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A STRATEGY FOR THE DEVELOPMENT AND STANDARDISATION OF MEASUREMENT METHODS FOR HIGH POWER/CAVITATING ULTRASONIC FIELDS

FINAL PROJECT REPORT

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ABSTRACT

This document presents the findings of a six month project completed on behalf of the DTI National Measurement System Policy Unit (NMSPU) by a consortium comprising the National Physical Laboratory (NPL) and the Institute of Sound and Vibration Research (ISVR), University of Southampton. The overall aim of the project was to assess the requirements for methods and standards for measuring high power/cavitating ultrasonic fields. Current progress made in this area of metrology has been reviewed during the project. In addition, through telephone interviews, four types of tailored questionnaires, and face-to-face discussions, over 70 users, manufacturers and academics working in the area of high power ultrasound have been contacted. This has yielded a considerable volume of information on the techniques currently being used and on the specific requirements for standardised methods, both now and in the future. Techniques in use have been critically appraised and prioritised in terms of their suitability for standardisation and their potential application in the remote and local sensing of high power ultrasonic fields. On the basis of the information gathered and the critical analyses completed during the project, a package of work is recommended to deal with the highest priority requirements in the field of ultrasonic cleaning. This involves the establishment of a reference ultrasonic cleaning bath in conjunction with the development of special sensors for monitoring acoustic field and cavitation characteristics. In the longer term, the other lines of approach to standardisation referred to in the report - applicable to medicine and sonochemistry - should also be considered.

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1 INTRODUCTION

This report describes the work undertaken for the DTI National Measurement System Policy Unit (NMSPU) during a six-month project entitled **Study to review progress, identify measurement methods and address implementation for remote and local sensing methods for the measurement of high power/cavitating ultrasonic fields**. The work was undertaken during the period April to September 1996, was coordinated by the Centre for Ionising Radiation and Acoustics (CIRA) of the National Physical Laboratory (NPL) and involved the participation of the Institute of Sound and Vibration Research (ISVR), University of Southampton.

1.1 OBJECTIVES

The need for the project arose because at present, there exist no well-defined, reproducible, traceable measurement methods for high power/cavitating ultrasonic fields. The overall aim of the project was to identify a route by which such methods could be developed and then incorporated into the measurement standards framework.

Three main objectives were identified prior to the project:

- to review technical progress in measuring high power / cavitating ultrasonic fields;
- to identify measurement methods for remote and local sensing of such fields;
- to recommend an implementation route, given the current state-of-the-art in measuring such fields.

1.2 BACKGROUND

High power ultrasonic fields and cavitation figure in a number of diverse application areas, from healthcare to sonochemistry. Measurement methods for these phenomena are important for two reasons. First, the cavitation process itself plays an important role in many processes such as the operation of lithotripters and in sonochemistry. Further, cavitation is known to have significant effects on the propagation medium, and in a number of medical applications such as hyperthermia and some surgery, the cavitation is highly undesirable. To predict and control the effects of the ultrasound and the associated cavitation, it is essential to have accurate and reproducible methods of measurement.

In addition, the EC Medical Devices Directive[1] requires that the acoustic output of devices be declared by the manufacturer. In the case of lithotripters, there is therefore an explicit need to measure high power ultrasonic fields. If end users are to make sensible use of experimental data, the measurements must be conducted in a consistent manner. This implies the need for standard measurement methods using calibrated instrumentation.

The knowledge base of measurement techniques applicable to high power and cavitating fields in the UK is distributed across a number of specialist research organisations, medical teaching hospitals and university departments. Two important centres of expertise lie in the National Physical Laboratory and the Institute of Sound and Vibration Research (ISVR) at the University of Southampton, who collaborated during the project which this report describes. To establish the measurement methods appropriate for extension of the existing standards framework to incorporate high power and cavitating ultrasonic fields, the progress made by research groups both within the UK and overseas was reviewed. Based on this review, it was possible the identify the most promising 'state-of-the-art' approaches which might form the basis for standard measurement methods.

The strategic importance of the development of reliable characterisation methods for high power ultrasound and cavitation was recently recognised in the preliminary results of the UK Measurement Foresight Programme where it was rated one of the top five requirements in the field of acoustics.

1.3 SEGMENTATION OF APPLICATION AREAS

High power ultrasound is used in a range of application areas and the review and technical evaluation of measurement techniques carried out in the project were undertaken in relation to these. This Section presents a segmental analysis of the application areas, highlighting the specific metrological requirements in each.

1.3.1 Medicine

Pulses of high pressure amplitude are used in lithotripsy to destroy renal calculi with cavitation playing an important role in the fragmentation process. Other applications include the use of high power focused ultrasound in cancer therapy and surgery, dental descaling and ultrasonic surgery in addition to whole or partial body immersion systems used for wound cleansing, healing and patient cleaning. In all cases of human exposure to ultrasound, there is a need for traceable measurements of the exposure to meet current or anticipated future regulatory requirements.

1.3.2 Sonochemistry

Sonochemistry uses high power ultrasound to initiate and promote chemical reactions and there has been a growing interest in the potential of the technology, along with a broadening of its application base. Sonochemistry processors consist of transducers and waveguides whose operation covers the range 10 kHz to 500 kHz, generating intensities close to the processor tips as high as a few hundred W cm^{-2}. Multiple sonochemical probes are now becoming incorporated in reactor systems to increase the power densities generated and improve material processing throughput. The importance of sonochemistry was highlighted in 1991, in a DTI-commissioned report[2] which identified Power Ultrasound as one of six 'hub' technologies whose implementation would lead to a cleaner environment. A meeting was organised by DTI Environment Division at Coventry University in December 1992 to consider the future of the technology, and a major conclusion was that the lack of reliable methods of measurement or monitoring is a major factor inhibiting technology development.

1.3.3 Ultrasonic cleaning baths

A third important application area addressed during the project was measurement methods for characterizing ultrasonic cleaning baths. These systems operate in the frequency range 20 kHz to 900 kHz, using relatively low intensities of the order of a few W cm^{-2} generated by single or multiple transducers. These baths are generally used for industrial cleaning of components and the sterilization of surgical instruments, although they can also be used to promote sonochemical reactions. One requirement for characterisation techniques highlighted during the project lay in the cleaning of critical components such as PCB's (in the microelectronics industry frequencies as high as 900 kHz are used), where the particular concern was component damage arising from the cleaning process. In the 1970's, considerable effort was devoted to the development of methods for the characterisation of these fields which culminated in the publication of International Electrotechnical Commission Technical Report

IEC 886[3]. However, no method has been shown to be capable of forming the basis for reference measurements, and therefore measurement standards have yet to be established. In the past five years there has been a re-awakening of measurement interest in this area, and this has been driven principally by the growing importance of quality systems such as ISO9000 and the stringent demands these place on industrial process control.

1.3.4 Industrial (non-cleaning) applications

Ultrasound is used in a whole range of industrial applications such as welding, machining and cutting as well as physical processes such as degassing, particle size reduction, waste treatment and homogenization. These applications span a number of industrial sectors such as those of the food and water industries. During the project, an appreciation for the breadth of applications was obtained with contact being made with groups using high power ultrasound in areas such as the de-inking of waste paper, waste treatment in both the water and petrochemical industries and thermosonication processing in the food industry. Characterisation of the ultrasonic fields produced by these devices is currently not performed, and the availability of measurement techniques would enhance performance in the development, manufacture and use of equipment.

2 CURRENT SCOPE OF THE NATIONAL MEASUREMENT SYSTEM

In view of the objectives of the project, it is appropriate to consider the measurement framework provided by the National Measurement System (NMS) and to describe the technical problems faced when attempting to derive physically meaningful measurements in the hostile environments established by high power ultrasound.

Currently, measurement standards developed and disseminated to users through the NMS in the field of waterborne sound cover the frequency range 10 kHz to 20 MHz at pressure levels of typically 10^5 Pa (about one atmosphere). The current NMS Acoustics Programme will extend this frequency range from 2 kHz to 60 MHz. The application of these standards has been primarily in the areas of medical ultrasound and underwater acoustics where the acoustic fields can be considered as propagating in a free-field environment. This is a fairly good assumption as they are generally pulsed or quasi-continuous wave (tone-burst) and it therefore becomes possible to perform reverberation-free measurements. In addition, the interaction of the sound field with the propagation medium can be predicted using simple progressive wave theory, albeit with the inclusion of nonlinear phenomena.

In contrast, high power ultrasonic fields lead to conditions which make conventional measurement of the fields difficult. Current methods of field characterisation suffer from a number of problems when applied to high power ultrasound, specifically reverberation and cavitation. Reverberation becomes important when, as is normally the case in high power ultrasound applications, continuous-wave sound sources are used. Furthermore, high power ultrasound is usually applied to a closed chamber, often leading to complex standing-wave pressure distributions. Measurements made using conventional devices are both difficult to undertake and interpret.

