6 dB below the sound pressure level of the noise as measured across the surrounding critical band (a ratio of 1:2.5). Under these circumstances the combination of tone and noise will have an overall sound pressure level (as measured over the critical bandwidth surrounding the tone) approximately 1.5 dB greater than the sound pressure level of the critical band of noise alone. Methods based on this type of ratio are often referred to as tone-to-noise ratio (T/N) methods. They appear to be well suited for isolated tones in broad-band spectra that are relatively flat.

A number of detection procedures have been developed which use octave band analysis. These include BS 4142: 1967⁴⁶. Methods which utilise more refined 1/3 octave band analysis include ISO 3891⁴⁷. In this procedure, applicable to aircraft noise, the presence of a tone is confirmed where the 1/3 octave band level

protrudes more than 2.5 dB above the level of the non-tonal noise in adjacent bands. This method adopts the principle of exceedance of a tone-to-noise ratio for identification purposes. However, work by Williams and Robinson⁴⁸ has shown that the bandwidth must be 1/9 octave or less to distinguish a noise judged to be distinctly tonal. 1/3 octave band is insufficient in objectively determining the presence of a subjectively detectable tonal noise.

A procedure has been set out by Flindell⁴⁹ for determining tone prominence based on the estimation of the sensation level of any identified tonal components above an appropriate masked threshold level. It is applicable for detecting continuous discrete tones in a steady broadband background noise⁵⁰.

The "prominence ratio" (PR) method has also been developed for characterising the perception of noise signals containing discrete tones⁵¹. The PR is the ratio of the total power in the critical band containing the prominent tone to the average power in the immediately adjacent critical bands. It appears that this ratio method is well suited to almost all types of signals including isolated tones, multiple closely spaced tones, and tones located in very irregular spectra. However, as with the T/N method, the applicability of this method to low frequency tones or to discrete tones containing strong harmonic components is questionable. Both the T/N and PR methods are referred to in Annex A of the ANSI standard S1.13:1995, "Measurement of sound pressure levels in air"⁵².

The HEAD BAS analysis suite calculates tonality using a procedure based on pitch analysis. This gives tonality in terms of tonality units (tu). A tonality of 1 tu is assigned to a 1 kHz sine wave at a level of 60 dB. The procedure is described in detail in reference⁴⁵.

4.4.6 Impulsivity

As with tonality, the impulsivity of noise has received considerable attention, in research on the assessment of environmental noise. The findings are again generally applicable in the context of product sound quality. The evaluation of the sound quality of impulsive sources, whether they be isolated impulses, such as closing doors on vehicles or domestic appliances, or repetitive impulses such as are produced by diesel engines, presents particular difficulties. No single measure of impulsivity has achieved universal acceptance and standardisation.

One rating method which has found its way into a number of standards for machinery noise emission, including computers and business machines⁵³, is based on a comparison of the readings on a precision sound level meter set to the S (Slow) time weighting with the readings when the meter is set to the I (Impulse) time weighting. The difference between the rms values of the sound pressure levels measured with the two different time weightings is taken as an indication of the impulsive character of the noise. A noise is considered impulsive if the difference is more than 4 dB.

In a study at NPL, Berry⁵⁴ compared the performance, in terms of the correlation with subjective annoyance data, of this measure, $L_{AI} - L_{AS}$, with that of a number of objective descriptors. These included the following.

Crest Factor

For this the signal was A-weighted and then sampled/digitised at 20 kHz. Then for each one second interval, the highest instantaneous value was found, and divided by the rms value for the whole one-second. The *crest factor* is 20 times the logarithm of the result.

The ISO descriptor (X)

This is closely related to the kurtosis of instantaneous values. For this a sampling rate of 5 kHz was used and the digitised sample values, v_i , processed according to the formula:

$$X = 10 \log \bar{I} \quad \bar{I} = \frac{1}{2500} \sum_{i=1}^{2500} \left[\frac{v_i^2 - S}{S} \right]^2$$

where

$$S = \frac{1}{2500} \sum_{i=1}^{2500} (v_i^2)$$

Standard deviation of $L_{Aeq(10ms)}$

A sampling rate of 20 kHz was used, and for each 10 ms period in a one-second interval, a value of $L_{Aeq(10ms)}$ was calculated to give a time-series. The *standard deviation* σ was calculated according to the formula:

$$\sigma^2 = \frac{1}{100} \sum_{j=1}^{100} (L_j - \bar{L})^2$$

$$\text{where } L_j = L_{Aeq(10ms)} \quad \bar{L} = \frac{1}{N} \sum_{j=1}^N L_j \quad N = 100$$

Kurtosis of $L_{Aeq(10ms)}$

Just as standard deviation is a measure of variability, so *kurtosis* is a measure of the “peakedness” of the distribution of values in the time series. It was calculated according to the formula:

$$k = \frac{\frac{1}{N} \sum_{j=1}^N (L_j - \bar{L})^4}{\left[\frac{1}{N} \sum_{j=1}^N (L_j - \bar{L})^2 \right]^2}$$

Salience of $L_{Aeq(10ms)}$

This was obtained by calculating the difference between the highest value of $L_{Aeq(10ms)}$ in a one-second interval and the value of L_{Aeq} for the one-second interval. There was a good correlation with the ISO

descriptor. This was similar to the result found in work on the evaluation of helicopter noise, which led to the development of the ISO descriptor⁵⁵.

Increment

The use of short-term L_{Aeq} was investigated further at NPL during the EC sponsored Joint Project on Impulse Noise⁵⁶. From this, a further descriptor was developed called *increment*, obtained by taking differences between successive values of $L_{Aeq(10ms)}$, and noting the maximum positive difference. The *increment* descriptor was found to be superior to the others in terms of correlation with subjective data⁵⁷.

Other measures

The development of a loudness meter based on ISO 532B⁴², but capable of displaying the temporal aspects of loudness, was demonstrated at Internoise 85 by Zwicker⁵⁸. Berry and Zwicker⁵⁹ described how the noise signals used in the NPL studies in reference²⁶ were re-analysed using this meter. A statistical measure N_{20} (the loudness exceeded for 20% of the time) was found to be preferable to the use of maximum loudness.

Russell⁶⁰ has described a Diesel Noise Quality analyser which measures the impulsive characteristic using a quantity derived from the ratio of the 4th power of the signal amplitude to the square of the variance.

In working towards the adoption of standardised measures of the sound quality of impulsive sources, two issues will predominate: the need to ensure that any measure can deal with a wide range of impulsive noises, and the question of the relationship between impulsiveness and other attributes discussed earlier in this section, such as roughness and fluctuation strength.

4.4.7 Articulation index and speech interference level

Some features of noise are not determined by a measure of sensation level but how the noise interferes with an activity e.g. understanding speech. When it comes to determining the extent of the masking of speech by noise, the pattern of the masking noise, as well as its loudness, is important. In general, low tones mask high tones better than *vice versa*. Speech signals are quite complex and the most effective masking noises are also quite complex. However, low bands mask most important low and high frequencies in speech. The frequencies that best mask speech are not the most annoying ones independent of their effect on ongoing activities. Most schemes, such as articulation index (AI) and the speech interference level (SIL), take this patterning into account.

For the articulation index, the frequency range from 250 to 7,000 Hz is divided into 20 bands, each of which contributes 5 % to the total intelligibility. In order to determine the AI for a particular noise, the difference in dB between the average speech level and the average noise level in each of these 20 bands is calculated, and the resultant numbers are combined to give a single index. Essentially, this process predicts how much masking of individual speech sounds will occur and then integrates this information.

For SIL, a commonly-used definition is the arithmetic average of the sound pressure levels in the three octave bands centred at the preferred frequencies 500, 1,000, and 2,000 Hz (abbreviated SIL 0.5, 1, and 2). Many variations of SIL in terms of the specific octave bands to be averaged have been suggested.

4.5 GLOBAL EVALUATIVE COMBINED INDICES

Since sound quality cannot be determined by psychoacoustic variables alone, a number of indices have been proposed that yield a global quality index. These however can only render reliable results for rather limited

well defined tasks. The following presents a number of these indices. Other indices have been developed, e.g. the Composite Rating of Preference (CPR)⁶¹. Many of these are unpublished and confidential since they are product specific and used by individual companies for competitive advantage. Since the majority of sound quality research work has been focused on automobile noise, most of these descriptors relate specifically to this type of source.

4.5.1 Acoustic Quality, Q

Genuit^{32,40} has examined the limitations of simple A-weighted descriptors for sound quality and has derived a combined index for acoustic quality evaluation termed Q . He concurs with others that if sound events are similar in terms of their temporal structures and spectral patterns and are only different in relation to absolute level or absolute loudness, the human ear is almost unable to detect the difference: in investigations regarding acoustic quality, the absolute variable, loudness or A-weighted SPL, is almost without significance. Temporal structures and spectral patterns are more important in deciding whether a sound makes an annoying or disturbing impression.

He suggests that the application of purely psychoacoustic indices is limited because of the following disadvantages:

- (1) The mathematical description of psychoacoustic variables is currently based exclusively on investigations using basic test signals in an anechoic environment. Their applicability in the case of complex sound situations including spatially distributed sound sources is limited.
- (2) Currently available psychoacoustic calculation techniques take into account neither the adaptive behaviour of human hearing nor its binaural characteristics.
- (3) A further disadvantage arises from the lack of standardisation of psychoacoustic calculation variables, which compromises the comparability of measurement results.

