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STANDARDS FOR A QUIETER WORLD; SOME ACOUSTICAL REFLECTIONS FROM THE UK NATIONAL PHYSICAL LABORATORY

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1. Introduction.

In 1931, in an early example of a general review article on noise and its measurement, Dr G.W.C. Kaye, who was at that time in charge of the Physics Department at the National Physical Laboratory (NPL), wrote in the journal "Nature",

" It was Lord Kelvin who said that once we find out how to measure a thing we begin to learn something about it. As regards noise, however, it is evident that the question of its measurement is one of some complexity, involving not only physics, but also physiology and psychology. Nevertheless it is clearly desirable that there should be a consensus of opinion on the choice of a system of physical quantities. They should be preferably of an absolute character, so as to assist, inter-alia: (a) in translating vague aural judgements and comparisons into facts and figures; (b) in elucidating the causes and characteristics of noises; (c) in comparing the results of different investigators; and (d) in setting up such arbitrary standards of noise as may be desired in the light of social technical or legal requirements." [1].

Thus from the early days of serious scientific interest in noise, there was recognition of the vital importance to the process of noise control of standardisation - of measuring instruments, measurement methods, of noise criteria. For more than 70 years, NPL has contributed to national and international standardisation in the field of acoustics, and through this process, NPL has in my view contributed to a quieter world, but in an ironic way, the work has itself gone on quietly in the background. It therefore seemed appropriate, in view of the theme of Internoise 97, to review, from my personal perspective, the contribution which NPL has made. The review is in two parts. The first covers the time from the origins of work on noise in the 20's to the beginning of the 1970's, when I started work at NPL, and the second the period since the 70's. The main emphasis will be on specification standards, but reference will be made to key aspects of the work on metrological standards, which of course, through the realisation of the basic standard of sound pressure, underpins all acoustical measurements. The paper will not deal with the processes of standards development, comprehensively described by Robinson [2].

2. Definitely before my time - from the origins of NPL to the Swinging 60's.

2.1 Origins.

Even before it officially existed, the embryonic National Physical Laboratory had strong links with the most famous acoustician of his time, Lord Rayleigh. A committee formed in 1895 to consider the establishment of a national laboratory, reported to the 1896 meeting of the British Association for the Advancement of Science in Liverpool. The third Baron Rayleigh, John W. Strutt, was one of the 14 members of this committee. The committee succeeded in convincing the Government of the day to set up an official "committee of enquiry" under the chairmanship of Lord Rayleigh. The committee's recommendations were accepted in October 1898, and financial aid was voted by Parliament - £4000 for 5 years as a grant in aid of the expenses of the Laboratory, and £12000 toward the erection of suitable buildings. An Executive Committee was formed in May 1899 with Lord Rayleigh as Chairman. The first Director, Dr (later Sir) Richard Glazebrook was appointed from 1 January 1900. Lord Rayleigh continued as Chairman of the Executive Committee until his death in 1918, and is known to have taken an active interest in the work of the Laboratory, in particular as President of the Advisory Committee for Aeronautics, which was formed in 1909 [3,4].

From its inception to the present day, the Laboratory has published an Annual Report. In the early days these were handsome leather bound volumes, but have now become glossy paperbacks. Perusal of these early volumes provides many fascinating insights into various aspects of the functioning of the Laboratory. Thus it is interesting to note, in the report for 1908, the use of the term "Computer". Closer inspection reveals this to refer to the staff grade of a particular employee, a Mr W H Brookes, whose job was presumably to undertake mathematical computations for the whole of the Physics Department.

2.2 Early reflections - the 1920's.

The first reference to work on acoustics comes in the Annual Report for 1925, when a Sound Division was set up in the Physics Department. In these early days the emphasis appears to have been on architectural acoustics, for example the application of sound-pulse photography to the study of waves in a model auditorium. Also in 1925 these techniques were used to investigate the possible use of hangars to screen "certain areas from the sound waves set up by the engines of stationary aeroplanes". It is etymologically interesting to note that the word "noise" was not used. International contacts were strong even then, with reference in the 1925 Annual Report to work on the acoustic properties of the Town Hall in Melbourne, Australia.

At around this time work began on the "absolute measurement of sound intensity" and four possible methods were investigated - a radiation pressure method, the Rayleigh disk method, refractometric measurements of density variations in air, and the vibrating diaphragm method. This work continued through the decade, with efforts mainly concentrated on the Rayleigh disk method. In view of more recent developments to be outlined in due course, it is interesting to note in the 1929 report, the summary of work on low-frequency calibration of microphones using an electrically driven pistonphone. A small mirror, rotated by the motion of the pistonphone, gave an indication of piston amplitude. Amplitude measurements, not necessarily reliable, were reported up to 1 kHz.

The first specific reference to "the study of noise" occurs in the report for 1928, but only by way of an example of the kind of scientific work which was suffering because of the lack of a dedicated laboratory building. For detail of early work on noise one has to wait until 1929 when mention is made of the first portable instrument for measuring the "mean sound presssure of sound in noises". Mention is also made of "aural measurements", which used the "Barkhausen" principle. This involved using a telephone earpiece in which the level of a reference noise could be adjusted in 14 steps to match that of the noise under investigation. See Figure 1. The scale of loudness was said to have been calibrated in absolute units by connecting the telephone earpiece, via an artificial ear canal, to a calibrated microphone .The first practical measurements involved the noise of aircraft, and were undertaken in close collaboration with the Royal Aircraft Establishment (now Defence Research Agency) at Farnborough. 1929 also saw the formation of the first ever government committee on noise, a sub-committee of the Aeronautical Research Committee.