If the acoustic pressure exceeds one atmosphere, acoustic cavitation can take place. Cavitation is a complex process involving the creation and activation of gas bubbles. Bubbles generated not only scatter the ultrasound but also generate harmonics, subharmonics and ultraharmonics of the fundamental acoustic frequency or may even lead to the emission of light through sonoluminescence. All of the application areas considered in this project utilise cavitation to invoke changes in the propagation medium and these secondary signals (acoustical or optical) may potentially be used to characterise the degree of cavitation occurring, enabling the process to be monitored and controlled.

3 REPORT PLAN AND RELATIONSHIP TO COMPANION REPORTS

The two literature reviews[4,5] represent an analysis and appraisal of those measurement methods which have been used to monitor and measure high power and cavitating ultrasonic fields. The two complementary reviews cover the technical areas of field measurement[4] and cavitation monitoring techniques[5] and this breakdown illustrates the sub-division of the work between NPL and ISVR during the initial stage of the project.

This document contains an overall description of the tasks undertaken during the project in addition to presenting its findings and recommendations. The project consisted of three distinct Phases dealing with the following:-

Phase I: the mechanics by which the information was gathered, principally through three primary sources: technical literature reviews, postal and telephone based questionnaires and face-to-face interviews carried out with key players in the high power ultrasound field. NPL was responsible for the development of the contact database, the questionnaires and the telephone interviews, and carried out all except one of the face-to-face discussions;

Phase II: information analysis, presented under a number of important headings. A key component of this report relates to an analysis of those measurement techniques which have been or are being used to characterise such fields, the aim being to establish which methods could be incorporated within the standards arena. NPL was responsible for developing the measurement technique scoring system, with the analysis of the techniques being carried out jointly by NPL and ISVR;

Phase III: utilising the information from the measurement technique analyses along with the questionnaire responses to recommend an implementation route for standardisation in the area of high power ultrasound. A number of options are presented and discussed in detail.

4 PHASE I - INFORMATION GATHERING

4.1 SCIENTIFIC LITERATURE

The review of cavitation monitoring techniques[5] was undertaken at ISVR using the BIDS search facility, and by systematically searching through the later issues of journals as received by the Hartley Library at the University of Southampton (such later issues would not have had time to come through onto the BIDS system). The literature consulted in previous publications was revisited, and new research identified was also investigated. Extensive use of personal contacts both in the UK and abroad was made to recommend key or Review works.

The review of field measurement techniques[4] was undertaken at the NPL library using the CD-ROM based INSPEC search facility, which contains abstracts from scientific journals and conference proceedings dating back to 1988. Typical keywords used in the search were: high power ultrasound measurement, cavitation measurement, ultrasonic cleaning measurement, sonochemistry measurement. The search produced in excess of 200 references, and the majority of these publications were obtained, either from the NPL library, or from the British Library. Further, the references contained in the articles themselves were also investigated, back to an approximate cut-off time of the 1960's, where it was apparent that few measurement techniques were being applied. However, some exceptions were found, for example in the use of thermal and erosive test methods.

4.2 PATENT SEARCH

NPL staff have had previous experience in undertaking Patent searches, and contact was made with the Patent Office Search and Advisory Service in Newport, Gwent, United Kingdom. Initially, a list of terms similar to those employed in the literature review was employed, using the Derwent World Patent Index, which covers patent documents from over 30 countries from 1974 onwards. This produced the search results shown in Table 1.

Search keywords	Number of hits
cavitation	4091
high power ultrasound	102
ultrasonic clean	2352
lithotripsy	178
acoustic bubbles	271

Table 1: Patent search hits obtained from various query terms.

Obtaining full abstracts for this large number of hits was deemed unnecessary, and after discussion, the global classification term "Measurement of mechanical vibrations or ultrasonic, sonic or infrasonic waves" was used as the starting point. The search was narrowed further by using the classification from a US patent that had been previously obtained for a multi-element thermal probe. This covered the "measurement of amplitude or power of acoustic waves in a fluid using electrical, optical and any other means", and produced 42 hits. A further search was undertaken of "measurement of mean amplitude, mean power or mean time integral of power of acoustic waves in a fluid", which produced 293 hits. The most relevant Patent abstracts from both searches can be found in Appendix A. The devices uncovered by the Patent search are described in the field measurement technique review[4] and are not repeated here.

4.3 ESTABLISHMENT OF CONTACT DATABASE

The generation of the contact database was conducted with the timescale of the questionnaires in mind: it was decided early on in the project that the first set of questionnaires despatched would be to an international list of recipients, for postal reply. To allow prospective repondents time to receive, consider and reply to the questions, the early stages of developing the database concentrated on the international scene. Firstly, committee activities and previous contacts made by the project staff were used to build up a worldwide list. This included the Ultrasonic Industry Association in the USA, the Ultrasonic and Acoustic Transducer Group (UATG) in the UK (which has a large international membership) and the Institute of Acoustics membership list. A list of approximately 80 contacts was produced from this, and a first "sift" was performed to reduce the list to those interested predominantly in high power applications of ultrasound.

The EC CORDIS database was examined via the RTD Partners list, to uncover information regarding

European Groups involved in research in this field. This was comparatively unsuccessful, with only one listed organisation in the ultrasonic field. Further online searches were conducted using the AltaVista search engine on the Internet, producing a vast number of hits for keywords similar to those employed in the Patent Search and Literature Review above. Again, these were narrowed down to potential questionnaire respondents and comprised organisations who were predominantly industrial manufacturers. At this stage, the international contact database was finalised in terms of questionnaire despatch.

A search was conducted of the KOMPASS UK Companies database to find any equipment manufacturers not previously uncovered. These were sifted according to annual turnover and product range.

A number of scientific meetings were attended by staff during the project and these were used to publicise the project aims and to extend the number of contacts. Dr. Bajram Zeqiri was invited to present a talk entitled "Measurement of Cavitation and Acoustic Power in Water" at the 1996 ETSU-sponsored Fluidsonics Seminar which focused on the use of high power ultrasound in a wide range of industries (the abstract may be found in Appendix B, along with the programme for the meeting in Appendix C). The meeting allowed contacts to be made with UK industry and academia, and the subsequent receipt of the attendance list provided a comprehensive cross-section of the UK high power ultrasound community. In addition, two other meetings took place during the project which also produced further contacts. Both were attended by Dr. Tim Leighton (ISVR). The first of these was a meeting on the bioeffects of high power ultrasound, held in Allerton, USA, and the second was the Fifth Meeting of the European Society of Sonochemistry, held in Cambridge, at which Dr. Leighton chaired an important session on cavitation.

An advertisement was placed in the June issue of "Sonic Pulse", the biannual UATG newsletter, describing the project objectives and inviting contributions from interested parties. A copy of this advertisement can be found in Appendix D. At this final stage, the overall contact database comprised approximately 130 names, and appropriate filtering produced a target list of around 70 contacts for questionnaire receipt.

4.4 TECHNICAL VISITS

From a combination of the contact database and early telephone discussions, a number of centres were identified to whom visits would be made, and at which face-to-face discussions of measurement issues would take place. The agendas set for each of the meetings were strongly based on the questionnaire from the appropriate market sector. Issues of measurement discussed during each visit have been subsumed into the questionnaire responses given in Section 5.2. The visits constituted a very valuable component of the project as they enabled manufacturers' facilities to be toured and high power ultrasound equipment to be seen in operation.

4.5 DEVELOPMENT OF THE QUESTIONNAIRES

4.5.1 Rationale of the questionnaires

It was felt that the technical literature review would uncover the vast majority of techniques which had been applied to characterising high power systems. Nevertheless, the questionnaires gave the opportunity of requesting information concerning measurement methods being applied in the field, with first hand accounts of the benefits and limitations of the methods. Particular emphasis was placed on obtaining information concerning techniques used "in-house", which had been tried and tested over a number of years, even though they were perhaps not widely reported. Other generic areas of information required were:-

- details of the respondent's application area;
- their views on the current and future needs for measurements in their area;
- the particular driving forces pushing for measurement techniques.

In the case of the UK contacts, the questionnaire was sent only to prime the respondent for an interview by telephone carried out about two weeks later. In the case of overseas contacts, the respondent was invited to complete the questionnaire and return it to NPL.

4.5.2 Formulation of the questionnaires

In the original project proposal submitted to NMSPU, the potential contacts were divided into four application areas: medicine, sonochemistry, ultrasonic cleaning and other industrial processing. A further refinement of the contact database was carried out, subdividing the list into the following groups:

- Academics;
- Manufacturers;
- Users;
- Consultants.

These four "market sectors" would form the basis for the questionnaire targeting, with different emphasis placed in various areas of the corresponding questionnaires produced, according to the market sector.