On the basis of his considerations, he has developed an innovative procedure for the determination of acoustic quality. This involves the continuous formation of a reference signal from a sound event as an average in the time and frequency domain. This provides an anchor sound from the sound event which can serve as reference for transient spectral or temporal variations in the signal curve. He obtains a single-value measure of acoustic quality from a complex algorithm containing: the mean values of the critical band levels over a period of 2 to 4 seconds, the mean value of the critical band levels over a much shorter period, weighting factors dependent on the critical band levels, and a function of the loudness and sharpness.

Genuit expresses the advantage of this technique as acoustic quality being determined without reference to a separate reference sound. It can also account for the adaptive behaviour of the human ear and does not depend on non-standardized psychoacoustic variables. On the other hand, this approach involves such complex signal processing techniques that for practical adoption it would have to be coded very efficiently and suitable means devised for verifying the code.

4.5.2 Annoyance index

This index was developed by AVL List GmbH, Austria. It combines four objectively measured parameters:

- (1) Loudness, according to ISO 532B
- (2) Periodicity, in terms of perceived fundamental repetition frequency
- (3) Sharpness
- (4) Impulsiveness, determined from kurtosis.

These have been combined on the basis of a series of subjective tests using paired comparisons to generate suitable regression analysis to provide one uniformly applicable formula for all the noises examined⁶². This global index was shown to be a useful instrument for the objective analysis of real engine noise. The index is very specific to the situations from which it is developed, though it could be tailored towards different sound sources by re-analysing the judgements. However, it would not be easy at this stage to have a universally applicable index to provide consistent results in a number of different situations.

4.5.3 Weighted Sensation Level Function, WSLF

In examining the acoustic quality of vehicle interior noise, Flindell and Lewis⁶³ have developed a new index, the Weighted Sensation Level Function, WSLF, based on the actual acoustic features present in the noise. They appear to agree with Genuit that simple physical measures, such as A-weighted sound level, provide only a relatively poor correlation with subjective response to vehicle interior noise. Also, simple measures do not provide sufficient information about the character of the sound. The listener generally concentrates on an evaluation of the separate sources contributing to the total sound, and might well find certain low level components particularly irritating.

The approach is based on feature detection (by exceeding a detectability threshold) and feature enhancement (drawing attention to the feature in the overall noise ensemble by increasing its sensation level above detectability). This is in line with an approach to environmental noise assessment proposed by Porter et al²⁷, where the main emphasis is on assessing the relative significance of individual components of features within an overall sound rather than on the overall sound *per se*.

The WSLF model takes a weighted sum of the degree to which each component (acoustic feature) sensation level separately exceeds a defined effective threshold. This means that separate component sensation levels below effective threshold do not count, and therefore only features that can actually be measured as contributing to an adverse response are included. The defined effective threshold represents the amount by which the sensation level of a separate component has to exceed zero before it actually becomes significant in terms of noisiness or acceptability, and would normally be in the range 0 to 10 dB. A multiplier is used to weight the relative importance of each component to the overall noisiness and acceptability, in the particular context being tested.

The WSFL function has shown, in a number of subjective listening tests, considerable potential, especially when compared to other measures. Inherent in this approach are important implications for noise control and assessing noise quality. It implies that reductions in the separate contribution made by individual components or features in the overall sound field, below the effective sensation level threshold for that component, will not give corresponding improvements in perceived sound quality. On the other hand, even small increases above the effective threshold might give significant reductions in perceived sound quality.

This approach appears to be fundamentally logical and has potential. However, it still needs further development if indeed it can be put to practical use to describe the sound quality of a product. The weighting functions can be derived for specific situations but depend on the context. Furthermore, improved measures of the sensation levels of particular features are needed to enable one to reliably determine the sensation level of an arbitrary feature in any masking noise in the general case.

This approach is similar to the Annoyance Index approach in that it examines a number of parameters and weights their contribution towards a final evaluative number. However it is dissimilar in the way that it quantifies a positive sensation level above a threshold.

4.5.4 Sensory pleasantness

This is a complex sensation that is influenced by auditory sensations such as roughness, sharpness, tonality and loudness, although it depends mainly on sharpness. Aures⁶⁴ proposed an index as a combination of these parameters. He defined this index as a sensory quantity, which means that it describes purely auditory attributes without considering other influencing factors like cognition.

4.5.5 Unbiased annoyance (UBA)

Annoyance is an expression often used because it is assumed that public reaction to noise is based on annoyance. However, use of this term has a number of disadvantages. First, it is not defined and therefore may have a different meaning to different people. Secondly, it is strongly biased and depends on the view of the listener towards the noise. Zwicker proposed a way to alleviate these inconsistencies by introducing an *unbiased annoyance* that does not depend on the relationship of the listener to the sources of noise. He showed that loudness is the main determinant of unbiased annoyance. Further work has shown that fluctuation strength and sharpness also have a role. Zwicker gave a formula for unbiased annoyance, UBA, containing the parameters: sharpness, fluctuation strength, N_{10} (the value of loudness that is exceeded 10% of the time), and a correction factor for the time of day. The tonal components of any noise are accounted for by using the appropriate loudness calculation procedure. These factors are explained with full details in reference⁴¹.

5 FEASIBILITY STUDY

5.1 INTRODUCTION

In the last section different physical measures were identified which can be used to quantify and express the sound quality of industrial products. The objective of the feasibility study was to examine how these might be applied to different types of product and how they might be integrated into the current system for describing the acoustic output of products. Five main criteria for assessing their suitability were adopted:

- ease of understanding
- practicality of application
- the adequacy with which the method represents the perceived sound quality
- compatibility with existing standards.
- reproducibility

The feasibility study was conducted in three stages: preliminary consultations, case studies and a round table discussion. These will be presented in turn, with the main findings collated at the end of the section.

It was originally intended to investigate the practical implementation of the sound quality measures identified in Section 4 using noise data on a number of different industrial products previously tested by NPL. However, preliminary consultations suggested that it is unlikely that a single measure will be appropriate for all types of product. It was therefore decided that it would be preferable to demonstrate the various measures on a more limited range of products, including more than one example of some of the product types. These "case studies" required the identification of additional noise recordings.

It was also intended to rate each of the measures against the criteria given above, using a matrix approach. However, since each measure appears to have particular merits depending on the product type, and there are "family connections" between some of the individual measures, it was not deemed sensible to analyse them in this way. Instead, the utility of the measures are discussed in the light of the results of the case studies.

5.2 PRELIMINARY CONSULTATIONS

A range of users of existing standards for noise labelling and potential users of complementary methods were identified and consulted. These included product designers, manufacturers and retailers, testing laboratories and government regulators. We also visited three key researchers involved with the development and use of complementary methods.

As a framework for these consultations, we used the questionnaire reproduced as Appendix A of this report, with the key headings summarised as,

- Views on existing product labelling situation.
- Requirements for noise labelling standards and regulations.
- Satisfaction with current standards and presentation of data.
- Suggestions for improvement.
- Information relevant to current standards development.
- Interests in complementary methods (knowledge, use, benefits and disbenefits).

- Views on practicality of application of complementary methods.
- Considered research needs.

In order to focus discussions on aspects pertinent to each individual's role, we decided that it was preferable to have detailed face-to-face discussions rather than simply sending out the questionnaire to large numbers of contacts. Appendix B summarises the contacts and organisations consulted, their type of interest or involvement in noise labelling and sound quality, and the form of consultation. The findings are presented with the overall findings in 5.5.

5.3 CASE STUDIES

The aim of the case studies was to apply some of the sound quality measures to a range of noises in order to test the utility of the measures against the criteria listed in 5.1. For this, pre-recorded noises from a number of domestic products were analysed using the HEAD Acoustics Binaural Analysis System (BAS). These included noise from a waste disposal unit, hairdryer, electric shaver, washing machine in various cycles, tumble dryer (with and without a characteristic squeak), three types of vacuum cleaner, extractor fan and tv test tone. The analysis results are shown in figures 2 to 9. The issues raised are summarised below.

Basic Analysis

A spectrogram of the noise from the tumble dryer with a squeak is shown in figure 2. The squeak can be observed at 1 sec, around 3 kHz. Although the squeak is one of the most prominent features of the audible recording, it shows hardly at all in the spectrogram. Thus although the spectrogram gives a complete frequency-time-level representation of the noise, it does not convey one of the main characteristics of the noise as perceived by the hearer. Neither could it be regarded as simple and comprehensible, despite being an example of "basic or standard analysis".

Loudness Algorithms

Figure 3 shows the calculated loudness of noise from a waste disposal unit according to ISO 532B, the only standardised method for calculation of a psychoacoustic metric. The left hand side of the chart is derived from FFT data and the right hand side from 1/3 octave band levels. (This example is only a demonstration and we should not place too much significance on the actual values displayed). The graphs show that the values are different depending on the base calculation data. Quality measures can vary with analysis algorithms between and even within analysis packages. There is therefore a need for standardisation of the metrics for obtaining consistent and reproducible results.

Options for Presentation of Sound Quality Metrics

Table 1 shows a range of sound quality metrics for a selection of the noises. It is not easy to pick out the main quality features of each sound from quick examination of the table. We therefore need to consider how we present the relevant information in a more meaningful way to the end user. This may involve the selection of the most appropriate descriptor to show the relevant acoustic feature through listening tests and calculation of a number of measures.

Let us assume, as an example, we have chosen the tonality descriptor as being the most appropriate for a given range of sounds. Figure 4 shows the tonality (as calculated in HEAD's tonality units (tu)) of the noise from the extractor fan, shaver and tv test tone. The figure indicates numerical values but it is almost impossible, in the abstract, to imagine the sound implied by these numbers or to judge whether the degree of tonality indicated is good, acceptable or poor.

