

Emerging new applications of nucleonic control systems in industry

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FOREWORD

This TECDOC presents a comprehensive review of the current status and future prospects of nucleonic gauge methodology and technology applied as nucleonic control systems (NCS) to a broad spectrum of industrial engineering processes. It presents the results of the IAEA's Advisory Group Meeting on Emerging New Applications of Nucleonic Control Systems in Industry, which was convened to discuss and evaluate the present 'state-of-the-art' of this field.

The TECDOC provides fundamental information on the principles of nucleonic gauges, their design, safe operation and applications. This covers both the more traditional and well established applications and methods as well as trends on emerging applications of new nucleonic gauges in modern industry.

A specific review is presented of nucleonic gauge methodology and technology as applied in international priority industrial sectors such as the petroleum industry, mining and mineral ore processing, material construction and environment. This information on nucleonic gauges, including the most relevant recent achievements and developments, effectively enhances and often replaces the existing related publications, many of which have lost their relevance.

Nucleonic control systems play a vital role to better industrial performance by assisting in the more effective exploration, extraction and processing of natural resources as well as in environmental monitoring. The report aims to increase awareness of NCS applications by the Member States of the IAEA and the various associated parties involved (government authorities, end-users and the general public) and assist by improving industrial performance and enhancing socio-economic benefit.

The IAEA is grateful to the participants of the Advisory Group meeting and to other experts in the field who contributed to this publication, in particular to J. Charbucinski, who drafted the principles of NCS methodology and technology. The IAEA officer responsible for the publication was J. Thereska of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

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1. INTRODUCTION

Nucleonic control systems (NCS) may be defined as being used for the "control by instrumental measurement and analysis as based on the interaction between ionising radiation and matter".

Several hundred thousand nucleonic control systems or nucleonic gauges are installed and operating in industry world-wide. They have been widely used by various industries to improve the quality of product by optimising processes and saving energy and materials. Their socio-economic benefits have been amply demonstrated and recognized. Trends in the industrialisation process of developing countries provide evidence that NCS technology will continue to expand and develop and play an ever increasingly important role in industry for many years to come.

The economic advantages to be gained from the use of nucleonic control systems vary greatly according to the application and the financial circumstances of different industries. The correct application of automatic process control systems almost inevitably leads to significant savings. They flow from savings of raw materials, reduced labour costs, the reduction of waste and rejects and enhancement of quality. Such instrumentation may be used inter alia for: on-line (process control), in-situ measurement (well logging), laboratory measurement (samples analysis), or mobile applications (on site measurements).

NCS instrumentation utilises the various types of interaction observed which occur between beta, gamma ray, X ray, neutron radiation and charged particles and material under investigation. These are typically: attenuation (single energy or dual/multi energy), scattering, excitation, nuclear reactions, secondary radiation emission, or even a combination of these processes. Nucleonic gauges include simple single parameter units such as: level gauges, bulk density gauges, thickness gauges, mass per unit area gauges, flow rate gauges, etc. More complex instrumentation includes nucleonic multi-component analysers using X ray fluorescence (XRF) and neutron activation analysis (NAA).

One of the most important advantages of NCS is that direct contact with the material being examined is not required. Consequently, these instruments are specially suited for example to high speed production lines or for systems operating at extreme temperatures. Measurements are accomplished non-destructively and without changing any properties of the examined material. The penetrating nature of high energy gamma radiation enables measurements to be made through the walls of sealed containers. The sampling volume of most of the NCS is usually larger than that sampled by other physical techniques and is usually much larger than assays normally collected for laboratory analysis. These systems are robust and usually versatile in their application to different materials and processes.

Many particularly simple, one parameter, static measuring nucleonic gauges are now commercially available from several manufacturers. The development of supporting technologies such as compact electronics, fast computers, high-resolution detectors, small reliable neutron tubes, and dedicated computer modelling codes has resulted in increased technical viability and economic acceptability of NCS. The development of the new generation of nucleonic devices is continually taking place. Some of the emerging significant types of NCS discussed here are not yet in the realm of commercially available services.

Over the years, the IAEA has contributed substantially to the development of industrial applications of NCS technology. Significant progress has been made, enabling IAEA developing Member States to introduce this technology in to well defined industrial processing fields. In select cases, national NCS groups have been established with an indigenous capacity to sustain and develop the technology further. There is a need to continue stimulating, maintaining and building consulting capability in interested developing Member States, and, where appropriate, support and train teams of skilled specialists to look after the NCS used in and appropriate to their industries. Their need is to calibrate and to check the safety of application and to advise their local industries in selecting and developing the appropriate NCS from a techno-economic point of view.

NCS technology competes well with conventional techniques in many relevant target areas which are defined in international priority industrial sectors, such as mining and mineral ore processing, environmental monitoring, paper and plastics industries, cement and civil engineering industries, oil and gas industries, where the benefits are enormous. New applications and techniques in NCS design, calibration, quality control and operation in these sectors is on-going.

This TECDOC provides the background information on the principle of nucleonic gauges, their design and applications. It addresses the nucleonic gauge technology fundamentals, its current status and future trends in many developed and developing countries. The report updates the information on nucleonic gauges with most relevant achievements and developments of recent years. It contains material which is relevant to the scientists and technicians who are active in nucleonic gauge design and calibration, prototype manufacturing, their safe operation and applications. The TECDOC also seeks to inform both the general reader and the non-specialist scientist about the application and impact of nucleonic gauges in modern society and create public and end user awareness of the safety and benefits of the technology. In addition, it aims to inform and interest managers and decision makers who are generally focused in areas outside of the specialised area of nuclear technology.

Because of the large number of applications and the great diversity of problems to which they are applied, it has not been possible within the framework of this TECDOC to deal with every type of industrial application of NCS. The instrumentation and the applications selected should be regarded as both typical and trend setting examples of current industrial use of NCS technology.

2. NUCLEONIC GAUGING PRINCIPLES AND TECHNIQUES

A nucleonic gauge consists of a suitable source (or a number of sources) of alpha, beta, gamma, neutron or X ray radiation arranged in a fixed geometrical relationship with one or more radiation detectors. NCS can be used for either static or continuous measuring applications. Some nucleonic gauges do not use radiation sources but are based on measurement of the natural radiation of an examined material. The two most commonly used gauge arrangements are transmission and backscatter.

When radiation passes through matter it is absorbed and scattered to a degree which depends upon the nature of the material and the type and energy of the incident radiation. A beam of radiation traversing a material is thus attenuated, where attenuation increases with

thickness, density and average atomic number of this material. When the thickness of a sample is constant the density of material can be determined from a measurement of attenuation of radiation beam. As well, the thickness may be determined if the density is constant. An instrument based on the above principle, where the sample is placed between source and detector, is known as a transmission gauge. Thickness and density may also be measured with the source and detector positioned on the same side of the examined material. An instrument based on this principle is known as a backscatter gauge.

As a general rule in measuring thickness (mass per unit area) and density, transmission geometry is used in preference to backscatter geometry as the sensitivity is higher and a more accurate result is usually obtainable. A preference for backscatter geometry is usually dictated by the practical conditions of the measurement.

For simplicity the nucleonic gauges can be divided into groups according to the main type of application:

- thickness and mass per unit area,
- level,
- density and bulk density,
- nuclear analysers,
- other (like moisture or hydrogen content, flow meters, etc.).

2.1. PRINCIPLES OF NUCLEONIC GAUGES

Most of nucleonic control systems are based on a few most common nuclear techniques which are briefly described below.

2.1.1. Natural gamma ray technique

The applications of natural gamma ray techniques to on-line, off-belt and *in situ* analysis are based on the correlation between natural gamma ray intensity measured in one or more pre-selected energy windows and the concentration of particular elements (e.g. U, Th, K) or the value of a given parameter of interest (e.g. ash in coal). The technique is based on the fact that geological strata or various types of ore (coal) contain various quantities of naturally occurring radioactive elements, such as uranium, thorium and potassium. These elements emit gamma rays of different energies which can be measured with spectrometric scintillation detector.

A typical example of the application of this technique is delineation of coal seams in coal deposits intersected by exploration or production borehole. Radioactive elements are present in shale and other sediments associated with coal seams. The level of radioactivity depends on petrographical type of inter-sediments. Shale will have higher radioactivity level than sandstone or mudstone, but lower than clay. On the other hand, there is very little natural radioactivity associated with the organic material of coal. Consequently, the minimal in the natural radioactivity profile will correspond to coal seams, and the maximal to clay or shale strata.

Inherent radiation of coal may be correlated with its ash content, because lower quality coals will have more mineral matter than good quality ones. Therefore, there is a possibility of

obtaining calibration equation in which ash content can be expressed in a function of measured natural radioactivity (in one or more energy channels). The natural gamma ray ash analysers may require different calibration for coals of different origin. This is due to the fact that the amount of natural radioactivity present in lithological strata is dependent on their mineral composition. The same amount of ash will produce more natural radiation if associated with shale in coal, than when mineral matter in coal is mostly of sandstone type.

On-the-belt applications incorporate large volume scintillation detectors. The detector is usually mounted between conveyor idlers directly under the centre line of the belt. The detector is shielded from radiation external to the conveyor load by a lead lining within the detector assembly, as well as an overbelt lead shield. A belt weigher is required to compensate for variable belt loading and to provide tonnage data for the calculation of mass-averaged ash content.

The natural gamma ray technique is intrinsically safe, as it does not require an external source of radiation, and simple in application. Due to the lower measured intensity, this technique may not be as precise when compared with the nucleonic techniques utilising backscatter or absorption of gamma quanta emitted by the radiation source in-built into the nucleonic control system. Other shortcomings of the technique include dependence of the naturally occurring radiation on the geometry and the distribution of coal and stone on the conveyor belt and varying level of background gamma-radiation around the sampling system (despite the application of lead shields).

Detectors applied in the natural gamma ray based nucleonic control systems are usually high volume scintillation crystals, the most popular being NaI(Tl). However, in some applications, where there is restriction to the size of the detector (e.g. well logging probes of small diameter), crystals of scintillators of higher efficiency (BGO and CsI) are commonly used.

Typical applications for on-line analysis of coal include:

- Mine grade control, providing prompt feedback to the mine face of raw coal ash content. For mines shipping unwashed coal, this monitor can be both a blending optimiser and a warning of out of specification shipments.
- Preparation plant feed monitoring, where advance knowledge of ash content can allow the plant to be optimised, or at least warned of excessively high or low ash coal.
- Preparation plant feedback control, monitoring product coal quality and contract specification compliance. Sudden changes in preparation plant output quality may indicate plant equipment malfunction.
- Train loadout control, monitoring reclaimed washed product or unwashed direct shipping coal from stockpiles. Knowledge of train quality assists in stockpile management and consignment control.

2.1.2. Dual energy gamma ray transmission

This technique is probably the most common nucleonic method for on-the-belt determination of ash content in coal. Ash content is determined by measuring the transmission through coal of narrow beams of low and high energy gamma rays. The absorption of the lower energy gamma rays depends on ash content, due to its higher average atomic number

than that of coal matter, and on the mass per unit area of coal. The absorption of the higher energy gamma rays depends almost entirely on the mass per unit area of coal in the beam. Ash content is determined by combining measurements of the two beams. The determination is independent of both the bed thickness and the mass of the coal.

To explain the underlying principle in more details it is necessary to introduce a simplified two component model of coal. In this model coal is regarded as having two bulk components, a combustible component (C, O, H) with an average atomic number of 6 and mineral matter component (ash) with an average atomic number around 12. Because of their lower atomic numbers, the elements comprising the combustible component possess lower mass absorption coefficients, μ , than those in the mineral matter component. This behaviour, however, only holds true for low energies, where photoelectric effect predominates. At radiation energies over 200 keV, the mass absorption coefficient depends almost entirely on electron density of material. The dual energy gamma ray transmission technique is used for the determination of ash in coal, by selecting two gamma rays energies where one at low energy is sensitive to the difference in the ratio of the mass absorption coefficients of the gamma rays between the combustible and mineral components whereas the one at high energy is much less sensitive to average atomic number and essentially detects only the total mass on the conveyor belt.

There are two possible configurations to the measurement of transmission of gamma rays at two different energies through varying thickness of coal on a rapidly moving conveyor belt. First, two separate source/detector assemblies, mounted in line, can be used (e.g. EG&G Berthold's Ash Monitor System LB420). A time delay is incorporated to ensure that outputs from the two assemblies refer to the same region of coal when ash content is calculated. In the second configuration both gamma ray sources are mounted in one lead container and a single detector in spectrometric regime is used to resolve the transmitted intensities of two different energy gamma rays (MCI's Coalscan 3500). In this configuration the low and the high energy gamma beams measure exactly the same coal volume. A single detector used eliminates necessity of correction for various detectors' characteristics.

In order to minimise interference from Compton processes in the flow material with scattering angles deviating remarkably from 0° , the gamma ray beams are collimated. The sources most commonly used are ^{241}Am for the low energy beam with a peak energy of 60 keV and ^{137}Cs or ^{133}Ba for the high energy beam with peak energies of 662 keV and 356 keV, respectively.

The combination of the low and the high energy channels accurately corrects for slow changes in the mass per unit area of coal. The measured ash of a standard sample remains constant to within ± 0.25 over a range of 100–230 kg/m². For the fast moving conveyor belt, errors in ash determination are introduced. In order to achieve acceptable accuracy for ash measurement of coal moving rapidly on a conveyor belt, the short counting time intervals must be used to minimise any errors in ash determinations caused by variations in the mass of coal passing through the beam during measurement. The mean ash content over long periods are calculated from averaging of many short time interval measurements. Errors in ash determination by this technique are also caused by composition changes. Iron oxides is the ash constituent having variations which cause the greatest part of the total error, which is especially true for high ash coals. Coals with high iron oxide content would require separate calibration equations.

The dual energy gamma ray technique possesses a number of advantages. It takes a more uniform vertical sample compared with backscatter technique. It is therefore much less sensitive to vertical variability of the load than the backscatter technique. Other important features of this technique are, ease of application to existing conveyor belts, acceptable accuracy for most applications, short analysis time, good radiation safety features, and moderate cost. Disadvantages of the dual-energy technique are that it tends to interrogate a smaller horizontal fraction of the load than do the backscatter and natural gamma systems, and its relatively high dependence on variable composition of ash. On-line analysers need to be carefully calibrated in order for good accuracy levels to be obtained. In particular, the samples that are used for the calibration need to be representative of the range of coals that are to be monitored. Therefore careful sampling is necessary, so that the samples will represent the full ash range and ash composition of the coal, in particular the iron oxide content.

2.1.3. Gamma ray backscatter

The gamma-gamma method, also known as the backscatter gamma ray method, provides the main basis for routine measurements of the ash content in coal seams and grade control of metalliferous ore for *in-situ* determinations. This technique is the most commonly used method in well logging. However, there are numerous applications of the gamma ray backscatter technique in on-the-belt applications.

The intensity of the gamma rays backscattered from the coal or ore matter is determined by both its bulk density and its overall chemical composition, which is often characterised by the equivalent (average) atomic number, Z_{eq} . Variations in mineral content reflect directly in the bulk density of coal provided the composition is reasonably constant. Thus the measurement of bulk density can provide information on raw ash content. However, the correlation between the bulk density and the coal ash is not universally good, which limits the method's accuracy overall. Another approach for coal ash determination is through its correlation with an average chemical composition of coal, described by Z_{eq} . The spectrometric gamma-gamma technique utilises information obtained from both energy regions (low, dominated by photoelectric absorption effect and strongly dependent on Z_{eq} and high, where scattering interactions predominate, dependent on electron density of the scatterer) for ash in coal or ore grade determinations.

The physical basis for density measurement by gamma ray scattering is the fact that the Compton cross section per electron is essentially independent of the atom in which the electron is bound. If the bulk sample (or lithology formation, for *in-situ* applications) is irradiated with gamma rays of initial energy below the pair production threshold (1.02 MeV) and detectors measures backscattered quanta of energies well above the photoelectric absorption region (say, 200 keV) the only interaction of consequence is Compton scattering. Thus, irrespective of the number of scatterings taking place in the formation, only the electron density (number per unit volume) determines the counting rate. This electron density is directly proportional to bulk density.

The use of photoelectric absorption in measuring formation (bulk sample) average atomic number, which then contributes to determination of ore grade or ash content, is made simultaneously with density measurements. The P_z factor, defined as a ratio of radiation intensity of scattered gamma rays in high energy spectral region, to radiation intensity measured in low energy region, is practically independent on bulk density and well correlates with Z_{eq} of investigated sample. The two energy regions are separated by an energy threshold

usually positioned between 100 and 300 keV. P_Z is thus a ratio which gives a rough measure of the shape of the backscattered gamma ray spectrum.

Variations of coal ash content can be directly translated into variations of coal Z_{eq} , giving therefore physical basis for coal ash determination through changes of chemical composition of coal. Since Z_{eq} is strongly dependent on the constituent element of highest atomic number, i.e. iron in ash, even small variation of such a constituent in a low atomic number matrix will cause significant variations in P_Z . Variable iron content in mineral matter is the most significant source of error for ash determination using this technique.

The gamma ray backscatter method has relatively good depth of investigation. The penetration range depends on the source-to-detector distance, source energy and density of the investigated medium. The depth is commonly considered to be the thickness of the material for which the count rate is 90% of that for infinite material. The 90% depth range is usually between 5 and 12 cm for typical gamma ray sources applied in this method (^{137}Cs and ^{60}Co) for bulk densities between 1.8 and 2.6 g/cm³. The depth range in coal is even greater and depends on coal ash content.

2.1.4. Pair production technique

Pair production is a process whereby a photon is replaced by a matched pair of opposite charged particles, an electron and a positron, travelling in opposite directions. Pair production is theoretically possible at high gamma ray energies above 1.022 MeV. In practice, however, the probability of this remains low until the gamma ray energy is well above this level. The positron will be progressively slowed down in an absorbing medium and will eventually annihilate by colliding with an electron. This process produces annihilation radiation of energy 0.511 MeV, which can be monitored with a spectrometric gamma ray detector. Because the pair production probability per unit weight is proportional to $\sum_i w_i Z_i^2/A_i$, where w_i , Z_i and A_i are the weight fraction, atomic number and atomic weight of element i , the intensity of annihilation radiation is dominated by the presence of elements of high Z .

The application of pair production to on-line ash measurement is based on exposing a sample of coal to a high energy gamma ray source (^{226}Ra , with a major energy line of 1.76 MeV, is often used) and measuring the emitted radiation with a spectrometric scintillation detector. Gamma ray intensities in two energy channels are measured. The 0.511 MeV gamma rays resulting from pair production, give a measure of the rate of pair production. The detector also measures the intensity in a lower energy window of scattered gamma rays by the coal. This second intensity is only dependent on the bulk density of the sample. Ash content is calculated from a two-variable calibration equation utilising both measured intensities.

There are two important advantages of this technique. It does not appear to be affected by particle sizes up to 50 mm and, more importantly, is much less sensitive to variations in ash composition, notably iron, than the dual energy gamma ray method or gamma ray backscatter method.

The application of this technique for ore grade determination is based on principle that the intensity of the annihilation radiation is dominated by the presence of the heaviest element

in the ore sample. Thus, in high grade iron ore, the pair production radiation intensity is strongly correlated with the iron concentration. In practice, as for ash determination, the intensity of the Compton scattering radiation must also be measured to compensate for variations in sample bulk density.

However, there are a number of disadvantages when using pair production technique. It represents a greater radiation hazard, due to the higher gamma ray source activity and energy and therefore requires significant lead and concrete shielding. The technique is sensitive to load geometry and therefore its application directly on conveyor belts is cumbersome. It is also much more expensive than the other techniques applied in similar applications.

The gamma ray source based techniques, both backscatter and absorption, are not element-specific and do not provide sufficient discrimination to measure the individual elements present in coal. They simply provide a measure of the average atomic number of the coal from which the total ash content can be determined. These techniques, however, can provide quantitative information about heavy element content in monometallic ore (e.g. iron ore).

The most common technique used for elemental analysis of coal, cement or metalliferous ore, is based on the excitation of nuclei in investigated medium by neutrons.

2.1.5. Neutron scattering techniques

In neutron sources (^{252}Cf , $^{241}\text{Am-Be}$) the energy of the neutrons produced are in the order of MeV. A succession of scattering events, most commonly in hydrogenous materials, can be used to reduce the high energies to thermal energies. In general more energy is lost by neutrons on collision with light nuclei than with heavy nuclei. Due to its light nucleus hydrogen is most effective in moderating neutrons from the source. As its major constituent of most liquids it is the dominant medium for the scattering of neutrons and allows detection of the liquid through container walls made of high atomic number materials.

Neutron-backscatter level and interface gauges require access to only one side of the vessel or pipe, and can 'see' through up to 100 mm of steel. They are particularly valuable for measuring the levels of corrosive or pressurised liquids, and can also be used to determine the interface between two immiscible liquids. When fast (high energy) neutrons emitted by the source collide with the nuclei of surrounding material their energy is moderated through scattering and a wide range of slow (low energy) neutrons is produced. The efficiency of the He-3 (or the BF_3) proportional detector is inversely proportional to the energy of the neutron and consequently responds better to slow, backscattered neutrons than to the direct neutrons from the source.

Another good example of the practical application of scattering neutrons is in the measurement of the moisture — water content (hydrogen density) of soils, coke or other materials. The moisture neutron gauges are much used in agriculture, civil engineering and coal industry.

2.1.6. Prompt gamma neutron activation analysis (PGNAA)

When a material is bombarded with neutrons, interactions with nuclei result in the emission of high energy gamma rays, at a variety of energy levels. The nuclear reactions excite gamma rays of energies specific to the target nucleus and the type of nuclear reaction. If the intensity and energy of these are measured by means of a suitable spectrometric detector, the type and amount of an element present can be determined. The gamma rays emitted may be classed as prompt, occurring within 10^{-12} seconds of the interaction, or delayed, arising from the decay of the induced radioactivity. Most research work has been undertaken in the field of prompt gamma neutron activation analysis (PGNAA). Two mechanisms predominate in the application of PGNAA to coal and metalliferous ores analysis: thermal neutron capture interactions; and inelastic scattering with fast neutrons. In the last 10–15 years PGNAA has been developed commercially for the bulk analysis of coal, cement and ores and also to the analysis of coal, cement and mineral slurries.

Due to its high hydrogen content, coal is an excellent matrix for this technique. The neutrons emitted are thermalized by colliding with the hydrogen nuclei present in coal, and they subsequently interact with the nuclei from the coal matrix. The compound nucleus formed in neutron capture decays almost instantaneously, emitting gamma radiation. Another advantage of the prompt neutron gamma technique for coal is that the major gamma rays produced by the main constituents of the mineral matter in coal (Al, Si, Fe, Ca, Ti, S) have energies above 3 MeV. However, the gamma rays produced by delayed neutron activation, neutron inelastic scattering, or natural radioactivity have energies mainly below 3 MeV; this level makes the PGNAA technique less sensitive to interferences from other neutron interactions.

Determination of the elemental composition of coal by neutron capture is based on measurement of the gamma rays released during the capture process. The intensity of the gamma rays emitted by a chemical element in the coal is determined by concentration of that element. In practice, this determination is complicated by the fact that the space-energy distribution of the neutron flux is perturbed by inherent variations in bulk density, hydrogen content, and elemental composition of coal. The difficulty can be overcome by normalising the count rate in selected spectral windows to that of the 2.22 MeV hydrogen peak.

Commercial PGNAA analysers use californium (^{252}Cf) as the excitation source and a large volume scintillation detector or a solid state detector for measuring the intensity of emitted gamma rays. An array of NaI(Tl) scintillators which are operated as a pair spectrometer have also been applied in commercial analysers. Such detector system provides marked improvements compared to conventional systems in the key area of spectral discrimination leading to better element differentiation, shorter measurement time and greater accuracy.

As with the other systems, elemental analysers need to be carefully calibrated in order to ensure that good accuracy levels are achieved. Each manufacturer has developed a proprietary calibration procedure and this is carried out at the factory before the analyser is delivered to the customer. The calibration is fine tuned by using coals from the site where the analyser is due to be installed. The coals used have to be carefully selected so that they are representative of the range of coals handled at the site. Elemental analysers will give good accuracy levels for the range of coals for which they have been calibrated. As with all other

on-line analysers, the accuracy is adversely affected when a coal varying markedly in composition from those used in setting up the calibration is analysed.

Although some elemental analysers are capable of using full flow, it is more usual for a side stream sampling system to be installed. The coal is fed through a hopper and feeder into the analyser. Feed rates can range from 5 to 500 t/h.