Initially, a core list of eight questions was drawn up which formed the basis of all four types of questionnaires despatched. These referred directly to the measurement parameters considered important, the measurement techniques currently applied, the benefits and limitations of these methods, and the anticipated future measurement needs. The NPL-CIRA marketing manager provided useful input into producing the questionnaire framework.

Building on this core of questions, the questionnaires were tailored to the specific market sectors reflecting anticipated differences in measurement emphasis. For example, it was felt that the measurement capabilities and needs of a hospital physics department would be very different from those of a small-scale ultrasonic cleaning bath manufacturer. Additionally, aspects such as the increasing measurement demands placed on companies by ISO9000 requirements were considered less relevant to a sonochemistry researcher. Considering these, and other issues (including observations derived from an early technical visit, which was used to pilot a preliminary version of the questionnaire), draft versions of four separate questionnaires were produced. A covering letter was also generated, and the first mailshot of 20 questionnaires was despatched to the international contact database in early June.

From the completed contact database, the list of questionnaire recipients in the UK was produced, and subdivided into three distinct batches: medical, sonochemistry and ultrasonics processing, which included cleaning. Within these three batches, the recipients were categorised according to the market sectors shown above. A revised version of the covering letter was produced, and the first UK mailshot for prospective interviewees was despatched to the medical community at the end of June, to 13 contacts. After a ten day period, the first set of telephone interviews were started. These were ordered such that the first few respondents were those well-known to NPL, thereby allowing a degree of questionnaire piloting to be performed on individuals, whilst still gathering useful information. During the course of the telephone interviews, certain minor amendments were noted as being required, mainly to question wording, and this information was used to refine subsequent questionnaires. The second mailshot was despatched to 9 individuals in the sonochemistry area in July. Completion of the technical visits also yielded extra contacts, spread across all application areas and market sectors. These additional contacts were combined with the final list of recipients, and the third mailshot (15 recipients) was despatched in the third week of July. The final versions of the manufacturer questionnaire and the associated covering letter used in both the international and UK mailshot can be found in Appendices E, F and G.

Telephone interviews typically lasted around 30 minutes, covering in depth the written questions, but also discussing to a further level any particular issues about which the respondent felt strongly. All but one of the telephone interviews was conducted to a UK respondent: the exception being to an American manufacturer, who, in their postal reply, described details of a sensor used in cleaning bath monitoring and this was felt worthy of further discussion. After the despatch of the third mailshot, contact was made via the Internet with a research group in South Africa which allowed 14 further questionnaires to be sent out via Email. The breakdown in numbers of the overall contact database over the four identified sectors is given in Figure 1, illustrating the distribution of the questionnaires despatched across the three application areas (ultrasonic cleaning and other processing have been combined under the "industrial" umbrella).

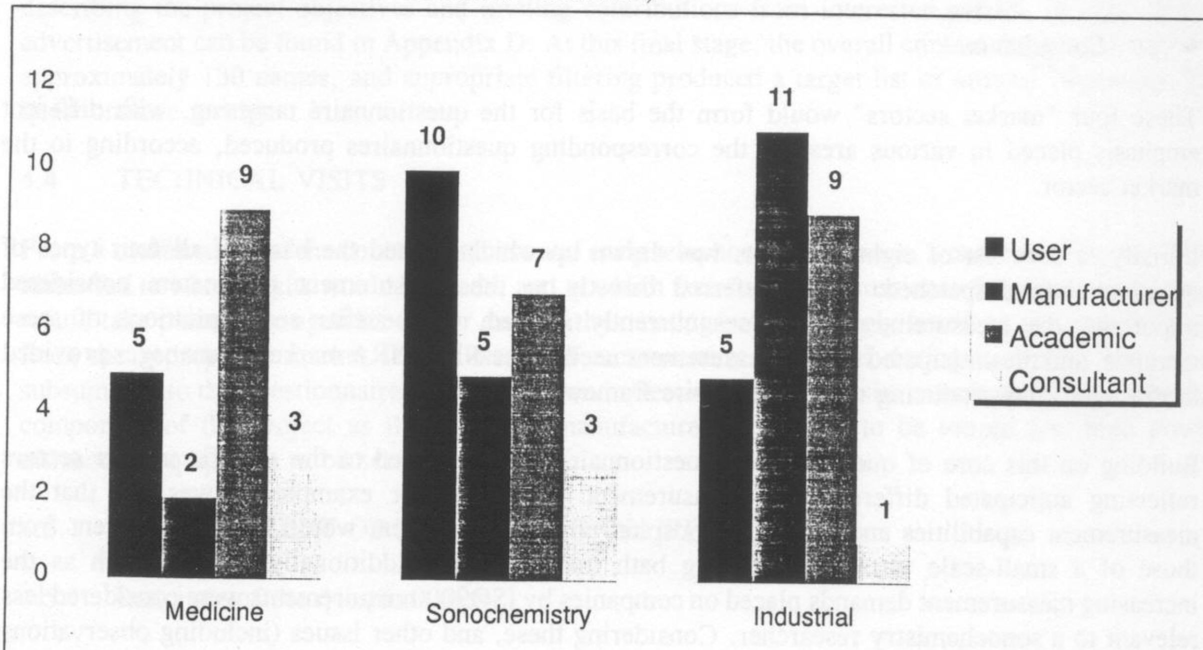

Figure 1: Diagrammatic representation of the contact database, subdivided over market sector and segmentation area.

5 PHASE II - ANALYSIS OF QUESTIONNAIRE RESPONSES

5.1 NUMERICAL ANALYSIS OF RESPONSES

The technical information derived from the questionnaire responses will be analyzed fully in section 5.2 in relation to the areas addressed in the questionnaire. The overall breakdown of numbers and hit rates are shown in Table 2.

Medium	Number despatched	Number of replies	% hit rate
Postal	20	12	60
Telephone	37	25	70
E-mail	14	5	36
Total	71	42	60

Table 2: Breakdown of the response rate of questionnaires provided through three different routes: purely postal, telephone and e-mail based questionnaires.

It should be emphasised that these hit-rate figures are exceptionally high and this in itself indicates the significant value the respondents attached to the project.

5.2 ANALYSIS OF TECHNICAL RESPONSES

Many of the repondents indicated a business or research interest in two or more of the application areas suggested (medical fields, sonochemistry, ultrasonic cleaning etc.). Most of the cleaning bath manufacturers produced devices in the 20 kHz to 40 kHz range, and the majority of sonochemistry equipment manufacturers and users referred to devices in the 20 kHz to 25 kHz range, operating over a wide range of powers.

5.2.1 Key areas of importance for measurements identified by manufacturers

Figure 2 illustrates the breakdown of responses to the questions relating to the particular area which respondents felt required the development of reliable measurement capability.

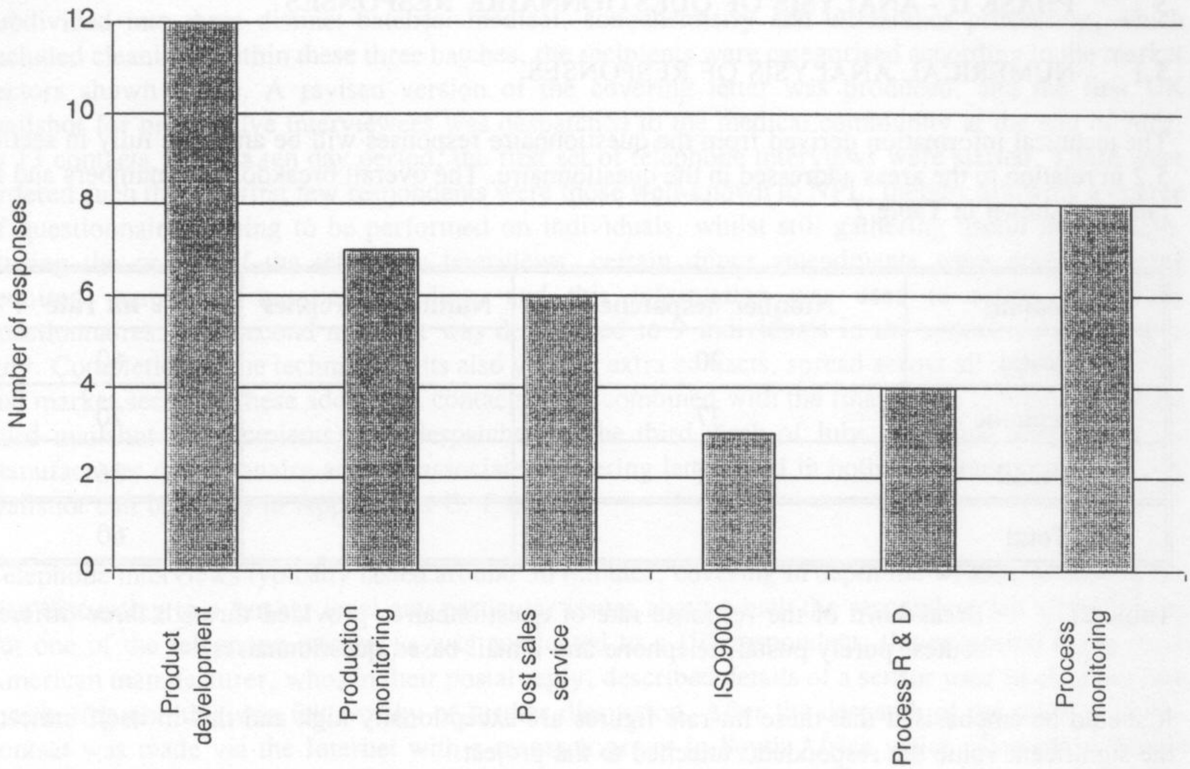

Figure 2: Key areas of the product development and application cycle requiring measurement and monitoring methods.