2.3 The 1930's.

A year after the very first mention of "noise", in the Annual Report for 1930, an extensive series of measurements was made on both interior and exterior noise of a range of aircraft types [5].

After several years of planning and preparation, the new building for work on acoustics finally opened in 1933. With considerable extension and modification the building remains to this day, as the Rayleigh Building. The new building included a larger lagged chamber than had been previously available and the report for 1934 notes the use of this chamber to extend the low frequency limit for the "field calibration" of condenser microphones. The first example is also recorded of an intercomparison of the absolute calibration of microphones between NPL and the Post Office Engineering Laboratory, with an average difference of 0.5 dB, over the frequency range 80 Hz to 6 kHz, being noted.

Work on a portable noise measuring instrument, first referred to in 1929, resulted, in 1934, in a forerunner of our modern sound level meters, shown here in Figure 2. One application was in an interesting series of tests conducted on the noisiness and "stridency" or harshness, of motor horns. See Figure 3. This is the first time that the issue of noise with strong tonal components appears to have been considered in the UK. The 1934 Annual Report refers to this instrument as an "acoustimeter", whilst the term "audiometer" is used for the instrument involving subjective comparisons of noises. The acoustimeter was arranged to give "equal meter indications for equally loud notes, whatever the pitch." The equal loudness contours of Fletcher and Munson [6], formed the basis of this equalisation. The indicator was designed to give a full indication of loudness in about 1/3 of a second after the application of a steady noise, "so that it roughly simulates the ear in this respect". The meter was described by Davis who also gave an interesting and valuable review of related work of others in the field at the time [7].

One of the key applications of the acoustimeter was in the study of motor vehicle noise in connection with the deliberations of another early example of a Government committee. This was the Ministry of Transport's arcanely named "Departmental Committee on Noise in the Operation of Mechanically Propelled Vehicles". Figure 4 shows some early measurements, on the NPL site, of the pass-by noise of a car.

The 1934 report also contains the first direct reference to the British Standards Institution (BSI) in the context of a recently proposed standard procedure for measuring the loudness of sounds. In essence this standardised the "equivalent loudness" as the intensity of an equally loud pure tone of 1000 Hz, with the zero loudness being 0.0002 dynes per cm^2 .

The importance of NPL work on noise is indicated by the publication in 1937 of one of the earliest reference texts on the subject, authored by A H Davis (8).

In 1938 the acoustimeter, now known as the objective noise meter, having been the subject of further improvements in performance, particularly in dealing with impulsive noises, was described in considerable detail by Davis [9].

2.4 The 1940's.

The Second World War did not mean the cessation of work on acoustics at NPL. Among the topics listed in reports were - the problems of reproducing the noise of tanks on sound films, sound insulation of aircraft cabins and reduction of noise from aero-engine test cells. Advice was sought in 1944 in the preparation of plans for the new House of Commons, to replace that destroyed in 1941.

Soon after the War, work on noise measurement was greatly assisted by the arrival of a new mobile laboratory - the first of its kind in the UK. This was said to have travelled more than 4000 miles in its first six months of operation, being employed in measurements of the noise from jet-engine test cells and investigations of noise reductions in new post-war factories.

The 1946 report records the hope that work would resume on further improvements to the objective noise meter. However this did not materialise and the NPL meter was eventually overtaken by developments elsewhere on sound level meters. Sadly the NPL Museum contains no remnants of this key work.

There were no major developments in work on basic acoustical standards, although the frequency ranges for microphone calibrations were extended by the introduction of the first anechoic wedge room-linings at NPL, and the construction of a special ducted enclosure.

2.5 The 1950's.

The 50's began with the start of 4 years of a major effort by Robinson and others on the re-determination of the equal loudness contours, extending the work of Fletcher and Munson in the USA and of Churcher and King in the UK [10]. The contours were first published fully in 1956 [11], and the Annual Report for 1957 notes provisional agreement by the recently formed Technical Committee 43 of ISO - itself only formed in 1953 - on the equal loudness contours and on the relation between the scales of loudness (sones) and loudness level (phons). The International Recommendation was published in 1961 [12], and the NPL work also strongly influenced the form of the weighting curves in the first ever international standards on sound level meters [13].

In response to growing demands for a standardised test of motor vehicle pass-by noise, initial subjective experiments, using real vehicles on a main road in the south of England were conducted by Robinson and others in 1959 [14]. These tests showed the superiority of the A-weighting. Soon after, more extensive tests with controlled pass-bys and a jury of listeners, established the necessary information on the relationship between subjective ratings and the meter readings [15]. The results of this NPL work were incorporated directly into ISO Recommendation R 362 [16].

The mid-50's also saw the beginning of studies on the measurement of noise from aircraft in flight which were to have a strong influence on the development of standards for the measurement and certification of aircraft noise in the following years. In 1954 Fleming supervised a large series of measurements on 4 fixed-wing aircraft and one helicopter, using fixed positions relative to take-off and landing. The work is of particular interest as these were some of the earliest tests to make use of weighting curves for sound level which had been standardised by ANSI [17].