Let us refer back to the colour energy labelling shown in figure 1. This format could be applied to the tonality sound quality metric as shown in figure 5. As a prerequisite to displaying the information in this way, the upper and lower limits would have to be derived (in this case they are simply zero and one) and the range divided into steps, judged subjectively equal.

This type of representation could be taken one stage further into a 'quality profile'. Figure 6 gives an example of the impulsivity, tonality and loudness profile of an arbitrary sound. The horizontal scale is divided into low and high. Practically, the location of the dividing line would require research to provide values for upper and lower limits and to scale the profile line accordingly.

Phasic Machines

Figure 7 shows how the loudness and fluctuation strength vary for noise from the washing machine in different operation cycles. In displaying reproducible noise data, practical consideration will not only have to be given to selecting the best measure but also to selecting the relevant cycle(s) of operation. One option would be to provide a measure integrated over all cycles.

Product Classes

Figure 8 shows how the roughness metric varies for noise from different types of vacuum cleaners. Using this type of information, the end user can see that although each cleaner has a similar sound pressure level, choices could be made about selection of an appliance based on its roughness value. Limitations do exist for judging a product using level data alone.

Presentation of Overall Sound Quality

The overall "sound quality" as calculated using the HEAD BAS system's algorithm for a range of sources is shown in figure 9. The algorithm is based on loudness, fluctuation strength, roughness and kurtosis. The algorithm can be tailored by the user.

We need to consider what is actually meant by a global quality measure in order to recognise its limitations for presenting meaningful information. It has been explained that sound quality is judged against a desired set of features. Figure 9 attempts to compare the overall sound qualities of a range of household appliances. The implication is that it is possible to define a desired set of noise features to cover all household appliances. However, given the range of sounds emitted by household appliances it is questionable whether this could be achieved with any useful precision. What is more relevant is the noise performance of a shaver relative to normal expectations of a shaver, which in turn will be based in large measure on the performance of other shavers. (One would not expect a shaver to have the noise characteristics of a washing machine.) We would argue, therefore, that any global measure needs to be source specific in order to be meaningful.

It is also essential to define the global sound quality measure in such a way that it generates a sensible scale. Figure 9 makes no judgement about whether a high sound quality rating is "good" or "poor" but a well-defined quality measure will provide a clear separation between noises judged subjectively to be "good" and "poor".

5.4 ROUND TABLE DISCUSSION

The aim of the round table discussion was to discuss with invited representatives the preliminary results from milestones 1 and 2 of the project (review of sound quality, candidate measures and preliminary consultation findings), to demonstrate the results of the case studies and to consider the research necessary

for the successful introduction of any complementary system of product labelling. It was held at NPL on 16th January 1997. The timetable and list of attendees are given in Appendix C. The points raised are collated within the next section.

5.5 OVERALL FINDINGS

5.5.1 Existing situation on noise labelling

The organisations consulted, involved in regulation and standards development, confirmed that the review of the existing situation included in section 2 is an accurate and comprehensive account.

It was generally agreed that noise labelling standards and regulations should be clear, based on reproducible test methods, and that the A-weighted sound power level is the most basic quantity that should be provided.

There was a widespread view that the general consumer does not understand the meaning of declared noise emission values, and there was support for improved forms of labelling. Some concern was expressed at the over-complicated nature of the various machinery noise emission standards which form the basis of noise labelling and declaration. End users are confused between sound power levels and sound pressure levels. It was suggested that, as in the computer industry, sound power be expressed in bels to help with the distinction. Some felt that logarithmic noise scales are intrinsically difficult for the consumer to understand - it is not obvious why a doubling of loudness equates to an increase in level of 10 dB. On the other hand, others were concerned that trying to change the labelling requirements may complicate them. Efforts may be better steered towards increasing educational efforts aimed at the general consumer about noise labelling. There was a view that, even if there is to be no change in the form of labelling, there should be efforts to simplify the process of arriving at the noise information on the label.

Those concerned with regulation were generally satisfied with the status quo, so any changes will have to be consumer driven. Such changes may in turn provoke a heightened interest in noise.

5.5.2 Complementary methods

The complementary methods described in section 3 were considered by interviewees to be comprehensive.

There is a widespread knowledge of, and interest in, complementary methods in the automotive industry, and a wide range of analysis systems are used. However there is a lack of detailed understanding of the underlying psychoacoustics, and of the limits of applicability of various metrics.

The benefits of introducing complementary measures are seen as providing improved marketing and sales tools and aiding the consumer in selecting one product over another when factors such as cost, efficiency and the noise level may be similar. A number of manufacturers expressed the opinion that they would like to be better equipped to compare products using such measures.

The disbenefits could include over-complicating the noise information provided, turning off the consumer, and identifying an ever-growing number of complementary measures that certain interest groups may lobby for, turning the measures themselves into a sub-industry which would defeat the whole purpose for the consumer. Furthermore if any introduction of supplementary measures is ill-managed, there could be a risk of introducing confusion.

Manufacturers can see the importance of sound quality to their customers and are now beginning to take up research. Much of it is aimed however at the internal customer, e.g. product design department, rather than the consumer, and therefore the issue of simplification is not addressed. The complementary measures are used ostensibly as a guide to design better products. However, across UK industry as a whole, there seems to be a low level of knowledge of sound quality concepts.

There is an urgent need for standardisation of the various metrics. To date, only the loudness of non time-varying sounds has been standardised. Even for loudness there is evidence of significant variation in results obtained using different sound quality analysis systems. Work is in progress in American and German standards working groups to examine the work required to standardise some of the metrics.

It is very unlikely that a single approach to sound quality measurement and labelling will be suitable in all cases, and across all sources; it will have to be source-specific. Furthermore, consideration must be given to sounds that are phasic, and whether, for these sounds, it is necessary to consider the worst case.

Consideration will have to be given to whether the end user will actually use the additional information. If this is not the case, then developing these measures further will be non-productive.

It was brought to our attention that previous efforts to introduce a global noise quality rating have failed. This work related to ISO 4871²⁶. Efforts were made to introduce a low/medium/good quality rating. The division was to be based on collating machinery noise data and drawing regression lines to divide up the scale. However, no agreement was reached and there was an obvious reluctance for manufacturers to have their products declared poor in quality.

5.5.3 Options for future noise labelling and declaration requirements

As we have seen, sound quality is multi-dimensional. For successful labelling, the dimensions would have to be reduced to a manageable number. Difficulties were recognised in having global indices derived from a number of dimensions, especially for use across product classes, since the set of desired features of each product class varies. A possible approach would be to use non-global ratings as building blocks to provide an overall profile of the noise e.g. as in figures 5 and 6. It was suggested that sound power, tonality and impulsivity data could provide a large proportion of significant information in this profile.

Apart from quantitative labelling, other schemes could be considered. Our attention was drawn to schemes in operation in a number of countries, such as the "Golden decibel" in France and 'Blue Angel' in Germany. These schemes give a 'quality stamp' to products whose noise levels fall a specific number of decibels below a defined limit value. There was general consensus that this would be an attractive approach to consider.

The consultations suggest a number of options for improving and enhancing noise labelling and declaration. These would be tailored to different product classes and include:

- (1) Changing the present system numerical label into a form which is more readily understandable by the consumer, e.g. using a colour coding scheme which places it in a range, or providing a 'quality stamp' to show that it lies at a certain level below an approved limit.
- (2) Adding more basic information to the label e.g. on the phases of operation, idling speeds etc.
- (3) Providing a framework for manufacturers to declare/display information about additional noise quality parameters (using complementary measures).

To avoid over-complicating the label, complementary information could be included in the manufacturers specification or information sheets.

Different end users may require different levels of information. For instance, a research and development engineer would require more detailed information than the consumer.

It was felt that it would be inadvisable to make the provision of sound quality data compulsory. However, if data is to be declared, it should be done in a comparable and standardised way.

5.5.4 Research Needs

It was the general consensus that small companies, who could not fund their own R&D programmes, would benefit from guidance on how to make optimum use of sound quality concepts. The following were suggested as issues that will need to be resolved through research:

- Standardisation of metrics.
- Standardisation on methods of measurement.
- Research into the variability and reproducibility of measures.
- Comparability of analysis systems.
- Value of a 'quality stamp' system in the UK.
- Opportunities for competitive advantages that could arise.

At a finer level of detail, the following research steps would have to be considered if a colour-coding or profiling system was introduced:

- (1) Division of products into classes, and for each class.....
- (2) Choosing or tailoring a relevant measure through listening tests and matching indices to obtain a consistent response.
- (3) Determining the upper and lower limits of the range of the chosen descriptor.
- (4) Subdividing the range and presenting the information about where a product falls in the range in a suitable manner e.g. colour coding.

The priorities for research were set out as short, medium and long term:

- Exploration of the feasibility of introducing the 'quality stamp' approach (e.g. Blue Angel), but call it the 'Bronze Bell/Golden Ear/Golden Trumpet/Quiet Award/Low Noise Rating/Hush Mark etc' (within 2 years).
- Standardisation of loudness, tonality and impulsivity metrics (5-10 years).
- Standardisation of other metrics (10-20 years).

6 CONCLUSIONS

There is a regulatory framework currently in force for the noise labelling and declaration of products which relates to both old-style and New Approach European Directives. Any changes to methods of labelling to express sound quality information should be considered as an extension and not an alternative to the current framework.

Sound quality is not an absolute parameter but orientated towards a certain product and customer. It depends on the overall perception of a noise source. There are a large number of descriptors available to describe sound quality. These can be considered as candidate options for forming the basis of an extension to current noise labelling methods. These complementary measures can be divided into those that describe individual acoustic features of the sound and those that attempt to combine the features into an overall perceptual index.