It is clear from the responses that there is a requirement for measurements in all of these areas, although the particular requirements in the various areas differ. The needs stipulated by respondents may be summarised as follows:-

- in the area of product development, a means to evaluate the process effectiveness of systems is required: it would be acceptable for such a method to be fairly complex and costly provided it were accurate, repeatable and accepted as an industry standard;

- in production monitoring, there is a need for methods which enable day-to-day consistency of device manufacture to be determined, for this area the devices need to be fairly simple, easy to use and yield rapid, reliable results;

- post-sales customer service - a simple means to diagnose a system in the field is required, this should ideally be a simple 'go' / 'no-go' test;

- ISO9000 - a means of measurement which yields quantitative information relevant to the process in question is required.

It should be noted that several respondents, mainly users of sonochemical equipment, although fairly happy to provide information regarding their broad activity areas, were unwilling to give specific details of their applications owing to reasons of commercial confidentiality.

5.2.2 Important acoustic and cavitation parameters

In many cases the replies obtained from the questionnaires indicated that the respondents were unsure or imprecise regarding parameters which they felt they had to monitor to control a process, and this probably reflects the lack of knowledge of the basic mechanisms occurring.

Acoustic field variables cited as being important by the respondents were acoustic pressure and acoustic intensity and their distribution through a reaction vessel, be it a cleaning bath or sonochemical reactor. Other parameters raised were the amount of acoustic energy being delivered to the medium (or some quantity related to it) and the acoustic energy density. Some respondents were less specific when the issue of cavitation was raised except to say that some measure of cavitation "quality" was required. Parameters indicated to be important were cavitation "strength", cavitation energy and the number of cavitation events taking place per unit time and their violence. One respondent in the sonochemistry area felt that the key requirement was to determine the amount of acoustic energy transferred into cavitation, as this represented the useful energy available to the process.

5.2.3 Measurement techniques used by participants - benefits and limitations

Almost all of the respondents indicated that they applied measurement techniques of some form to characterise either the operation of the transducers or the resultant effect on the system in question. Many monitored non-acoustic parameters such as frequency, and the electrical power delivered to the transducer, using a wattmeter, or the acoustic power delivered to the reaction vessel using calorimetry. The latter involves measuring the temperature rise in the vessel containing a known volume of fluid, over a certain time period. Whilst these are useful, low cost techniques for ensuring some level of quality and reproducibility in measurement, they are clearly restricted in the information they provide regarding the sonochemical or cleaning processes taking place. Although a power assessment could correlate fairly well with reaction yield obtained, the usefulness of calorimetry was cited as being limited due to its non-existent spatial resolution and poor accuracy. As a consequence, these methods have not been analysed further. Without exception, all other techniques indicated by respondents had also been covered in the literature review and these are analyzed in Section 6 of this report.

5.2.4 The need for and value of standardised measurement methods

In general, the replies received indicated that there was considerable support for the development of standard methods and an indication of the wide range of perceived benefits this would bring was given by many respondents. These have been grouped below:-

- a uniform traceable base for measurement would be invaluable for the checking of equipment performance and the comparison of test results with published data, obtained by different groups of workers, from different equipment or the same equipment operating under different conditions;
- they would aid and accelerate the fundamental understanding of the cavitation processes taking place, leading to process optimization, reliable scale-up and aiding in the development of new devices and applications;
- in the area of medicine, such methods would improve the specification of safety levels, lead to improved control of surgical procedures and the better planning of treatment regimes.

However, some manufacturers felt that customers were happy with the reliability of relatively simple measurements such as transducer displacement, but felt that more information regarding mechanisms and theoretical understanding would be useful. A few saw relatively little benefit in the standardisation of measurements feeling that equipment had now become of good quality and customers would not be interested unless a specific fault arose during operation.

5.2.5 Standard sonochemical reaction

Responses here were strongly polarised. Some felt that such a reaction could potentially be useful and lead to the ability to compare results directly as indicated in Section 5.2.4. A number of candidate processes were cited: a reaction based on hydrogen peroxide kinetics, a colorimetric based reaction such as that suggested by Weissler, the Fricke reaction, or a dosimeter based on a free radical scavenger such as terephthalic acid. The need for well specified cavitation nuclei was also identified. Another observation made was that such a reaction should be related directly to the process being modelled or investigated and there could be a need for a range of standard reactions of different chemical mechanisms. A number of these reactions is described in Section 3.5 of the companion cavitation literature review[5].

The alternative view was that it was primarily more important to understand the basic mechanisms of cavitation, and that an inappropriately applied reaction could well inhibit real technical progress. On more practical issues, one respondent felt it would be extremely difficult, if not impossible, to establish identical conditions for any comparison, owing to the sheer range of parameters which affect reaction rate.

5.2.6 Future technological developments and time-scale

Where time-scales were quoted by respondents, these were generally driven either by legislative pressures or by the increasing proliferation of medical procedures. Generally, however, feedback indicated that any standards effort applied to this area should necessarily be long-term, the important issue being one of gaining a fundamental understanding of cavitation and bubble dynamics. One leading academic felt that the standardisation of cavitation could not be achieved without this fundamental understanding although they also indicated that it would be useful to start the standardisation process on the basis of current knowledge.

Some of the companies felt that, purely from their perspective, there would not be a great need to develop reliable measurement methods except in the case of bespoke systems where the engineering specification was unusual. However, there was also a general perception that in future the customer would provide the impetus to develop such methods. One cleaning bath manufacturer indicated that, in time, the customer would become more knowledgeable, more critical and require continuously optimised ultrasonic cleaning efficiency. Simple and moderately-costed measurement techniques were required from equipment development through to the end-user stage of the manufacturing cycle. A sonochemical user in the food processing industry felt that the development of such methods was vital in gaining regulatory approval of the more safety critical applications of ultrasound. A number of comments were made relating to the need to develop a fundamental understanding of the relationship between cavitation and the process in question: a prominent academic cited the absence of such measurement techniques being a fundamental limitation to the exploitation of high power ultrasound in a scientific manner.

One cleaning bath manufacturer indicated that users working to the requirements of ISO9000 were demanding increasingly tighter control on the part being cleaned and felt that in approximately two years, customers would expect this to be part of the service provided by the company. In the medical field, it was felt that reliable measurement methods would be essential for ensuring the proper development of ultrasonic surgical applications, which it was anticipated would come into general use within 5 to 10 years. Associated with this, the need for measurements would be driven by the pace of developments in the field of medical ultrasonics in general, exemplified by an observation that over the last twelve months, fifteen new contrast agent companies had been set up in the USA alone.

A respondent in the water industry investigating the application of high power ultrasound in sludge treatment to reduce the use of chemical solvents, commented that although there was currently no specific legislation restricting the use of such chemicals in the water industry, this would probably be in place in the next 5 to 10 years making the use of ultrasound attractive, although its viability at an industrial level still had to be proven.

6 PHASE II - ANALYSIS OF MEASUREMENT TECHNIQUES

6.1 SUMMARY OF CANDIDATE MEASUREMENT TECHNIQUES SCORED

The literature reviews completed in the two distinct areas - field measurement and cavitation monitoring - in combination with the responses obtained from the questionnaires were used to produce a shortlist of candidate measurement techniques. For the field measurement area these were identified as follows:

- Optical interferometry
- Discrete thermal methods, utilising embedded thermal probes
- Electromagnetic probe
- Hydrophone - piezoelectric
- Hydrophone - fibre-optic
- Semi-quantitative effects - Sarvazyan dye etc.

In addition, optical measurement of the tip displacement of the sonifying device was included, as it was used by a number of questionnaire respondents.

For monitoring inertial cavitation, the following eight techniques were identified:-

- Sonochemistry - spin trapping in conjunction with Electron Spin Resonance
- Sonochemistry - terephthalic acid
- Broadband acoustic emission
- Sonoluminescence
- Erosion - soil removal (for example radioactive soil)
- Erosion - aluminium foil (characterisation by pitting or light transmission)
- Erosion - lead balls or stainless steel ball bearings (weight loss)
- Bio-effect (haemolysis).