2.2. THICKNESS AND MASS PER UNIT AREA GAUGES

Nucleonic thickness gauges were the first type of radioisotope instrument to be developed commercially and they have now been in use by industry for about 50 years. Following advances in detectors, electronic components and circuitry, these instruments have now been developed to a high degree of reliability and accuracy. Thickness and mass per unit area measuring gauges, including coating thickness meters, have found applications in a wide range of industries. The paper, chemicals and plastics industries and the basis metal industry are the main users of nucleonic thickness gauges. The thickness gauges are usually based on beta particles and gamma rays transmission and backscatter. Nucleonic thickness gauges are considered to be a mature technology and very little R & D effort is presently directed towards redesign.

Beta particles have been used extensively in NCS instrumentation for measurements of the thickness of either low density materials like paper and plastics or thin metal foils, usually in beta-transmission geometry. Another application is measurement of the thickness of coating of sheet materials using beta-backscatter technique. It needs to be noted that X ray fluorescence gauges have practically replaced beta-backscatter gauges due to provision of a higher instrument sensitivity. The most common beta-emitters applied in nucleonic thickness gauges are $^{90}\text{Sr}/^{90}\text{Y}$, ^{85}Kr , $^{106}\text{Ru}/^{106}\text{Rh}$, ^{147}Pm and ^{204}Tl .

Thickness gauges based on the transmission of high energy gamma radiation (typical gamma radiation emitters — ^{60}Co and ^{137}Cs) are employed extensively in the production of many hot and cold rolled metals. Metal sheet thicknesses from a few millimetres to 15–20 cm are measured. Due to a tight collimating incorporated in nucleonic thickness gauges, there is often a necessity for a strong radioactive source (GBq — range). Some specific applications require use of gamma- ray emitters in the backscatter geometry. Typical applications include measurements of wall thickness of pipes, tanks and process vessels.

2.3. LEVEL GAUGES

Nucleonic level gauges are widely used for the measurement of fluid levels in containers and process vessels. These gauges are also used for measuring the interface between solid and fluid fractions (or between fractions of different densities) in storage tanks. Although as a general rule nucleonic level gauges are only installed when conventional instruments have proved unsatisfactory, there are many instances where their performance and reliability have been so impressive that they have been introduced, even when other types of level gauge could have been used.

Nucleonic level gauges have been in the realm of commercially available equipment and service for quite some time. Therefore, there is practically no research carried out in this segment of NCS.

Chemical processing plants with vessels of all sizes, often containing corrosive, viscous or frothy liquids and sometimes under extreme conditions of temperature and pressure, are the main users of this type of gauges. Other typical applications include package monitors in various branches of manufacturing industry, silos control in the sugar industry, pulp level monitoring in the paper industry, petroleum industry, etc. Similar to thickness gauges and density gauges, these gauges are often incorporated into a system of automatic process control.

2.4. DENSITY (BULK DENSITY) GAUGES

Density gauges (mostly operating in transmission geometry) are widely used in the production of cement, glass, tobacco products, paper, plastics, as well as in a variety of processes in the chemical industries, petroleum and gas industry and mineral processing of coal and ore. Measurements of density are usually used for quality control of manufactured product (e.g. concentration of a product in chemical or food plants, detection of individual non-standard cigarettes at a production line in the tobacco industry, etc.), or control of technological process (e.g. measurements of density in slurries for control of beneficiation process). Beta and gamma radiation sources used in density gauges are generally the same as those used in thickness gauges.

Backscatter density gauges have been successfully applied to the measurement of soil density in civil engineering. Two general types of soil-density gauges are in use: the subsurface type (the so-called 4p geometry) and the surface type (2p geometry). The subsurface backscatter density gauge has found wide applications in the petroleum and gas industries as well as in the coal, metalliferous mining and exploration industries. The gamma-gamma logging method, also called density-log is one of the most used well logging techniques. The individual gauges (logging tools) differ from each another with regards to the technical design (like source-to-detector distance, number of detectors, collimator design, etc.) but conceptually they all are the backscatter density gauges.

2.5. NUCLEAR ANALYSERS

A nuclear analyser consists of a suitable source of radiation (a radioisotope source or a generator) and a spectrometric radiation detector (usually a scintillation detector or a semiconductor detector). There are basically two types of nuclear analysers; energy specific (e.g. PGNAA, DGNAA, X ray fluorescence) and non-specific.

As a method of analysis, measurement of backscatter X and gamma radiation is non-specific. Binary systems can however be analysed provided the scatter cross-sections of the two elements are very different. Complex materials can be analysed if they behave effectively as binary systems. Coal ash analysis is a typical example of a binary system analysis. In a simplified two component model of analysed material coal is regarded as having two bulk components, a combustible component (C, O, H) with an average atomic number of 6 and mineral matter component (ash) with an average atomic number around 12.

Dual energy gamma ray transmission is probably the most common nuclear analyser for on-line determination of ash content in coal. Ash content is determined by measuring the transmission through coal of narrow beams of low and high energy gamma rays. The absorption of the lower energy gamma rays depends on ash content, due to its higher average atomic number than that of combustible coal matter, and on the mass per unit area of coal.

The absorption of the higher energy gamma rays depends almost entirely on the mass per unit area of coal in the beam. Ash content is determined by combining measurements of the two beams. The determination is independent of both the bed thickness and the mass of the coal.

This dual or multiple gauge approach is often used in applications of the transmission method for eliminating, or at least minimising, measurement influences. Analysis of materials travelling on fast moving conveyor belts requires that errors introduced by varying load of the belt are eliminated. There are two possible configurations of equipment for the measurement of transmission of gamma rays at two different energies through varying thickness of material on a rapidly moving conveyor belt. In the first, two separate source/detector assemblies, mounted in line, are used. In the second configuration both gamma ray sources are mounted in one lead container/collimator and a single detector in the spectrometric regime is used to resolve the transmitted intensities of two different energy beams. In this geometry the low and the high energy gamma beams measure exactly the same volume of examined material. A single detector eliminates the need to correct for individual detectors' various characteristics.

The sources most commonly used are ^{241}Am for the low energy beam with a peak energy of 59.5 keV and ^{137}Cs or ^{133}Ba for the high energy beam with peak energies of 662 keV and 356 keV, respectively.

The backscatter gamma ray method provides the main basis for routine *in-situ* determinations. This technique is the most commonly used method in well logging. Typical applications include analyses of binary type materials (examples: the determination of ash content in coal seams, grade control of metalliferous ores). The high energy component of recorded backscatter radiation is well correlated with the bulk density of investigated material, whilst a ratio of the high energy component to the low energy backscatter gamma rays is directly proportional to an average atomic number of the material. Certain properties of the analysed material can be determined through spectrometric measurements of backscatter gamma radiation.

When a material is bombarded with neutrons, interactions with nuclei result in the emission of high energy gamma rays at a variety of energy levels. The nuclear reactions excite gamma rays of energies specific to the target nuclei and the type of nuclear reaction. If the intensity and energy of these are measured by means of a suitable spectrometric detector, the type and amount of an element present in the analysed sample can be determined. The gamma rays emitted may be classed as prompt, occurring within 10^{-12} seconds of the interaction, or delayed, arising from the decay of the induced radioactivity. Consequently, two major types of nuclear analysers are in use, based on either prompt gamma neutron activation analysis (PGNAA), or delayed gamma neutron activation analysis (DGNAA). Most research work and commercialisation has been undertaken in the field of PGNAA. Two mechanisms predominate in the application of PGNAA: thermal neutron capture interactions, and inelastic scattering with fast neutrons. PGNAA technique has been employing commercially for the analysis of coal, cement, metalliferous ores, non-metallic materials in bulk samples and slurries.

Commercial PGNAA analysers predominantly use Californium (^{252}Cf) as the excitation source and a large volume scintillation detector or a solid state detector for measuring the intensity of emitted gamma rays. An array of NaI(Tl) or BGO scintillators which are operated as a pair spectrometer have also been applied in commercial analysers.

X ray fluorescence analysis is applied in continuous analysis of most elements in slurry or solution streams as well as in dry material streams. Single element probes with a scintillation detector and the multi element probes containing a solid state detector are used. The applications include base metals, industrial metals, gold, iron ore, paper manufacture, alumina industry, chemical industry, smelter feed streams, mineral sand, and others. The XRF analysers are energy specific. The most important shortcomings of these analysers are their very limited depth range and dependence on matrix type and grain size.

Many nuclear analysers are now commercially available from several manufacturers. However, the design of new nuclear analysers is still taking place. Research groups working outside the manufacturing industry are doing most of the development work leading to future generation.

3. CURRENT STATUS OF NCS APPLICATIONS

In a number of areas of industrial application nucleonic gauges have become firmly established. They have world-wide acceptance and in many instances there appear to be no alternatives. Information extracted from early equipment was limited and often crude. But the development of supporting technologies such as compact electronics, fast computers, high-resolution detectors, small reliable neutron tubes, and dedicated computer modelling codes has resulted in increased technical viability and economic acceptability of NCS. Various industries in many countries are now using nucleonic control systems as routine tools. There is a continuous increase in the total number of NCS installations. The most typical users of this technology are industries in which the technical and/or economic performance is substantially improved by the application in NCS. These industries include:

- petroleum and gas,
- mining (metalliferous ores, coal, minerals, raw materials),
- metal industry (ferrous and non-ferrous),
- paper, textile, plastics and rubber manufacturing industry,
- chemical industry,
- cement industry.

Other industries — users of NCS in a less critical way, include:

- civil engineering,
- food industry,
- environment control,
- tobacco industry,
- composite materials, aerospace,
- waste water treatment plants,
- nuclear fuel cycle industry,
- agriculture and forestry industries.

The intrinsic advantages of nucleonic gauges are that they provide measurements which:

- are non-destructive,
- are non-intrusive,
- provide required information in real-time,
- due to penetrating character of gamma and neutron radiation, sample larger volumes, thus providing better averaging of measured parameters,
- are able to operate from outside the system (measurements on abrasive and corrosive materials or on materials at extreme temperatures can be accomplished),
- offer greatly reduced maintenance problems, due to absence of moving parts in non-contact gauges,
- are successfully applied through vessels, pipes, heat insulators or refractory materials,
- provide relatively high accuracy and sensitivity (from some 0.1% to some %).

Many NCS, particularly simple — one parameter measuring gauges, are now commercially available from several manufacturers. However, a significant number of NCS are not in the realm of commercially available services. The development of next generation nucleonic devices is still taking place. Harmonious interactions between the research groups in universities or nuclear research centres and the NCS manufacturing industry will lead to successful implementation of new, more powerful, nucleonic control systems.

Some types of NCS have reached a nearly stable rate of increase of number of installations:

- level and level fill, thickness, density gauges,
- on-line ash in coal analysers, airborne dust monitors,
- well logging tools,
- analysers for the mineral and metal industries,

The main negative parameters (non-technical) affecting the use of NCS are:

- Reluctance on part of public, associated with public perception of waste disposal problems of nuclear power in industry, nuclear accidents in power reactors like Three Mile Island, Chernobyl, loss of radioisotope sources by hospitals and NDT service companies.
- The lack of a world-wide uniform set of regulations and of a standardised legislation for these regulations. There are almost no internationally accepted rational standards and regulations for nucleonic instrumentation design and fabrication, installation, training and certification of operators, safe disposal of the sources at the end of life of the source, or eventual maximum life of utilization of nucleonic equipment.
- Complex licensing procedures and often irrational decisions concerning license approval, resulting in long times for approval and in effect delay in installation of nucleonic gauges.

- Increasing cost of licensing procedures, often incorporating a bond for future source disposal and lack of well established mechanisms for radioactive source disposal.
- General philosophy of the industrial manufacturers of nucleonic instrumentation is extremely proprietary and directed towards a one-of-a-kind design & production, giving a limited choice of commercial designs that are available for adaptation or modification.
- Trend towards using non-ionising radiation equipment for a measurement whenever possible, even if the competing technology is inferior.
- Relatively low number of examples of transfer of technology, or research contracts between commercial manufacturers and R&D laboratories, as well as generally, the curricula in universities do not take into account NCS technology.

The future for NCS in industrial application depends upon many factors. Where their unique properties match the dominant requirement, then an extension in the intensity and range of applications can be expected. However, sustainable development of the supporting technologies and continuing economic viability of the areas in which they are presently used need to be demonstrated. In some areas of application competing non-nuclear techniques will inevitably reduce the scope of applications. On the other hand, the combined use of nuclear and non-nuclear methods (e.g. on-line analysis of coal for ash and moisture) will provide more complete analytical information, widening the range of applications for NCS.

The use of nucleonic gauges in industry has been steadily increasing world-wide. This increase is certain to continue with the continuously increasing demand for automation and quality control and the overriding need for more efficient and economically viable industrial processes. The technology transfer to developing countries will have a significant impact on the future of NCS technology.

4. TECHNICAL FACTORS AFFECTING DEVELOPMENT OF NCS

There has been very significant progress in the electronics associated with radiation detection and in the development of new detectors in recent years. This is true also for computers necessary for data reduction and readout. For example, computers that are extremely fast, have very large memories and are much more reliable have become available at very low cost. Multichannel analysers are now available that are very fast and stable and have a large number of channels (up to 16 000). Significant strides have also been made in the overall stability of radiation detection systems especially spectrometry systems.

One of the most significant changes in recent years has followed the introduction of on-line processing and display. A large amount of operational information can now be collected, processed and displayed on demand. Commercial availability of ever-faster microprocessors has facilitated provision of quantitative information obtained from on-line analysis and standardisation of complex spectrometric data.

Detector technology is rapidly changing and a number of solid state and other detectors are presently being developed that can be operated without cooling. However, there is still a need for a very high counting rate, high total efficiency, ambient temperature operation

industrial detector. Such a detector would have a counting rate high enough to follow fast process transients with good accuracy. It would have a total efficiency large enough to significantly reduce the required source intensity and it would be rugged and robust so that it could operate without failure for long periods in an industrial environment.

X ray tube technology has rapidly improved recently and X ray tube sources are beginning to replace radioisotope sources for low-energy applications. They have become more stable and rugged and have the advantage that their disposal or loss is not a problem. Generation of required energy of X ray flux is facilitated by selection of appropriate target (anode) material. Typical target materials include Ti, Cr, Fe, Co, Ni, Pd, Ag, Ta, W, Re, Pt and Au. The most common fields of applications of X ray tubes include on-line elemental analysis, particle size analysis, density measurements, and thickness gauging and process control.

The main advantages of using X ray generators for industrial applications are:

- significantly higher (of a few orders of magnitude) photon output when compared with isotopic sources,
- the possibility of generating a practically monochromatic X ray flux of energy the most suited for a given application,
- intrinsic “switch off” capability, eliminating radiation hazard associated with isotopic sources.

Other generators of radiation are also being developed, particularly practical neutron sources and high energy photon sources. There is also a need in some cases for the development of specific radioisotope sources. In some cases, such as X ray excitation sources and spontaneous fission neutron sources, there is a need for a radioisotope source with a longer half-life. There may be alternative sources to fill this need that could be produced with development of sophisticated production methods. Such sources would greatly benefit the NCS industry if they could be produced for a reasonable cost.

In some cases alternative measurement principles are being investigated that allow significant source intensity reduction. For example, gamma ray backscatter density devices with very small source-to-detector distances are being used with license-free or near license-free source intensities. These devices offer acquisition of fully spectrometric data (usually on-line processed) in an ultimately safe way in routine operations.

Simulation of nuclear radiation measurement applications by computer modelling is fast emerging as a standard procedure. This is not being done uniformly by the NCS industry, but small pockets of the industry are making strides in this area. The ready availability of massive computational capacity has had a major effect in extending the problems to which nucleonic techniques can contribute. Indeed, many of the environmental and industrial applications of radioisotopes involve the verification of predictive models.

The recent availability of low-cost fast computers combined with rapid software development has contributed to more common applications of Monte Carlo simulation techniques. Monte Carlo simulation, as led by the nuclear oil well logging industry, is being used routinely by a number of NCS industries. Dual and multi gauge techniques are being developed by several NCS industries and statistical multivariate analysis methods are being

tried for NCS applications. There is also a significant trend to use more of the spectral data that is available.

The issue of ecologically sustainable development (ESD) has had a major impact on the application of NCS, particularly since 1992 Earth Summit in Rio de Janeiro. Nuclear technology offers the exciting prospect of contributing both to a reduction of environmental impact for each unit of production and to the formulation of a scientific basis for ESD policy. Nucleonic control systems are now applied to a wide range of industries where they lead not only to improvements in product or process quality, but also to reductions in the materials and energy usage and hence environmental impact. Typical examples of such applications include coal blending, mineral processing, and iron and steel and paper manufacturing.

There are certain NCS measurement techniques that are facing serious technical competition from non-nuclear methods. Microwave or capacitance techniques for moisture measurement, coriolis techniques for fluid mass flow, and electrical techniques for industrial tomography are pertinent examples. In some cases these techniques might completely eliminate the need for a nuclear technique, while in others, advantages and disadvantages must be weighed for a particular application. Also, in some cases a non-nuclear technique might be incorporated into a NCS to widen and improve its performance (e.g. multi-parameter measuring nuclear analysers). In any case it would be useful to have information on these emerging new competing technologies — possibly in the form of an inventory.

5. EMERGING NEW APPLICATION TECHNIQUES AND TRENDS

Nucleonic control systems have undergone impressive changes since the introduction to industry of early models of thickness, level and density gauges in the 1950s. The reasons and background for these changes have been described in the previous sections. In this section, some of the more typical and/or important new trends and emerging application techniques will be briefly discussed.

The development of new NCS technology needs enhancement in hardware and software. The observed trends and new developments include the:

- use of low activity sources;
- replacement of radioactive sources with radiation generators;
- development of new detectors with higher efficiency and better resolution, operating at room temperature;
- development of high count rate nuclear electronics;
- development of next generation nuclear analysers for multi-elemental analysis;
- enhancement of software programmes for data acquisition and processing, including multivariate analysis for calibration and 3-D visualisation software packages;
- use of Monte Carlo simulation for design optimisation, calibration and data processing;
- introduction of expert systems for the NCS field;
- extending the use of the spectral data that is available from multichannel spectrometric measurements;

- implementation of imaging techniques;
- designing and manufacturing of portable nucleonic gauges.

Some actual examples of new application techniques that have industrial interest are:

Dual gauge approaches, X ray transmission and backscattering gauges were reported in the past for measuring aluminium thickness containing impurities. Presently many different kinds of measurement combination have come to be used such as: dual energy γ ray transmission, simultaneous use of fast neutron and γ ray transmission, neutron capture γ rays with γ ray backscattering, etc.

- Multiphase fraction meters. The meters are used for simultaneous measurements of oil, water and gas component fractions.
- Flow ionisation techniques. This technique enables the measurement of small amounts of aerosols (0.1 mg/m^3).
- Beta-albedo absorption techniques. These technique enable the measurement of thin films (1 to $10 \mu\text{m}$).
- Use of fast neutron multiple reflections with extra slowing down. This technique enables significant enhancement in hydrogen and/or moisture measurement sensitivity.
- Low activity gauges, enabling ultimately safe measurements.
- Portable computed tomography scanner for imaging wooden power poles.

Simulation of nuclear radiation measurement applications by Monte Carlo analysis is fast emerging as standard procedure. The main factors contributing to this include the general availability of excellent and user friendly general purpose Monte Carlo codes, recent availability of low-cost fast computers and reported successes of Monte Carlo simulation in diverse fields such as medical and industrial applications. Arguably, the most important area of Monte Carlo simulation use in NCS technology is in design of new instrumentation. Computer simulation avoids the excessive cost and time demands of an experimental program to accomplish the same objective. Another area of use is error analysis of data acquired from nucleonic gauges.

An example of the application of Monte Carlo simulation for designing nucleonic gauges is the design of a new and improved neutron moderation oil well logging tool for porosity measurement. The aim of computer simulation was to improve the design of the tool by increasing the counting rate while maintaining high porosity sensitivity and minimising the environmental effect. The major design parameters for the logging tool include: source-to-detector spacing, detector sizes and pressures (for proportional ^3He counters) and shielding materials. Several borehole-rock formation parameters affect the tool's response. Experimental verification of optimum tool design would be both expensive and time consuming.

Expert systems for nucleonic gauge design are being introduced to assist optimisation of various components of NCS. The database of an expert system includes characteristics of radionuclides and industrially available sealed sources, photon cross sections, build-up factors, specific dose constants, physical properties of absorbers, characteristics of detectors and properties of shielding materials. For a given application the system allows the

determination of a suitable radioactive source, its required activity, expected counting rates and dose rates.

A portable computed tomography scanner has been specifically designed and developed for the pole industry, where a need for regular inspection of wooden poles is of a high priority. The scanner provides continuous imaging of an inspected pole by using transmission of low energy gamma rays from an ^{241}Am source. The use of precision engineering, modern electronics and computing power have resulted in production of a portable device tailored to a specific need.

Dual or multi beam gauges are still undergoing significant improvement and further development despite their long presence on the market. Several combinations utilising various nuclear physics techniques and radioisotopes are currently applied in dual and multi beam gauges. Basically, these gauges are used for a more accurate determination of the parameter of interest with elimination or at least minimisation of measurement interferences.

A typical example is on-the-belt determination of ash content of coal independent of the thickness and vertical segregation of the coal on the conveyor belt. The main disadvantage of the technique is that its accuracy is affected by changes in chemical composition of ash. Three energy gamma ray transmission or combination of dual energy gamma ray transmission with backscatter technique have shown only marginal improvements compared to dual-energy transmission gauge alone in this particular case.

Multi beam gamma ray transmission gauges capable of measuring of multiphase mixtures of crude oil, water and gas have been recently developed for the oil industry. Knowledge of the flow rates of each component, in each well pipeline feeding to the production platform, is required for production control. One of such multiphase flow meters (MFM) is based on the computer processed transmission measurements utilising ^{241}Am , ^{133}Ba and ^{137}Cs gamma ray sources. The individual components are first used to identify the flow regime. They are then combined in models of the identified flow regime to give the flow rates of each component. Another MFM uses various energy lines of ^{241}Am for dual- and multi-beam determination of the three phases. A novel measurement concept based on multiple energy gamma ray absorption permits multiphase flow measurements free of salinity variations influence.

Dual-gauge techniques were also developed for gamma-gamma backscatter gauges employed in well logging and for neutron moderation gauges for measuring formation porosity in oil well logging. Borehole logging probes used for geotechnical/engineering application often use a single gamma ray source and two detectors at various spacing from the source. Ratio of two scattered beams recorded by the two detectors provides information about formation density free of influence of borehole cavities, casing and mud cake.

A recently developed technique for assaying quality of low rank coals applies a single detector and a single neutron source of high-energy neutrons (such as $^{241}\text{Am-Be}$ or $^{238}\text{Pu-Be}$). The detector records two physically different beams; one of 4.43 MeV resulting from neutron inelastic scatter from carbon nuclei, and the second beam (of multi-energy lines) originated from thermal neutron capture reactions with hydrogen and other coal constituents.

One of the present trends is combining nuclear gauges with non-nuclear techniques for obtaining more comprehensive information. For example the addition of a microwave beam to

on-line coal analyser permits the determination of coal moisture with higher accuracy than that obtainable with a neutron moisture gauge. Nuclear gauges, in many specific applications, can only benefit from introduction of complementary non-nuclear devices providing information otherwise not available from NCS only.

Apart from the majority of NCS that apply substantial activity of radioisotopes there is a number of ingenious small nucleonic gauges using low radioactivity sources, under 3.7 MBq, as this activity is defined in many countries as the minimum activity of a radioactive source requiring a licence for possession, use and transport of radioactive substances. There are many different types of low activity gauges operating in diverse industrial applications:

- Airborne dust monitors for environmental monitoring, utilising β -particles attenuation by deposited dust on a filter paper. ^{147}Pm or ^{14}C β -sources of less than 3.7 MBq are applied.
- Soil compaction gauges for civil engineering utilising both transmission and backscatter of neutrons and gamma rays for measuring the degree of soil compacting. ^{252}Cf and ^{60}Co sources of less than 3.7 MBq are applied.
- Portable level gauges utilising low activity gamma ray sources of ^{137}Cs or ^{60}Co in transmission geometry are used for inspection of the content of fire extinguishers.
- Low radiation intensity spectrometric gamma-gamma tools utilising 1.1 MBq ^{137}Cs source are used for the mining industry in well logging applications.
- A coal face analyser utilising 2.4 MBq gamma ray activity for coal bulk samples and *in-situ* analysis on coal face is used in the coal mining industry.
- A gap meter gauge, utilising low activity ^{252}Cf neutron source in backscatter geometry is used for inspection of the gap between the foundation and the bottom plate of oil-storage tanks in petroleum industry.