We should consider the role of these metrics. For design purposes or evaluation, metrics which describe the individual acoustic features can be used to describe the sound, to compare sounds or to identify aspects of the sounds which may require specific attention when improving the perceived sound quality. Metrics which provide a global evaluation, by combining the indices in some way, can describe an estimated overall percept of the sound and could provide a comparison of sounds of similar products. Since an overall evaluation is dependent on source type, it may be difficult ever to develop a global index that is independent of the actual source type.

The only descriptor that is standardised is the loudness metric. Other metrics have been expressed in terms of different mathematical algorithms and implemented using different computational tools. This may lead to inconsistencies in calculated descriptors when applying these different tools. Consideration should therefore be given to standardizing the most common descriptors and methods of calculation such that like can be compared with like.

It is unlikely that the science of sound quality actually requires more metrics to be developed. To further this science, consideration should be given to increasing our understanding of the current metrics, and how these relate to an overall percept, and to presenting the information in a meaningful way to the end user. The demand for extended noise labelling is increasing as more emphasis is placed on the sensory perception of products. It is likely therefore that the development of sound quality metrics for use within a product development framework will be customer rather than regulation driven.

This study has investigated the use of standard methods of measuring the acoustic output of industrial products, and the concept of 'sound quality', to define types of industrial products or grade examples of the same type. The report has consolidated information about how the sound quality of products should be defined, measured and how to integrate it into the existing regulatory and standards framework. There would be benefits to the consumer and users from improved methods of presenting noise information on products, but we are still a long way both in time and effort from successfully integrating complementary measures of sound quality into the existing noise labelling framework.

We now need to consider the way forward. Research can be set out to do this in terms of short, medium and long term timescales: exploration of the feasibility of introducing the 'quality stamp' approach (within 2 years), standardisation of loudness, tonality and impulsivity descriptors (5-10 years), standardisation of other metrics (10-20 years).

7 ACKNOWLEDGEMENTS

The investigation described in this report was funded by the National Measurement System Policy Unit of the Department of Trade and Industry. The support of the Department is gratefully acknowledged. NPL would also like to thank all those who provided valuable feedback and participated in discussions. We would also like to thank John Shelton from Acsoft for assistance with the analysis of the sounds.

8 REFERENCES

- [1] Council Directive 70/157/EEC of 6 February 1970 on the approximation of the laws of the Member States relating to the permissible sound level and the exhaust system of motor vehicles. Official Journal of the European Communities, N° L 42, page 16.
- [2] Council Directive 78/1015/EEC of 23 November 1978 on the approximation of the laws of the Member States relating to the permissible sound level and exhaust system of motorcycles. Official Journal of the European Communities, N° L 349, 13.12.1978, page 21.
- [3] EC Directive 84/533/EEC of 17 September 1984 on the approximation of the laws of the Member States relating to the permissible sound power level of compressors. Official Journal of the European Communities, N° L 300, 19.11.1984, page 123.
- [4] EC Directive 84/534/EEC of 17 September 1984 on the approximation of the laws of the Member States relating to the permissible sound power level of tower cranes. Official Journal of the European Communities, N° L 300, 19.11.1984, page 130.
- [5] EC Directive 84/535/EEC of 17 September 1984 on the approximation of the laws of the Member States relating to the permissible sound power level of welding generators. Official Journal of the European Communities, N° L 300, 19.11.1984, page 142.
- [6] EC Directive 84/536/EEC, of 17 September 1984 on the approximation of the laws of the Member States relating to the permissible sound power level of power generators. Official Journal of the European Communities, N° L 349, 300, 19.11.1984, page 149.
- [7] EC Directive 84/537/EEC, of 17 September 1984 on the approximation of the laws of the Member States relating to the permissible sound power level of powered hand-held concrete breakers and picks. Official Journal of the European Communities, N° L 300, 19.11.1984, page 156.
- [8] EC Directive 86/662, of 22 December 1986 on the limitation of noise emitted by hydraulic excavators, rope-operated excavators, dozers, loaders and excavator loaders. Official Journal of the European Communities, N° L 384, 31.12.1986, page 1.
- [9] EC Directive 84/538/EEC of 17 September 1984 on the approximation of the laws of the Member States relating to the permissible sound power level of lawnmowers. Official Journal of the European Communities, N° L 300, 19.11.1984, page 171.
- [10] Council Directive 86/594/EEC of 1 December 1986 on airborne noise emitted by household appliances. Official Journal of the European Communities, N° L 344, 6.12.86, page 24.
- [11] Council Directive 92/75/EEC of 22 September 1992 on the indication by labelling and standard product information of the consumption of energy and other resources by household appliances. Official Journal of the European Communities, N° L 297, 13.10.92, page 16.
- [12] International Electrotechnical Commission IEC 704-3: 1992 Test code for the determination of airborne acoustical noise emitted by household and similar appliances. Part 3. Procedure for

determining and verifying declared noise emission values.

- [13] Council Directive 89/392/EEC of 14 June 1989 on the approximation of the laws of the Member States relating to machinery. Official Journal of the European Communities, N° L 183, 29.6.89, page 9.
- [14] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3740:1980, Acoustics - Determination of sound power levels of noise sources - Guidelines for the use of basic standards and for the preparation of noise test codes.
- [15] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3741:1988, Acoustics - Determination of sound power levels of noise sources - Precision methods for broad-band sources in reverberation rooms.
- [16] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3742:1988, Acoustics - Determination of sound power levels of noise sources - Precision methods for discrete-frequency and narrow-band sources in reverberation rooms.
- [17] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3743-1:1994, Acoustics - Determination of sound power levels of noise sources using sound pressure - Engineering methods for small moveable sources in reverberant fields - Part 1: Comparison method in hard walled test rooms.
- [18] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3743-2:1994, Acoustics - Determination of sound power levels of noise sources using sound pressure - Engineering methods for small moveable sources in reverberant fields - Part 2: Methods for special reverberation test rooms.
- [19] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3744:1994, Acoustics - Determination of sound power level of noises sources using sound pressure - Engineering method in an essentially free-field over a reflecting plane.
- [20] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3745:1977, Acoustics - Determination of sound power levels of noise sources - Precision methods for anechoic and semi-anechoic rooms.
- [21] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3746:1995, Acoustics - Determination of sound power level of noise sources using sound pressure - Survey method using an enveloping surface over a reflecting plane.
- [22] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3747:1987, Acoustics - Determination of sound power levels of noise sources - Survey method using a reference sound source.
- [23] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 9614-1:1993, Acoustics - Determination of sound power levels of noise sources using sound intensity - Part 1: Measurement at discrete points.

- [24] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO DIS 9614-2, Acoustics - Determination of sound power levels of noise sources using sound intensity - Part 2: Measurement by scanning.
- [25] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 75741:1985, Acoustics - Statistical methods for determining and verifying stated noise emission noise values of machinery and equipment - Part 1: General considerations and definitions.
- [26] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 4871;1984, Acoustics - Noise labelling of machinery and equipment.
- [27] Porter N.D., Flindell I H., and Berry B.F., An Acoustic Feature Model for the Assessment of Environmental Noise, Acoustics Bulletin, November/December 1993, pp40-48.
- [28] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 8204: 1994, Quality Management and Quality Assurance - Vocabulary.
- [29] Blauert J., Product Sound Assessment: an enigmatic issue from the point of view of engineering, Proceedings of Internoise '94, Yokohama, Vol.2, p851-862, 1994.
- [30] Jekosch U. and Blauert J., A semiotic approach toward product sound quality, Proceedings of Internoise 96, p2283-2288.
- [31] Lyon R.H., Theory of Sound - or is it noise. Proceedings of the Institute of Acoustics, Vol 17, Part 4, p1-7, 1994.
- [32] Genuit K., Objective evaluation of acoustic quality based on a relative approach, Proceedings of Internoise 96, p3233-3238, 1996
- [33] Blauert J. and Jekosch U., Sound quality evaluation, a multi-layered problem, Proceedings of EAA Tutorium, Antwerp, March 31, 1996.
- [34] Blauert J. and Genuit K., Evaluating sound environments with binaural technology - some basic considerations, J. Acous. Soc. Jpn (E), 14, 3, 1993.
- [35] Genuit K., Bertolini T., Brass O., Hegel S. and Veil T., A proposal for aurally-adequate assessment of electric miniature motors (in German), Fortchr. Akust. DAGA 96, Deutsch. Ges. Akust., D- Oldenburg, 1996.
- [36] Kuwano S., Namba S., Yamasaki T., and Fujiwarra S., Noise reduction in electric appliances - subjective attitudes to its cost, Proceedings of Internoise '94, Yokohama, p827-832, 1994.
- [37] Keiper W., Sound evaluation in the product cycle, Proceedings of EAA Tutorium, Antwerp, March 31, 1996.
- [38] Bodden M., Instrumentation for sound quality evaluation, Proceedings of EAA Tutorium, Antwerp, March 31, 1996.