2.6 The 1960's.

In 1962, with input from NPL, ISO issued a draft procedure for evaluating the noise around an airport from measurements made only under the flight path. To test out this procedure, measurements were made, in collaboration with Rolls Royce Ltd at their test site at Hucknall, on a Meteor aircraft. These involved a grid of 39 points over an area of 10 square miles. The draft procedure was shown to give good agreement between predicted and measured levels. In 1965, further measurements were made which involved the combined resources of seven laboratories and a test area of 24 square miles [18]. The ISO Recommendation R507 was first published in 1966 [19].

As well as these examples of work on purely objective measurements, NPL retained an interest in subjective response to aircraft noise. Some early examples of controlled subjective tests occurred during the 1959 Farnborough Air Show. These involved a jury of listeners, 1600 in total, in groups of about 100, rating recorded aircraft noises and synthetic noises using the paired-comparison technique. The objective was to see whether the relative ratings of the noises would be in accordance with the recently developed "noise assessment scales" of Stevens [20] and BBN [21], the latter being the early form of the perceived noise level scale. Perceived noise level was found to perform slightly better than Stevens phons [22]. In 1960 a similar experiment using 570 subjects was conducted at NPL, but this time the sounds were recordings of helicopters. The conclusion from this experiment was that Zwicker phons were superior to PNL or Stevens phons. The A-weighted sound level was noted to be as good as Stevens phons in ranking either loudness or "disturbance" [23]. In 1961 the first experiments using actual aircraft flyovers took place at that year's Farnborough Air Show [24]. Over 3 days, 60 subjects made judgements on rating scales of noisiness and intrusiveness, see Figure 5. Objective measurements were made in dB(A) and PN dB . Amongst the interesting results, it was found that subjects judged sounds heard indoors more severely than sounds of the same level heard outdoors. The difference was about 18 dB(A). See Figure 6. This difference was much the same as the noise reduction provided by the building. It was suggested that this "projection effect" was due to subjects making a subconscious allowance for the building attenuation. The result was confirmed in tests carried out at the 1964 Air show, using 148 subjects [25]. It is interesting to note that the same effect has subsequently been found by a number of researchers [26].

In 1963 Robinson compared the results of the aircraft noise tests with the earlier judgement tests on motor vehicles [27]. See Figure 7 .This result represents one of the earliest inputs to the debate which has ensued ever since concerning the need for "source corrections" to harmonised noise scales.

The importance of the role of NPL was recognised in 1961 by the choice of the Laboratory to host the very first major international conference on noise ever held in the UK [28]. 300 delegates from world-wide spent 3 days attending 25 presentations and a number of demonstrations of noise analysis equipment and exhibits illustrating the principles of noise control. The demonstrations included one of the earliest known applications, certainly in the UK, of a digital computer - the NPL ACE machine - to the calculation of PN dB and loudness by the Zwicker and Stevens methods. The details of the calculation procedure for the Zwicker method, which used 30 seconds of computer time per noise, were published later [29].

The 1961 conference coincided with the start of deliberations of the Government committee on the Problem of Noise, known as the Wilson committee after its Chairman, Sir Alan Wilson, FRS. NPL staff made a substantial input to the committee and several of the previously cited scientific papers were reprinted as appendices to the Report [30]. The Report formed the basis for much of the developments which which were to follow in UK legislation on noise, and was regarded for many years as a vital reference text by practitioners of all kinds.

Also in this very productive period of the mid-60's, NPL staff were involved in pioneering studies concerning sonic booms, at a time when concern was growing that the development of supersonic passenger transport would lead to exposure of the general population to this unusual form of aircraft noise. In addition to studies of subjective effects [31], Robinson developed a variant of the Stevens loudness calculation procedure [32]. NPL's work on the techniques required for the accurate physical measurement of sonic bangs had a profound influence on the development of the relevant ISO standard [33], but standardisation of methods for evaluation of subjective effects did not proceed. With the disappearance of the threat of widespread exposure, interest in the topic in the UK dwindled, and in fact ISO formally withdrew ISO 2249 in 1995.

The 60's was also a productive time in the field of occupational noise. Although the first schemes for the research are said to have appeared in the late 50's, the origins of one of the most extensive and influential studies ever undertaken of the relationship between occupational noise exposure and hearing levels of industrial workers, can be seen in the NPL Annual Report for 1962. The project was jointly run by NPL and the UK Medical Research Council. Audiometric field work began in July 1963 with the aid of a new mobile audiometric laboratory [34] and continued for more than 5 years. A new mobile noise measurement laboratory was used to obtain details of exposure in a range of factories across the UK. The study involved both retrospective analysis on 759 exposed subjects and a prospective study with serial audiometry on 493 subjects. Even before final completion of the work, an interim report which described how noise level and duration could be combined into single measure termed noise immission, led to radical revisions of draft recommendations on hearing conservation being considered by ISO [35, 36]. The study is described in full in the book by Burns and Robinson [37].