In order that the methods be judged in an objective fashion, a scoring system was developed based on a number of attributes considered to be important in assessing the suitability of the technique for standardisation. These attributes were broadly subdivided into three global areas, as listed in Table 3.

It should be noted that although sonoluminescence is identified here, and hence referred to in later sections of the report, the technique of chemiluminescence is assumed to fall under the same banner. The key differences between the two techniques are in timing (chemiluminescence persists for a fraction of a second longer than sonoluminescence) and the dopant required, which becomes a matter of cost. The salient attributes of these two techniques is nominally identical, and a discussion of each may be found in the accompanying ISVR report[5], Section 3.4.

Global area	Scoring system attribute (the stronger the attribute, the higher the score, 1-10)
Practical aspects related to the use of the measurement technique	reliability, able to cope with extremes of field conditions
	insensitivity to position
	flexibility/transferability/versatility
	small size, low weight, compactness
	low cost (device, instrumentation and operator, ease of use)
Measurement technique fidelity	good spatial and temporal resolution, wide bandwidth
	accuracy (random uncertainties, signal-to-noise, sensitivity etc.)
	traceability, established track record
	predictability of device response
	measured parameter known
Value of the measurement to the monitoring of the process	lack of invasiveness/perturbation
	relevance to process in question
	ability to measure a range of parameters
	real-time/near instantaneous

Table 3: Summary of measurement technique scoring system attributes, considered under the three global categories.

6.1.1 Practical aspects related to the use of the measurement technique

The first area considered was the practicality of using the measurement device or technique. Issues addressed were cost, the compactness and complexity of the system, its ruggedness and its ability to cope with a range of measurement conditions. Another issue was the versatility of the device or technique, for example, if it could be applied to a range of high power systems or if its use was restricted to one particular application. Another factor, which might be beneficial in the use of the technique as a routine tool, was its insensitivity to positioning in the acoustic field.

6.1.2 Measurement technique fidelity

Attributes considered and scored against under this global category included the spatial and temporal (bandwidth) resolution. Here, a decision was made to score the potential accuracy of the method against idealized field conditions. Problems encountered with implementation in a 'real' complex environment would result in a low score under the category described below, the "Value of the measurement to the monitoring of the process" (6.1.3). Other important considerations were the measurement traceability aspects, the predictability of the device response and whether the parameter actually measured or monitored by the technique was well established.

6.1.3 Value of the measurement to the monitoring of the process

Attributes considered here related to how invasive the technique was and how relevant the determination of the parameter was to the process in question. Ideally, it would be beneficial for the quantity measured to relate directly to the phenomenon driving the process forward (mainly cavitation, but not exclusively so). For situations where it is not clear which parameter is indicative of the process, it is useful for the method to be able to measure or derive a range of parameters. The final attribute related to whether or not the technique was real-time, clearly an essential requirement for any on-line process monitoring. It should be noted that in assessing the value of the measurement to the process, it was assumed that the process is promulgated by cavitation although, as noted in the cavitation monitoring report[5], other mechanisms arising from microstreaming or radiation forces can be responsible for the observed effect in certain applications. In the context of the current report, if a measurement technique responded directly to pressure (specifically peak-rarefactional pressure) or a direct consequence of the cavitation (free radical etc.) then it scored fairly highly in this category.

6.1.4 Scoring protocol

A sample proforma is given in Appendix H. The scoring process involved allocating scores in the range 1 to 10, against each attribute listed. Owing to the fewer attributes in the third category "Value of the measurement to the monitoring of the process", this would introduce a slight in-built bias against this category. It was felt that the three global categories should be given equal weighting and therefore scores for this category were normalized to a score out of 50 in each Section, giving a total mark out of 150.

In any such rating process, there are a number of concerns regarding its efficacy and the justification behind the scores. These concerns relate principally to the existence of any in-built bias which may exist within the project team (the possible dependence of the results on personal subjective views) and whether the project team has the necessary expertise in all of the areas covered. In order to minimise these uncertainties the following precautions were put in place:-

- independent scoring of the field measurement techniques was undertaken by the two NPL members of the project team, and selected techniques were scored at ISVR;
- scoring for the cavitation monitoring methods was performed at ISVR, and both NPL project staff scored selected techniques: sonoluminescent, erosive, broad-band acoustic emission and sonochemical (terephthalic acid/ESR);

- in areas where expertise within the project team was considered not to be specialist or where it was felt corroboration was required, independent scoring of the methods was obtained by experts. This was completed for the electromagnetic probe and the two sonochemical techniques (ESR and terephthalic acid).

Typical agreement between cross-checked scores was within 10%, for the overall mark out of 150.

6.2 RESULTS OF MEASUREMENT TECHNIQUE SCORING PROCESS

6.2.1 Field parameter measurements

The results of scoring the seven techniques presented in 6.1 are given in Table 4, where they have been listed in order of their overall score. Also presented are the individual scores for the three global areas presented in Sections 6.1.1 to 6.1.3. An analysis of the scores is presented in Section 6.3.2.

Measurement technique	**Score (max=150)**	**Practical aspects related to the use of the measurement technique (max=50)**	**Measurement technique fidelity (max=50)**	**Value of the measurement to the monitoring of the process (max=50)**
Piezoelectric hydrophone	116	31	46	39
Fibre-optic hydrophone	114	31	40	43
Optical interferometry	110	26	46	38
Discrete thermal methods	93	34	32	27
Electro-magnetic probe	90	34	29	27
Tip displacement measurements	88	28	40	20
Semi-quantitative effects	67	40	10	17

Table 4: Summary results of measurement technique scoring system for the seven field measurement techniques considered. Overall scores are presented alongside individual scores obtained in the three global areas.

6.2.2 Inertial cavitation monitoring methods

Methods of detecting inertial cavitation collapse given in the ISVR report[5], Section 3, were scored using the same proforma. The results of scoring completed on the eight techniques presented in 6.1 are given in Table 5, where they have been prioritised in terms of overall score. Also presented are the individual scores obtained under the three global areas given in Sections 6.1.1 to 6.1.3.

Measurement technique	Score (max=150)	Practical aspects related to the use of the measurement technique (max=50)	Measurement technique fidelity (max=50)	Value of the measurement to the monitoring of the process (max=50)
Broadband acoustic emission	113	37	37	39
Sonoluminescence	110	27	42	41
Sonochemistry - terephthalic acid	96	37	33	26
Bio-effect Haemolysis	94	36	31	27
Sonochemistry - spin trapping (ESR)	91	26	36	29
Erosion - soil removal	83	38	22	23
Erosion - aluminium foil pitting	80	41	20	19
Erosion - lead blocks	79	42	19	17

Table 5: Summary results of measurement technique scoring system for the eight cavitation monitoring techniques considered. Overall scores are presented alongside individual scores obtained in the three global areas.

6.3 MEASUREMENT TECHNIQUE SCORING PROCESS - ANALYSIS OF SCORES

6.3.1 'Gold' standard and 'rugged' measurement techniques.

It is useful to consider the relative merits of the techniques considered in Sections 6.2.1 and 6.2.2 with two particular types of measurement in mind. The distinctly different requirements of these were touched upon in Section 5.2.1 in considering the responses given by contacts. It is possible to differentiate between two types of technique. The first, a "gold" standard technique, would provide high accuracy, usually at some cost, and would provide fairly detailed information regarding the mechanics of the process in question. Such a technique was highlighted by the respondents as being important in equipment development, where accuracy and general fidelity is important. The second is a "rugged" technique, which would be easy to implement, cheap, and would therefore be replaceable in terms of its use in hostile and damaging fields. Another important property vital to the day-to-day routine use is its speed, as a user will not wish to painstakingly and accurately align the device for maximum signal and will not want to 'map' the field in any way. This implies the need for a spatially integrating sensor and this in itself has interesting implications for current calibration techniques which are generally geared to 'point' calibrations in a known free-field.

It should be noted that in terms of the objectives of NMSPU and of this report, and in particular the need to identify those measurement techniques which might be brought into the standards area, the 'gold' standard methods are of greater interest. Nevertheless, the 'rugged' techniques and the possibility of cross-calibrating with a 'gold' detector are clearly very important in terms of dissemination.

6.3.2 Field measurement techniques

The measurement techniques considered in this Section are those which determine the local properties of the acoustic field. The results of the field measurement analysis shown in Table 4 illustrate the relatively high scoring of techniques which fundamentally determine acoustic pressure, such as the piezoelectric and fibre-optic hydrophones, the high scores arising through the "Measurement Fidelity" and "Value" global areas. These devices can be used to provide absolute measurements of pressure traceable to National Measurement Standards and their behaviour and response is relatively well understood and well characterised. They score relatively lowly on "Practical Aspects", owing to the difficulty in interpreting measurements in reverberant environments, their relative expense and their need for precise positioning in standing-wave fields. High quality devices tend to be expensive and fragile, so their use in routine measurements in hostile environments would be limited. The pressure sensitive measurement techniques also score highly in that they may used to detect the signals produced by inertial cavitation collapse, and their use for this purpose is considered in Section 6.3.3 (broadband acoustic emission). Respondents indicated that problems with hydrophone measurements lay primarily in the interpretation of the complex signals and in their sensitivity to hostile environments.