- [39] Sottek R., Signal processing model of the human auditory system, PhD Thesis, June 1993.
- [40] Genuit J., and Poggenburg J., New approaches to transferring the term 'sound quality' into practice-related solutions, Proceedings of the Engineering Integrity Society Seminar on Advances in sound quality and engineering development techniques, Varity Perkins, Peterborough, 23 October 1996.
- [41] Zwicker E. and Fastl H., Psychoacoustics, Facts and Models, Springer Series in Information Sciences, Springer-Verlag Berlin Heidelberg, 1990.
- [42] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO R532, Method for calculating loudness level, 1971.
- [43] Aures W., Berechnungsverfahren für den Wohlklang beliebiger Schallsignale, ein Beitrag zur gehörbezogenen Schallanalyse, PhD Thesis, TU München, 1984.
- [44] Fastl H., The psychoacoustics of sound-quality evaluation, Proceedings of EAA Tutorium, Antwerp, March 31, 1996.
- [45] Head Acoustics, BAS 4.1 Binaural Analysis Manual, 1995.
- [46] BRITISH STANDARDS INSTITUTION, BS 4142 Method for rating industrial noise in a mixed residential and industrial area, 1967.
- [47] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3891, Acoustics - Procedures for describing aircraft noise heard on the ground, 1978.
- [48] Williams P. and Robinson D.W., The detection and tonal character of tones and other narrow band stimuli, ISVR Technical Report No. 159, February 1988.
- [49] Flindell I.H., The detection of discrete tones in broadband background noise in respect of a typical residential development, ISVR Contract Report 92/35, December 1992.
- [50] Porter N.D., The Assessment of Industrial Noise - Subjective Listening Tests and Objective Assessment Procedures, NPL report RSA(EXT) 0057C, June 1995.
- [51] Bienvenue G.R. and Nobile M.A., The prominence ratio technique in characterising perceptions of noise signals containing discrete tones, Proceedings of Internoise '92, Toronto, Canada, July 20-22, 1992.
- [52] AMERICAN NATIONAL STANDARDS INSTITUTE, ANSI S1.13-1995, Measurement of sound pressure levels in air.
- [53] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 7779: 1988. Acoustics - Measurement of airborne noise emitted by computer and business equipment.
- [54] Berry B.F., 1987. The evaluation of impulsive noise. NPL Acoustics Report Ac 111.

- [55] Berry B.F., Fuller H.C., John A.J. and Robinson D.W., The rating of helicopter noise: development of a proposed impulse correction. NPL Acoustics Report Ac 93, 1979.
- [56] Rice C.G, Annoyance due to impulse noise, CEC studies. Final report ISVR Memorandum 690, 1989.
- [57] Berry B.F. and Bisping R., CEC Joint Project on Impulse noise: Physical quantification methods. Proc. 5th International Congress on Noise as a Public Health Problem. Vol 3. 153- 158, 1988.
- [58] Zwicker E., Deuter K., and Peisl W., Loudness meters based on ISO 532B with large dynamic range. Proc Internoise 85. Vol II. 47-56, 1985.
- [59] Berry B.F. and Zwicker E., Comparison of subjective evaluations of impulsive noise with objective measurements of the loudness-time function given by loudness meter. Proc. Internoise 86. Vol II. 821-825, 1986.
- [60] Russell M.F., Nikokiroulis N. and Sekowski H., Subjective assessment of diesel vehicle noise, Proceedings of FISITA'92 Congress, Paper C 389/044, Institute of Mechanical Engineers, London 1992.
- [61] Callow G.D. and Hedges R., The subjective response of occupants to noise inside vehicles, Motor Industry Research Report 1979/1 and Diesel Engined Vehicle Addendum, 1979.
- [62] Beidl C.V., Application of the AVL annoyance index for engineering noise quality development, Proceedings of EAA Tutorium, Antwerp, March 31, 1996.
- [63] Flindell I.H., Lewis C., Acoustic features in vehicle interior noise quality, Proceedings of Internoise 96, Liverpool, p2479-2484.
- [64] Aures W., Der sensorische Wohlklang als Funktion psychoakustischer Empfindungsgrößen, Acustica 58, 1984.