6. RADIATION PROTECTION AND SAFETY

6.1. INTRODUCTION

Ionising radiation can be very hazardous to humans and steps must be taken to minimise the risks. This Section provides only a brief summary of some of the principles of radiation protection associated with the use of sources of ionising radiation used in nucleonic gauges. In order to concentrate on the important principles a certain fundamental level of knowledge of radiation physics has been assumed (e.g. there is no explanation of quantities and units as this information is available in many of the IAEA's publications if needed).

The essential requirements for protection from ionising radiation are specified in the international basic safety standards (BSS). The standards state that the prime responsibility for radiation protection and safety lies with the licensee, registrant or employer. Some of the fundamental requirements of the standards relevant to nucleonic gauges are discussed in this section, but the standards should be consulted in full for a comprehensive understanding of their requirements.

6.1.1. Principles of dose limitation

The principles of dose limitation are briefly summarised below:

- no application of radiation should be undertaken unless justified,
- all doses should be kept “as low as reasonably achievable (ALARA principle), economic and social factors being taken into account,
- in any case, all individual doses must be kept below dose limits.

It should be emphasized that the most important aspect of dose limitation, assuming that the practice is justified, is to keep radiation doses as low as reasonably achievable.

6.1.2. Dose limits

The application of dose limits should not be of relevance to gauge operators as their radiation exposure should be low. This sub-section has, however, been included for completeness.

Occupational dose limits

Occupational dose limits are chosen to ensure that the risk to radiation workers is no greater than the occupational risk in other industries generally considered safe. Radiation doses must always be kept as low as reasonably practicable, but some industries may require employees to routinely work in high radiation areas and therefore dose limits are required. The BSS specifies that doses to individuals from occupational exposure should not exceed:

- (a) an effective dose of 20 mSv per year averaged over 5 consecutive years;
- (b) an effective dose of 50 mSv in any single year;
- (c) an equivalent dose to the lens of the eye of 150 mSv;
- (d) an equivalent dose to the extremities (hands or feet) or the skin of 500 mSv in a year.

If apprentices aged 16–18 years of age are required to use sources as part of their training, the relevant annual occupational dose limits are:

- (a) an effective dose of 6 mSv;
- (b) an equivalent dose to the lens of the eye of 50 mSv;
- (c) an equivalent dose to the extremities or skin of 150 mSv.

Public dose limits

If the use of nucleonic gauges may lead to the public being exposed, then the following dose limits must not be exceeded:

- (a) an effective dose of 1 mSv in a year;

- (b) in special circumstances, an effective dose of up to 5 mSv in a single year, provided that the average dose over five consecutive years does not exceed 1 mSv per year;
- (c) an equivalent dose to the lens of the eyes of 15 mSv in a year;
- (d) an equivalent dose to the skin of 50 mSv.

As mentioned above, the dose limits should be academic because routine doses should be significantly below these limits, provided the correct procedures are followed.

6.2. ADMINISTRATIVE REQUIREMENTS

6.2.1. Authorisation

In order to control the use of radiation sources and to ensure that the operating organization meets the requirements of the BSS, the legal person responsible for any radiation source, unless the source is exempted, will need to apply for a license or registration from the national regulatory authority. Therefore, prior to procurement of a nucleonic gauging system, a user will need to submit to the regulatory authority an application form. The information furnished in this form should include details of the gauging equipment, the purpose for which it will be used, its make and model, details of the storage facility and installation site, information regarding handling personnel such as their qualifications and radiation safety training, and radiation measuring instrument. The approval certificate from the country of origin should also be enclosed for nucleonic gauges purchased abroad. After ensuring that the gauge demonstrates a safe working life, permission for installation of the gauge may be issued with certain terms and conditions. These include safe storage of portable gauges and gauges awaiting installation, submission of reports to regulatory authority on safe installation as well as regular physical inventory check of sources and gauging devices, leak test reports, maintenance of records on radiation levels measured around the installed gauges and regulatory compliance for safe disposal of nucleonic gauging device/source.

6.2.2. Inspection and enforcement

The regulatory authority may inspect the registrant/licensee to audit their provisions for radiation safety and to physically inspect the premises. Enforcement action may be taken against the operating organization if the level of radiation protection and safety are considered unacceptable.

6.3. TYPES OF GAUGES

There are basically three main categories of nucleonic gauges used in industry:

- Transmission gauges, used to measure density, thickness, etc. The source housing and the detector are on opposite sides of the material and the radiation is attenuated as it travels through the material. Typical beta source activity ranges from 40 MBq to 40 GBq, whilst gamma sources activities are between 0.4–40 GBq. X ray generators may also be used.

- Backscatter gauges, used to measure thickness of coatings, well logging, etc. The detector and source housing are on the same side of the material and therefore the detector has to be shielded from the primary radiation. The radiation enters the material, interacts with it and scatters back out. Typical beta source activities usually range from 40–200 MBq whilst gamma sources are up to 100 GBq.
- Reactive gauges (e.g. used for elemental analysis). Certain low energy gamma and X ray sources can cause fluorescent X ray emissions in the material being investigated. Typical source activities range from 200 MBq–40 GBq. X ray and neutron generators may also be used.

TABLE. RADIOACTIVE SOURCES TYPICALLY USED IN NUCLEONIC GAUGES

Radionuclide	Type of radiation *
Promethium-147	Beta
Thallium-204	Beta
Krypton-85	Beta
Strontium/Yttrium-90	Beta
Americium-241	Gamma
Caesium-137	Gamma
Cobalt-60	Gamma
Americium-241/beryllium	Neutron
Iron-55	X ray
Cadmium-109	X ray

* This is just the radiation of primary interest for the gauging application. The radionuclides may emit other radiations (e.g. americium-241 also emits both gamma and alpha radiation).

6.4. SOURCE CONSTRUCTION AND GAUGE HOUSING

The radiological safety evaluation consists of two components: one is the safety design approval or type approval of the gauge, as discussed here, and the second is the radiation safety framework at the user industry.

Installed gauges should be type approved by the regulatory authority. Both the radioactive source and the housing should comply with international standards, e.g. ISO–2919 (1980) for radioactive sources, the equivalent national standards or have the approval of the regulatory authority of the country of origin.

The aforementioned standard defines tests for the radiation source based on its use to ensure that the integrity of the source is maintained during normal use as well as under foreseeable accidental conditions. The tests for sources include low and high temperature test, external pressure, impact, vibration and puncture test. The integrity of the source is evaluated based on the activity released after each test.

For the source housing, the specific standard is ISO-7205 (1986). The standard specifies the built-in safety features to be incorporated in the design, construction and use of gauging devices, to ensure adequate safety of persons working with or in the vicinity of the gauges. Particular emphasis is placed on designing built-in safety so as to minimise leakage radiation on and around the gauging device, the reliability of the gauging device and its components to withstand special environmental conditions, and endurance with long term use.

The minimum test requirements include high and low temperature tests for normal use and an elevated temperature test for accident conditions. Levels of leakage radiation are measured on and around the gauge for both the beam 'ON' and 'OFF' condition to ensure safety of the persons working in the vicinity. A vibration test is also performed on a gauge that intended to be used in locations where there is likelihood of mechanical vibrations.

6.5. MANAGEMENT REQUIREMENTS

An effective management infrastructure is necessary to ensure that a high standard of radiation protection and safety is maintained and that the BSS requirements are met. It is important that the organizational arrangements allow a free flow of safety related matters between the various levels. Written policies should demonstrate management's commitment to safety and the responsibilities of each individual need to be identified. Some organizations may need to consult qualified experts for advice on specific areas of radiation protection (e.g. which radiation monitors to use). The scope and role of these experts should be clearly defined. Quality assurance programmes should ensure that radiation protection and safety measures within the organization continue to be effective.

6.5.1. Safety culture

Management should foster and maintain a safety culture within their organization. A questioning and learning attitude towards protection and safety should be promoted, and complacency discouraged. Policies and procedures need to be established to ensure that safety and protection have the highest priority. The roles and responsibilities of individuals need to be clearly defined and training provided where this is needed.

6.5.2. Local rules and supervision

Employees should follow the procedures specified in local rules to ensure that an adequate level of protection and safety is maintained during normal daily work with the gauges. In order to provide adequate supervision of protection and safety and to ensure the local rules are obeyed, licensees will normally need to designate a radiation protection officer (RPO). Management should ensure that the RPO is delegated the appropriate authority to ensure that operating procedures and local rules are followed. The RPO should also have the authority to stop any working practices they consider unsafe.

6.5.3. Quality assurance

Assurance that radiation protection and safety requirements are being satisfied should be achieved through formal quality control mechanisms and procedures for reviewing and assessing the overall effectiveness of protection and safety measures. Systematic audits and reviews should detect and result in correction of systems that do not function.

6.6. PRACTICAL PROTECTION FOR GAUGE USERS

The practical elements to radiation protection are: time, distance, shielding and prevention of access. These are discussed in detail below.

6.6.1. Time

Radiation is normally emitted from a source at a constant rate and this is measured in microsieverts per hour ($\mu\text{Sv/h}$) or millisieverts per hour (mSv/h). The shorter the time a person spends in the radiation field the lower the radiation dose will be to that individual. It is therefore advisable not to linger in areas where there may be high radiation levels and any work done close to a source should be done efficiently. This will help to ensure that the radiation risks are kept as low as reasonably achievable.

6.6.2. Distance

Radiation levels decrease rapidly with increasing distance and it is therefore important to never directly handle radiation sources. Specially designed tools with long handles must always be used if a source is to be replaced or manipulated .

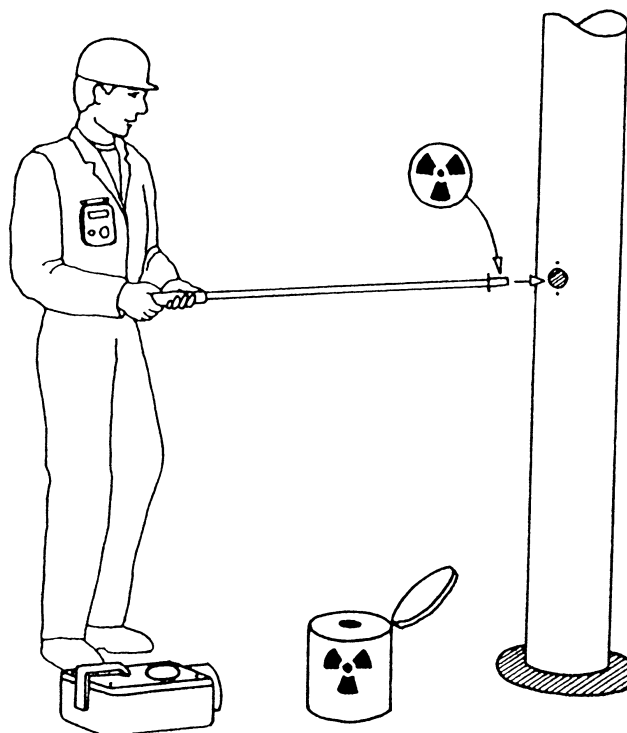


Figure 1: A long handling tool is used to transfer a gamma source from its transport container to the gauge.

6.6.3. Shielding

The main consideration for gauges is to prevent access to the high radiation levels close to the source. This can be achieved by providing an adequate thickness of suitable shielding material around the source. The amount of shielding required will be determined by

the type and energy of the radiation and the activity of the source. For example several centimetres of lead may be required around a gamma source or a several millimetres of aluminium around a beta source. The environment in which the gauge will be used should also be considered when deciding on the material and design of the shielding (e.g. high temperature or corrosive chemicals could significantly reduce the effectiveness of the shielding).

6.6.4. Prevention of access

In many cases it is not possible to fully shield the source and the material to be examined. It will, therefore, be necessary to prevent access to any areas of high radiation by using shutters (manual or automatic), mechanical guarding or interlock systems. In some cases the designation of controlled areas may be additionally required in order to restrict access to authorised persons only.

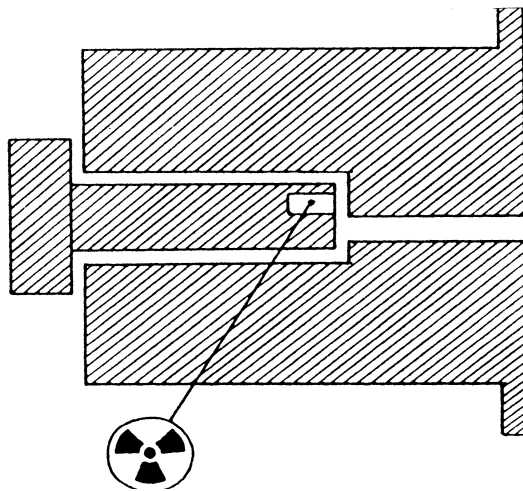


Figure 2: A gamma source housing (sectioned) with its shutter closed.

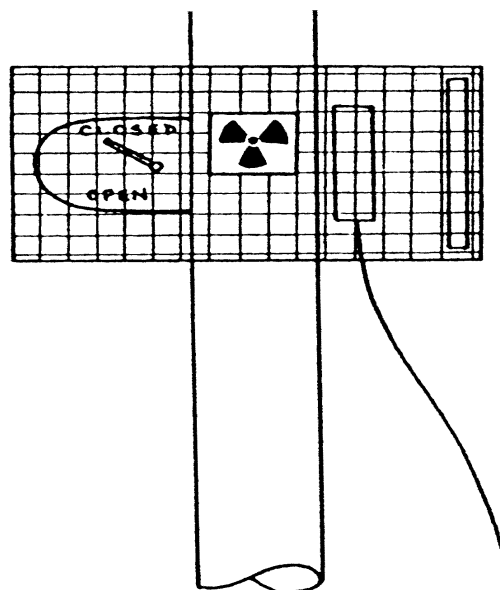


Figure 3: A mechanical guard and beam stop prevent access to the primary beam of a transmission density gauge.

6.7. PORTABLE GAUGES

The use of portable gauges can present additional hazards if they are not used safely. It is not always possible to utilise interlocked shutters to shield the source and, therefore, care must be taken not to irradiate persons when the primary beam is exposed. Prevention of access may not always be possible by using physical barriers so other means must be used e.g. the establishment of a controlled area, use of portable barriers, suitable warning notices.

Additionally, the gauging device should also be capable of withstanding the rigors of shipping and transportation should be done in compliance with IAEA's regulations for the safe transport of radioactive material or the equivalent national transport regulations. Sources are normally shipped in specially designed containers called Type A or Type B.

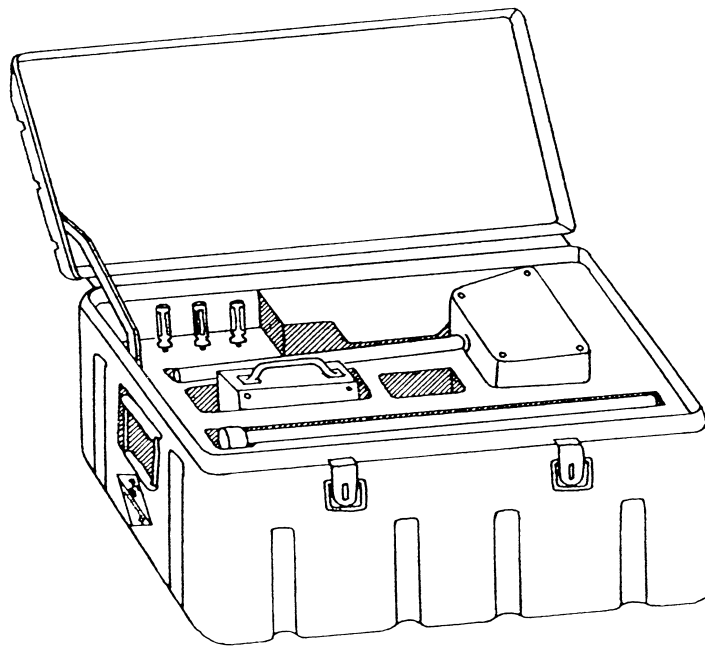


Figure 4: A transport container for a portable gauge.

6.8. WARNING NOTICES

All radiation sources should display the radiation trefoil to warn of the potential hazard. Details of the radionuclide, activity on a specified date and serial number should be included on a label permanently attached to the source housing. Any shutters should be clearly marked to indicate the status of the source to persons in the vicinity. X ray equipment should also display a clear indication when radiation is being generated. Notices should state whether any controlled areas are designated around the gauge.

6.9. RADIATION MONITORING

6.9.1. Dose rate monitoring

Portable dose rate monitors can be used to measure radiation levels (normally in microsieverts or millisieverts per hour) around gauges. Monitoring may be carried out for several reasons, for example to:

- check the shielding around a gauge is intact;

- check a shutter is closed before carrying out maintenance on or close to a gauge;
- check the radiation levels around a shipping container to ensure it is safe to transport;
- confirm the extent of a controlled area around a gauge;
- check the shielding around a source storage facility is acceptable.

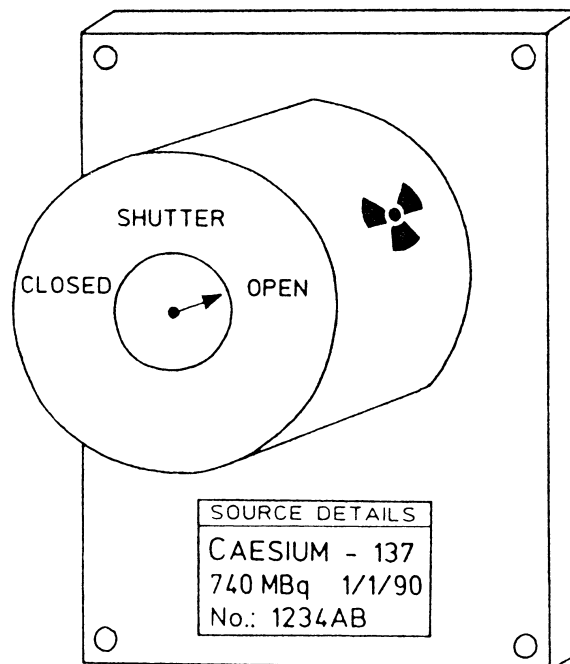


Figure 5: Clear markings on the outside of the gauge source housing.

There are many different types of radiation monitor and it is important to ensure the correct one is used otherwise incorrect assumptions may be made which could lead to persons being inadvertently exposed, possibly to high levels of radiation. For example special monitors are needed to detect neutron radiation, monitors used to detect gamma radiation may not detect beta radiation. Persons carrying out monitoring should therefore be trained, follow approved procedures and keep appropriate records of the radiation levels measured.

All monitors should be routinely calibrated (normally annually) by a qualified expert.

6.9.2. Personal monitoring

The dose rate monitors discussed above can be used to indirectly estimate the radiation dose to a person who works in the area where the measurement was made. In some situation, however, workers may be required to wear personal dosimeters to assess their accumulated individual dose over a period of time, perhaps because they are carrying out maintenance on several gauges or perhaps are working with portable gauges.

There are several different types of personal dosimeter that gauge users may encounter, but they can be divided into categories: those that give a direct reading of accumulated dose and those that require processing by a laboratory (e.g. film badge or thermoluminescent dosimeter (TLD)). The type of dosimeter required and where/when it should be worn will normally be advised by the radiation protection officer.

6.10. STORAGE AND SOURCE ACCOUNTANCY

6.10.1. Storage

There will be occasions when sources need to be stored. For example, portable gauges not in use, gauges removed from a production line during maintenance, old gauges awaiting disposal, etc. To ensure the safety and security of the sources the storage facilities should:

- provide adequate shielding,
- be secure (i.e. locked when not in use),
- not be used as a general storage area for other goods,
- be fire proof and not contain other hazardous materials (e.g. flammable liquids),
- be dry,
- be appropriately labelled (e.g. radiation trefoil and warning notices in a local language).

6.10.2. Source accountancy

Records need to be kept which show the location of each source at all times. National regulations may specify how frequently the accountancy checks need to be carried out, but in general, the following can be applied:

- Sources in permanently installed gauges should be accounted for at least once per month.
- Sources in portable gauges should be accounted for every day they are out of the store and once a week when they are in storage.

6.11. MAINTENANCE AND LEAK TESTING

6.11.1. Maintenance

Nucleonic gauges are often used in harsh environmental conditions which may result in the radiation safety and protection of the gauge be adversely affected, for example; shielding may be degraded, shutters may stick, warning notices may become illegible, etc. It is therefore important that gauges are included in a routine maintenance schedule. Persons carrying out the maintenance work need to be aware of the radiation hazards and be appropriately trained. When working close to a gauge a radiation monitor should always be used to confirm that any shutters are fully closed and that the source is fully shielded.

6.11.2. Leak testing

When a new radioactive source is purchased it should be supplied with a certificate confirming that it is free from contamination. Periodic re-checks need to be carried out by an appropriately trained and qualified person to ensure that the structure of the source remains intact. Gauges that are used under harsh environmental conditions (e.g. high temperature, corrosive chemicals, high levels of vibration) may need to be checked more frequently. The intervals for leak testing should not normally exceed two years (and may be more frequent), but this will normally be specified by the regulatory authority.

6.12. DEALING WITH EMERGENCIES

Before first using any nucleonic gauge the operating organization should carry out an assessment to identify any abnormal situations that may occur and to estimate the magnitude of the hazard. Contingency plans should be prepared and rehearsed so that if an accident does occur the plan can be quickly implemented to regain control of the situation and therefore mitigate the consequences. Several accidents from the use of nucleonic gauges in industry have already occurred. These were mainly due to the sharp, unexpected rise of temperature in the process causing the melting of the gauge and source; and to the accidental loss during borehole logging. Special measures were taken in these cases, isolating the area and temporarily closing the process line or the hole. Other examples of potential accidents to be considered are: lost or stolen source, other forms of physical damage to the gauge (e.g. crushing), jammed shutter, transport accident, suspected exposure of persons, leaking source, etc.

6.13. SOURCE DISPOSAL

The disposal of used radioactive sealed sources is a major concern that needs to be considered by the industry. All such sources must be disposed of safely, in compliance with national regulations and this should be done promptly without extended periods of storage. In many cases the sources can be returned to the original supplier but the question of eventual disposal (and costs) is a matter that should be taken into consideration when initially purchasing a nucleonic gauge.

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COUNTRY REPORTS

NUCLEONIC GAUGES IN THE AUSTRALIAN MINING AND EXPLORATION INDUSTRIES

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Abstract

On-line and *in-situ* nucleonic analysis systems have found widespread application in the Australian metalliferous mineral and coal industries. The rapid and reliable response of these systems has led to improved exploration and better control of mining and mineral processing. This paper reviews both types of nucleonic control system (on-line and *in-situ*) available in Australian exploration and mining market.

1. INTRODUCTION

Nucleonic gauges have been widely used in many countries by various industries to, improve the quality of product, optimise the process, save energy and materials. Nuclear Control Systems (NCS) include on-line gauges for process control such as thickness, density and level gauges, nucleonic analysers providing information about parameter of interest of investigated medium (i.e. ash in coal, iron grade of iron ore), portable gauges for *in situ* measurements of physical and/or chemical properties as well as nucleonic instrumentation for downhole measurements in exploration and mining applications.

The application of on-line and *in situ* analysis techniques and instrumentation in the mineral and energy industries opens up new possibilities for the improved control of various mining activities. Areas of mining applications of NCS include the exploration stage, mine planning, the development and production stages, and mineral processing. The first stages (from exploration to an early phase of production) involve mostly utilization of *in situ* gauges. These gauges are used for delineation of metalliferous ore bodies, coal seams and petroleum or gas-bearing strata as well as for provision of some analytical information before exploitation of the explored deposit. The on-line gauges dominate in the last phase of mine production and mineral processing.

In the mining industry there is no viable alternative to NCS for provision of reliable information in real time. Instead of manual sampling followed by laboratory assaying at a later time, rapid and relatively accurate analyses can be provided in real time for improved process control. In most uses of NCS sampling volume is larger than in other physical techniques, and much larger than assays collected for laboratory analysis. The level of accuracy for quantitative determinations by NCS is usually lower than the accuracy of chemical/instrumental laboratory analyses. However, quoted accuracy for conventional laboratory assaying does not take into account large errors introduced by sampling and the reduce volume of the sample. How well the final sample taken for instrumental analysis represents the parent ore body is always the question.