In contrast to the hydrophone case, the electromagnetic probe scores highly in terms of the practicalities of its use, as it exhibits exceptional ruggedness under the extreme conditions produced at the focus of a lithotripter. However, its versatility and general applicability to a range of high power, continuous wave applications is unproven and as it is likely to perturb the acoustic field to a significant extent it cannot be considered to be non-invasive. There is still some uncertainty regarding the parameter or field characteristic to which the probe responds, although recent unpublished results indicate that the response of the probe is related in some way to collapse cavitation (see Section 5 of NPL review report[4]).

Although in principle, displacement measurements of the transducer tip may be made *in situ*, the determination is generally made with the vibrating probe air-loaded with its displacement being determined using an optical microscope, laser or fibre-optic vibrometer. These measurements can be made relatively accurately and cheaply, although, as commented by a number of the respondents in the project, measurements of displacement did not necessarily relate simply to the resultant cavitation occurring within the particular application, be it surgical or sonochemical.

Discrete thermal methods (NPL review report[4]; Section 4.1) score lower than might be expected. The score for the "Value" is relatively low, as the device responds to time-averaged intensity which does not necessarily bear any direct relationship to cavitation. The low score produced by "Measurement Fidelity" arises from the complex interaction between the absorbing material and the acoustic field which is difficult to model and requires a knowledge of the low-frequency propagation parameters of the materials used. On the positive side, thermal probes can have exceptional spatial resolution and are relatively cheap and readily replaced. This means that positioning of the active element is critical in the field, although multi-element sensors along the lines described in the NPL review report[4] (Section 4.1.2) may alleviate this problem by averaging over a significant region of space. It is possible to envisage a sensor which can be placed in a vessel and manually scanned by hand around various sites in the enclosure, the associated electrical circuitry analysing the signals to establish some average or peak parameter derived over a time scale of a few seconds. Such a device would prove invaluable in the day-to-day testing requirements identified earlier, especially if the measurement could be completed on an absolute, traceable basis. This concept is taken further in the recommendation in Section 7.2. Weaknesses cited by respondents when commenting on discrete thermal probes were the fragility of the devices and the potential for self-seeding of the reaction medium due to erosive cavitation effects.

6.3.3 Inertial cavitation monitoring techniques.

There are three distinct groupings of cavitation monitoring scores. The first of these incorporates the top two techniques suggested by the scoring system, those of broadband acoustic emission and sonoluminescence, both of which may be considered remote techniques. The overall scores for each of these were very similar. In comparison to sonoluminescence, acoustic emission methods are relatively easy to apply, as the former requires blackout conditions and is only appropriate in optically transparent media. Furthermore, the equipment associated with the detection of light emission is relatively expensive (ISVR review report[5], section 3.4). Each technique scores highly in terms of the "Value" global area providing detection and monitoring which is directly related to cavitation and offering the potential of either remote or local detection of the cavitation events. Sonoluminescence provides substantially better spatial resolution than broadband acoustic emission. The comment should be made that for some of the sonochemical systems under consideration, it may not be possible to use local measurement methods of determining the field properties and cavitation dynamics as the conditions are so hostile. In these cases, remote methods, utilising sonoluminescence techniques or acoustic emission could be exceptionally valuable. Of the two, it would appear that acoustic emission monitoring may be more readily applied to industrial systems, although clearly the ability to detect the cavitation signals (generated by cavity implosion producing spherically divergent shock-waves) generated some distance away from the position of the cavitation cloud or region of activity, will require the acoustic losses in the medium to be fairly low and would therefore perhaps be more appropriate for low viscosity fluids.

A number of the respondents in the project had used cavitation monitoring based on broadband acoustic emission detected using a piezoelectric sensor and their comments are informative, if inconclusive. One cleaning bath manufacturer used a cavitation probe which comprised a PZT transducer which was used to monitor the white noise signal produced by the cavitation. They used this in-house and claimed that, subject to identical conditions being produced in the cleaning bath, the probe was reproducible to $\pm 10\%$. The device was considered to be rugged and reliable, and provided a response which was independent of temperature, but was only relative. Several had been sold to users who wanted to monitor the output of their cleaning baths. No information was provided on the bandwidth of the receiver or the construction of the device. In contrast to this, a second manufacturer of cleaning baths stated that, in their experience, a cavitation probe was difficult to use reproducibly, that its output was temperature sensitive and that the restricted bandwidth of the device produced misleading measurements. A particular limitation noted by the respondents, principally when used for cleaning bath measurements, was the poor spatial resolution of the devices, i.e. it was impossible to tell exactly where the cavitation signals arose from within the liquid. For passive detection of cavitation it was also difficult to distinguish between the number of bubble collapses occurring and their violence.

The second grouping of methods includes sonochemical or biological techniques where the cavitation occurring within the medium results in a change in chemical concentration of a particular species. The determination of the yield of the species, through chemical analysis or an alternative route, is thought to provide a direct indication of the cavitation occurring. In the case of spin trapping, the cavitation generated free radicals are scavenged and stabilised and their concentration determined using electron spin resonance (ESR). In the case of the terephthalic acid, the concentration of free radicals is determined using a colour change. All three techniques have limitations, in that they are not real-time, require specialist facilities and provide no spatial resolution, although conceptually at least, small phials or aliquots of material may be placed at various positions in the field to map the cavitation activity in a system. This type of technique may have potential long-term application as a dosimetric determination of the extent of cavitation.

The final class of cavitation techniques are those related to cavitation erosion or soil removal, and three particular implementations were scored: standard soil (e.g radioactive), aluminium foil and the loss in mass of relatively large bodies such as lead balls or ball bearings. The low overall score arises primarily through the low "Value" score, concerns here being the progressive soiling and self seeding of the medium through the removed deposits of the soil/foil/lead. It is possible that this may be overcome using a suitable protocol, although this must be carefully studied and validated. There is also a problem with mechanism specificity, other non-cavitation based mechanisms such as microstreaming leading to removal of soil. The method is not quite real-time but could possibly be made so (ISVR review report[5] Section 3.7). The major advantage of this type of technique lies in its simplicity and exceedingly low implementation cost and it can supply some information regarding the location of cavitation activity. A surprisingly large number of questionnaire respondents indicated that provided standardised conditions were set up and a stringent protocol used, measurements of soil removal or erosion could be completed reproducibly. They used this type of method as an in-house tool to qualitatively check on the performance of their equipment. A standard erosion test set consisting of a series of ceramic rings was supplied to NPL by a manufacturer during the project.

6.4 SUMMARY OF MEASUREMENT 'STATE OF THE ART'

The literature reviews, discussion with key contacts and the technical appraisal of measurement methods has indicated that the most attractive methods which hold potential for measurement standardisation involve the use of hydrophones. In a sense, this is to be expected, as the development of these devices has been instrumental in bringing the reality of calibration, traceability and measurement standardisation to the area of medical ultrasound. The development of hydrophone-based techniques hence forms an important component of the implementation strategy presented in Sections 7 and 8. Furthermore, the analysis of Section 6.3.3 illustrated that in cavitating ultrasonic fields these devices respond to the acoustic signals generated by cavitation collapse, and under the general heading of "broad band acoustic emission" this type of technique was felt to be the most attractive for deriving physically meaningful information about cavitation whose implementation could be appropriate in industry.

It is appropriate here to describe briefly some recent work undertaken on the characterisation of ultrasonic surgical devices[6] whose properties are similar to sonochemical instruments, generally operating in the frequency range 20 to 60 kHz. This work lends weight to the belief that by measuring the acoustic pulses produced by cavitation collapse, an estimate may be made of the energy of the collapse. In this study the energy associated with cavitation occurring around the tip of the device in water was determined by recording the acoustic shock waveform using a wide-bandwidth hydrophone positioned at some reference distance away from the probe tip. Shock waveforms generated by the cavitation collapse at the tip, and the energy associated with each cavitation collapse event were estimated by determining the pulse-intensity integral of the shock wave and extrapolating back to the tip surface, assuming that the cavitation collapse acted as a monopole source. The authors used a low frequency, underwater acoustics type hydrophone to determine the acoustic energy in the main beam and in combination with the high frequency shock wave measurements, they were able to observe the gradual transfer of energy from the acoustic beam to cavitational energy as the displacement of the surgical tip was increased.