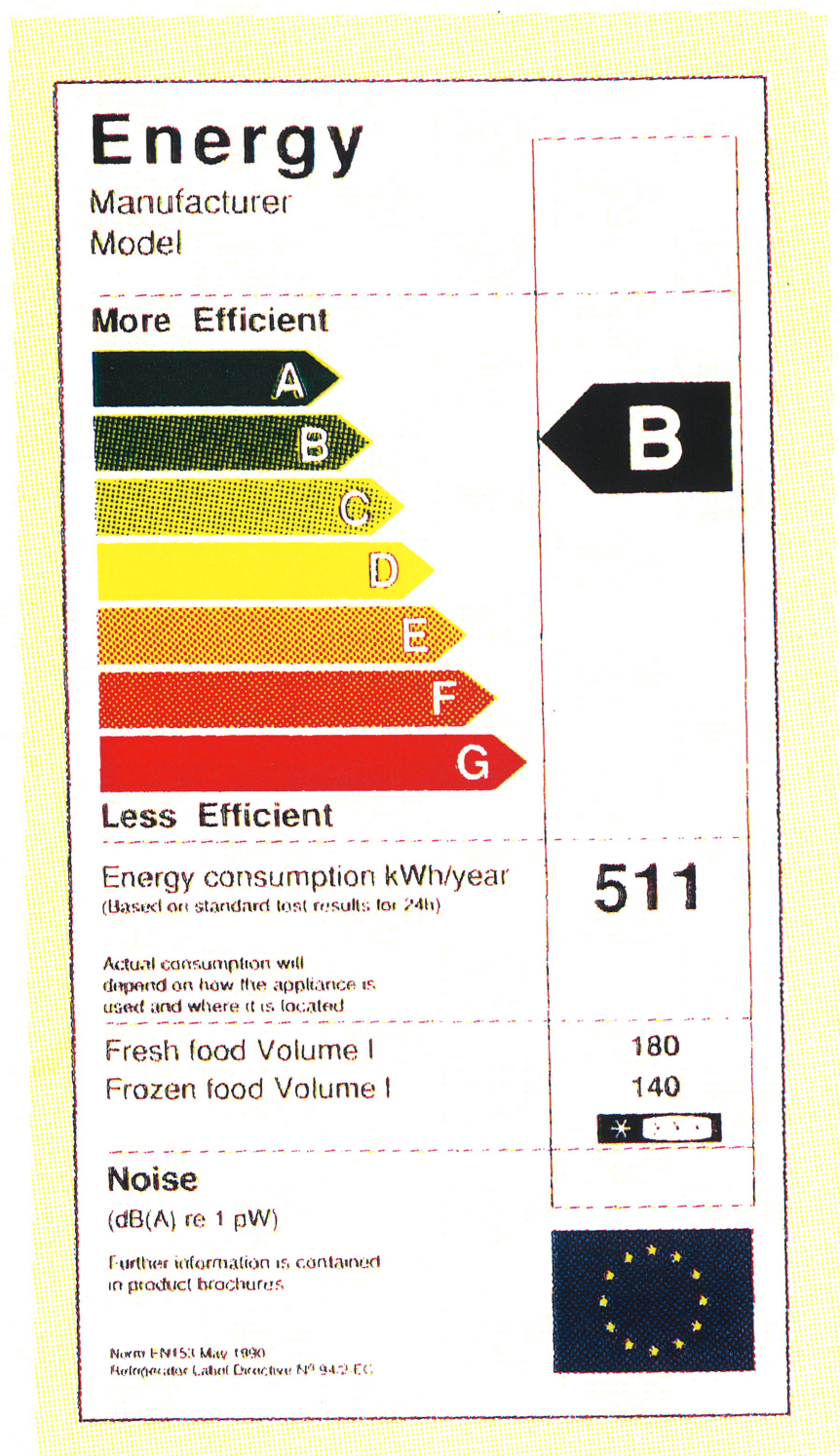


Figure 1: Example of energy label

Left Spectrum

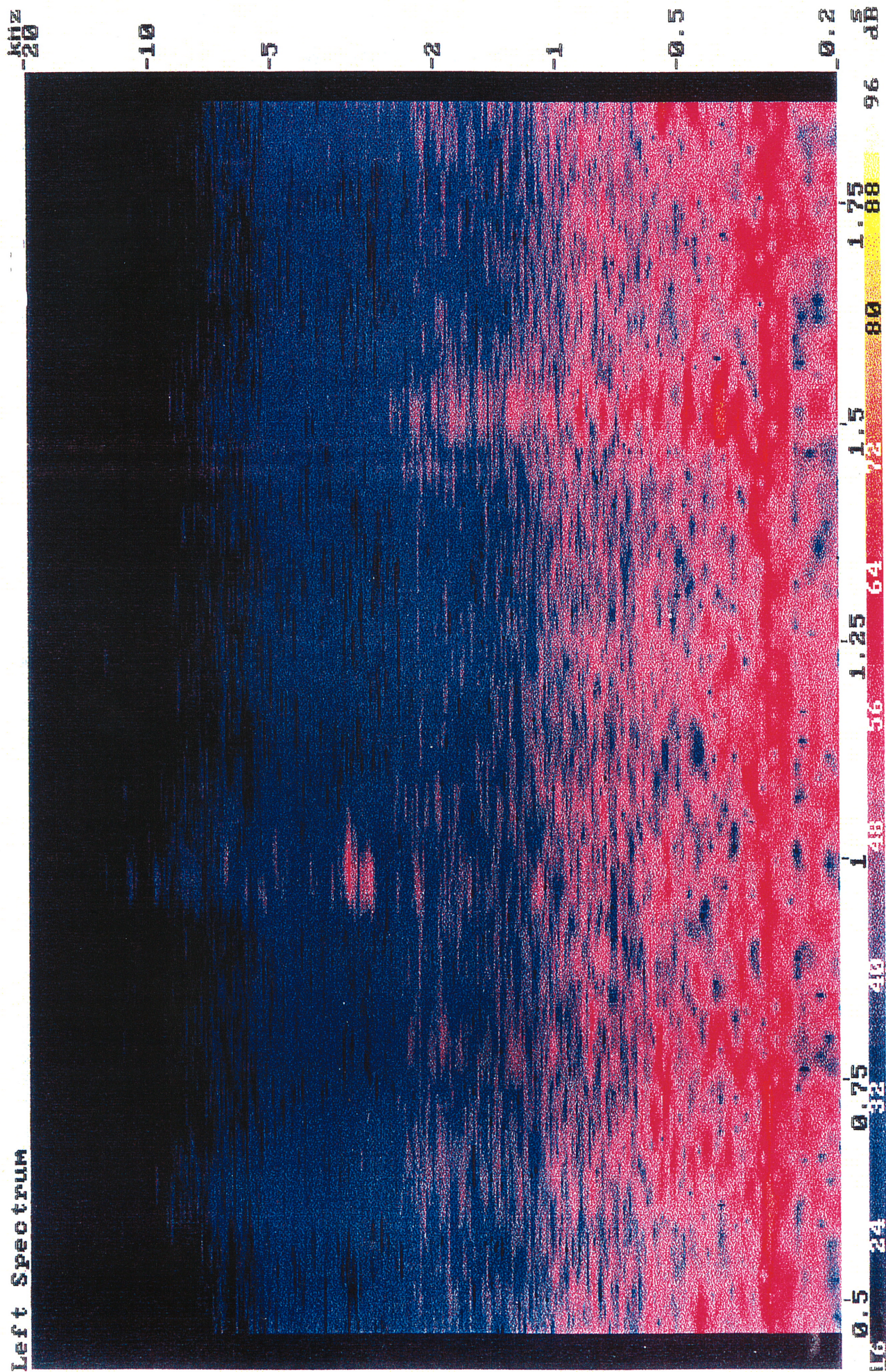


Figure 2 Spectrogram of noise from tumble drier with squeak. Time (seconds) is displayed on horizontal scale, frequency (kHz) is displayed on vertical scale, sound pressure level (dB) is represented by colour spectrum.

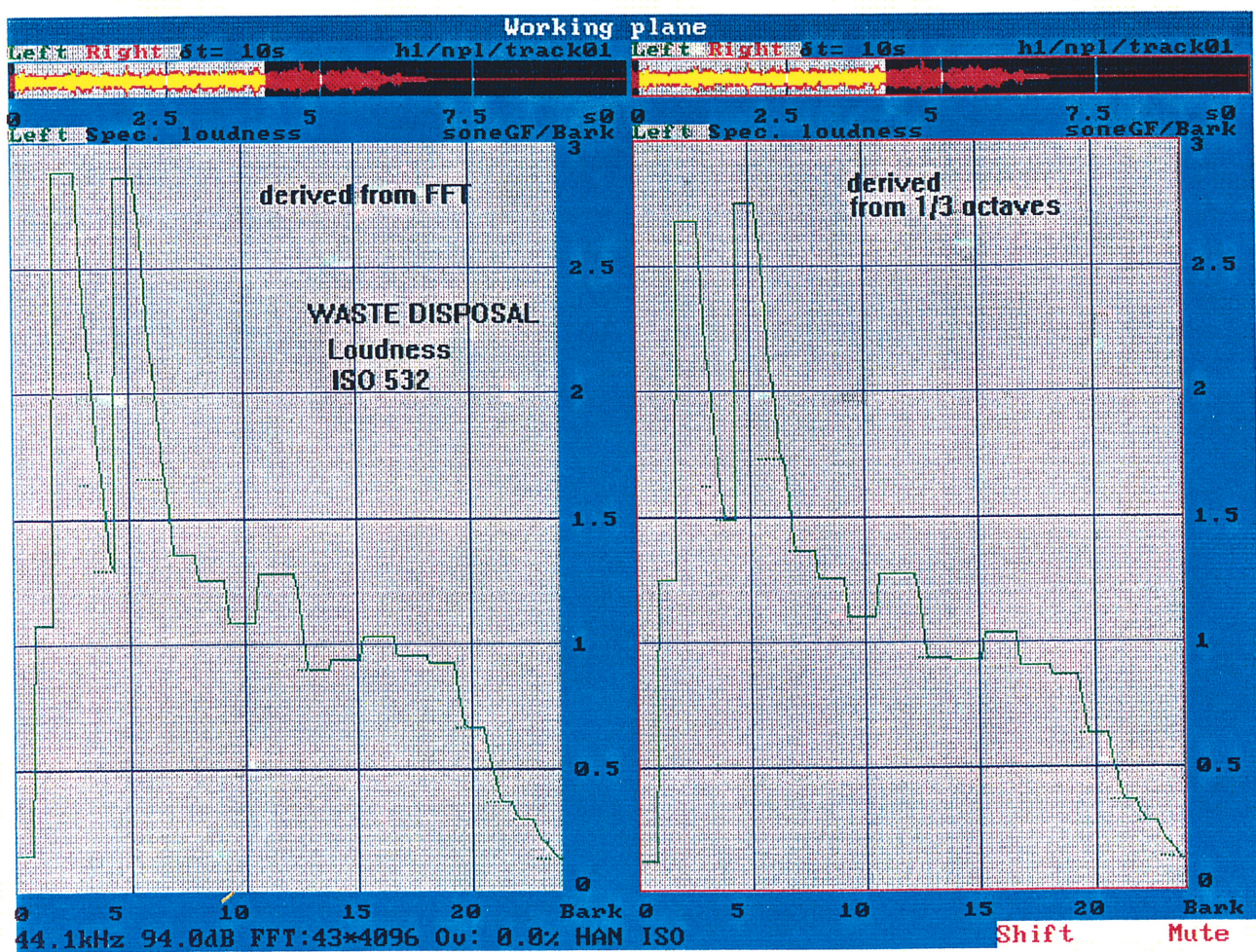


Figure 3: Loudness of noise from waste disposal unit. Frequency (Barks) is displayed on horizontal scale, specific loudness (soneGF/Bark) is displayed on vertical scale.