Nuclear analytical techniques can be used to determine various components of a mined product that have a bearing on its efficient use and environmental effects. The spectrometric techniques that have been applied to on-line and *in situ* measurements provide the means for detection and quantitative determination of specific elements. This ability, coupled with an improved understanding of the application of nuclear techniques in

heterogeneous media, has provided the scope for new applications. Nuclear techniques have begun to spawn a variety of different measurements that can be applied to the solution of complex problems, often in conjunction with other types of measurements. As a result there has been a rapid increase in the application of on-line and *in situ* nucleonic analysers over the last 15–20 years, in the mineral and coal mining industries.

The mining and processing of natural resources is expected to continue for many years to come and will probably intensify owing to its continuing importance to the socio-economic well-being of many countries. Such activities would proceed irrespective of the use of NCS. However, the application of nucleonic gauges, through better process control, would at least lead to economically viable and environmentally less disruptive extraction of mineral resource.

2. NUCLEONIC GAUGES FOR ON-LINE ANALYSIS

This section briefly reviews the nuclear techniques and instrumentation commonly applied in Australian mining industry for on-line analysis of mined and/or processed mineral product. Only very brief description of the particular types of gauges is provided, as the detailed information is available from other sources.

Nucleonic instrumentation developed and manufactured by two Australian companies is the most commonly applied in the Australian mining industry. Australian Mineral Development Laboratories Ltd (Amdel) produces and sells analysis instrumentation and process control packages for the mineral processing industry (in-stream analysis systems for slurry and solution streams). Mineral Control Systems Ltd (MCI) has specialised in the development and manufacture of the COALSCAN range of on-line coal quality analysis systems.

2.1. Density Gauges

Density gauges provide continuous on-line measurements of the density and/or % solids of slurry or solution streams in pipes (on-pipe configuration) or in open tanks (immersion probe). Over nine hundred and eighty Amdel's density gauges are now installed in various mines and mineral plants across Australia.

The Amdel **AM870 High Performance Density Gauge** and **AM871 Immersion Probe** are designed around a microprocessor-based signal processor, which may be coupled with an on-pipe source/detector unit or an immersion probe. The measurement is performed in narrow beam gamma ray transmission geometry. A 50mm x 50mm scintillation detector and gamma ray source of typically 750 MBq activity are the basic components of the measuring head. Automatic gain stabilisation for high precision measurement and source decay compensation are incorporated in the gauge. Typical density operating range is 0-10 g/ml. The microprocessor can calculate SG, % solids, gms/litre or solids mass flow.

Ronan Engineering (Aust) Pty Ltd also supplies density gauges for the Australian industry. The **X96N Density Monitor** provides density/% solids monitoring of products in the process pipe. Two types of detector are used; scintillation detector or ionisation chamber detector. The Cesium-137 isotope is used as the source of radiation. Over 290 X96N gauges are installed across Australia.

2.2. Thickener Interface Gauges

The Amdel **Thickener Interface Gauge (AM204 & AM542)** provides continuous on-line measurement of the level of the liquid/solid interface in thickeners and counter-current decantation washers. The gauge also determines the span of the transition zone. This information can be used for better control of flocculent addition rates. The density profile can also be displayed. The Thickener Interface Gauge determines the interface level by measuring natural radioactivity at various levels in the thickener using an array of up to twelve detectors mounted vertically in a 50mm diameter stainless steel probe. The gauge has no moving parts and the detectors used in the probe are rated to 110 °C. Amdel has installed 35 units across Australia, mostly in thickeners and CCD washers in Alumina plants and in Mineral Processing plants.

2.3. In-Stream Analysis Systems

In-stream analysers provide on-line assay information to allow better control of the mineral processing plant. A variety of applications include Mineral Concentrators, Coal Washeries and Mineral Sands Concentrators.

The Amdel **In-Stream Analysis (ISA) Systems** are of modular structure which enable flexible configurations to measure as many streams as required and up to 8 elements in each stream. ISA provides continuous and intermittent assays by using Multi-Element ISA probes, Single-Element probes and Density probes. All probes are immersion probes. The first two are based on energy dispersive X ray fluorescence analysis. The Density probe provides measurement of pulp density and is used in conjunction with one or more Single-Element probes. The probe contains a scintillation detector to measure attenuation of gamma rays transmitted as a collimated beam through the slurry. The Single-Element probe measures one element per probe and contains a scintillation detector for spectrometric measurements of characteristic and scattered X rays. The Multi-Element probe contains a solid state detector and is capable of measuring up to 8 elements and pulp density (based on the scattered X rays) simultaneously. The Multi-element probe is particularly useful for slurries having very low concentrations of valuable minerals as occur in some residue streams. The much better X ray resolution of the solid state detector increases accuracy of analysis. The ISA systems are installed at over 40 locations throughout Australia and analyse over 370 streams. The systems are widely used for the better control of mineral concentrators with reported improvements in mineral recoveries often in the range 1–2%.

The Amdel **OLA-100 Universal On-Line Slurry and Solution Analyser** provides continuous analysis of both light and heavy elements in slurry and/or solution streams. The OLA-100 uses the PGNA technique for analysis. Due to the high penetration of both the neutrons and resulting gamma rays, the measurement is less affected by variation in mineralogy, matrix or particle size. The instrument is based on a solid state detector and Californium-252 neutron source, up to 4000 energy channels are used for data acquisition. Sixteen streams at North Parkes, Mc Arthur River and Mt Keith are analysed using the OLA-100 analyser.

Table 1 summarises the Australian and world-wide installations of the two most commonly applied Amdel products; the In-Stream-Analysis family of systems (ISA, DSA, OLA and CSA) and the Density Gauge.

The Amdel **Coal Slurry Analyser (CSA)** provides on-line measurement of ash and solids content in coal washing plants. A set of three CSA probes is immersed into the slurry stream. The Ash Probe uses a source of low energy X rays and a scintillation detector in backscatter geometry to measure the ash content of the slurry per unit volume. This probe also measures the concentration of iron for necessary corrections to ash and density determinations. The Density Probe measures the slurry density (%solids) using a source of gamma rays (370 MBq Cs-137) and a scintillation detector in a gamma ray transmission geometry. The Aeration Probe measures the amount of air in the slurry and provides a correction to the density probe signal for effects of aeration. The probe uses a low intensity Am-Be neutron source and a thermal neutron detector in a transmission geometry. Twenty five streams at various Australian collieries are analysed with the CSA system.

TABLE 1: AMDEL NUCLEONIC GAUGES WORLD-WIDE INSTALLATIONS

Gauge	Australia	North America	South America	Asia	Africa	Other	Total
ISA gauges (No. of streams)	377	41	82	148	78	104	830
Density gauges	354*	--	28	118	4	66	570
Total	731	41	110	266	82	170	1400

*) 45 gauges installed outside the mining industry are included.

The Amdel **Dry Stream Analyser (DSA)** provides continuous on-line analysis of dry material stream. The most typical application in the mining industry is for Mineral Sands. The DSA measures% Ti, Fe, Zr, Ce, Hf, etc. in rutile, ilmenite, zircon and monazite product streams. High-energy resolution (solid state detector) XRF technique is applied. A sample of the main stream is diverted to the analyser. The main applications are in measurement of the final product streams for quality control. Seven DSA systems operate at various Australian mineral sands mines.

More detailed description of nucleonic instrumentation applied in mineral and coal slurries can be found in a number of publications [1–5].

2.4. Coal Ash Gauges

The technical and economic benefits of the on-line analysis of coal for ash content have been recognised for several decades. However, reliable and relatively accurate ash monitors for conveyor belt applications have become available only in the last 10–15 years. Recent years have seen the development and commercial availability of a variety of nucleonic gauges for on-line and bulk analysis of coal (and minerals). Improved performance of these instruments have been mainly associated with the development of new or improved techniques, the development of fast and stable electronics and the availability of new range of fast, reliable and inexpensive microprocessors.

The ash content of coal can be determined by gamma ray techniques, which depend on two basic facts; that ash has an effective atomic number greater than that of the combustible matter and that the natural gamma-radiation of coal is well correlated with ash content. Three types of on-line ash gauges, which are in widespread routine use in Australian coal operations, are based on dual-energy gamma ray transmission, pair production and measurement of natural-radioactivity of coal. The gauges are manufactured and marketed by MCI as **Coalscan** ash monitors [6]. Coalscan analysers operate both as on-belt and off-belt systems depending on the type of analyser. Only two analysers (utilising dual transmission and natural gamma-radiation) are used directly on-belt; the others require use of a sample by-line.

The MCI Coalscan monitors are used in a wide range of applications including mine grade control, raw coal monitoring, coal sorting, coal blending, stockpile management, power station feed monitoring and blending, and ash monitoring at coal shipping ports. The typical advantages of their applications include continuous product monitoring, increased recovery of product specification coal, reduced penalties from off spec coal, reduced power generation costs resulting from ash control in feed, improved blending, automatic rejection of high ash coal and direct alternative to coal preparation for high quality coals.

Dual energy gamma ray transmission (DUET) gauges are the most widely used in the coal mining industry for the on-line monitoring of the ash content of coal. Ash content is determined by measuring the transmission through coal of two narrow beams of low- and high-energy gamma rays [7, 8]. The absorption of the lower energy gamma rays depends on ash content, due to its higher average atomic number than that of coal matter, and on the mass per unit area of coal. The absorption of the higher energy gamma rays depends almost entirely on the mass per unit area of coal in the beam. Ash content is determined by combining measurements of the two beams. The determination is independent of both the bed thickness and the mass of the coal. The main advantages of the DUET gauges are simplicity, direct on-belt measurement and relatively low cost. The most important disadvantage of this technique is its relatively high dependence on variable composition of ash (high Fe and Ca content).

The MCI **COALSCAN 2500** and **COALSCAN 3500** analysers are the DUET type gauges. They both use Cs-137 as the high gamma ray energy emitter and Am-241 for providing the low energy beam of gamma-radiation. A single scintillation detector measures intensities of collinear beams originated from Cs-137 and Am-241 sources. The Coalscan 3500 is claimed to be the most extensively used on-line ash monitor throughout the world. Fifty-one units have been installed in Australian coal mines, and 130 systems operate throughout the world. The measuring head of the Coalscan 3500 is mounted on a C-frame design, which ensures precise alignment of source and detector assemblies. The C-frame swings off the conveyor (when empty) to provide an automatic standardisation and a calibration check. The Coalscan 2500 is a cheaper version of Coalscan 3500 with some of the features stripped off (e.g. no automatic standardisation/calibration check). Only one unit is installed in Australia, but with another 82 units operating throughout the world the Coalscan 2500 has become the second most widely used model of all Coalscan systems.

The MCI **COALSCAN 4500** is the pair production ash gauge [9]. The gauge measures the intensities of Ra-226 gamma rays backscattered by the coal and resulting from pair production type of interaction and Compton scattering. Both interactions depend on the bulk density of the coal; the pair production also depends on the average atomic number of the coal. By combining spectrometric measurement of the resulting gamma ray intensities, the ash content can be determined. The gauge also incorporates a moisture monitor that uses a

capacitance technique. A major advantage of the Coalscan 4500 is that it is about four times less sensitive to variations in ash composition than the DUET gauges. The biggest disadvantages are use of high activity Ra-226 source, high sensitivity to the coal geometry and a necessity for a sample by-line. Eleven Coalscan 4500 systems have been installed in Australian coal mines.

The MCI **COALSCAN 1500** is an economical on-belt ash monitoring system utilising the natural gamma ray activity of coal. The technique is based on the observed correlation between the ash content and the natural gamma ray activity of coal due to the presence of uranium, thorium and potassium in mineral matter of the analysed coal [10, 11]. The correlation between the ash content and natural gamma-radioactivity of coal holds good for bituminous, sub-bituminous and lignite coals, as well as raw and washed products. However, different coals require separate calibrations. The gamma ray detector is very large, typically a $10 \times 10 \times 40$ cm NaI(Tl) scintillation crystal with low intrinsic natural radioactivity. To minimise the effects of cosmic radiation, and hence improve the sensitivity of the monitor to changes of ash content, a thick (10 cm or more) lead shield surrounds the detector and also is mounted above the conveyor. The natural gamma ash monitors are inexpensive compared with most other ash analysers, free of artificial radiation sources and, most importantly, are relatively insensitive to variation in ash composition, moisture content and particle size. However, a disadvantage is that coals from seams of different source materials and/or depositional environment would usually require different calibrations. Eighteen Coalscan 1500 analysers operate throughout Australia.

The Prompt Gamma Neutron Activation Analysis (PGNAA) technique is the only technique available, which can be classified as a direct method of measuring the ash content of coal from its elemental constituents [12]. In principle, a large number of elements present in coal matter can be determined through the neutron capture reactions of thermal neutrons with the nuclei of atoms forming the coal and mineral matter. The determination of some of the ash constituents (like sulphur or slagging index influencing elements) is very important for the coal plant management. Commercially available PGNAA gauges employ Cf-252 neutron sources and NaI(Tl) scintillators for the detection of prompt gamma rays. GAMMA-METRICS (USA) and MCI (Australia) are the major manufacturers and suppliers of the PGNAA gauges.

The MCA **COALSCAN 9000** and **COALSCAN 9500** systems are PGNAA gauges. The less expensive 9000 model applies a single large NaI(Tl) scintillator and off-belt ash monitoring is done on a vibrating tube by-line system. The 9000 model offers handling capacity of 1-5 t/h. Both systems incorporate a separate and independent gamma transmission gauge for bulk density determinations and a fully integrated microwave moisture analyser. The 9500 model has been engineered as a fully integrated, single enclosure measurement unit, which accepts coal via a chute with up to 100 t/h handling capacity. This model incorporates the Harwell Spectrometer system, which offers a vastly improved signal-to-noise ratio, resulting in much better definition of elemental peaks in the recorded spectrum. The incorporation of the Harwell Spectrometer results in a more stable calibration, valid over a wider range of coal types. The coal attributes measured by Coalscan 9500 include: ash, sulphur, moisture, carbon, hydrogen, nitrogen, chlorine, and ash parameters; silica, alumina, iron oxide, calcium oxide, sodium oxide, potassium oxide and titanium oxide. The derived parameters include, among others, specific energy, ash fusion temperature, and volatile matter, sulphur emission potential, ash emission potential and oxygen. Nine Coalscan 9000 operate throughout Australian coal plants. System 9500 has been marketed for the last 2-3 years only, and to date six 9500 models have been installed in Australia.

Table 2 summarises installations of all types of MCI COALSCAN technology both in Australia and world-wide.

A single unit of the MCA **COALSCAN 9100** was installed at Loy Yang B Mine of the State Electricity Commission of Victoria to measure ash, moisture, specific energy and sodium content of low rank brown coal [13]. The analyser uses a high-energy neutron source to excite the 4.43 MeV inelastic scatter gamma ray from carbon. The gauge uses a high efficiency BGO detector for improving spectral quality of recorded data, and applies the shaker tube geometry for off-belt analysis. A microwave moisture measurement device is incorporated in the analyser.

TABLE 2: COALSCAN COAL ASH ANALYSERS WORLD-WIDE INSTALLATIONS

Model	Australia	North America	India	China	Other	Total
COALSCAN 1500	18	--	--	--	8	23
COALSCAN 2500	1	59	1	15	7	83
COALSCAN 3500	51	34	27	--	18	130
COALSCAN 4500	11	--	--	--	1	12
COALSCAN 9000	9	13	--	--	--	22
COALSCAN 9100	1	--	--	--	--	1
COALSCAN 9500	6	1	--	--	2	9
Total:	97	107	28	15	33	280

2.5. On-line Analysis of Iron Ore

The minor constituents in iron ore cause a range of quality control problems. One of the methods which can be applied to on-line analysis of iron ore is the natural gamma method. The relevance of the spectrometric natural gamma technique to iron ore is that the naturally occurring radioisotopes are concentrated in the clay minerals which are constituents of the gangue material mined with the ore. These isotopes are generally absent from the matrix of pure iron ore. As a consequence of the fact that the isotopes are associated with kaolinite, they are also associated with alumina. Alumina content of Australian iron ore is strongly correlated with the thorium activity of the ore. In addition, it is possible to determine the manganese content of iron ore from the potassium gamma ray activity [14]. The MCI **IRONSCAN 1500** is a commercially available gauge for monitoring these constituents of iron ore. Two such units are installed at the Hamersley Iron mines in Western Australia.

The pair production technique can be used to determine the average atomic number. In a binary component system made up of hematite/goethite and shaly rock the iron ore grade may be measured directly instead of the average atomic number. The MCI **IRONSCAN 4100** is a gauge based on the pair production technique for the application in on-line analysis of iron ore [15]. The applied technique is the same as for the Coalscan 4500. Three Ironscan 4100 analysers have been installed in Hamersley Iron operations.

3. NUCLEONIC GAUGES FOR *IN-SITU* ANALYSIS

The metalliferous mining and coal mining industries of Australia have increasingly recognised the need to obtain rapid and reliable *in-situ* analysis of particular parameters of the mined product, often on a stratigraphic basis. The parameters required would depend on the phase of mining and the particular resource industry concerned. Usually, the most sought parameters are those that may affect the subsequent beneficiation process. Borehole logging is now perceived by these industries as the fastest approach to the pre-exploitation stage of mining operations in yielding a relevant, although limited, set of geological/geochemical information.

The standard grade control procedure at most metalliferous ore mines is conducted by sampling and assaying drill cuttings from large diameter production holes, or particularly during the exploration stage by assaying core samples obtained in diamond drilling. This approach offers full, detailed chemical and mineralogical assay data. On the other hand, the sample collection, the sample preparation and the assay methods entailed are highly intensive in labour, time and capital. One of the major problems facing the grade-controller is the time taken to receive grade information about ore from the samples collected. In current sampling practices at various mines, the best sample turnaround time is 24 h, but usually it takes two to three days, and even up to a week, depending on the number of samples sent for assaying and the backlog at the laboratory. Further, the highly precise and detailed laboratory measurements of drill samples may fail in giving realistic evaluations of deposits, because of either sampling or intrinsic geostatistical problems.

Nuclear well logging, apart from its capacity for delivering data rapidly, also has the advantage that the penetrating nuclear radiation used for the measurements effectively yields much larger sample volumes than either percussion or core drill samples. For a 10 m regular grid of production (blast) holes of average depth of 20 m and average density of ore equal to 2.8 g/cm^3 each hole represents an ore-block of 5600 t. A sample of around 4 kg (taken manually from the cone of drill cuttings) with all accumulated errors of drilling and sampling represents the 5600 t ore-block, giving a sample to ore-block ratio of approx. 1:1 400 000. The PGNA log has an effective sampling radius of 0.3 m. The overall sample for a 20 m log is taken from 30.6 t of ore resulting in a sample to ore-block ratio of approx. 1:180. This “radiometric sample” is without the inherent sampling inaccuracies of any manual technique, and gives a far better ratio of sample to ore. Also, information is obtained in real time.

Among many physically different well logging techniques, nuclear well logging is practically the only technique that has the capacity for providing quantitative *in-situ* grade control in real time. Unlike on-line gauges, *in-situ* nucleonic gauges are usually not owned by the mining companies. The logging is typically provided by the commercial logging companies on a contract basis.

3.1. NON-SPECTROMETRIC LOGGING TOOLS

In the mainstream of mining, commercial operators use mainly natural gamma ray, gamma-gamma and neutron-neutron logging, with the latter used for porosity measurements. BPB Instruments Ltd is the biggest contract logging provider in Australia, particularly in coal mining and exploration. Geoscience Associates Pty. Ltd, Surtron Technology (the major provider of contract logging in iron ore mining) and Groundsearch Ltd are the other principal

contract logging providers. Those four logging well logging companies have around 90–95% of market share. A few smaller contractors service the remaining 5–10% of the mining market.

Another Australian company, Auslog Pty. Ltd supplies a major share of geophysical borehole logging equipment used by coal miners, mineral developers, explorers, groundwater and geotechnical engineers. The core activity of Auslog is the design, manufacture and sale of geophysical well logging equipment. Auslog equipment dominates the Australian market, with an increasing percentage of production being exported. Among nuclear components of Auslog non-spectrometric digital logging systems are a natural gamma ray tool, a gamma-gamma tool, the Microdensity tool and a neutron tool. Ninety Auslog logging systems operate across Australia.

The commercially available nuclear non-spectrometric borehole logging technologies are mostly used for ore body (coal seam) delineation. Natural gamma ray methods identify zones of contrast in natural activity, while gamma-gamma methods are used either to identify zones of different density, or alternatively, to give a quantitative measure of formation density. Formation density measurements have a further important application in resource mining, based on apparently good correlation between the formation density and the mineral content in coal or ore [16]. Most of the commercial density gamma-gamma logging tools utilise radioactive sources having high activities (2000–6000 MBq). They are perceived as being not sufficiently safe for mining personnel and for the environment, say in the case where a tool is irretrievably jammed down a borehole. This factor has been mainly responsible, so far, in dissuading many mining companies from becoming owners of downhole nucleonic gauges. The miners perceive such ownership as also appropriating a potentially costly responsibility for radiation protection and education of personnel. This problem is not satisfactorily overcome by using commercial contractors, although that stratagem places legal responsibility with the contractors.

While the non-spectrometric approach is satisfactory for many mining applications, the non-spectrometric tools can neither accurately identify the chemical nature of the deposit nor provide, with confidence, the ore grade or the chemical concentration of key impurities. The techniques which are essential both for identification of elemental (radioisotopic constituents) and for accurate estimation of elemental constituents in the ore are those which are spectrometric.

3.2. SPECTROMETRIC LOGGING TOOLS

Spectrometric methods have a capability for detecting and recording, differentially, various probe-response events, e.g. those due to different gamma ray energies. This capability is important for identifying and estimating particular elemental constituents of the matrix, because in nuclear reactions these constituents emit gamma-radiations of characteristic energies, and the intensity of the specific radiation emitted is proportional to the elemental concentration of the relevant constituent in the matrix.

CSIRO Exploration and Mining has developed a spectrometric borehole logging technology, known as **SIROLOG**, for routine applications in mining deposits of coal and iron ore [17]. Auslog Pty. Ltd is a licence holder for production and marketing of SIROLOG technology. SIROLOG includes a family of different nuclear spectrometric *in-situ* analysis techniques and instrumentation. In all SIROLOG systems, the tool is the generic part which varies between types of nuclear logs applied. Those developed and commercially available

from Auslog include a natural gamma tool, a combined gamma tool, a gamma-gamma tool, a PGNAA tool, and a low radiation intensity tool.

Spectrometric downhole instrumentation has definite advantages over non-spectrometric technology. Temperature and other drift of the detector and electronics can be overcome through intrinsic gain stabilisation. A single detector can be used for recording different logs based on different nuclear interactions (e.g. the combined gamma tool, where a single spectrometric scintillation detector monitors both natural gamma-radiation and backscatter gamma-radiation). But probably the most important advantage is that spectrometric tools apply gamma ray sources of 1–3 orders of magnitude weaker than the typical gamma ray source used in a non-spectrometric density tool. This feature makes the tool safer for mining personnel and more environmentally friendly.

Callide Coalfields is routinely using SIROLOG technology (gamma-gamma and PGNAA methods and tools) for their black coal mining operations [18, 19]. Units of SIROLOG technology (natural gamma and gamma-gamma methods and tools) have found commercial applications at the Tom Price, Paraburdoo and Channar mines of Hamersley Iron [20]. The State Electricity Commission of Victoria routinely applies SIROLOG combined gamma tool for investigation of the brown coal lithology, in order to delineate the coal, clay and sand strata [21].

A fully spectrometric Low Radiation Intensity Tool, based on the backscatter gamma ray method, is now commercially available from Auslog. The tool has been designed as an intrinsically safe nucleonic gauge, providing *in-situ* information about formation density and its average atomic number. The two configurations of the tool (known as the Zero Probe and the Low Activity Probe) apply gamma ray sources of 1.1 and 1.9 MBq activity, respectively [22]. The physical design of the tool is such that it utilises single-scattered gamma quanta to provide information about the bulk density of coal (ore), whilst multi-scattered quanta of lower energies carry information on the average chemical composition of coal (ore). The tool geometry gives the advantage of a probe with the best possible bed resolution.

3.3. MEASUREMENTS ON THE COAL FACE

The coal mining industry requires *in-situ* analysis of coal quality at the final exploration and pre-mine planning and production stages. Coal face analysis would be mainly applicable to the production phase in open-cut pits and underground mines. The problem for coal mining companies to avoid at the coal face is diluting the coal with waste, in situations where coal and waste are visually indistinguishable. The use of quantitative face ash analysers would permit selective mining. Coal ash determination on the coal face has received less attention than coal ash measurement in boreholes or on conveyor belts. The technical challenges are to design and construct a coal face analyser which is safe, accurate, portable and manoeuvrable.