7 PHASE III - A RECOMMENDED IMPLEMENTATION ROUTE

7.1 OVERVIEW

Although there is some commonality between the requirements of the various application areas highlighted earlier, they may be treated distinctly differently. For the purposes of the analysis given in this Section, three different application areas will be considered: medicine, sonochemistry in combination with industrial applications (non-cleaning) and finally ultrasonic cleaning. Applications such as water waste treatment have been included in the industrial area.

The three generic application areas are addressed in Tables 6, 7 and 8. For each area, two lines of approach to the development and standardisation of methods of measurement are suggested, derived from requirements identified during the project. The point should be made that the potential for new activity in this area is limitless and the project team were aware that any recommended strategy to NMSPU should appreciate its role in the development, maintenance and dissemination of measurement standards, and also be aware of the need to ensure that the cost of any work to NMSPU is commensurate with the benefit to UK society. It is for this reason that an attempt has been made to prioritise the work activities through a range of criteria such as cost, time-frame for dissemination, and dissemination route along with the industrial or health and safety drivers pushing for the development of the measurement standards infrastructure. This prioritisation has been done fairly crudely, but it is useful in providing guidance on the strategy to be recommended to NMSPU, both short and long term.

7.1.1 Medical applications

For medical applications, the need to develop wide-bandwidth, high-sensitivity focused-bowl type receivers has been highlighted in Table 6. Calibrated receivers of this type would be used to provide estimates of the cavitation collapse energy from events at specific sites *in vivo*, for example occurring during lithotripsy. This generic type of device has also been identified in relation to ultrasonic cleaning in Table 8 and is described later.

The second work area relates to the development of a cavitation dosimeter. This would be based on some kind of free radical scavenging technique where the aim is to characterise the ability of a medical ultrasonic system to induce cavitation events under prescribed, controlled conditions. The driving force here is principally the safe use of diagnostic ultrasound and the concept is along the lines of the dosimeters used in ionising radiation. In principle the 'dose' measurements could be made by an independent laboratory equipped with suitable facilities.

There are several reasons for believing that the development of a dosimeter is premature. First, there is no consensus on the most appropriate candidates for the reaction, some of which are given in the ISVR review report[5], Section 3.5. Probably most importantly, and it will be a recurrent theme in number of areas covered in this Section, the basic cavitation process is not sufficiently understood for us to be confident that the ability of the medical system to produce inertial cavitation is actually being characterised. Additionally, for diagnostic systems, there must be some concern as to whether the techniques are sufficiently sensitive. For the dose measurements to be put on an absolute basis there will be a need to develop a reference cavitation facility, and this could potentially be expensive. This may be an area which requires addressing by NMSPU in the future.

7.1.2 Sonochemistry

For sonochemistry, Table 7 highlights the development of reference facilities for cavitation, based on single bubble cavitation events and a reference cavitation cloud, the latter being of more relevance to the conditions produced in the industrial uses of ultrasound. The type of work envisaged is described in detail in the ISVR review report[5]. The facility involves the setting up of a reference cavitation field either of cylindrical or spherical geometry and perhaps utilising artificial nucleation sites. The aim is to cross-correlate the response of a range of detectors based on sonochemical, sonoluminescence and acoustic techniques (see ISVR review report[5], Section 4). The prescribed work is likely to be costly and the dissemination route largely knowledge-based, through the fundamental data derived from the cavitation dynamics study.

Other potential work areas were considered in the sonochemistry area. One such area was the development of a reference cavitation fluid, probably consisting of a fluid containing a prescribed number of nucleation sites (contrast agents or latex spheres). There is no doubt that such a fluid would be extremely useful, provided its performance and stability were validated in some way. For the performance, one would ideally like to 'measure' the acoustic emission produced by the nucleation sites under controlled conditions and relate this to the cavitation 'power' of the acoustic field being applied. Currently, this may be difficult to do, although it is possible to envisage a loop sonochemical reactor being flushed with a water mixture, a certain volume of nucleation sites of a specified type being externally introduced at some instant of time and the broadband acoustic emission signal being measured for the first pass of the nucleation sites through the cavitation zone. This procedure may overcome the problems of secondary seeding of the fluid by the remnants of the nucleation seeds following their cavitation. The detector (pressure sensor) would be positioned at a specific point in the reactor tube, indeed it may be included as an integral part of the reactor, the surge of cavitation signals being used as a measure of the reactor performance on a relative basis.

Line of approach to standardisation	Activities	Cost and other requirements	Time-frame for dissemination and dissemination route	Scale of need
Development of new focused sensors for passive detection of cavitation bubble collapse	Production of focused bowl type of sensor, consisting of a single sensor or an array of sensors; requires wide bandwidth, high sensitivity devices; could use array of fibre-optic sensors	Cost: low to medium. Needs special device development, thin film piezo sensors. The focused sensors need to be calibrated using spherical source methods.	Medium term time frame. Need development of sensors and validation of performance. Route: via calibrated sensors.	Medium. Safety considerations related to the *in vivo* detection of bubble collapse. Main driver is health and safety, although the development of such devices will have broader industrial applications - see Table 9.
Development of a reference cavitation dosimeter	Using terephthalic acid or spin trapping of free radical species produced by cavitation (in combination with ESR), specifically for systems generating low 'accidental' cavitation activity.	Medium to high. Validation of the method would be the costly part. Will probably require the development of a reference cavitation facility (see Table 7).	Medium to long-term. Dissemination would be via the material. Basically provides a test of the system to cavitate.	Low to medium. Driver: health, in particular the safety of diagnostic ultrasound.

Table 6 Medical applications: analysis of the need for measurements and measurement standards for high power ultrasound and cavitation

Line of approach to standardisation	Activities	Cost and other requirements	Time-frame for dissemination and dissemination route	Scale of need
Development of a reference cavitation facility - a single-bubble facility.	Investigation of single seeded cavitation event; aim is to investigate and study the dynamics of bubble collapse through acoustic detection methods and sonoluminescence.	Cost: high. Need multi-ported system able to take a range of detectors, equipment costs high. Able to accept a range of test samples of material.	Longer term activity. Route: could be used as reference facility to insonate samples under a range of conditions.	In long-term, importance to industry will be high due to the increased understanding of bubble dynamics. Driver: various, industry health and safety.
Development of a reference cavitation facility - bubble cloud facility. **(See ISVR Report[5], Section 4).**	Well defined cylindrical or spherical geometry high power field using known nucleating species (contrast agent or ionising radiation source), facility used to cross-correlate response of a range of detectors. Could potentially be a reference sonochemical reactor.	Cost: high. Need multi-ported system able to take a range of detectors, equipment costs high. Able to accept a range of test samples of material.	Longer term activity. Route: could be used as reference facility to insonate samples under a range of conditions. Facility could be used to cross-correlate sensor response.	In the long term, high. The configuration is representative of situation in many sonochemical systems, therefore will provide valuable information on monitoring of these processes.

Table 7 Sonochemistry: analysis of the need for measurements and measurement standards for high power ultrasound and cavitation

Line of approach to standardisation	Activities	Cost and other requirements	Time-frame for dissemination and dissemination route	Scale of need
Development of a reference cavitation facility - a single-bubble facility.	Investigation of single seeded cavitation event; aim is to investigate and study the dynamics of bubble collapse through acoustic detection methods and sonoluminescence.	Cost: high. Need multi-ported system able to take a range of detectors, equipment costs high. Able to accept a range of test samples of material.	Longer term activity. Route: could be used as reference facility to insonate samples under a range of conditions.	In long-term, importance to industry will be high due to the increased understanding of bubble dynamics. Driver: various, industry health and safety.
Development of a reference cavitation facility - bubble cloud facility. **(See ISVR Report[5], Section 4).**	Well defined cylindrical or spherical geometry high power field using known nucleating species (contrast agent or ionising radiation source), facility used to cross-correlate response of a range of detectors. Could potentially be a reference sonochemical reactor.	Cost: high. Need multi-ported system able to take a range of detectors, equipment costs high. Able to accept a range of test samples of material.	Longer term activity. Route: could be used as reference facility to insonate samples under a range of conditions. Facility could be used to cross-correlate sensor response.	In the long term, high. The configuration is representative of situation in many sonochemical systems, therefore will provide valuable information on monitoring of these processes.

Table 7 Sonochemistry: analysis of the need for measurements and measurement standards for high power ultrasound and cavitation

Line of approach to standardisation	Activities	Cost and other requirements	Time-frame for dissemination and dissemination route	Scale of need
Development of a reference ultrasonic cleaning bath	Establishment of a controlled cleaning bath characterised using a range of conventional sensors; established and used as a test-bed to investigate a range of techniques, including sonochemical or dosimetric.	Cost: low. Need scanning and analysis system. Small hydrophones exist to characterise the bath.	System used as test bed to validate the various test methods indicated below.	High. Driver: industrial, including energy efficient processes.
Development of new sensors for ultrasonic cleaning baths	(a) Development of acoustic 'energy-density' probe using a multi-element design, potentially could be done using thermal or piezo arrays (b) Development of focused piezo receiver to establish the cavitation signal from a specific point or volume in the cleaning bath.	Medium. Validation of the method would be the costly part. Medium to high, requires the development of novel sensors and their validation under controlled conditions. May require specialist calibration facility developments.	Medium to long-term. Medium to long-term. Dissemination of both sensors would be through traceable calibrations.	High. Driver for industry is ISO9000 as well as the improved understanding and control of cleaning processes. Also, health and safety involving whole person ultrasonic immersion systems.