After preliminary work at the end of the previous decade, the gradual move from the reliance on the Rayleigh disc method for absolute calibration, towards the use of reciprocity, gathered momentum. At the Baden-Baden meeting of IEC TC 29 in 1962, Working Group 13 "Absolute calibration of microphones" was established to formulate an international standard. NPL was involved, along with the national standards laboratories of six countries, in an international intercomparison [38]. A draft standard for calibration of one-inch microphones by the reciprocity technique was developed, validated at NPL by Delany [39], and eventually published [40]. Work began on extension to half-inch microphones, and also on improvements to diffraction corrections required to derive free-field sensitivity.

3. Late reflections, from the 1970's onwards.

I started work at NPL on November 2 1970, and initially I worked on the development of recommended maximum background noise levels for audiometry [41]. Soon after that I switched my primary research interests to environmental noise. For this part of my review I shall consider primarily work in which I have personally been involved, and describe developments chronologically within each subject area. Because of limitations of space and time, this review cannot be all embracing, but the interested reader is referred to the index of NPL publications which has been produced regularly since 1960, and which can be obtained from the author.

3.1 Harmonisation of noise ratings.
My arrival at NPL co-incided with the rapid growth of interest in the question of unification or harmonisation of the wide range of noise indices then in use. Robinson had just published an early paper on the topic which introduced the concept of Noise Pollution Level [42]. I reviewed the different noise indices then used in the UK for traffic, aircraft and industrial noise, and showed how, using L_{Aeq} as an intermediate measure, one could derive "equivalent values" of the separate indices [43]. Over the next few years, NPL and other organisations and individuals contributed to the deliberations of the UK Noise Advisory Council which had become concerned at the multiplicity of noise immission measures in use in the UK for planning and regulatory purposes [44]. The need for a reference work on general concepts, methods of measurement, and prediction was met by the "Leq guide" [45] which was compiled and edited by NPL staff and which had a significant impact on developments within the UK in subsequent years. A few years later, the Department of the Environment (DoE) commissioned NPL to undertake a wide-ranging review of the use of L_{Aeq} in the UK [46]. This review considered current applications, recent policy assessments, international developments, subjective reaction to different noise sources, the comparison of L_{Aeq} and other measures as predictors of subjective reaction, and recent developments in measurements and prediction practices. The work on subjective reaction to different sources was published for Internoise 83 [47]. The review also highlighted the need for further research on industrial and impulsive noise, and this resulted in the studies described in the next section. The general move in the UK towards the use of L_{Aeq}-based indices continued with the change from the use of Noise and Number Index for civil aircraft noise [48], and the formulation of noise compensation measures for military aircraft noise in terms of L_{Aeq} [49]. At the International level, a key event was the publication of ISO 1996 in 1981 [50].

The slow process towards eventual harmonisation still continues in the late 90's , with the long awaited revision of UK planning guidance [51] which uses L_{Aeq} for all noise sources, and with the recent publication of a Green Paper from the European Commission on Future Noise Policy[52]. The Government of the Netherlands, through its Health Council, has recently formed a new multi-national Committee of experts, on which NPL is represented, to consider and report on a "Uniform noise exposure metric". The Committee has held a plenary meeting and it is hoped that the report will appear soon after Internoise 97.

3.2 Subjective and objective assessment of industrial noise, including tonal and impulsive components.

At Internoise 85, the first results were published of a series of experiments on the dependance of annoyance on basic physical parameters of impulsive noise, such as decay time and repetition rate [53]. In collaboration with the late Professor Zwicker, the results were re-analysed using the newly developed digital loudness meter [54]. The detailed report on this work appeared in 1987 [55]. The best fit between objective and subjective data was obtained using a descriptor developed in earlier NPL work on helicopter noise [56]. The report also proposed the use of descriptors of impulsiveness based on very short-term L_{Aeq} time-series. NPL then became involved in collaborative studies funded by the EC. These involved subjective tests in laboratories in the UK, Italy and the Netherlands, and objective analyses at NPL and the University of Dusseldorf. This led to the development of the "Increment " descriptor [57]. See Figure 8.

With the aim of refining current standard methods for rating industrial noise, work began in 1990 on a 3 year project funded by the UK DoE. A review of related practices in 20 countries was undertaken [58]. Also an extensive programme of subjective listening tests was conducted on the judged annoyance of specific types of industrial noise, including combinations of tonal and impulsive noise [59]. Follow-up work has concentrated on the issue of tonality [60]. The work has led to the development of a fundamentally new approach to noise assessment based on the acoustic features present in the noise environment [61].

At the level of national standards, NPL has lead the Committee of the BSI revising the 1967 edition of British Standard 4142 to make use of L_{Aeq}, and producing the 1990 edition [62]. Further revisions have recently resulted in a 1997 edition. Contributions have also been made to the work of the ISO Working Group 45 in revising the impulse corrections in ISO 1996 Part 2. The Working Group is now continuing with the bigger task of a complete revision of ISO 1996. The first meeting was held at Internoise 96.

3.3 Aircraft noise.

When the original schemes for noise certification of aircraft were introduced in 1967, the requirement was for measurements with a microphone height of 1.2m above ground surface level. Such measurements are of course subject to the effects of cancellation and augmentation due to interference between the incident and ground-reflected waves, resulting in distortion of the true free-field spectrum. An extensive series of experimental and theoretical investigations by NPL showed the benefit of using a ground-plane microphone arrangement. The arrangement has now been included in the standards for the certification of light propellor aircraft.[63,64].

NPL hosted the inaugural meeting of ISO TC43 Working Group 43 in May 1994 , and is actively contributing to its work on the revision of ISO 3891 [65].