CSIRO Exploration and Mining has developed such an instrument [23], the Coal Face Ash Analyser which is commercially available from the producer, Auslog Pty. Ltd. The analyser uses two gamma ray microsources Ba-133 and Cs-137 of activities 1.8 and 0.35 MBq, respectively. The caesium source is used for gain stabilisation only. The analyser works as a backscatter gamma ray type instrument. The coal face ash analyser does not require special shielding and does not expose the user to unacceptable levels of radiation.

The analyser needs to be calibrated for different types of coal.

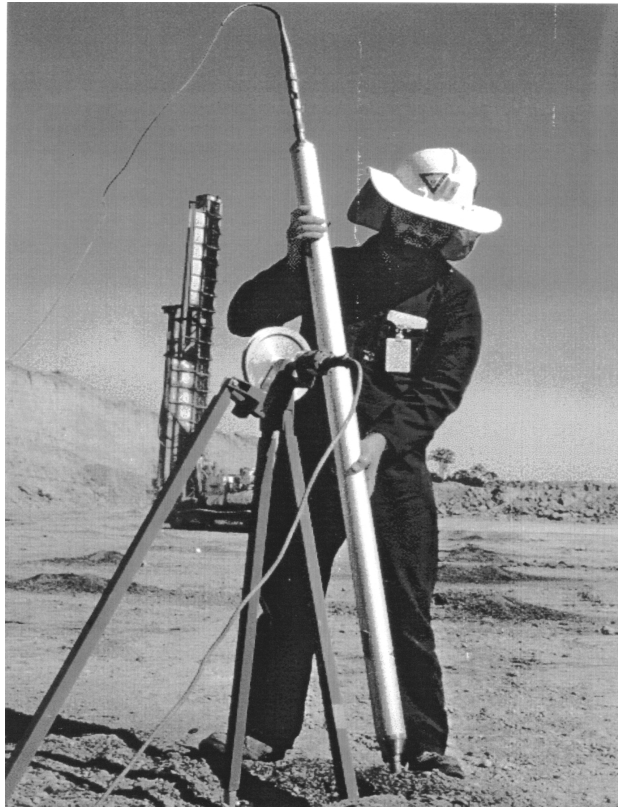


Figure 1: Low radiation intensity spectrometric borehole logging probe for qualitative and quantitative analysis of mineable resources.



Figure 2: Low activity portable coal face ash analyser for differentiating coal and look alike sediments.



Figure 3: COALSCAN 3500 on-belt coal ash analyser for on-line ash monitoring. It contains Cs-137 and Am-241 gamma sources.

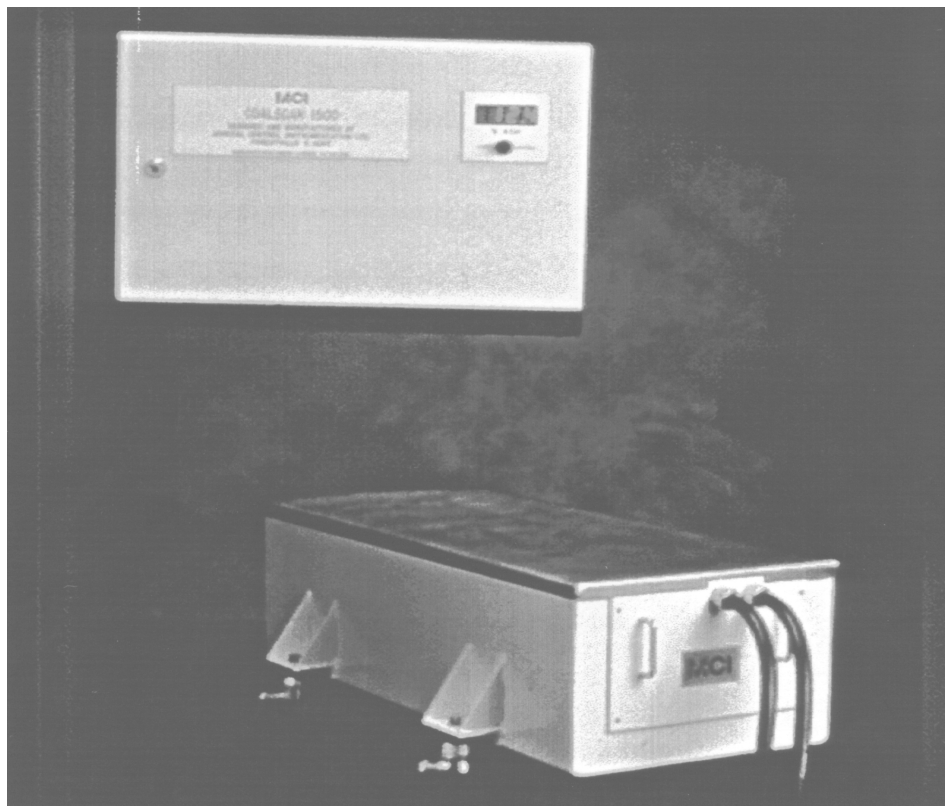


Figure 4: COALSCAN 1500 on-belt ash monitor utilising the natural gamma ray activity of coal. The gamma ray detector 10x10x40 cm NaI (Tl) scintillator shielded surrounds in 10 cm lead.

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PROJECT DEVELOPMENT AND COMMERCIALISATION OF ON-LINE ANALYSIS SYSTEMS

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Abstract

A project team first in the Australian Atomic Energy Commission (AAEC) and since 1982 in CSIRO has developed many on-line analysis systems for the mineral and energy industries. The development of these projects, usually lasting 7-10 years, has followed a common pattern of laboratory R&D, field trials, commercialisation and technology transfer. This successful pattern is illustrated using examples of the development of systems for the on-line analysis of mineral slurries, for determination of the ash content of coal on conveyors, and for determination of the flow rates of oil, water and gas in pipelines. The first two systems, licensed to Australian companies, are used world-wide. They are now the market leaders for radioisotope gauges in their application field. The third, the multiphase flow meter, was licensed in 1997 to an international company. This meter has even greater potential than the other two systems for economic benefit from its use and for numbers of installations.

INTRODUCTION

Radioisotope techniques are the basis of many on-line analysis systems that are now widely used in the mineral and energy industries [1]. These on-line systems are adopted by industry because the speed of response of conventional sampling and analysis techniques is often too slow to meet the requirements of control of mining and processing operations. The cost of the radioisotope gauges is often recovered in 3-9 months due to savings resulting from improvement to the control of operations.

The author initiated Australian research into radioisotope systems for on-line analysis in the early 1960s whilst in the Australian Atomic Energy Commission (AAEC). This led to the development and field testing of a system for the in-stream analysis of mineral slurries that was commercialised in 1972. It is now used world-wide in mineral concentrators.

The research team broadened its interests in the 1970s to include the on-line analysis of coal. The team transferred to CSIRO in 1982. Since then, research has been expanded to cover a wider field of technologies that now includes radioisotope, microwave, ultrasonic, laser and capacitance techniques. The application area has been broadened to include the determination of flow rates of multiphase mixtures in the oil and power industries, and of the particle size of materials in various industries.

The research team, now in the CSIRO Division of Minerals, has built up considerable experience in the research, development, field testing and commercialisation of on-line analysis systems. A successful pattern for the development of these projects has been established and demonstrated in practice.

This paper discusses the pattern for project development and commercialisation of on-line analysis systems. The aims of the projects and occurrence of economic benefits are discussed first. Three examples are then given to illustrate radioisotope systems for on-line analysis.

PROJECT AIMS AND BENEFITS

In the AAEC and CSIRO, systems for on-line analysis are developed to increase the productivity of the Australian mineral and energy industries, and to provide economic benefit to Australia.

The economic benefit sought is predominantly the improvement to the processing of the minerals based on use of the instrument, rather than from its sale. To ensure the early realisation of these benefits to Australia, the AAEC and CSIRO have given high priority to commercialisation and technology transfer of the analysis systems to licensees.

Sales of the instruments discussed and their derivatives have been significant, however, about A\$80 million since the 1970s.

ANALYSIS OF MINERAL SLURRIES

On-stream analysis of mineral slurries is required to achieve better control of flotation concentrators. The need is to determine the valuable mineral content of various slurry streams about the plant.

The AAEC, over the period 1963–1973, developed and field tested radioisotope techniques for the on-stream analysis of metalliferous mineral slurries. They were based on several complementary radioisotope X ray fluorescence, and X ray preferential absorption, techniques [2]. The solids fraction was determined by gamma ray absorption. The radioisotope sources and X ray detectors were incorporated into probes that are immersed directly into the plant streams.

The introduction of on-stream analysis has had an immediate impact on control of flotation concentrators. Within a few months of installation, the recovery of valuable minerals is often increased by 1–2% due to better control of the plant.

ASH IN COAL ON CONVEYORS

The on-line determination of the ash content of coal on conveyors is required in a wide range of applications including mine grade control, raw coal monitoring, coal sorting, control of coal preparation plants, product blending, and stockpile management and blending.

The AAEC initiated research into on-line ash gauges in the late 1970s, and the project team completed the field trials in the 1980s after their transfer to CSIRO. The ash content of coal is most simply determined by dual energy gamma ray transmission techniques [4] that depend on the fact that ash has an effective atomic number greater than that of the combustible matter. Other ash gauges were developed at the same time, but it is the DUET gauge that is now in most widespread use [5].

The net benefits in productivity flowing from the use of the 39 Coalscan ash analysers installed in Australia by 1988 were estimated by independent consultants to be US \$130 million over a five year period [6].

FLOW RATES: OIL, WATER AND GAS

Pipelines carry multiphase mixtures of crude oil, formation water and gas from oil wells to production separators. The flow rates of oil, water and gas, from each well, must be measured to provide information necessary for the control and optimisation of oil field production. The oil industry wants to determine the flow rates directly in the pipeline carrying the multiphase mixtures. These multiphase flow meters (MFMs) would replace the current practice of using single-phase meters to monitor the outputs of a test separator.

CSIRO developed and field tested a gamma ray MFM over the period 1989–1997. It is based on use of two specialised gamma ray transmission gauges and pressure and temperature sensors [7, 8].

The potential market for MFMs is very large. World wide, there are about 10 000 wells offshore, and a further 900 000 onshore. The current market is mainly for offshore applications, on platforms and subsea. The applications onshore are expected to be mainly for wells with higher oil and gas flow rates where the cost of the MFM is justified.

The application of this meter should lead to the reduction in capital costs of new platforms and of subsea piping from wells to central facilities, and to better reservoir management, production allocation, and optimisation of total oil production over the field lifetime.

DEVELOPMENT, FIELD TRIALS AND COMMERCIALISATION

The following are the normal stages of a project in on-line analysis, from selection of the project to the successful commercial exploitation of the on-line system in industry:

- selection of specific industries that will gain large economic benefit from use of on-line analysis systems,
- assessment of the key requirements for analysis in the industry,
- a rough assessment of various techniques which may be used for this application,
- assessment of on-line analysis instruments currently being developed elsewhere or in routine use, including their shortcomings,
- preliminary laboratory research and development to gain some experience with the various techniques,
- more detailed discussion with industry of their requirements, best done on-the-spot at their operations,
- soliciting financial support for the project, undertaking the sponsored project which involves laboratory R&D and field trials,
- final reporting of the sponsored project,
- selecting a licensee and negotiation of the commercial Agreement, and
- transfer of the technology to the licensee.

The projects often take 7–10 years to complete because they involve not only the R&D, but also field trials, commercialisation and technology transfer. For example, the MFM project was conceived in 1988 and began in 1989. The MFM was licensed in 1997.

Some of these stages of development of a project are now discussed in more detail.

Selection of specific industry

This selection is not particularly difficult in Australia. The mineral and energy industries world-wide have great need for on-line analysis. These industries in Australia are very large, with annual production of coal, metalliferous minerals and oil being respectively valued at AS 8 (export only), 3.5, and 5 billion. The metalliferous mineral production quoted relates only to those minerals for which on-stream analysis has been proved effective. For example, gold is excluded because it occurs at very low concentrations in ore and analysis is beyond the reach of radioisotope technology.

On-stream analysis leads to the more efficient processing and recovery of minerals. Even though the increase in recovery will be fairly small, a 1% increase applied industry wide in these three industries would lead to savings to Australia of \$160 million a year. The realization of this magnitude of savings is the challenge for the Australian developers of on-stream analysis systems and for Australian industry.

Targeting key analysis requirements

The most critical stage of the whole project is the targeting of the key requirements for on-line analysis in the particular industry area. The researcher must understand why these key areas are important, how the analysis system can be used to increase or improve production, and what economic benefit can be gained by industry from their use. Frequent contact with a wide range of people in industry is essential, both by direct contact and by attending industry conferences.

I have found that there may be one, or a few at best, persons in industry who clearly see the key analysis needs of their industry and are prepared to be the industry champion of the project. It takes time and perseverance to find this person. Whilst in the AAEC, I had been working in the field of on-stream analysis of mineral slurries for nearly three years before finding this champion. He understood the real needs for on-line analysis, and I knew the emerging radioisotope technologies that could be further developed for use in on-line analysis of mineral slurries. The project soon became more focused, and developed more quickly.

Who initiates the project?

Conventional wisdom is that industry should initiate projects because only they understand their priorities. However, research groups have a better grasp of emerging technologies, and have a better understanding of what is technically feasible. Who initiates the project does not matter. It is critically important that the industry requirements, the emerging technologies and the understanding of technical feasibility, are all incorporated.

In most of my projects, I have made the first approach to industry because I have sensed the importance of newly developing technologies. Industry followed up my approach with input of their critical needs, their enthusiasm for the developing project, and their ideas for, and support during, field trials.

Planning the project

Once the key analysis problem is identified, preliminary R&D are often required before the main directions of the project can be defined. This work may take 3-6 months, and is nominally funded by the research organization.

The research organization then prepares a more detailed plan of the project, including both laboratory R&D and field trials. There is frequent interaction with industry during this planning stage. The detailed plan is then submitted to potential industry sponsors, especially to those who would have a strong vested interest in the successful development of the analysis system.

During planning, I estimated that the MFM project would take six years to complete. The project was set up in three two-year stages. The first involved only laboratory research, and included gaining more experience with the oil industry. The second and third stages involved both laboratory R&D and field trials.

Funding the project

Funding sources for the three analysis systems

The source of the funds to support projects has changed greatly during the period covered by the development of the three analysis systems discussed in this paper. In the 1960s, the AAEC directly funded the R&D of the mineral slurry analyser. Industry part funded the costs of the field trials, the AAEC covering the scientists' salaries and overheads. In the late 1970s/early 1980s, the AAEC and CSIRO funded most of the R&D of the ash gauge, with significant additional funding being supplied by NERDDC, a Government body for funding energy research based on competitive bidding. In the 1990s, CSIRO directly funded about 50% of the \$4M total cost of the MFM project. Oil companies and ERDC (a successor of NERDDC) funded the other 50%. They directly funded part of the CSIRO R&D, and essentially all of their and CSIRO's costs in field trials.

The royalties later gained from commercial sales of the analysis systems have not been included in the above sources of funds. The royalties from ash gauge sales, shared between the AAEC, CSIRO and NERDDC, were about \$1.3 million. Based on MFM sales predictions, CSIRO could receive about \$2M over the first five years. This would cover the total CSIRO cost of development of the MFM, and further royalties after 2002 would provide a positive return on the investment. Under internal financial policies, the project team has had no access to such royalty streams in the past, and apparently will have no access to it in the future.

Funding for the MFM project

There was no previous contact with the oil industry and hence funding the MFM project was a challenge. The Australian Mineral Industries Research Association Ltd. (AMIRA) was approached. This company, set up by the mineral industry, provides links between industry requiring research to be undertaken and research organizations that could undertake it. It does not itself undertake R&D. It has an excellent record of achievement with the metalliferous mineral industry, and were then expanding their efforts, and had contacts with, the petroleum industry. Finance was sought from the oil industry and AMIRA coordinated the research project.

To enhance the chances for gaining financial support, the project was deliberately set up in three two-year stages. After the successful completion of one stage we sought financial support for the next. This reduced the financial risk to sponsors and provided better direction for subsequent stages. From the beginning, the oil companies were told that it would take six years to develop the MFM. The total support requested for the first stage was only \$120 000. This covered some laboratory R&D. We gained experience with the oil industry, and felt we gained the confidence of our sponsors. The bulk of the funding was required for the second and third stages that included the field trials.

Ownership of intellectual property

Intellectual property (IP) in these projects usually consists of patents and know-how. There was limited patent cover for the three analysis systems described above: for one of the XRF techniques used in the mineral slurry analyser, none for the ash gauge, and for a specific part of the MFM. However, know-how was extremely important for the mineral slurry analyser, sufficiently important for the ash gauge to give the licensee a five-year lead on the world market, and is very important for the MFM.

The ownership of the intellectual property is negotiated at the beginning of the project when its value is uncertain. Some of the technology will have been developed by the research organization prior to the commencement of the project, but more will be developed during it. Ownership is usually a contentious issue. I consider that the research organization should retain the IP rights because

- to ensure success in commercialisation, rights usually must be exclusively licensed,
- usually only the research organization has sufficient knowledge of the product to transfer the technology to the licensee, and
- the loss of the IP rights may limit the contribution the research organization can make to applying the technology to other fields of application and other industries.

The issue of ownership of intellectual property is often resolved by advising the company who wants it that they can have it but must pay the total cost of the background knowledge, the project itself, and technology transfer. The company then takes on the whole risk of the project. My experience with on-line analysis projects is that companies will not take on this risk. The AAEC or CSIRO retained ownership of all the intellectual property developed during the three on-line analysis projects described above.

Field trials

Field trials are essential to all on-line analysis projects. They contribute vital information on the state of development of the system, and may indicate where improvements are necessary. They determine the accuracy of analysis achievable in industrial conditions. This is of particular value to the project sponsors, as they can then plan with confidence the installation of the future commercial on-line system. The researchers learn much about the industry during a field trial, and may find new application areas for the system and bring to light new analysis-areas for future research.

There were six field trials of the system for the in-stream analysis of mineral slurries. This large number was essential because of the range of elements to be analysed (iron, nickel, copper, zinc, tin and lead) and the range of different XRF and XRA techniques that had to be

developed and proved. These radioisotope X ray techniques were new to the mineral industry, and an important part of the field trials was proving that the systems were practical.

CSIRO proved the ash gauge in trials at one pilot plant and two coal washeries. These demonstrated to the coal industry that on-line ash gauges were sufficiently accurate and reliable for their routine use.

CSIRO tested and demonstrated the performance of the MFM in three field trials, two on offshore oil platforms and the third on an island fed from oil platforms offshore. Each trial led to further laboratory R&D, improving the technology between each trial. The last trial was on the West Kingfish platform in the Bass Strait. The MFM has been in routine use there since completion of the trial in 1995. The MFM was further tested in 1996 at Texaco's multiphase flow loop near Houston [8] to gain experience with a wider range of flow conditions. Further loop trials will be undertaken to improve the calibrations for liquids and gas flows.

Commercialisation

This Section covers the areas of when should the prospective licensee be introduced into the project, the selection of the licensee, checking the intent of the applicant for the license, and negotiating the commercial agreement. The whole process of selection of the licensee to completion of commercial agreement is slow. In my experience, it has never been achieved in less than one year, and often takes considerably longer.

When to bring in the potential licensee?

Conventional wisdom is to bring the licensee into the project soon after its commencement. This should add value to the project by having the licensee influence the course of its development, and allow the licensee to gain experience in manufacture of the instrument to be used in field trials. It was not known a potential licensee prepared to commit their own funds to a significant extent in the early stages of projects. The risk for them is too great. They have committed funds to the research organization after the analyser has been proved in field trials. The best was to keep potential Australian licensees informed about the setting up of new projects and progress in their development. This has given them time to make an early assessment of the market.

Selection of licensee

The key requirement in selection of the licensee is establishing its capability to develop and exploit the market for the on-line analysis system. The licensee should have established good contact with the industry where it is to be used, and preferably have experience with the technology being exploited.

Amdel and Philips Industries were chosen in 1971 as joint licensees for the mineral slurry analysis system. Both had good contact with the metalliferous mineral industry in Australia, and Philips had considerable experience with X ray techniques and with the development of instrumentation. The basis was that Philips would manufacture the system, and Amdel would be responsible for installation and calibration. The potential sales to the Australian market were high because of the large number of mineral concentrators here. It was intended that the experience gained in Australia would be used later to develop the world market.

Mineral Control Instrumentation Ltd. (MCI) was chosen as licensee for the ash gauge. Since three MCI staff had previously worked at Amdel, MCI had considerable experience in radioisotope and nucleonic instrumentation technology. They had no experience with the coal industry, but formed links with a firm of engineering consultants to the coal industry. The Australian coal industry is large and the experience gained first in Australia again was later used to develop the world market.

The licensing of the MFM was considerably more difficult than for the other systems. At least part of the problem was the need to address both international and Australian markets at the same time. Unlike the other two systems, the local market was insufficient to use as a base for subsequent world sales. In addition, the nature of the oil industry makes it a global business, not a regional one. A limited number of major companies dominate the oil industry.

CSIRO policy is to give preference where possible to licensing Australian companies. Two attempts were made to do this with the MFM, both involving the linking of an Australian company (one had no previous experience in the oil industry) with a large international instrumentation company already servicing the oil industry. This linkage was essential to exploit the international market. Both attempts failed. The first probably failed because the overseas company felt uncertain about tying up with a technology and manufacturing operation based in Australia. The second failed because of a takeover bid and subsequent policy changes in the overseas company at a critical stage of discussions with them.

Learning from the above experience, CSIRO Minerals accepted that the MFM should be directly licensed to an international company that services the oil industry. With the benefit of hindsight, this is a more appropriate route to exploitation of the MFM. Two international oil services companies, both potentially very good licensees, expressed immediate interest. It was licensed to one of them, Kvaerner FSSL of Aberdeen, in 1997. Kvaerner service the oil industry world-wide, have experience in the development of instrumentation for the oil industry, and are one of the few companies world-wide who have expertise in subsea engineering.

Is the licensee applicant serious?

Companies express interest in taking up the license for various reasons, including serious intent, the desire to gain information in an area of their interest, and in rare cases, I suspect to gain the license to keep the analysis system off the market. The applicants are entitled to some information on the system to enable them to make a better assessment of its viability for successful commercial exploitation. The companies must decide whether the product fits in with their immediate objectives, if the timing is right for their company, and are the decision-makers in the company enthusiastic.

Once the research organization has decided to proceed further with a specific applicant, it is sensible to test the seriousness of their intent. One way to do this is to offer them priority right to negotiate for a set period of time in exchange for a sum of money that is refunded on successful conclusion of the license agreement.

Negotiations

The developer and potential licensee have many interests in common. Both want to see the technology transferred rapidly to the licensee, to see the gauge developed quickly into a

commercial product, and to see it gain widespread use in industry. These common interests drive negotiations towards success.

It seems that the best approach to commercial negotiations of on-line analysis systems is similar to the best practice of negotiations in many other areas. Find out what are important needs for both parties. Discuss these in detail to see if agreement is possible. Make sure that these are jointly acceptable before detailed negotiations of terms take place. Do not put forward conditions that the other party cannot accept, but be prepared to have to seek another licensee if agreement on fundamental issues cannot be resolved.

Contentious issues are often financial, both in the immediate funding of technology transfer and further system development, and in royalties. At this stage, the research organization may no longer have access to funding from industry sponsors, and requires finance to cover the costs of technology transfer and further development of the analysis system. The licensee has a negative cash flow whilst taking on the technology, modifying it to ensure a marketable product, and marketing it. The licensee usually prefers to fund the research organization from royalties on sales. This limits its risk, but transfers some of the risk to the research organization if future sales are overestimated. Both parties must be prepared to take on some of the future risk.

The costs of the transfer of technology are considerable and are mainly covered by the licensee. After licensing, the research organization usually undertakes further R&D to simplify the analysis system and to extend the range of its applicability. This may be covered, at least partly, by having the licensee fund the research organization from an extra margin on the sales price for the initial sales of the system (if the system is successful).

Royalties are a complex issue and depend on many factors including patent cover, the value of the know-how, the availability on the market of competitive systems, the extent to which industry needs the product, and the savings resulting from its use. Royalties are usually decided on a specific case basis.

Comments on negotiations with licensees

The negotiations for a license for the mineral slurry analyser were complex because four parties were involved in the Agreement. The negotiations would have been much simpler if only the AAEC and one negotiator, representing both Amdel and Phillips, had been involved.