Table 8 Ultrasonic cleaning: analysis of the need for measurements and measurement standards for high power ultrasound and cavitation

7.1.3 Ultrasonic cleaning

Given its extensive and long-standing use in the UK, it is our view that ultrasonic cleaning presents the most pressing need for development of measurement standards, and the work identified in Table 8 is regarded as the top priority for new investment. Two lines of approach to standardisation are suggested. The first involves the setting up of a reference ultrasonic cleaning bath, and details of the characteristics of the bath are given in Section 7.2. One of the aims of the work would be to gain experience of measuring cavitating fields in reverberant environments using a range of conventional measurement devices. It is also recommended that new measurement sensors for ultrasonic cleaning baths are developed, and two types of sensor are highlighted, details of each being given in Section 7.2. The aim would be to use the reference facility as a test-bed to investigate and validate the performance of the devices. Should the devices be successful, calibration methods would have to be developed enabling reliable dissemination of the standard techniques. It should be noted that such devices would also have important applications in both the sonochemical and medical ultrasound areas.

A work area which has not been mentioned in Table 8 is the potential of developing a standardised erosion test suitable for industrial use. The availability of a reference facility may make this worth investigating, although the problems with this type of method have been documented in the ISVR review report[5]. Over a longer term it may be appropriate to revisit this method to investigate its suitability for standardisation, as some derivative of the technique is fairly regularly used, albeit on a relative level. However, at the moment it is deemed to be fairly low priority.

We now expand in greater detail on our recommendation for the development of a reference ultrasonic cleaning bath facility and of two new types of sensor for cleaning bath measurements.

7.2 RECOMMENDED WORK PACKAGE

We recommend that NMSPU should consider setting up a reference ultrasonic cleaning bath facility, the specification and purpose of which would be as follows:-

- operating frequency 25 kHz to 50 kHz, volume approximately 0.2 m^3, facility includes scanning capability for sensors of various types, including small hydrophones and discrete thermal sensors;

- the conditions in the cleaning bath should be precisely monitored and controlled: this encompasses both the electrical drive to the transducers, and the temperature, dissolved gas content and level of the water;

- using existing hydrophones, the acoustic pressure distribution and cavitation signatures produced in the cleaning bath will be well characterised, to the extent that the bath can be considered as a reference facility;

- the reference cleaning bath will then form a test bed in which new sensors can be developed, tested and validated.

Two specific types of sensor are required:

- an acoustic energy-density probe, along the lines of the multi-element thermal probe considered in Section 4.2 of the field measurement report[4], but which probably does not utilise embedded thermocouples;

- a sensor which monitors cavitation collapse in the bath, through an analysis of the frequency spectrum received.

It must be emphasised that although applications of these sensors over the short term may be very much tailored to measurements on ultrasonic cleaning baths where time-averaged intensities are fairly low (a few W cm^{-2}), should they be successfully developed, they could potentially be ruggedised for use in more hostile environments such as sonochemical reactors.

One issue to be raised is the risk to NMSPU in undertaking this work, particularly in the area of novel cavitation sensor development. There is no doubt that the technical difficulties of characterising cavitation are significant, for many of the reasons previously described. However, it should be emphasised that considerable progress has been made over the last fifteen years in the area of ultrasonic field measurement. Our understanding of such measurements has increased dramatically and this progress has partly been made possible through the availability of high quality hydrophones which provide the spatial and temporal resolution required to characterise the pressure distribution. These hydrophones were developed with NMSPU funding and mean that measurements made in the UK and worldwide are now traceable.

8 PHASE III - AN OVERALL STRATEGY FOR NMSPU

During the formulation of the recommended work package given in Section 7.2, the following considerations had a major impact on our thinking:

- The potential benefits of the proper and effective exploitation of high power ultrasound in industry are considered to be sufficiently great to justify the allocation of NMSPU resources;
- The level of initial effort should, however, be limited, and in the short-term should be directed towards the development of calibrated sensors of proven performance, usable at an industrial level.

The recommendations concerning the strategy which NMSPU should adopt in relation to the development of measurement standards for high power/cavitating ultrasound fields may be summarised as follows:

- NMSPU should strongly consider funding the pilot work outlined in detail in Section 7.2 in the area of ultrasonic cleaning bath characterisation;

- NMSPU should consider this activity in the area of high power ultrasound as part of a long-term development strategy - a fundamental understanding of cavitation dynamics will not develop overnight but is likely to be incremental; the recommended work areas given in Section 7.2 will significantly aid the development of this understanding;

- over the next ten years and beyond, there will continue to be considerable activity in the area of high power ultrasound/acoustic cavitation, both within the UK and worldwide. This will inevitably lead to a wider application base, increasing further the need for understanding and characterisation of the processes taking place. It is important that NMSPU keeps a watching brief on progress in this area to ensure that the National Measurement System feeds off any important developments.

9 SUMMARY

This report describes a study undertaken for NMSPU to investigate the need for measurement methods and standards in the area of high power ultrasound and cavitation. The three objectives and associated findings were:

To review technical progress in measuring high power / cavitating ultrasonic fields:

- reviews of the technical literature covering measurements of field properties and cavitation have been undertaken by NPL and ISVR;
- up-to-date information regarding the techniques being adopted by industry and academia has been obtained through detailed questionnaires and technical visits to key centres - in total, responses from 49 centres were obtained;
- information retrieval was undertaken over four principal application areas, the responses indicating a strong need for the development of measurement standards.

To identify measurement methods for remote and local sensing of such fields:

- a short-list of candidate measuring and monitoring techniques has been produced covering both the field and cavitation areas;
- the suitability of these methods for standardisation was critically assessed using a specially developed scoring system;
- those deemed most suitable for standardisation were techniques based on the use of pressure sensitive devices (hydrophones) in conjunction with broadband acoustic emission, closely followed by sonoluminescence, for the monitoring of cavitation.

To recommend an implementation route, given the current state-of-the-art in measuring such fields:

- a range of options for work required to develop a standards infrastructure has been discussed and analyzed;
- in the short-term it is recommended that NMSPU establish a reference ultrasonic cleaning bath and develop special sensors, based on field measurement and cavitation monitoring concepts;
- over a longer time frame, NMSPU should consider developing a reference cavitation facility, based on a bubble cloud.

10 ACKNOWLEDGEMENTS

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Appendix A: SUMMARY OF PATENT HITS UNCOVERED

Originator details	Date, patent no. (US unless stated)	Description of device	Principle of operation
Edward Pedziwiatr	18/7/95, 5433102	Standing wave column-like probe containing particles (silver) in a fluid contrasting base	Particles migrate to nodes when probe placed in standing wave fields generated by cleaning baths
H Mitome	31/10/89, 4878210	Enclosure containing liquid and small polyester beads, with a transducer at one end: has a transparent wall enabling visualisation of 3-D sound field	Particles migrate to standing wave nodes when transducer switched on. Device developed for use in ultrasonic cleaning bath field representation
Assaf, Robertson, Watmough	12/6/90, 4932250	Linear coated thermocouple array, with each of a number of junctions on a base wire connected to a monitor	Incident ultrasound beam on junctions causes temperature rise which is depicted on monitor as a visual indication of transducer output
Reichenber, Naser	21/3/89, 4813415	Sensor for lithotripters comprises a means of holding a metal foil at focus of shock wave source.	Incident shock wave causes a deformation in foil which can be optically measured (depth, location etc.) to obtain data on shock wave geometry and power
Christman	26/2/85, 4501151	Coated thermocouple-containing acoustically-absorbing body mounted on support, with reference thermocouple outside body	Incident ultrasound causes measurable temperature rise indicative of energy.
Gabrielson, Lauchle, McEachern	21/2/95, 5392258	Sensor comprising two hydrophones and a moving coil geophone in a cylindrical case	Geophone is a velocity sensor, hydrophones detect acoustic pressure. Device produces true acoustic intensity information
US Navy	1/1/91, 4982375	Probe consisting of two or three dimensional hydrophone arrays in symmetric and asymmetric configurations	Cross-spectral density technique used to provide information on acoustic intensity distribution from hydrophone outputs
Olsson	19/6/85, GB 2115152	Resonator tube used to measure acoustic pressure at closed end	Used in cleaning baths to provide acoustic pressure information using data on gas density, velocity and tube radius