In late 1979 NPL were asked by the UK Ministry of Defence to develop a mathematical model for the prediction of noise around military airfields. The resulting model AIRNOISE was completed in 1981, and has since been used extensively in the determination of housing zones eligible for compensation [66]. In 1990 attention turned to the problems of low-altitude flying. A controlled field trial was conducted on 6 types of military jet aircraft flown straight and level at heights between 100 and 250 feet, at various speeds and engine power settings. The results of the work had a direct influence on standards of a different kind, namely the rules governing the allowable altitude and speeds in the UK low-flying system [67]. A prediction model - FLYBY- was developed, and found to give accurate estimates of the time-history of the noise of low-flying aircraft [68]. An important parameter governing the subjective response to such noise is the rate of change of noise level at the beginning of the event, or onset-rate. The problem of the lack of a standard for the measurement of the onset-rate was addressed in 1995 [69].

3.4 Developments in acoustical standards.
In 1977 details were published of a new laser-pistonphone, developed at NPL by Rennie, in order to extend the lower frequency limit for absolute calibration [70]. The device was further refined by Barham in 1993 [71], thus completing the process started in 1929. During the 1980's, most effort was applied to the extension of the standard for reciprocity calibration to half-inch microphones, and a major comparison of national standards of sound pressure was undertaken [72]. More recently IEC have reviewed IEC 327 and brought it up to date in a new series of Standards, IEC 1094 - Measurement microphones. These include a primary method for free-field calibrations [73].

With the growing interest in techniques of sound intensity measurement, the need arose for a standard specifying minimum requirements for instruments. NPL contributed to the development of IEC 1043 and developed a service for periodic verification [74]. NPL has also taken the leading role in development of a new British Standard for the verification of sound level meters [75], and in current work of producing a new international standard for sound level meters [76].

4. Summing the reflections - thoughts on the future.
In looking back over the years one is struck by the similarities, between the early years and now, in the basic aspects of the noise problems under consideration, and by the lack of real progress in key areas, despite the passage of time, and much research. Thus in the description of the 1938 acoustimeter or objective noise meter, one can see early evidence of the magnitude of impulse "corrections", which have only recently, nearly 50 years later, been the subject of amendments to ISO 1996. But one is also struck, naturally, by the differences in the methods used in the research, arising from the developments in technology, and the ease with which one can now accomplish complex tasks. One example would be the generation of signals for subjective testing, where space-consuming and power-hungry hardware has been replaced by the PC and software, in many cases readily

available via the Internet. But of course it is the very ease with which one can generate such signals and perform complex analysis tasks, which has itself led to the proliferation of possible ways of assessing noise. Another example would be the availability of lasers and optical techniques, now used in microphone calibration.

As we look to the future, it is clear that technological developments in the late 1990's will not only continue to influence the techniques applied in research on noise and its effects, and work on the realisation of primary standards, but will also change the very infrastructure by which the process of standardisation happens. A number of standards bodies, including the Audio Engineering Society, are already using FTP (File Transfer Protocol) servers to give committee members online access to documents, and email for discussion groups. A European consortium on Internet working for Standardisation, which includes BSI, is urgently evaluating a number of possible future strategies. There are obvious advantages in speed of working and a broader base for comments etc, but the problems of achieving consensus are likely to increase.

In this paper, I have attempted to describe some of the key threads running through NPL research on noise since its origins in the 1920's, and to show how the research has influenced standards for a wide range of acoustical applications. I have also given examples of the ways that NPL research has been used by Government Departments and Committees in the framing of key items of legislation, guidance etc. I believe that the work of NPL, and the contributions of other organisations and individuals involved in research, and in the process of standardisation, have provided essential tools to help all those engaged in the essential task of international noise control - and so have helped to make a quieter world.

5. References.

1. G. W. C. Kaye, 1931. *Noise and its measurement*. Nature. **128**. No. 3224. 253-264.

2. D.W. Robinson , 1981. *NPL and acoustical standardization*. Acoustics Bulletin. April 1981.

3. E. C. Pyatt, 1983. The National Physical Laboratory - a history. Adam Hilger, Bristol

4. H. Barrell, 1964. *The Rayleighs and the National Physical Laboratory*. Applied Optics. **3**. No. 10. 1125-1128.

5. A. H. Davis, 1930. *The causes of noise in aircraft*. Aircraft Engineering. November 1930. 227-274.

6. H. Fletcher and W. A. Munson, 1933. *Loudness, its definition, calculation and measurement*. J. Acoust Soc. Amer. **5**. 82-108.

7. A. H. Davis, 1934. *The measurement of noise* . Engineering. **138**. 663- 666.

8. A. H. Davis, 1937 Noise. Watts and Co. London

9. A. H. Davis, 1938. *An objective noise meter for the measurement of moderate and loud, steady and impulsive noises*. Journal of the Institution of Electrical Engineers. **83**. 249-260.

10. B. G. Churcher and A. J. King, 1937. The performance of noise meters in terms of the primary standard. Journal of the IEE. **81**. No. 487. 57.

11. D. W. Robinson and R. S. Dadson, 1956. *A re-determination of the equal-loudness contours for pure tones*. British Journal of Applied Physics. 7, 166-181.