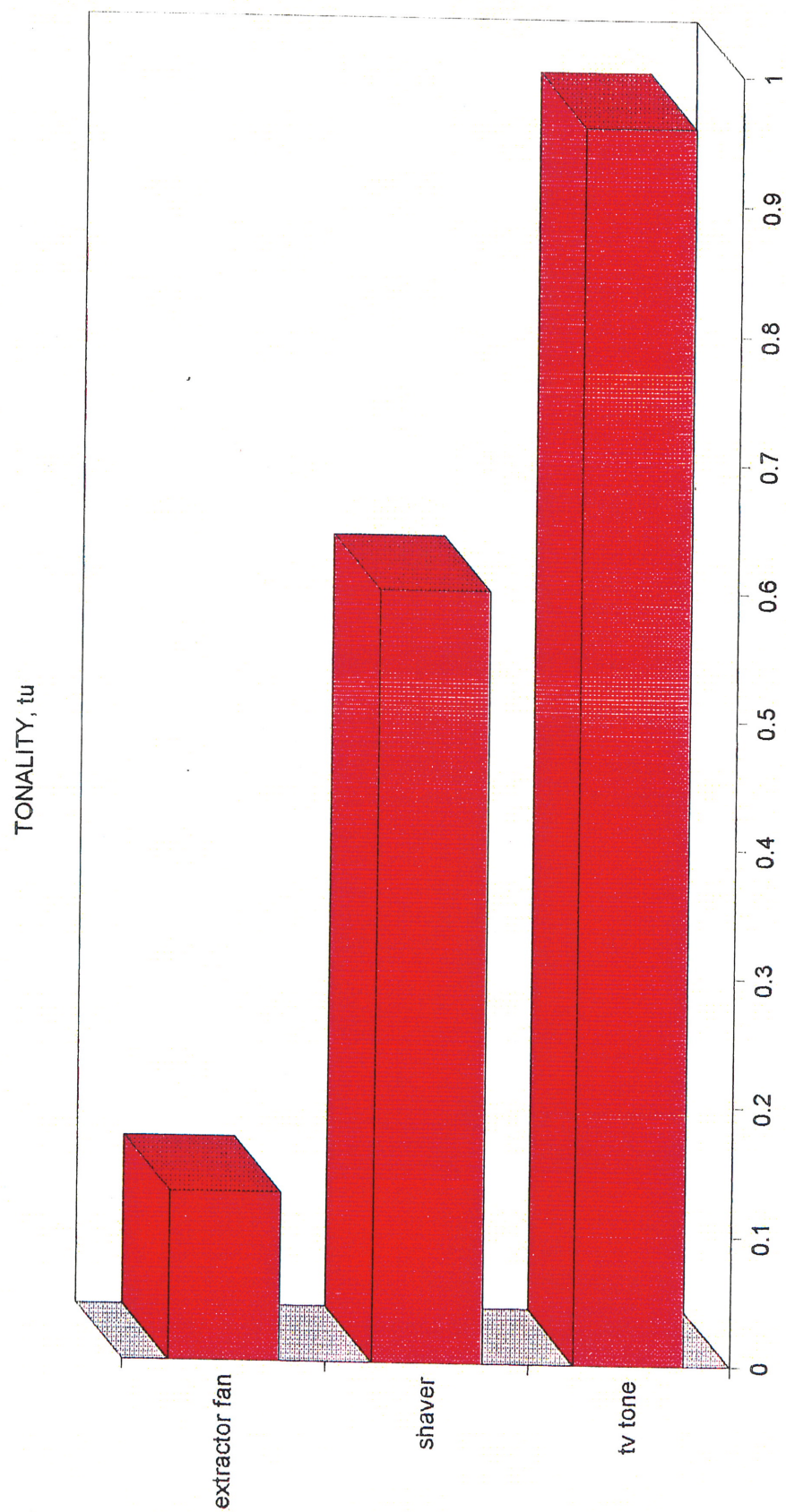


Figure 4: Computed tonality for three noise sources

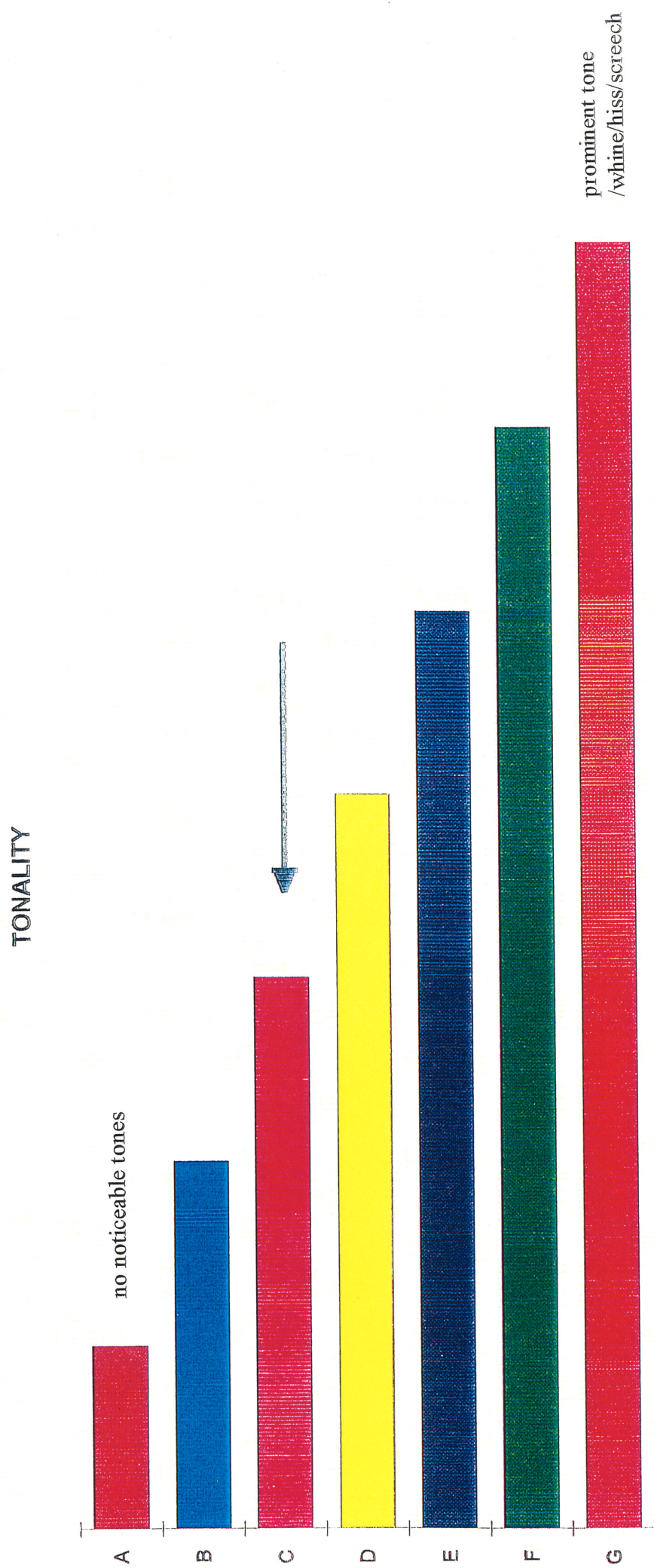


Figure 5: A colour coding scheme for tonality

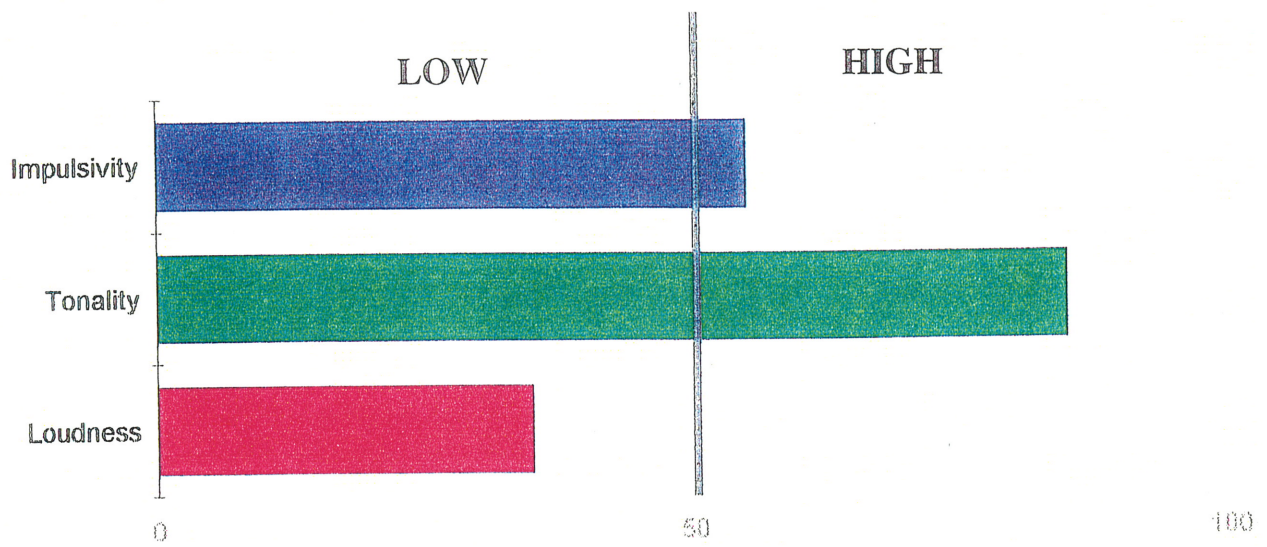


Figure 6: Example of a 'quality profile' for an arbitrary noise

PHASIC MACHINES

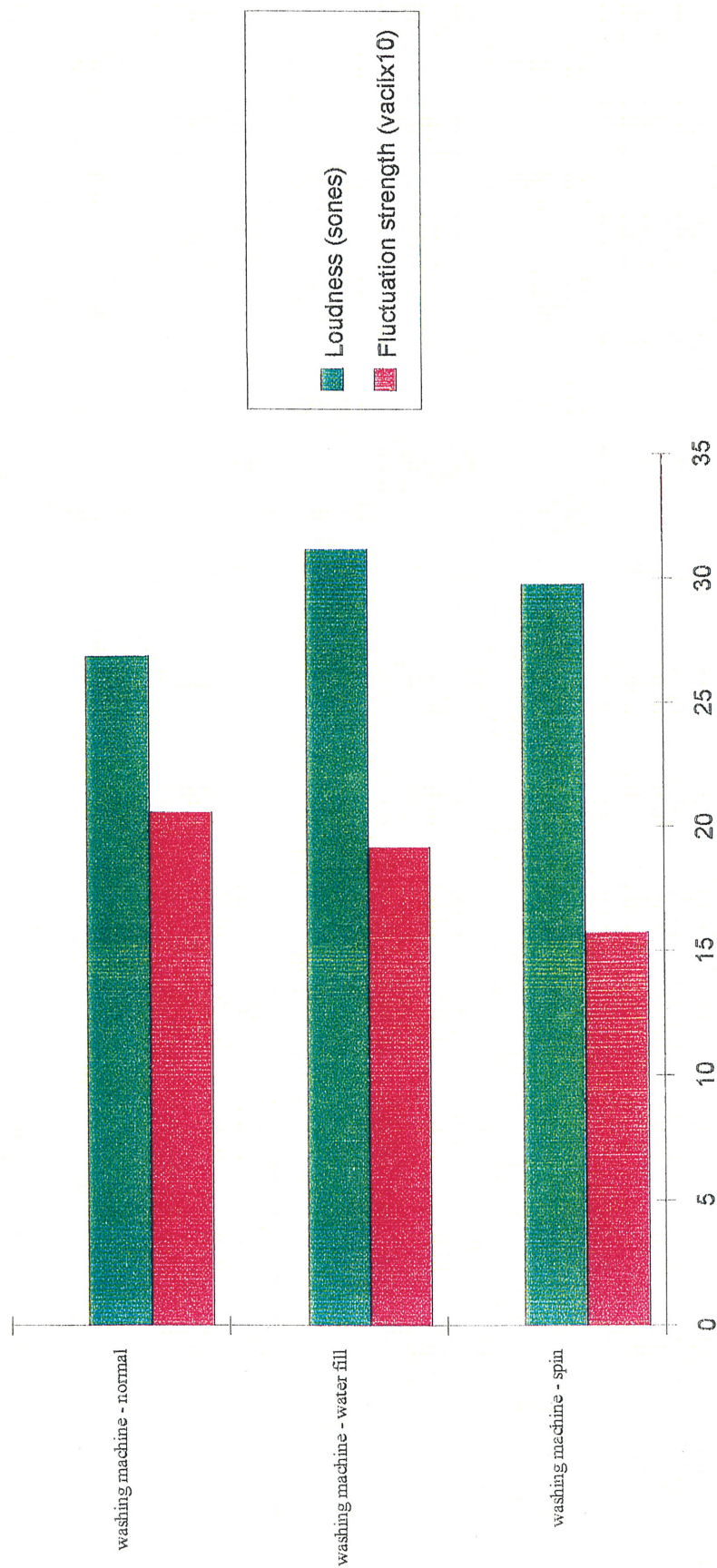


Figure 7: Loudness and fluctuation strength of noise from a washing machine in different operation cycles