The negotiation with MCI of the agreement for the ash gauge was much simpler because only CSIRO and MCI were involved.

The negotiations with potential licensees for the MFM took place over a three-year period, and were successful only after CSIRO decided to negotiate directly with an overseas company. The negotiations with Kvaerner FSSL Ltd. of Aberdeen were made somewhat more complex because of distance. Considerable telephone and written discussion took place before it was possible to schedule the first meeting that was held in Houston. However, the communications then became rapid because of use of email. Even so, the first meeting was held 14 months before the signing of the contract. A greater number of face to face meetings may have speeded this up, but again the cost and complexity of arranging such meetings increase with distance.

Technology transfer

The time and resources needed for technology transfer depend on the complexity of the analysis system, its stage of development, and the licensee's experience with the technology. Licensees usually underestimate the time and resources required to transfer the technology. From the experience, it has been achieved best when technical staff of the licensee work with research organisation staff on the project for a few months, and jointly undertake either a plant trial or the first commercial installation. The following summarises experiences in technology transfer with the above three on-line systems.

Amdel

The mineral slurry analyser was Amdel's first involvement with radioisotope techniques and with the development of instrumentation. An Amdel physicist spent one year at the AAEC laboratories, undertaking both laboratory work and field trials with AAEC staff. This was critical to the success of the technology transfer. The AAEC had proved the on-stream analysis technology in field trials using laboratory equipment. Amdel and co-partner Philips Industries Ltd. designed the industrial system. The AAEC had to supply backup support on technology for about five years after the first commercial sale to industry. The experience Amdel gained with the on-stream analysis system led to Amdel becoming the world market leader in radioisotope on-stream analysis of mineral slurries. Amdel have introduced solid state detectors into the radioisotope X ray system, and broadened the application area to include analysis of dry powders, solutions, and coal slurries. Total sales exceed AS 50 million. Amdel undertake their own R&D into new analysis systems.

Mineral Control Instrumentation (MCI)

MCI obtained the license for two on-line ash gauges in 1982. They had considerable expertise in on-line analysis and radioisotope techniques. CSIRO had used laboratory electronics in the field trials. MCI had to design electronics and mechanical equipment suitable for long-term industrial use. Although the license agreement was signed in 1982, CSIRO continued R&D and proving of the ash gauges until 1986. The technology was transferred over a three-year period. MCI now market two models of the ash gauge as the Coalscan 2500 and 3500 ash monitors. They have installed over 210 monitors world-wide, with total sales exceeding AS 30 million. The monitor is the world market leader in on-line ash gauges based on gamma ray techniques. MCI now successfully undertake their own R&D into new coal analysis systems.

Kvaerner FSSL

CSIRO commenced transfer of the multiphase flow meter technology to Kvaerner FSSL Ltd. in December 1996. A Kvaerner staff member visited CSIRO at Lucas Heights in two separate visits for a total time of about 6 weeks. Otherwise, contact has been by email and by telephone.

The transfer of the technology was greatly simplified compared with the previous cases because, in the period 1985–1995, CSIRO Minerals had developed considerable expertise in the electronic and mechanical design of industrial gauges. The CSIRO MFM was at a far greater stage of industrial development than the previous instruments because, for field trials, the MFM had had to meet the unusually high standards of safety mandatory on offshore platforms. The transfer of mechanical and electronics design was in the form of engineering drawings.

A CSIRO scientist took part with Kvaerner in the setting up of the first MFM they manufactured and in the first loop trial at the National Engineering Laboratory, Scotland. CSIRO is continuing to transfer technology to KFSSL and to undertake R&D into the MFM calibration for liquids and gas flows.

CONCLUSION

The AAEC and CSIRO have over the last 35 years very successfully developed on-line analysis systems for use in the mineral and energy industries. The development of these systems has led to the establishment of Australian technology in the forefront of on-line analysis systems for the world market. The successful pattern of laboratory R&D, field trials, licensing, and technology transfer developed has been discussed in relation to three analysis systems developed.

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CURRENT STATUS OF NUCLEONIC GAUGE APPLICATIONS IN BRAZIL AND THE NEEDS FOR THE TECHNOLOGY IN LATIN AMERICAN COUNTRIES

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Abstract

Brazil is actually the only country in Latin America that design and manufacture nucleonic gauges in industrial scale for internal market and export. There are some local companies that manufacture or assemble simple first generation nucleonic gauges for density, level and thickness gauges for pulp and paper industry, metallurgy and mineral ore processing and beverage packaging. There is apparently a market saturation due to economic crisis, public concern and licence procedures.

1. INTRODUCTION

There are, presently, 256 industrial installations registered in the “Comissão Nacional de Energia Nuclear — CNEN” as active users of nucleonic gauges, mostly from pulp and paper industry, mining and metallurgy, and beverage packaging. Five or six local companies construct and/or assemble density, level and thickness/area-weight nuclear gauges, most of them using know-how from foreign manufacturers.

Along the last two years there was a noticeable saturation of the market, concomitantly with the decrease of the industrial growing and, (in some cases), with the significant reduction of the demand of such applications originated initially by the necessity to satisfy the ISO 9000 requirements for quality certification.

The introduction of NCS in industry faces growing difficulties due to the high conventional technology competition, to public concern against radioactive materials, and licence procedures.

The Brazil and Latin America market is quite large for wider use of nucleonic gauges in industry. Looking into the trends in industrialisation of developing countries in the Region, there is evidence that nucleonic gauge technology will continue to play an important role in industry for many years to come. The national capability and infrastructure exists for extending further this technology. More should be done for public acceptance and end users awareness on safety and benefit of the technology.

2. INDUSTRIAL APPLICATION OF NUCLEAR GAUGES IN LATIN AMERICA

The first nucleonic gauges were installed by the end of the fifties, as being parts of the machines and installations of some industrial processes or were imported and installed later in Latin America subsidiaries, by decision of their foreign headquarters. The major part of other types of nuclear gauges as portable probes for well logging, mineral analysis and pavement compacting control, were introduced mostly by companies that provide engineering services.

Short time later, in several Latin America countries, research institutes belonging to national atomic organizations or universities undertook the development of prototypes. In some specific cases these activities were the starting point for transferring the NCS technology to private firms.

- lack of information at the company top management level on the availability and advantages of NCS applications, due to inexperience of their own personnel or insufficient knowledge from the local representatives of foreign suppliers,
- prevention of potential customers against the use of radioactive material in their installations;
- inadequate radiation safety rules (too ambiguous or unnecessarily rigorous) with regard to some particular applications, complicated and/or delayed licensing processes, insufficient advice on the required procedures;
- reluctance of potential users, particularly small and medium-sized companies, to introduce technologies dependent on foreign provision of equipment, spare parts and technical assistance;
- local market demand not enough to sustain profits for national enterprises intending to produce and sell NCS and related technical services;
- resistance of some categories of employees against the introduction of technological innovations that could involve additional professional challenges and responsibilities..

2.2. Needs for NCS in the industry of Latin America countries

Obviously, any measurement and control system that contributes to improve the quality of materials and the output rate of manufacturing processes permit also a reduction of production costs and a series of other direct and indirect benefits that can be finally assessed in terms of an increase of profits for the company. The cost/benefit ratio is more favourable for on line measuring systems (which is one of the inherent characteristics to most NCS) and for large scale production processes.

Taking in mind that many Latin America countries already have important and modern industries in the fields of mining and metallurgy, petrochemicals, paper and cellulose, plastics, beverages, etc., it is evident that to get optimum operating conditions it will be necessary to introduce the NCS technology in the respective processes, as it was done years ago with great success by the developed countries.

In spite of the affluence of NCS due to the preceding considerations, the Latin America industry still has necessities to be satisfied either through the installation of gauges were they do not exist or by substituting (or upgrading) obsolete systems.

This subject was treated, among other matters, in a tentative project elaborated by the IAEA and UNIDO, in 1995, aimed to implement a “Regional Programme on Quality Management and Control Including the Use of Nuclear Related Technologies for Latin America and the Caribbean”.

As a preliminary part of that project a survey was performed among enterprises of fourteen countries to identify the status of the included questions and the priorities attributed by entrepreneurs to the need of changing the prevalent conditions. The author of this paper collaborated with the IAEA in the preparation of the questions regarding the most widely used applications of radioisotopes and ionising radiation, from tracers to radiation processing, and afterwards, in the analysis of the answers. The conclusions on the questions concerning specifically to NCS, can be summarised as follows:

- (1) Eight countries assigned high priority (from 1 to 3 in a scale of 10) to satisfy the need of new techniques (different from classic ones) for improving the quality of their products. The examples on classic control methods considered in this question were deliberately referred to measurement problems that could be solved through the use of NCS (thickness, area-weight, density/moisture, chemical composition, etc.). Thus, the answers represent an evidence that, at the time of the survey, there was an opportunity for the NCS to compete successfully against the conventional techniques.
- (2) As in the previous case, some companies were strongly interested in introducing technological innovations in their processes and products. Nine countries attributed priorities from 1 to 3 to this possibility, so nucleonic gauges might be included among the required innovations.
- (3) The access to information on industrial applications of radioisotopes, still appears to be a relevant problem in the Latin America industry because 7 participant countries gave priorities from 3 to 5 to its solution.
- (4) Seven participant countries gave priorities from 1 to 5 to the use of nuclear techniques for controlling the quality of the manufactured products. This indicates, in agreement with the first conclusion, that the industries of the region had a real necessity of such techniques.
- (5) Seven countries assigned priorities in the range of 1 to 6 to the importance to prove and test the advantages claimed with regard to the radioisotope techniques, as a previous step towards their acceptance. This indicates the convenience that the manufacturers of NCS or their representatives implement such tests as an effective way to promote their sales.
- (6) In two of the most industrialised Latin America countries, the prevention against the use of nuclear techniques still represents a great obstacle for the acceptance of NCS.
- (7) Nine participant countries asked for change of classic measurement systems to improve the technology, which is in coincidence with the first conclusion that some inherent limitations of classic methods for the control of industrial processes could be overcome with the use of nucleonic gauges.

3. INNOVATIONS IN NUCLEONIC CONTROL SYSTEMS

Among the innovations that certain manufacturers introduced along recent years in some types of their NCS, it can be mentioned:

- a) substitution of ion chambers by solid state detectors to increase the detection efficiency and thus to allow a reduction of the source activity; for some specific measurement conditions.
- b) substitution of radioactive sources of low energy gamma rays by X ray tubes of small size;
- c) enhanced software programs for modern data handling and statistical process control.

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THE CURRENT STATUS OF NUCLEONIC GAUGE ACTIVITY IN CHINA

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Abstract

The nucleonic gauge technology in China is in full development. The nucleonic gauges are widely used, mainly in metallurgy, coal, cement and rubber industries. The simple first generation of nucleonic gauge is locally designed and manufactured in industrial scale by many institutions and enterprises. The local market is large and far from being saturated. The quality and reliability of nucleonic gauges and their integration into the control system are still concern. Research and development is going on to improve the quality and to design and produce second generation of multibeam and multienergy nucleonic gauges.

INTRODUCTION

The nucleonic gauges and control systems are widely being used in many industries in China. At the beginning of the development of nucleonic instrumentation industry in 1950's, China copied indiscriminately the experience of the Former USSR. From the 1960's onwards, China began to develop its own industrial nucleonic gauges.

At present, there are more than 180 companies in China which develop and produce nucleonic gauges. More than 40 types of nucleonic gauges are being produced so far. The industrial nucleonic instrumentation includes nucleonic level and density gauges, weight and thickness gauges, neutron moisture and density-moisture gauges, content analysers, and some simple nucleonic control systems as well. These gauges played an important role in the modernisation of conventional industry. They were successful in reducing energy consumption, increasing the quantity of goods and controlling quality of products.

With the development of research in the field of nucleonic control systems, more and more nucleonic gauges are used in monitoring and controlling industrial production processes.

The nucleonic gauges were rapidly increased from 1988 to 1997. From only 6,000 sets of nuclear instruments in 1988, there were about 38,000 sets by the end of 1995. The number of nucleonic gauges including level switches amounted to more than 45,000 sets in 1996. This progress is shown in Figure 1.

Due to many advantages, nucleonic gauges are widely being used not only in metallurgical, coal, cement and rubber industries, but also in computed tomography and digital radiography.

Research and development of nucleonic gauges are still in process. Compared to some developed countries, nucleonic gauges used in China are not of high quality and are not accredited to international standards. In order to improve reliability and stability of these gauges, a lot of work still needs to be done. Most of the nucleonic gauges are of simple nature and are not part of the control system. In many factories or plants, NCS are still being imported from abroad.

Number of sets (in thousands)

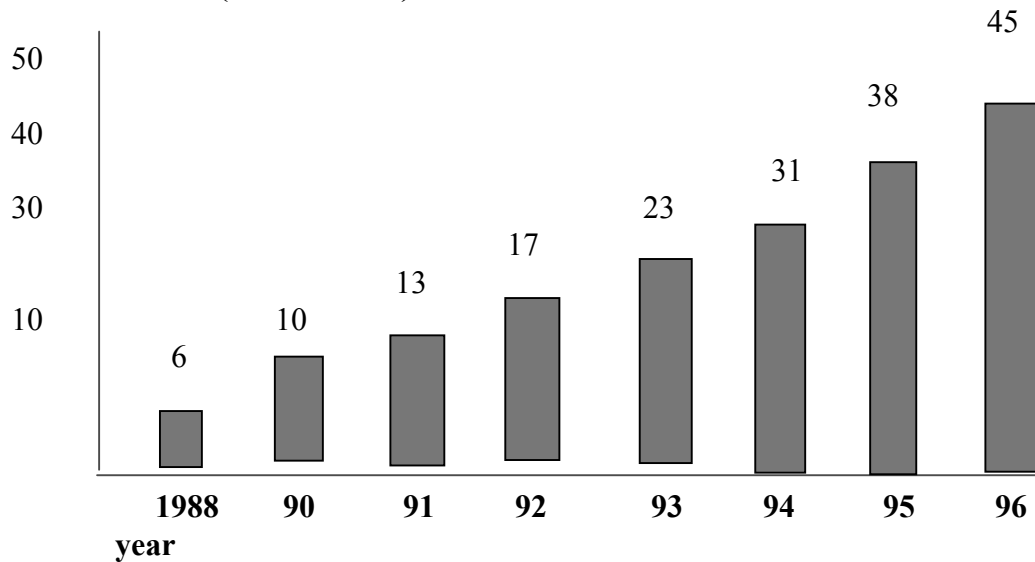


Fig. 1. Progress in number of nucleonic gauges.

The principle of nucleonic gauge

The nucleonic gauge usually consists of three parts, i.e. a radiation source, a detector and an electric measuring instrument. The radiation source emits radioactive rays. The detector is used to convert energy or density of the rays into electric signals. The electronic measuring instrument is used for the processing of the electronic signals.

Beta, X and gamma, and neutron sources are used as radiation sources and detectors include ion-chamber, scintillation detector and proportional counter. Beta and X ray have a shorter range due to their strong ionisation ability, thus they can only be used in measuring the property of thin layer materials. Neutron and gamma ray have a very strong ability to penetrate a mass, so they can be used in measuring the property of bulk materials.

The industrial nucleonic gauges mainly include three kinds of gauges. First, the intensity measuring type gauges, such as thickness, density and weight gauges. Second, the spectrometric analysis type gauges, such as X-fluorescence analysis, and third, the imaging type gauges, such as computed tomography and digital radiography.

There are two configurations of source, detector and material. In transmission configuration, source and detector are arranged at both sides of the object which is to be measured (see Figure 2).

In the scattering configuration, source and detector are arranged at the same side of the object which is to be measured (see Figure 3).

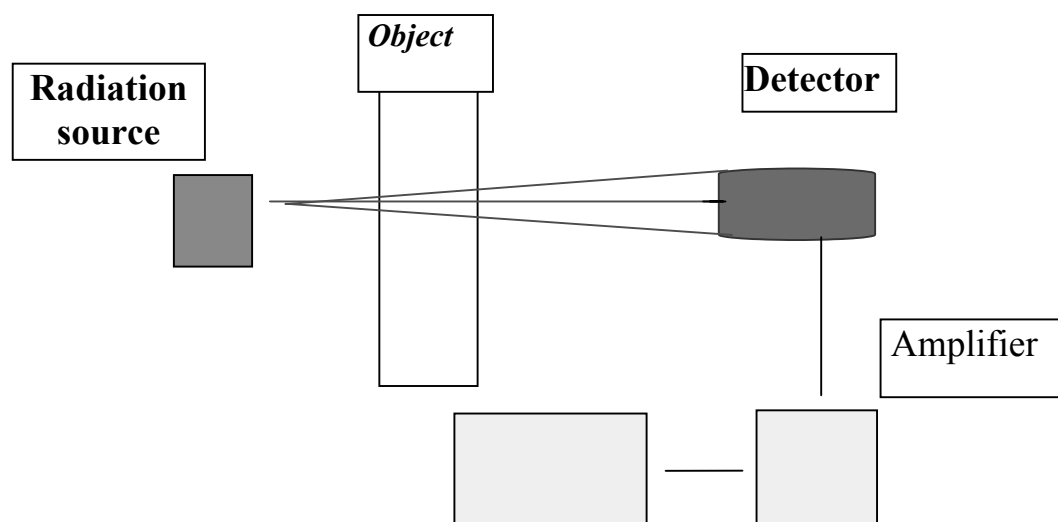


Fig. 2. Transmission method

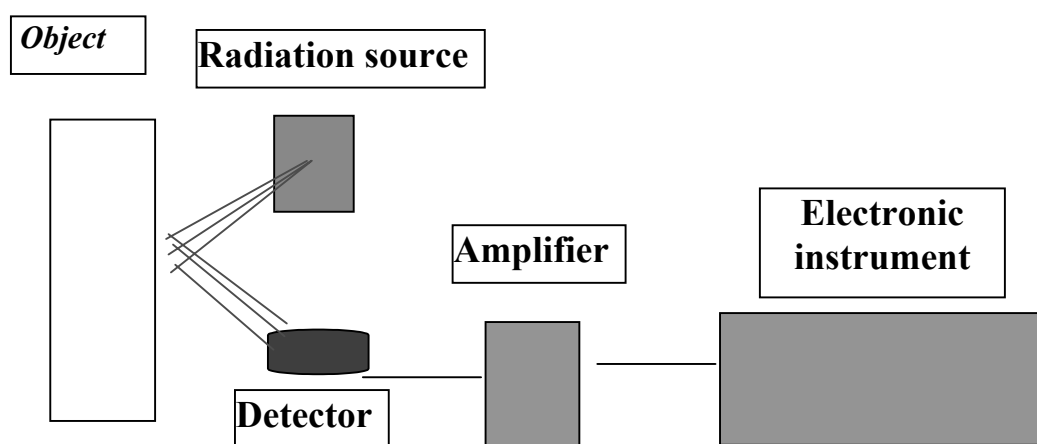


Fig. 3. Scattering method

Case-study types of nucleonic gauges manufactured in China

The major nucleonic gauges manufactured in China are described below:

1) Nucleonic level gauge:

The nucleonic level gauge is one of the simplest gauges in industrial nucleonic instrumentation. It is widely used in industry, especially for measuring materials having high temperature and pressure, as well as for combustible, explosive, toxic or erosive materials in hermetically sealed vessels. This measurement is not affected by chemical composition and physical conditions of materials. Nucleonic gauges are widely used in cement and chemical plants, oil refineries and steelwork activities in China. They have been contributing to a huge

economic benefit. For example, at many cement plants, there were increases of more than 30% in production, bringing the total income to approximately US\$ 11 million per year. Until 1996, about 12 000 sets of nucleonic level gauges were installed in China. There are produced simple relay (switch) type and more complicated continuous level nucleonic gauges. Figure 4 shows the principle of a switch nucleonic level gauge:

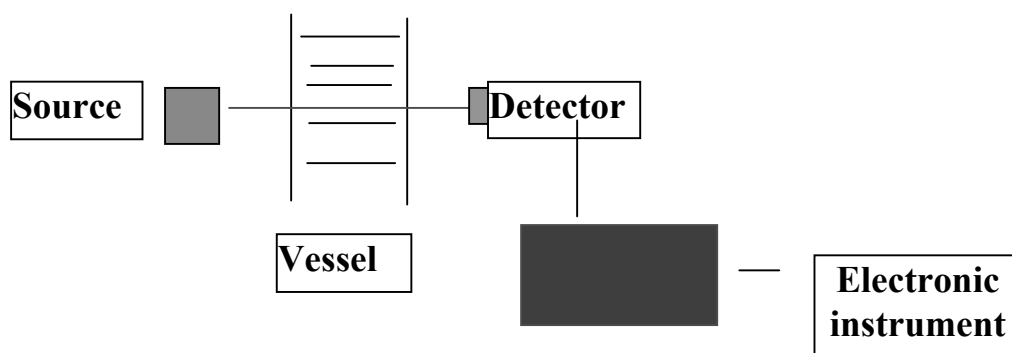


Fig. 4 . Principle of nucleonic level switch

Figure 5 (a) shows a multi-detector system used for continuous level measuring. It can be used for liquid, slurry or solid materials. Figure 5 (b) shows a continuous level measurement system using a long detector.

2) Thickness Gauge

Several kinds of thickness gauges have been designed and used in Chinese industry. Some examples of thickness gauges are steel thickness gauge for strap mill, paper and plastic thickness gauge and many other thickness gauges for measurement of material thickness. The following three types of thickness gauges are produced and commonly used in China.

a. Steel thickness gauge

There are more than 100 small and middle-sized strap mills in China, which produce about one million tons of hot and cold steel strap per year, including many kinds of special steels. The ^{241}Am gamma ray source and high pressure Xenon ionisation chamber with thin window is used recently.

The thickness gauges produced by INET come in different types to meet the demands of various users. They are of low cost and are widely used by local industry, about 500 sets of thickness gauges produced by INET are being used by 70 users in 20 provinces and cities during last 11 years. One set was installed and is still in use in Thailand.

Figure 6 shows that the amount of thickness gauges increased by 50 sets per year from 1992 to 1994, and by approximately 60 sets per year from 1994 to 1997. A rough estimation shows a profit of over US\$ 30 million per year, as a result of improved performance and optimised processing.