12. International Organization for Standardization, 1961. *Normal equal loudness contours for pure tones and normal threshold of hearing under free-field listening conditions*. ISO Recommendation R 226. First edition.

13. International Electrotechnical Commission, 1961. *Recommendations for sound level meters*. IEC Publication 123. First edition.

14. D. W. Robinson, W. C. T. Copeland, and A. J. Rennie, 1961. *Motor vehicle noise measurement.* The Engineer. **211**, 493-497.

15. C. H. G. Mills and D. W. Robinson, 1961. *The subjective rating of motor vehicle noise*. The Engineer. **211**, 1070 - 1074.

16. International Organization for Standardization, 1964. *Measurement of noise emitted by vehicles.* ISO Recommendation R 362. First edition.

17. N. Fleming, 1954. *Measurement of noise on the ground from aircraft in flight*. J. Royal Aeronautical Society. **58**. 245-248.

18. W. C. T. Copeland and E. G. Saunders, 1966. *Evaluation of noise around an airport*. NPL Applied Physics Report. AP 24.

19. International Organization for Standardization, 1966. *Procedure for describing aircraft noise around an airport.* ISO Recommendation R 507. First edition.

20. S. S. Stevens, 1956. *Calculation of the loudness of complex noise*. J. Acoust. Soc. Amer. **28**. 807-832.

21. Anon, 1958. *Studies of noise characteristics of the Boeing 707/120 jet airliner and of large conventional propeller driven aircraft*. Report of Bolt Beranek and Newman Inc. to the Port of New York Authority.

22. W. C. T. Copeland, I. M. Davidson, T. J. Hargest and D. W. Robinson, 1960. *A controlled experiment on the subjective effects of jet-engine noise.* J. Roy.Aero Soc. **64**. 33-36.

23. D. W. Robinson and J. M. Bowsher, 1961 . A *subjective experiment with helicopter noises.* J. Roy. Aero. Soc. **65**. 635-637.

24. D. W. Robinson, J. M. Bowsher and W. C. T. Copeland, 1963. *On judging the noise from aircraft in flight.* Acustica, **13**, 323-336.

25. J. M. Bowsher, D. R. Johnson and D. W. Robinson, 1966. *A further experiment on judging the noisiness of aircraft in flight.* Acustica, **15**, part 5. 245-267.

26. I. H. Flindell, 1982. *Community response to multiple noise sources*. PhD thesis. ISVR University of Southampton.

27. D. W. Robinson, 1963. *Recent advances in the subjective measurement of noise*. Proceedings of the 4th ICA. Copenhagen. Book II. 157-178.

28. National Physical Laboratory, 1961 *The Control of Noise*. NPL Symposium No.12.

29. J. M. Bowsher and D. W. Robinson, 1963. *Calculation of Zwicker phons on a digital computer.* Nature. Vol. 200. 553-555.

30. *Noise. Final Report of the Wilson committee on the Problem of Noise*. 1963 Cmnd 2056. HMSO.

31. D. R. Johnson and D. W. Robinson, 1967. *The subjective evaluation of sonic bangs.* Acustica. **18**. 241-258.

32. D. R. Johnson and D. W. Robinson, 1969 *Procedure for calculating the loudness of sonic bangs.* Acustica. **21**. No 6. 307-318.

33. International Organization for Standardization, 1973. *Description and measurement of physical properties of sonic booms.* ISO Standard 2249.

34. W. C. T. Copeland, L. S. Whittle and E. G. Saunders, 1964. A *mobile audiometric laboratory.* J. Sound Vib. 1. 388-401.

35. D. W. Robinson and J. P. Cook, 1968. *The quantification of noise exposure*. NPL Aero Report Ac 31.

36. International Organization for Standardization, 1971. *Assessment of occupational noise exposure for hearing conservation purposes.* ISO Recommendation R 1999 (superseded by ISO Standard 1999 in 1975).

37. W. Burns and D. W. Robinson, 1971. Hearing and noise in industry. HMSO. London.

38. M.E.Delany and A.J.Rennie, 1964. *The absolute pressure calibration of condenser microphones* . NPL Applied Physics Report AP 14.

39. M. E. Delany, 1968. *Condenser microphones and their calibration*. NPL Aero Report Ac33.

40. International Electrotechnical Commission, 1971. *Precision method for pressure calibration of one-inch standard condenser microphones by the reciprocity technique.* IEC 327.

41. B. F. Berry, 1973. *Ambient noise limits for audiometry*. NPL Acoustics Report Ac 60.

42. D. W. Robinson, 1971. *Towards a unified system of noise assessment.* J. Sound Vib. 14, 279-298

43. B. F. Berry, 1974, *Equivalent values of traffic, aircraft and industrial noise.* NPL Acoustics Report Ac 65.

44. The Noise Advisory Council, 1975. *Noise Units.* London HMSO.

45. The Noise Advisory Council, 1975. *A Guide to the Measurement and Prediction of the Equivalent continuous sound level Leq.* London HMSO.

46. B. F. Berry and R. F. Higginson, 1982. *A review of the use of* L_{Aeq} *in the UK for the evaluation of environmental noise*. NPL Acoustics Special Report S12.