PRODUCT CLASS - VACUUM CLEANER

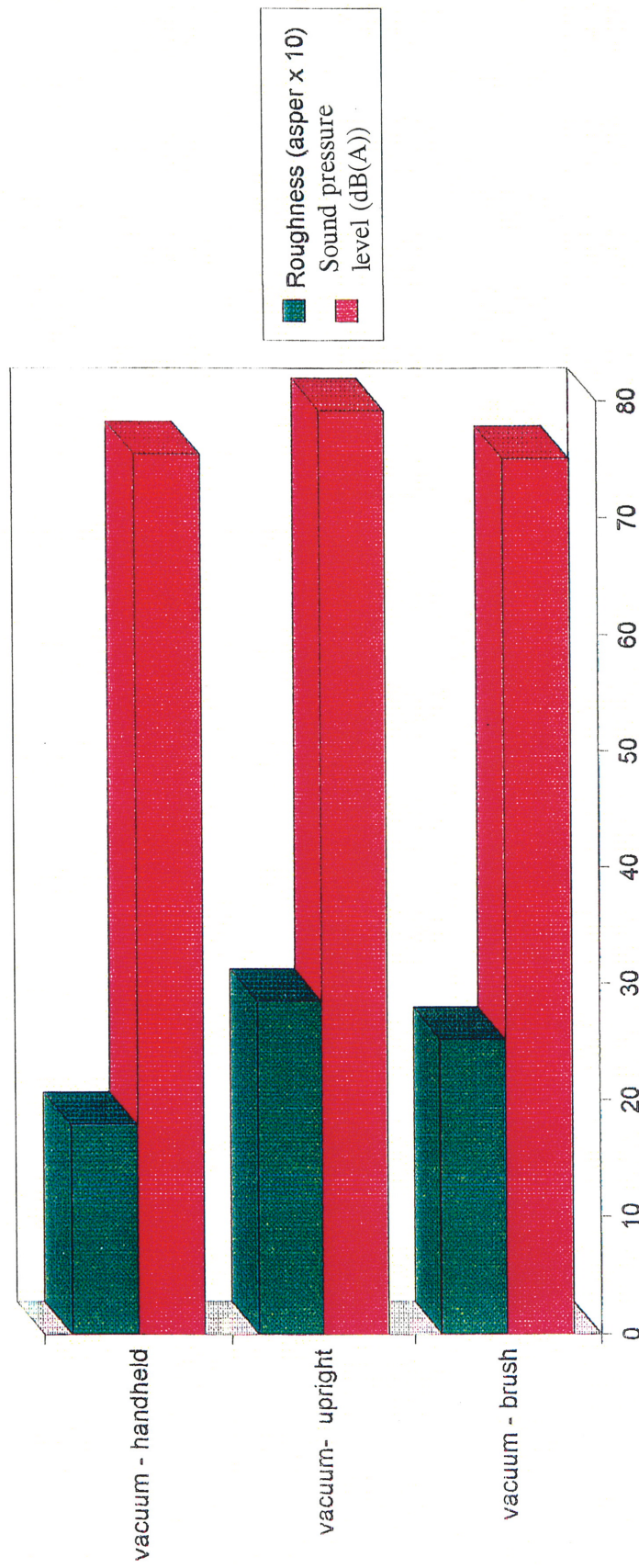


Figure 8: Roughness and level of noise from three types of vacuum cleaners





Figure 9: The 'sound quality' of various appliances (as computed from the default HEAD Acoustics BAS algorithm)

CIRA(EXT)021
January 1997

Appendix A: Questionnaire

**STUDY TO INVESTIGATE STANDARD METHODS FOR MEASURING SOUND QUALITY OF
INDUSTRIAL PRODUCTS (Ref: AM0504)**

QUESTIONNAIRE

We would be most grateful if you could answer the following questions. We ask that you read the accompanying letter first. Please continue your answers on a separate sheet where necessary.

ABOUT YOU

Name:

Company:

Address:

Telephone number:

Fax number:

Email address:

Job title and role:

(please include information on how your responsibilities relate to product labelling)

THE EXISTING NOISE LABELLING SITUATION

Appendix 1 attached to this questionnaire (*this is a summary of section 1 of this report*) represents our view of the present situation of product noise labelling with respect to regulation and standardisation.

1. In your view, have we made any errors or omissions ? (If so, please give details)

2. In what way does your company comply with or use these requirements ?

3. What are your requirements for noise labelling standards and regulations ?
(we need to consider wording to determine whether these are the requirements the interviewee has for the standards or what the standards require of the interviewee)

4. Do existing noise labelling standards meet all your requirements ?

5. Are you satisfied with the form of presentation of the labelling information (usually given as below) ?

6. Do you think that customers/users understand its meaning ?

7. How would you improve this presentation ?

COMPLEMENTARY NOISE LABELLING METHODS

The description or rating of the acoustic output is primarily in terms of such quantities as A-weighted sound pressure level and sound power level. It is accepted that these quantities represent the best currently available compromise between the conflicting needs to describe adequately the effects of noise, and the requirement for practical, economical physical measurements. However, we are trying to establish the general level of interest in additional and complementary methods for noise labelling. A number of candidate options for these complementary measures under consideration are given in Appendix II attached to this questionnaire (*this is a summary of options described in section 4 of this preliminary report*).

We would value your contribution to the development of any complementary measures, should this proceed.

8. What applications can you foresee for such complementary measures ? (We could give examples here e.g. marketing ploys, relating to subjective response, communicating perceived quality with listener etc ?)
9. What do you see as the *benefits* of adopting complementary measures?
10. What do you see as the *disbenefits* of adopting complementary measures?

11. Appendix II attached to this questionnaire (*this is a summary of options described in section 4 of this preliminary report*) gives a number of candidate options for describing the sound quality of industrial products currently under review by NPL. Please could you indicate which ones you are aware of ?
12. Do you know of any other descriptors/methods not included in this list ? Please describe.
13. Please identify any of the methods which you have actually used and give circumstances.
14. Do you have any comments on the practicality of applying these methods ?

FOLLOW ON WORK

15. Please indicate here if you would be willing to contribute in telephone discussions or a personal visit by us in the following phases of our work.
Telephone: **Yes/No** Visit: **Yes/No**

NPL thank you for your contribution. Please could you return this questionnaire to Nicole Porter, Acoustics Branch, National Physical Laboratory, Teddington, Middlesex TW11 0LW (Ref: AM0504)

Appendix B: Details of Preliminary Consultations

ORGANISATION	Contact person	Type of interest/involvement	Form of consultation
Department of Trade and Industry	Mr Bill Osborne	Regulatory body	Discussions
Health and Safety Executive	Mr Harry Lester	Regulatory body	Letter + telephone discussion
Engineering Integrity Society Conference	Various	Research and application	Discussions
Hotpoint	Mr Ian Hale	Product design	Discussions
Higginson Acoustics	Mr R F Higginson	Standards development	Letter and discussions
Technical University of Munich	Professor Hugo Fastl	Research and standards	Discussions
SAS Systems, Essen, Germany	Professor Rolf Bisping	Research and standards	Discussions
ISO Working Group 28	Dr W Lang	Standards development	Discussions
IBM Acoustics Laboratory USA	Dr Matt Nobile	Testing laboratory Research Standards development	Letter and discussions

Appendix C: Details of round table discussion meeting

Sound Quality of Industrial Products (AM0504)
Meeting held on 16th January 1997
10.00am, Globe Room, Bushy House, NPL

TIMETABLE

- 0945: Coffee and tea
- 1000: Welcome by Chairman of Meeting
By Bernard Berry, Head of Audiometric and Noise Standards
- 1005: The NMSPU Acoustics Programme
General description to be presented by Dr Graham Torr, Head of Acoustics Branch.
- 1010: General Description of Research Project "Study to Investigate Standard Methods for Measuring Sound Quality of Industrial Products" and Aim of Workshop
To be presented by Nicole Porter
- 1020: Short Review of Sound Quality and Complementary Sound Quality Measures
To be presented by Nicole Porter using audiovisual examples
- 1050: Initial Research Findings
To be presented by Nicole Porter
- 1115: Round Table Discussion, Part I
Views, in particular, from those not already consulted on
(1) the existing noise labelling situation (requirements, form of labelling, understanding and presentation of labels),
(2) complementary noise labelling methods (applications, benefits, disbenefits).
- 1215: Lunch
- 1315: Round Table Discussion, Part II
Continuation of Part I and general views on
(1) the feasibility of introducing complementary measures,
(2) the preferred presentation of any labels,
(3) research requirements.
- 1600: Summary and close of meeting

CIRA(EXT)021
January 1997

Sound Quality of Industrial Products (AM0504)
Meeting held on 16th January, 1997
10.00 am, Globe Room, Bushy House, NPL

LIST OF ATTENDEES

Ray Brookes	-	Consumers Association
Richard Gillham	-	Perkins Technology
Roger Higginson	-	Higginson Acoustics Ltd.
Thomas Hugin	-	Hotpoint Ltd.
Harry Lester	-	Health & Safety Executive
David Newton	-	Edwards High Vacuum International
Alan Saunders	-	
Bill Osborne	-	Department of Trade and Industry
Karen Taylor	-	
Miles Pixley	-	JCB Research Ltd.
Graham Reed	-	Department of Trade and Industry
Mike Russell	-	Lucas Diesel Systems
Mark Sawyer	-	AIRO
Bernard Berry	-	NPL
Hilary McNeill -	-	"
Richard Payne	-	"
Nicole Porter	-	"
Graham Torr	-	"