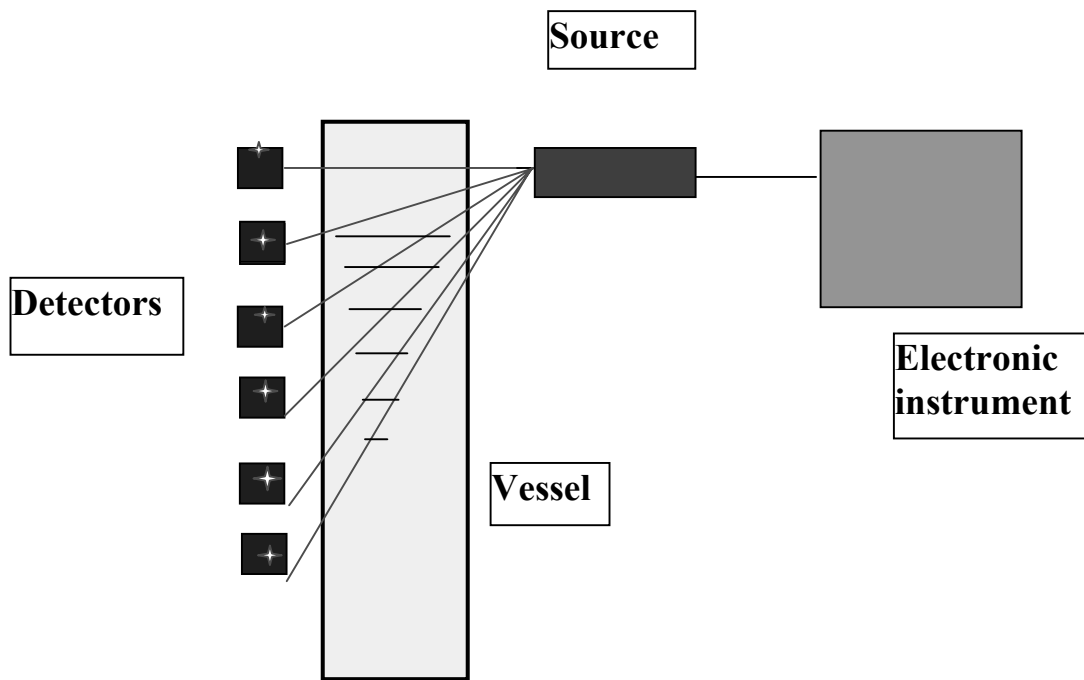


Fig. 5 (a) Multi-detectors continuous nucleonic level gauge

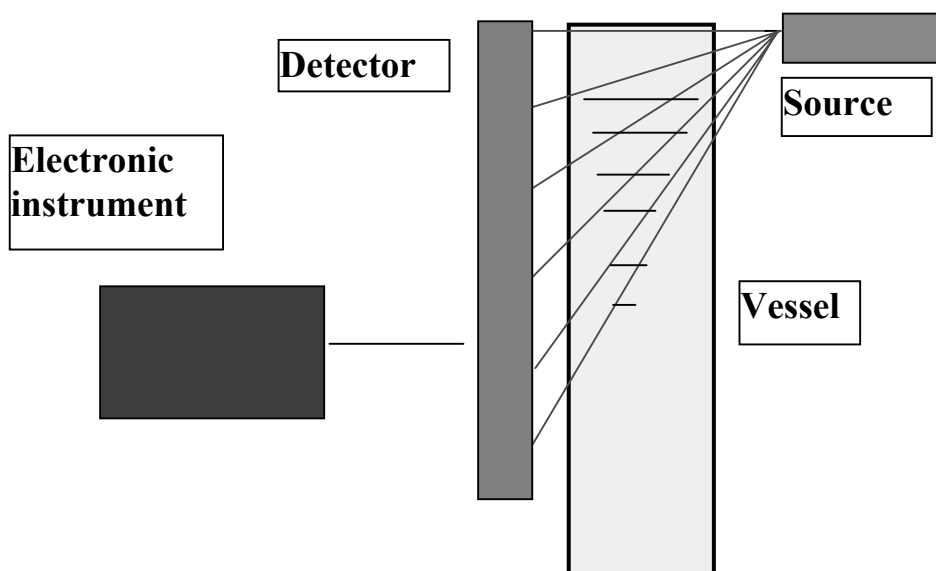


Fig. 5 (b) Long detector continuous nucleonic level gauge

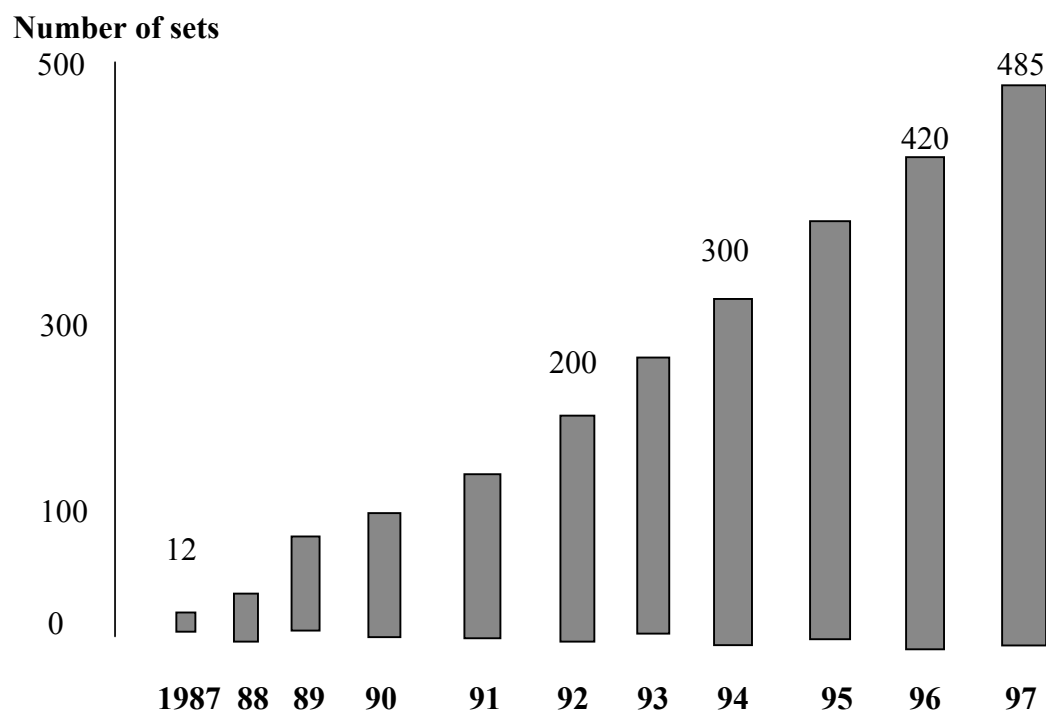


Fig. 6: Progress in number of thickness gauge in use

b. Other thickness gauges

Nucleonic gauges for paper and plastic basis weight monitoring play an important role in paper and pulp industry in China. The beta sources Kr-85 and Pm-147 are mostly used.

3) Nucleonic weigh scale

The nucleonic weigh scale is a mass flow meter. The gamma rays are attenuated during their penetration into materials. Gamma rays received by a sensor mounted beneath a belt conveyor are converted to the mass flow rate and the variation of total weight of material is displayed on a computer. Examples of nucleonic weigh scales include mineral ore belt, helical, chain, fender, vibration and pneumatic conveyers. They are widely used in cement, coal refining, mining, chemical and mineral ore processing plants.

Nucleonic weigh scales have been produced since 1983. The first gauge made in China was designed by INET and used in Beijing Second Coal Plant in 1987. Since then, according to the technical scheme that was developed by INET, several companies have produced many nucleonic weigh scales. Cs-137 and a long ion chamber detector are mostly used. A linear sealed source is being used recently to improve the performance of these gauges.

Recently, with the development of long ionising chambers, nucleonic weigh scales became of great importance to the cement industry. Nucleonic weigh scales are the most commonly used gauges in China. There are about 80 companies that produce nucleonic weigh scales in China. They produce more than 700 sets per year. At the end of 1997, about 6500 sets were installed in various plants in China.

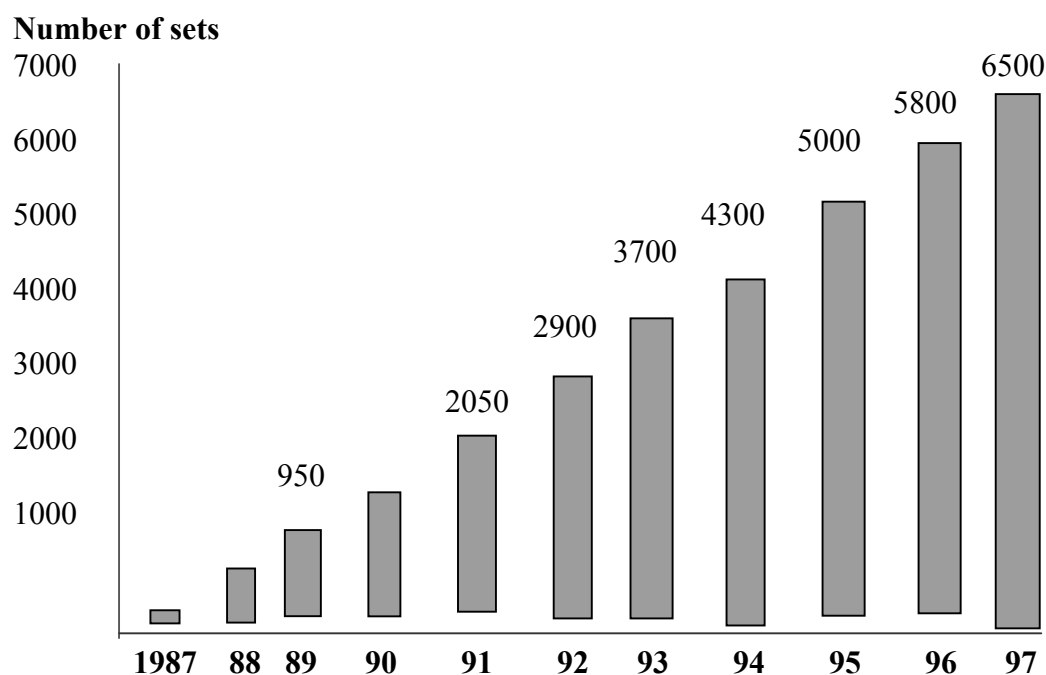


Fig. 7: Progress in number of nucleonic weigh scales

APPLICATION OF NCS IN INDUSTRY

Table 1 summarises the nucleonic gauges installed in Chinese industry.

TABLE 1: MAIN APPLICATIONS OF NCS IN INDUSTRY

Nucleonic Gauge	Industrial field
Thickness	Iron & steel, paper-making, chemical, non-ferrous metals, construction
Level	Iron & steel, chemical, cement
Density	Mining, Iron & steel, chemical, cigarette
Moisture content	Iron & steel, civil engineering
Weigh scale	Cement, coal, chemical, Iron & steel, power, mining
Well-logging	Petroleum, coal, mineral

In cement industry, the need for level gauges is huge. About 2300 sets are required for controlling the process of clinker production in rotary kilns. A large number of nucleonic weigh scales and X ray fluorescence analysers are also needed for monitoring the cement raw material. The cement industry, consisting of 10 000 cement plants, is the biggest market of NCS in China.

Nucleonic instrumentation in civil engineering is largely applied. Portable density and neutron surface density-moisture gauges are used for measuring density and moisture content of soil, cement, concrete and asphalt in highways, bridges, harbours, dams and buildings.

TABLE 2: APPLICATIONS OF NCS IN LARGE IRON AND STEEL PLANTS

NCS	BS	BT	SH	PZH	AS	W H	TS	CQ
Level	29	10	8	4	5		70	2
Moisture gauge	15	6	2	4	2	4		4
Weigh scale	8	12	10			14	16	2
Density gauge	9						60	
Thickness gauge	21	17	14	12	8	42		
Content analyser		2				13	2	
Aligning gauge	6	8		2	4			
Slab position detector	15					18		
Continuous level gauge	6		16		12			1
Coating mass gauge	1							
Tuber wall thickness measuring system	2							
Total	112	55	50	22	31	91	148	9

CONCLUSIONS

The nucleonic gauging activity in China is in expansion. Research and development are in process in many nuclear institutions for design and manufacturing of prototypes of more advanced double-beam and multi-beam gauges.

The nucleonic instrumentation industry is producing a large number of simple nucleonic gauges with common use in Chinese industry. The need for more nucleonic gauges is quite evident in huge Chinese market.

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AN EXPERT SYSTEM FOR THE CONCEPTION OF INDUSTRIAL GAUGES BASED ON BETA, GAMMA OR X RAY TRANSMISSION (JANU)

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Abstract

A knowledge based software (named JANU expert system) for radiogauges design mainly density, thickness, mass per unit area, level and two-phase flows gauges, was prepared recently. Its aim is to optimise the different components of a transmission gauge (radioactive source, detector, electronic device, collimators and shielding), taking into account parameters and constraints linked to the configuration (nature and composition of materials, presence of shields and walls, ...), as well as users requirements (accuracy, counting time, beam collimating, duration of tests, ...). The database includes characteristics of radionuclides and industrial sources, photon cross sections, build-up factors, specific dose constants, physical properties of elements, usual scintillation detectors and shielding materials. It allows the determination of the most suited emitter, as well as a precise characterisation of a given emitter, including required source activity, expected counting rates, dose rates, etc. It has been extended to X rays generators, voltage and current intensity replacing in this case the energy and activity of the source. Information supplied by JANU has been validated by applications developed during the past 30 years. Its choices have always revealed most judicious and in general, numerical results in good agreement with experiments. Thus, it has become an essential and reliable tool for gauge designers.

1. INTRODUCTION

Radiogauges optimization, mainly density, thickness, mass per unit area, level and two-phase flow gauges (void-fraction, concentration, ...), requires routine operations that lead the engineer to consult a wide range of documents: tables of radionuclides, catalogues of industrial sources, tables of photon cross sections, build-up factors, physical properties of elements, chemical composition of materials and other handbooks.

Besides, the approach of the designer involves acquired experience and can be easily formulated.

These considerations brought the Service d'Application des Radioelements (SAR) Saclay, to develop a knowledge based software for the composition of industrial gauges involving beta, gamma or X rays transmission.

2. SYSTEM OVERVIEW

JANU is an expert system, comprising a knowledge base as well as a physical and nuclear database. Its aim is to optimise the different components of a transmission gauge (radioactive source, detector, electronic device, collimators and shielding), taking into account parameters and constraints linked to the configuration (nature and composition of materials, presence of shields and walls, ...), as well as users requirements (accuracy, counting time, beam collimating, duration of measures, ...). It has been extended to X rays generators, voltage and current intensity replacing in this case the energy and activity of the source. It has been written in PDC-PROLOG and runs on IBM-PC compatibles.

The database includes characteristics of radionuclides [1] and common industrial sources, photon cross sections [2], dose build-up factors [3], specific dose constants [4, 5], physical properties of elements, usual scintillation detectors and shielding materials.

Among the main features of the system, we can point out:

- automatic recognition of complex chemical formulae;
- calculation of their corresponding mass attenuation coefficients;
- classification and sorting (the best first) of emitters into two categories, suited and unsuited;
- precise characterisation of a given emitter, including required source activity, self-attenuation, dimensions, radiotoxicity, manufacturer, expected counting rates, etc.;
- information concerning unsuited emitters, including the reason for it and replacement solutions;
- radiation dose rates and shielding calculations; – radioactive decay corrections;
- estimation of the influence of variations of the measured parameter on precision, required activity and counting.

Optimization of the energy of the emitter is based on radiogauge sensitivity considerations [6]. Configuration and user requirements may give rise to unsuited emitters if one of the following criteria is encountered:

- the required activity (respectively current intensity) or the corresponding counting rate is too high;
- the half-life of the emitter is too short compared to the duration of measurements;
- the tested material or the presence of shields produce a considerable amount of bremsstrahlung compared to beta emission (case of beta emitters).

Concerning the choice of the electronic equipment, it mostly depends on required counting rates, and one of three classical devices is proposed by the system.

3. CASE STUDY

Suppose we want to measure about 50% in volume of vapour, in a freon gas-liquid flow, with 5% of accuracy and 95% of confidence, each measure lasting utmost 0.5 seconds. We are looking for a solution involving a gamma emitter, beta emitters being declared unsuited by the system. Other relevant user parameters are summarised in Figure 1. Notice that the duration of tests remains unknown. As a consequence, radioactive decay, if any, will not be accounted for.

The choice of the crystal is users free: only its thickness is optimised, and this involves maximum available activity and detectors efficiency considerations. However, the system will complain if the choice reveals irrelevant and propose a more appropriated list. After choosing a detector from a menu, we get the “optimization menu” represented in Figure 2. Its review would be beyond the scope of the present paper. Topics C, E and F are illustrated in figures 3 to 5.

TWO-PHASE FLOWS MEASUREMENTS

Problem : void fraction measurements in a two-phase freon gas-liquid flow

Phase N° 1: freon - C(13.89%) H(1.17%) Cl(41.00%) F(43.94%) Density : 1.1

Phase N° 2: freon - C(13.89%) H(1.17%) Cl(41.00%) F(43.94%) Density : 0.05

Mixtures' thickness or pipe diameter (cm) : 1.2

Pipes walls and shields :

Cu (100.00%) Density : 8.94 Overall thickness (cm) : 0.2

Type of emitter : gamma

Mean void fraction : 0.5

Precision (%) : 5

Confidence interval (%) : 95 (2 sigma)

Source to detector distance (cm) : 5

Detector collimation : height (cm) : 2.5 width (cm) : 2.5 depth (cm) : 1

Source collimation : none

Counting equipment : scaler

Counting time (s) : 0.5

Duration of tests : undefined

Background (cps) : 4 Standard deviation (cps) : 0.2

F1 - Modify F2 - Save F10 - Run Esc - Main Menu

Figure 1: Example of users input parameters.

OPTIMIZATION MENU

- A - Classification of emitters (best suited first) and main results
- B - Information about the best suited emitter
- C - Information about any suitable emitter
- D - Information about any unsuited emitter
- E - Why a given emitter is considered as unsuited. Advice for use
- F - Required activity and counting versus measured parameter
- G - Required activity versus detector dimensions
- H - Radioactive decay correction versus duration of tests
- I - Radiation doses and shielding
- J - Edit data
- K - Modify detector
- L - Modify data
- M - End

↑ ↓ - Up/Down Return (or F10) - Select Esc - Cancel

Figure 2: Optimization menu.

EMITTER : Am 241 (gamma)
Energy (keV) : 60 (35.9%) Half Li fe (years) : 432.7
DETECTOR : NaI (TI) Standard thickness (cm) : 2.50
Efficiency (%) : 100 [greater than 99% beyond 0.195 cm thickness]
MINIMUM ACTIVITY (mCi) : 25.0
MAXIMUM AVAILABLE ACTIVITY (mCi) : 225
SUGGESTED SOURCE : source CEA/DPR of 25.0 mCi and 4 mm active diameter
RADIOTOXICITY : Equipment submitted to PREFECTORAL DECLARATION
TOTAL ATTENUATION COEFFICIENTS (cm². g⁻¹) : Phase 1 : 0.2925 Phase 2 : 0.2925
CONTRAST : 0.184 SENSITIVITY :
 - Count-rate variation for 1% of the measured parameter : 0.184%
 - Measured parameter variation for 1% of increase of the count-rate : 5.43%
Number of half thicknesses of the mixture : 0.29
Number of half thicknesses of the walls : 4.10 TRANSMISSION I/I₀ : 0.058
INCIDENT FLUX (particles. s⁻¹.cm⁻²) : 50267
EXPECTED NET COUNTS :
Nominal counting (counts) : 47126
Nominal count-rate (counts.s⁻¹) : 94251
Count rate phase 1 alone (counts.s⁻¹) : 78391
Count-rate for an empty pipe (counts.s⁻¹) : 1.15 E+ 05
ELECTRONIC DEVICE : Novelec type fast ictometer
PRECAUTIONS : temperature stabilization or regular calibration

F1 - Print

Return (or F10) - next

Figure 3: Information concerning a suited emitter.

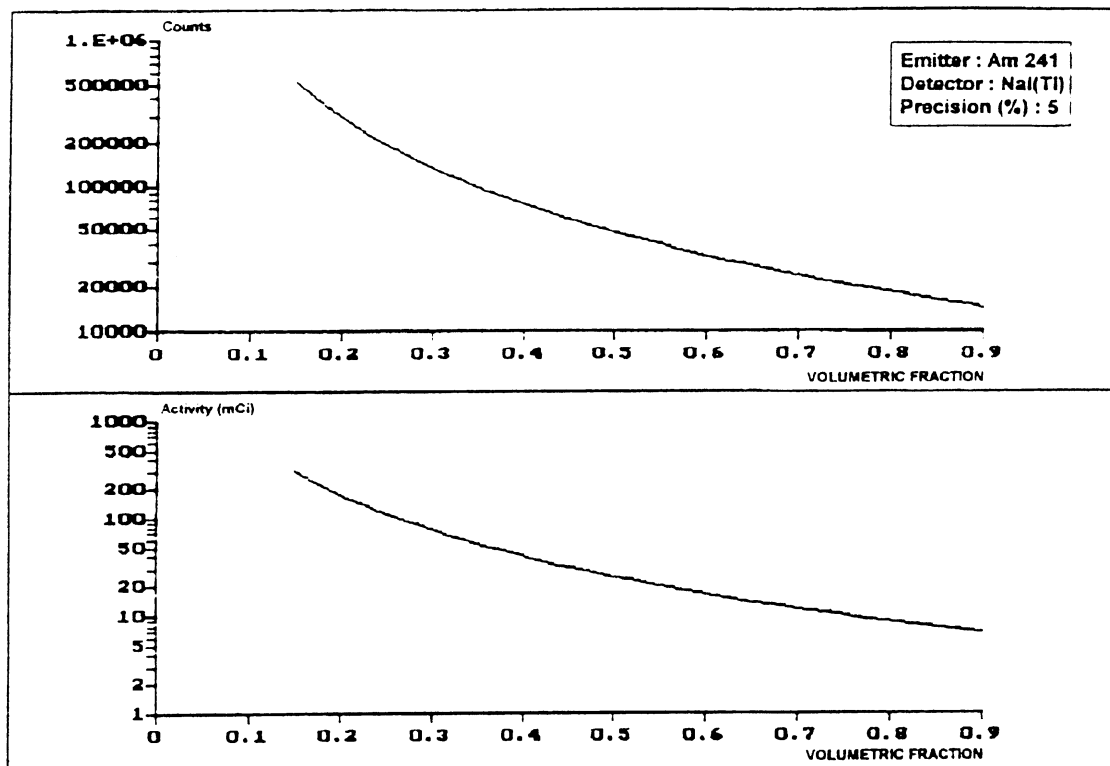


Figure 4: Minimum activity and counting versus measured parameter.

Emitter : Cs137 Detector : NaI (TI)

With Cs 137 [662 keV],

because of the TIME allowed for the measurement and the desired PRECISION, you need at least 1.43 million counts per second.

But, with a NaI cristal, even with a high speed electronics (NIM type with pulse amplifier and discriminator), one can hardly reach 250 000 counts per second.

The best would be to try one of the following detectors : [CsI, CsF].

Otherwise, with a NaI and 250 000 counts per second :

- either you keep the same counting time (0.5 s) and your measurement will be 2.39 times less precise,**
- either you count 5.7 times longer in order to obtain the desired precision (5%).**

F1 - Print Return (or F10) - next

Figure 5: Why is an emitter unsuited ? Advice for use.

Let us take Am-241 as an example of a suited emitter (Figure 3). In fact, the user having decided not to account for radioactive decay, the system will propose I-125 (half-life, 59.9 days), as the most suited emitter. For Am-241, the minimum counting required in order to obtain the desired accuracy is found to be equal to 47126 counts. From this, the minimum activity and the source are defined. As it was pointed out before, the counting rate defines the electronic device; in the present case, a fast icrometer is needed. Finally, since we are looking for a precision on statistical fluctuations of gamma emission better than 1%, regular calibration is recommended.

Counting and activity strongly depend on void fraction, as shown in Figure 4. Moreover, with a source collimator diameter less than 4 mm, Am-241 would become unsuited, Gd-153 providing a possible replacement solution, unless the use of a X-rays generator is considered.

Cs-137 is found to be unsuited because of the lack of contrast. As a result, a high counting rate is needed and the system mainly suggests to use a detector other than a NaI crystal, or increase the counting time (Figure 5).

4. INDUSTRIAL APPLICATIONS

Some applications either used to validate the system or developed taking into account its results are:

- in-line control of gas level in lighters;
- hair spray, perfume, or any liquid level control;
- in-line control of glass manufacturing;
- thickness measurements of cigarette paper, bank-notes, lead containers;
- mass unit area control of tarred felt, nickel foils on metallic substratum (Ni-Cd electrodes for batteries);

- void fraction measurements in two-phase flows;
- mud concentration measurements in pipes (management of dams, waste plants, rivers and wadis in spate), etc.

5. CONCLUSIONS

Information supplied by JANU has been validated by applications developed during the past 30 years. Its choices have always revealed most judicious and, in general, numerical results in good agreement with experiments. Thus, it has become an essential and reliable tool for gauge designers. By systematic research and routine calculations it has considerably unproved experts efficiency.

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PRESENT STATUS OF NCS IN FRANCE

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Abstract

About 3700 industrial plants are presently using nucleonic gauges for various aspects of production quality. The major industrial end users are oil and gas industry, coal and mineral ore processing, paper and plastic industries. New development in nucleonic instrumentation and processing software is going on.

1. SAFETY AND LEGAL CONSIDERATIONS

According to the French regulations, any industrial plant, or public or private laboratory which wants to hold and use radioisotopes, must obtain an a priori authorization by an inter-ministerial commission (CIREA).

The file must contain information concerning:

- pertinence of the use of radioactivity versus other non health hazardous techniques
- specifications of the sealed radioisotopic sources
- specifications of the equipment containing the sealed radioisotopic sources (sale authorization is necessary for each model)
- safe handling, operation and checking orders
- qualification of the personnel, at least, one “competent person in health physics” must be trained and certified in the plant or laboratory
- health physics instrumentation available
- identification of the approved control body, contracted for annual control (dose rate and non contamination measurements).

Moreover the dealer of a radioactive source must sign a commitment to take the source back and take care of its safe disposal, at the request of the end user and, in any case, after 10 years of use. A corpus of particular recommended conditions of use exists for different applications. ISO standards, when available are mandatory, both for the sources and for the equipment containing sources.