47. B. F. Berry, 1983. L_{Aeq} *and subjective reaction to different noise sources, a review of research*. Proc. Internoise 83. **2**, 993-996

48. J. B. Critchley and J. B. Ollerhead, 1990. *The use of Leq as an aircraft noise index.* CAA DORA Report 9023.

49. A. Boardman, 1985. *The review of the UK MoD's compensation arrangements near military airfields.* Proceedings of the NATO/CCMS Conference on Military aircraft Noise. H-3 to H-8.

50. International Organization for Standardization, 1981. *Acoustics - description and measurement of environmental noise. ISO 1996 Part 1.*

51. Department of the Environment, 1994 . Planning and Policy Guidance Note24, Planning and Noise.
52. European Commission, 1996. Green Paper on Future Noise Policy. COM (96) 540.
53. B. F. Berry, 1985. *Evaluation of impulsive environmental noise: Laboratory studies of annoyance reactions.* Proc. Internoise 85. **2**. 921-924.
54. B. F. Berry and E. Zwicker, 1986. *Comparison of subjective evaluations of impulsive noise with objective measurement of the loudness-time function given by a loudness meter.* Proc. Internoise 86. 821-824.
55. B. F. Berry, 1987. *The evaluation of impulsive noise*. NPL Report Ac111
56. B. F. Berry, H. C. Fuller, A. J. John and D. W. Robinson, 1979. *The rating of helicopter noise: development of a proposed impulse correction* NPL Report Ac 93.
57. B. F. Berry, 1989. *Recent advances in the measurement and rating of impulsive noise.* Proc. 13th ICA. Belgrade. **3**. 147-150.
58. N. D. Porter, 1995. *The assessment of industrial noise - a review of various national practices.* NPL Report RSA(EXT) 0057B.
59. N.D. Porter, *The assessment of industrial noise - subjective listening tests and objective assessment procedures.* NPL Report RSA(EXT) 0057C.
60. N. D. Porter, 1995. *The detection of complex tones in noise*. Proc. Institute of Acoustics. **17**, part 5.19-26.
61. N. D. Porter, I. H. Flindell and B. F. Berry, 1993. *An acoustic feature model for the assessment of environmental noise.* Acoustics Bulletin. Nov/Dec. 1993.
62. British Standards Institution, 1990. *Method for rating industrial noise affecting mixed residential and industrial areas.* BS 4142:1990.
63. R.C.Payne, 1987. *Noise levels from propellor-driven aircraft measured at ground level and at 1.2m above the ground.* NPL Acoustics Report Ac 110.
64. ICAO Annex 16. Chapter 10.
65. P. J. Dickinson, 1996. *Towards a new ISO 3891*. Proc. Internoise 96. Book 6, 3281-3286.
66. B. F. Berry and R. J. Weston, 1990. *Noise from military airfields in the United Kingdom*. Proc. Internoise 90. 413-416.
67. B F Berry, R.C.Payne and A L Harris, 1991. *Noise levels of military aircraft at Exercise Luce Belle*. NPL Report RSA (EXT) 14.
68. B. F. Berry and J D Speakman, 1992. *A prediction model for noise from low-altitude military aircraft* .
Proc. Internoise 92. **2**, 889-894.
69. B.F.Berry, 1995. *Towards a standardised descriptor of the impulsive noise caused by low-altitude military aircraft*. Proc. Internoise 95, **II**, 879-884.
70. A.J.Rennie, 1977. *A laser pistonphone for absolute calibration of laboratory standard microphones in the frequency range 0.1 Hz to 100 Hz*. NPL Acoustics Report AC 82.
71. R. G. Barham, 1993. *The NPL laser pistonphone*. J. Low Frequency Noise and Vibration, **12**, 36-38.

72. G.R.Torr and D.R. Jarvis, 1990. *A comparison of national standards of sound pressure*. Metrologia, **26**, 253-256.
73. D. R. Jarvis, 1995. *Measurement standards for acoustics*. Proc. Institute of Acoustics. **17**, Part5, 47-52.
74. D. R. Jarvis, 1992. *Instruments for the measurement of sound intensity: calibration and performance tests.* Proc. Euronoise 92, Book3,759-766.
75. N. E. Milton, 1995. *Verification of sound level meters to BS 7580 Parts 1 and 2.* Proc. IoA, **17**, Part 5, 57-61. 1995.
76. S. P. Dowson, 1996. *Sound level meters - Specification standards and testing*. Institute of Acoustics Bulletin. March/April 1996. 5-8.

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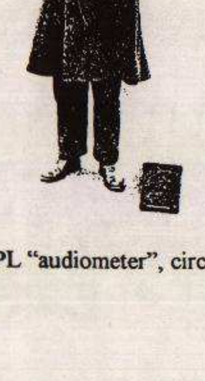


Figure 1. NPL "audiometer", circa 1929.

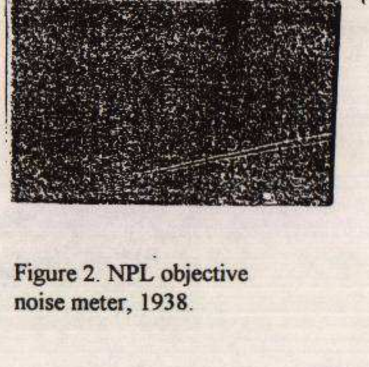


Figure 2. NPL objective noise meter, 1938.

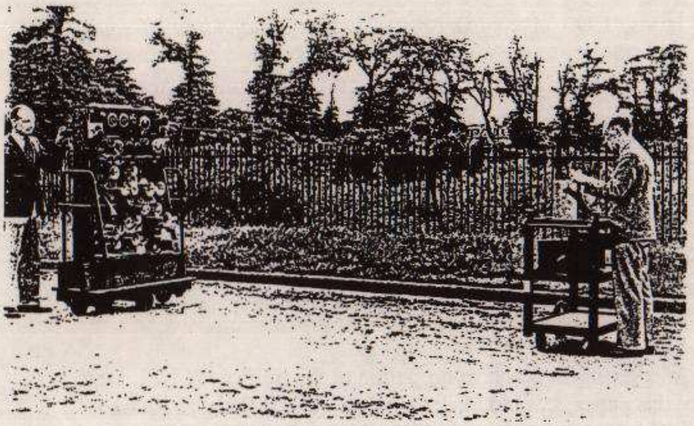


Figure 3.
Noise of
motor horns,
1929.

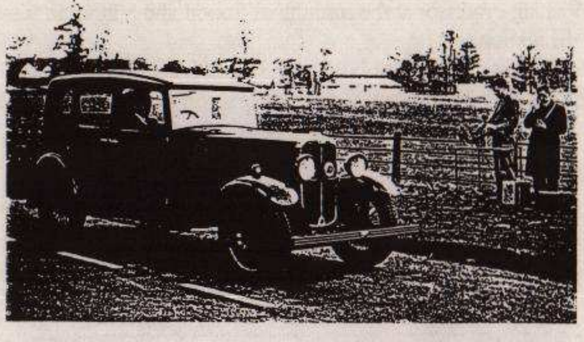
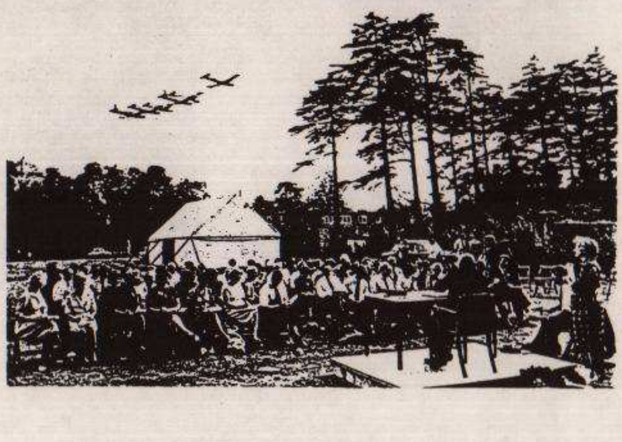


Figure 4.
Motor vehicle noise, 1934.

Figure 5.
Outdoor judgements
of aircraft noise, 1961.



STANDARDS FOR A QUIETER WORLD

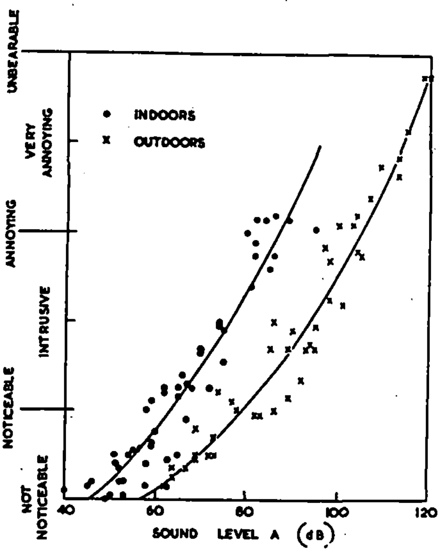


Figure 6. Indoor and outdoor judgements of aircraft noise, 1961.

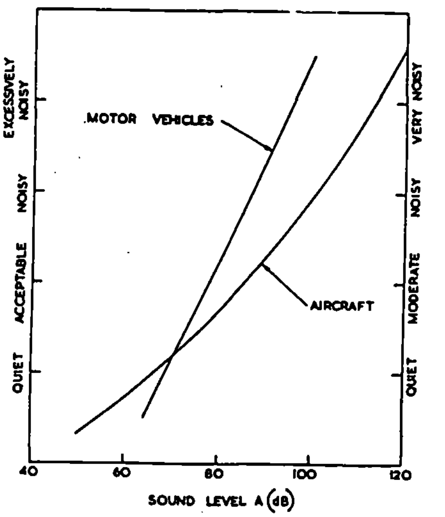


Figure 7. Comparison of noisiness judgements, 1963.

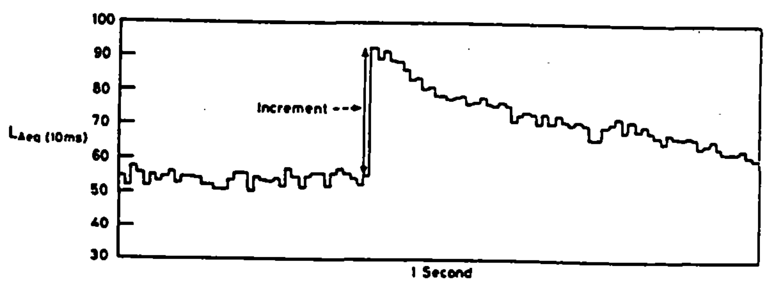


Figure 8. "Increment" descriptor of impulsive noise.