2. USERS

The publicly available statistics are the following (Ref.: CIREA — end 1995):

<u>TOTAL NUMBER OF USERS:</u>	4860
- INDUSTRY & RESEARCH (EXCLUDING MEDICINE)	3660
- MEDICINE & MEDICAL RESEARCH	1200

MAIN INDUSTRIAL USES:

	USERS	DEVICES
IRRADIATORS	50	160
GAMMA RADIOGRAPHY APPARATUS	260	930
LEVEL MONITORS	510	1600
DENSITY GAUGES	550	1600
THICKNESS & MASS PER UNIT AREA GAUGES	310	2350
MOISTURE GAUGES, & MOISTURE/DENSITY GAUGES	470	1020
ANALYSERS	330	440
ELECTRON CAPTURE GAS CHROMATOGRAPHS	550	1250
MISCELLANEOUS SEALED SOURCES		750
TRACERS & NON SEALED SOURCES	910	

Classically, the main industrial sectors using NCS are: petroleum & gas, chemistry, coal, raw mineral materials transformation, metallic ores prospecting & transformation, metals, paper, rubber & plastics. Similarity can be observed with data published by developed countries like Japan.

3. TRENDS

3.1 Competition

- Concerning ionising radiation based devices, severe competition exists with systems using X ray generators, specially for β particles or low energy gamma rays ($E < 200$ keV). This is due to:
 - improved technology of low power, high stability high voltage units and tubes,
 - higher photon flux output;
 - safety considerations (files much easier to fill in).
- Concerning non-ionising radiation based devices, competition with a larger palette of physical type of measurements; sonar, radar, ultra-sound, laser, infra-red, microwave, nuclear magnetic resonance, etc., all techniques which do not require safety files.

3.2 Remaining inherent advantages of NCS

NCS provide the following measurements:

- non-destructive, non intrusive, non contact, continuous, possible through vessels, pipes (metal, glass, plastics), and heat insulating or refractory materials;
- with rather high sensitivity (some 0.1% up to some%);
- stable;

- with the possibility of taking profit of various physical interactions between radiation and matter, like attenuation (electrons, photons, neutrons), mono-chromatic or
- di-chromatic, scattering, secondary radiation (XRF, (n,gamma), (gamma,n)).

3.3 Remaining favoured areas of NCS

- mass per unit area (or thickness), from bible paper up to high thickness steel sheet; density;
- level (one shot or continuous);
- analysis (XRF, specially for portable devices);
- gas chromatography (electron capture)

3.4 Some new trends

- Multi energy (gamma-photons) or multimode (photons + other ionising radiation): petroleum, foundry, accumulators, plastics.
- Imaging gauges, using array detectors (some discrete scintillators or array of about 1000 silicon photodiodes coupled with scintillator and COD), technology derived from bone density measurement devices or from scanning radiography.
- Multi phase flow density and/or flow rate measurement (using real time correlation)
- Sensors integrating 2 different physical principles, like β -attenuation and infra-red reflectometry, or laser and β -attenuation.
- High count rate nuclear electronics (some 10^6 pulses/s)
- Modelisation using simulation (radiation transport codes like MCNP)
- Simulation for the choice of the best practical arrangement source/object/detector (expert systems like JANU code)

4. ACTIVE INDUSTRIES AND R & D LABORATORIES

4.1. Industry

There are few French manufacturers of NCS:

- Environment SA
Monitors of dust particles concentration in air, by β -absorptiometry on fibre glass tissue filter.
- ex-NUCLEOMETRE, formerly manufacturer of thickness, density and level gauges, merged with FAG — FRIESEKE & HOEPFNER (Germany), now Division of THERMO ELECTRON (USA).

4.2. R & D Laboratories

CEA-SAR, SACLAY, 30 persons, industrial problems solving Laboratory, including small scale manufacturing and site implementation, technology transfer if existing market.

Main recent developments:

- On-line resin fraction and mass per length unit of preimpregnated composite fibres ribbons (boron, carbon, glass, kevlar) by beta backscattering.
- Imaging gauge by X ray or gamma absorptiometry, mono or dichromatic, scanning mode or tomographic mode. Applications: wood products, oil reservoirs rocks geological cores, lead batteries, loaded rubber, porous or sintered materials.
- On-line nickel based electrolytic material mass per unit area measurement, by beta absorptiometry; applications: electrical car batteries production.
- Analysis of uranium and plutonium in nuclear fuels reprocessing plants or MOX fuel pellets production plants (by gamma-X ray fluorescence).
- Control of neutron poison concentration in neutron absorbing materials: B or Cd in steel sheets, B in silicon rubber sheets, B in colemanite mortar structures, etc. (by neutron flux depression or neutron transmission).

BRGM (National geological survey) ORLEANS, was active in X ray fluorescence, (n,gamma), (n,n) analysers or logging tools for ores prospecting and treatment. No more production activity in this area.

LCPC (Civil engineering national laboratory), active in designing and manufacturing of gauges for site measurement in road, dam, harbour, airport construction (density, moisture gauges including on-board vehicles designed equipment).

IRSID (iron industry USINOR research laboratory) MAIZIERES LES METZ, active in development of on-line high temperature thickness gauges for steel sheets.

Central research laboratories of industrial groups like ELF, MICHELIN, PECHINEY do they one R & D on the subject, without any publication.

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THE PROGRESS AND TRENDS IN THE NUCLEONIC GAUGE TECHNOLOGY: EXPERIENCE AND CONTRIBUTION OF JAPAN

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Abstract

Most of major nucleonic gauges in Japan have already passed the period of saturation in number of use in big industries. On the other hand, however, small gauges with low activity sources are expected to increasingly diffuse into smaller industries. There have been so far more unique gauges and more interesting applications in small gauges using low activity sources, which are free from legal regulation. Still at present new applications with advanced technology are being developed using such small sources. Description is given on the current status of nucleonic gauges with emphasis on development of new techniques and applications.

1. INTRODUCTION

The current state of nucleonic gauges in Japan could not be explained without review of the historical background and also social, economical and industrial environments related to application of radioactivity and radiation.

Most of the Japanese have latent fear against radioactivity and radiation, which is often called a kind of allergy, originated from exposure to the atomic bombs in 1945. This tendency has been enhanced by environmental pollution problems caused by rapid economic growth in this half a century. According to such a social situation, governmental regulation or guidance on the use of radioactivity has been gradually strengthened.

In industrial field, major nucleonic gauges had been widespread obviously during the period of the high growth of Japanese economy in the past [1]. This spread was achieved mainly by big industries of both the gauge manufacturers and users. Afterwards, however, the production of a large number of nucleonic gauges stopped actually due to the saturation in big industrial users. The era of big industries is considered to have terminated at that time in the development and production except a few kinds of large-scale apparatus, for instance, big computed tomography systems. Instead, small companies including venture business are being expected to implement the development and production of small, but unique nucleonic gauges, which employ usually low radioactivity sources.

As another important point, Japanese industry at present is characterised by the manufacturing industry based on imported raw materials, because of no significant natural resources inside the country. For this reason, any appreciable development has not been made of the technology in that field until now.

2. STATISTICS OF MAJOR NUCLEONIC GAUGES

Figure 1 shows changes with the year in the number of users of radioisotopes and radiation generators, in the statistics annually published by the Japan Radioisotope Association. The total number of users in various fields and the number of industrial firms that is the largest field had both continued to increase similarly until very recent years.

In the field of industrial firms, users of about 90% are employing only gauges or apparatus with sealed radioactive sources in recent years. As clearly seen in Fig. 2, many kinds of nucleonic gauges with a few exceptions stopped to increase or turned to decrease at the middle of the 1970's [1]. The turning point in the growth curves was much earlier than the saturation period mentioned above with respect to the number of users in Fig. 1. This corresponds to the fact that the increase in the number of users in recent years is mainly due to small users employing only one or two particular equipment, probably gas chromatography apparatus with an electron capture detector. On the contrary, the majority of major gauges shown in Fig. 2 have been used in big users utilising a lot of nucleonic gauges at each site of factory, such as paper, steel and chemical industries.

It may be noteworthy that a recent increase in number of thickness gauges is due to that of the paper and pulp industry. On the other hand, the gas chromatography apparatus, which are also increasing in very recent years, are diffused into a variety of fields.

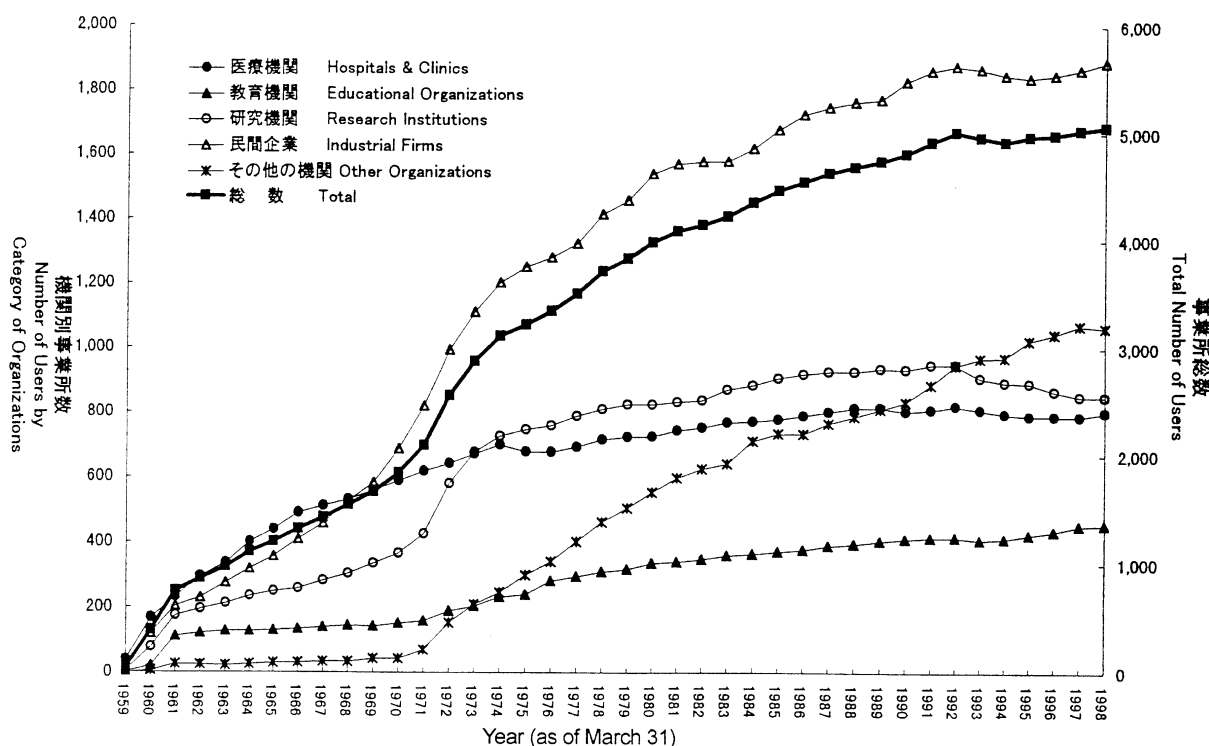


FIG. 1. Changes with the year in the number of users of radioisotopes and radiation generators (from "Statistics on the Use of Radiation in Japan" edited by the Science and Technology Agency).

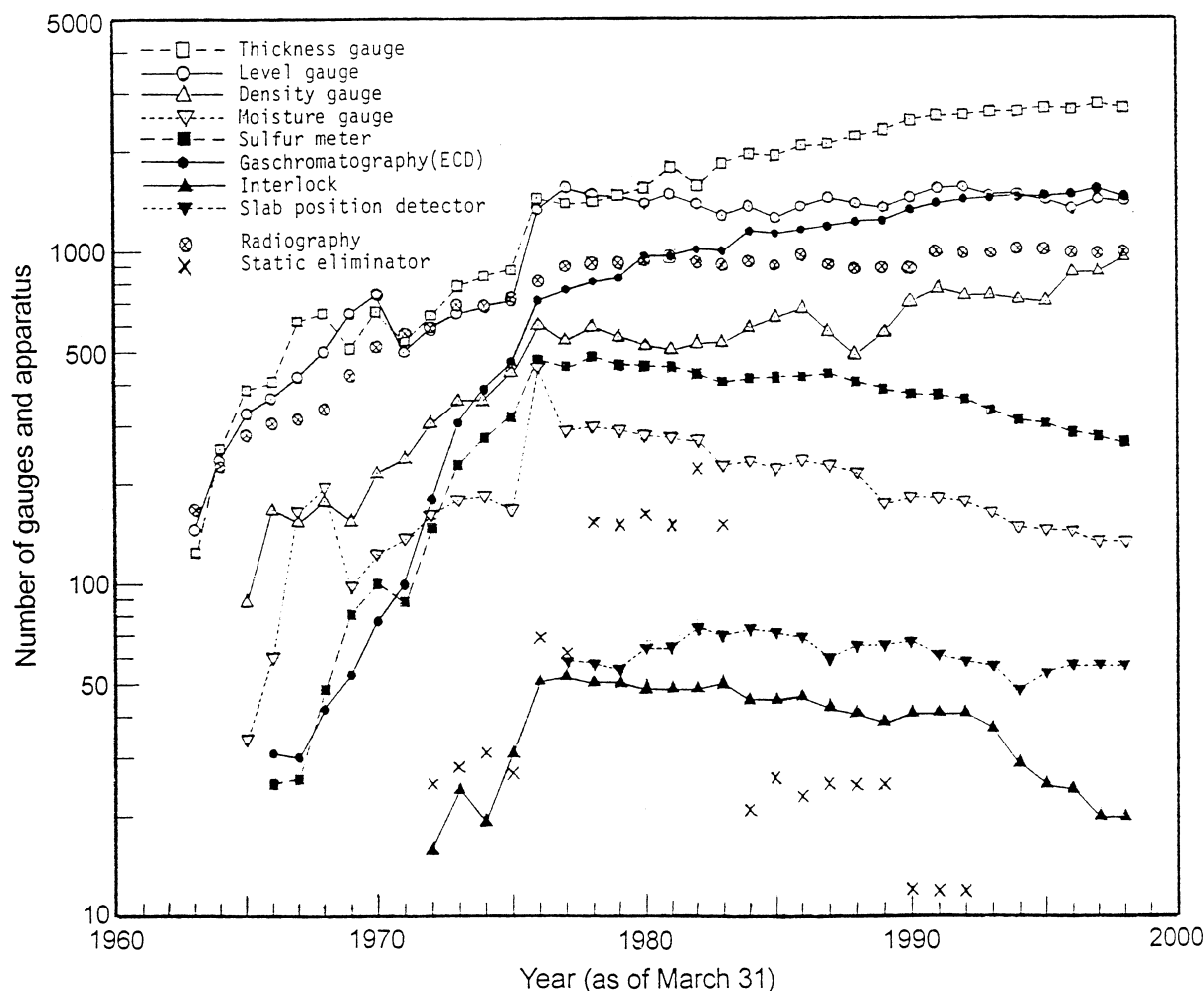


FIG. 2. Changes with the year in the number of radioisotope equipped gauges and apparatus in use in industrial firms except research institutions. (Same source as FIG. 1).

3. APPLICATIONS OF NUCLEONIC GAUGES WITH LOW ACTIVITY SOURCES

Nucleonic gauges with low radioactivity sources of 3.7 MBq or less, which are exempted from licensing legal regulation, have been promoting in many fields. The number of these gauges is not well known, because of lack of any official statistics based on the regulation.

3.1. Gauges Diffused on the Basis of Designation by the Authorities Concerned

Airborne dust monitors

Airborne dust monitors utilising a simple technique of β ray attenuation by deposited dust on a filter paper, as shown in Figs. 3 and 4, and Photo 1 and 2 [2] have been widely diffused for measuring the mass concentration of particles in air. In 1981, the Environment Agency of the Japanese Government had specified two methods in the notification for this measurement: one was this method and the other a non-nucleonic method (piezoelectric balance). Thereafter, the former prevailed much more than the latter, because of its suitability to automatic regular measurement due to almost troubleless operation and quick maintenance capability. Nearly 1800 sets of the nucleonic method are presently in routine use for continuous observation of

the air pollution at environmental air monitoring stations in all districts of Japan [3]. In these dust monitors, ^{147}Pm or ^{14}C β ray sources of less than 3.7 MBq are employed.

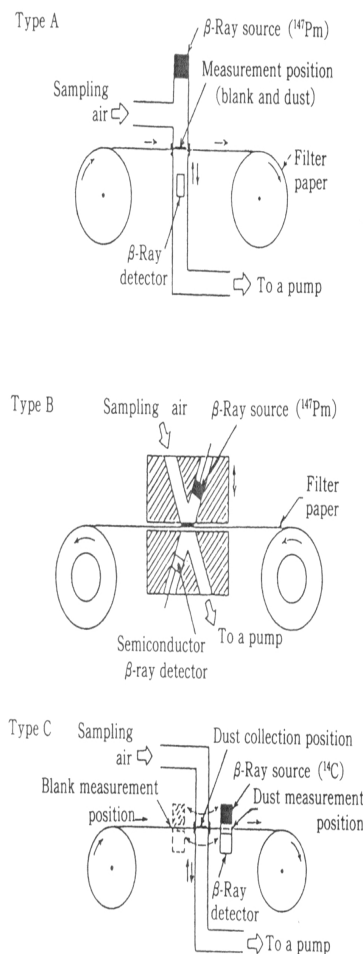


FIG. 3. Schematic drawings of airborne dust monitors. Types A and B: measurement is carried out while dust is being collected. Type C: Measurement is made before and after dust collection by moving a source detector set from the left to the right measurement position.

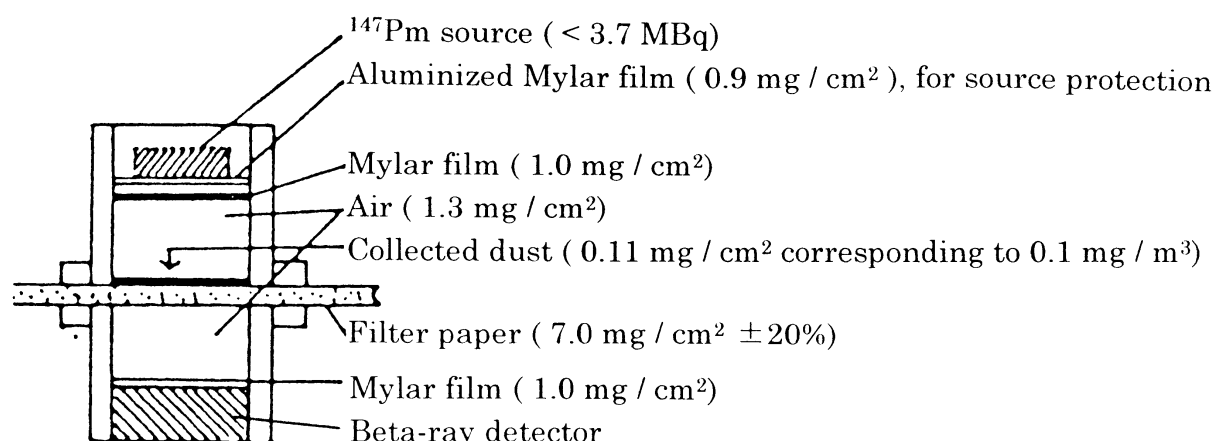


FIG. 4. A typical example of the measuring part of beta ray absorption in the airborne dust monitor.

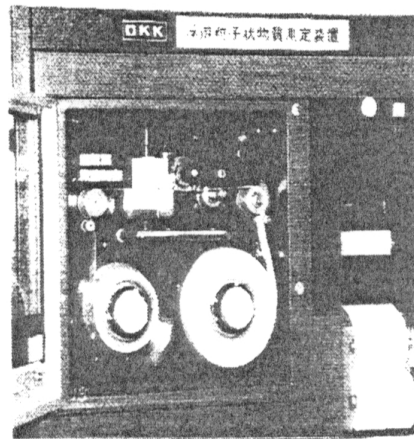


Photo. 1 Dust collection and measuring part.

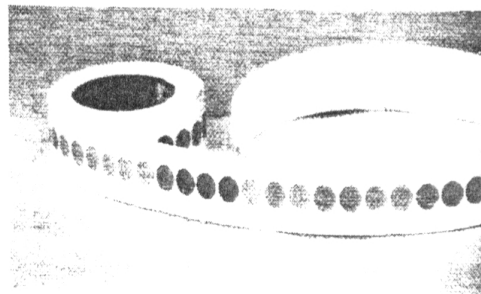


Photo. 2 Collected dust on a rolled filter paper.

Soil compaction gauges

A surface-type soil compaction gauge consisting of neutron moisture- and gamma ray density-gauges [4] has come to be widespread after the middle of the 1970's in the field of civil engineering. Although the basic conditions of the spread had been arranged by the society of that field for long years, an important factor in the success was the use of low activity sources of less than 3.7 MBq (^{252}Cf and ^{60}Co -) as well as the technical improvement by using the transmission measurement for both fast neutrons and gamma rays, as shown in Fig. 5. Thus, in 1985 the Japan Highway Public Corporation adopted the improved gauge as the only tool for measuring the degree of soil compaction of embankments in all the construction works. Later in 1996 the Ministry of Construction authorised the use of nucleonic compaction gauges including backscattering type also. At present nearly 1000 sets of the compaction gauges are estimated in possession by construction firms [4].

In other application of nucleonic compaction gauges, a new trial was made of a measuring robot which can move freely with wheels on the surface of land, using a backscattering geometry for both neutrons and gamma rays [5]. The same type gauge has been employed in the development of an automated pavement construction system [1, 6].

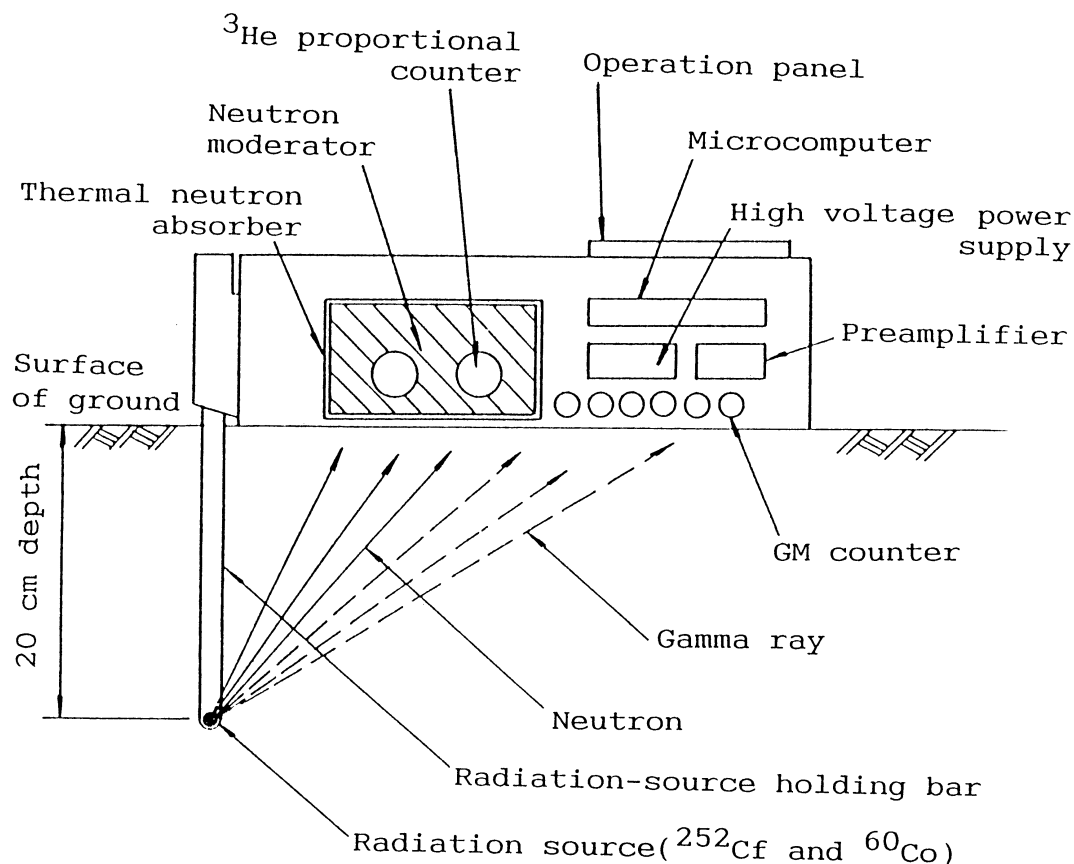


FIG. 5. Schematic drawing of a typical soil compaction gauge adopted by Japan Highway Public Corporation.

Portable level gauges

Portable level gauges utilising the attenuation of gamma rays from a weak source of less than 3.7 MBq (usually ^{137}Cs or ^{60}Co), such as shown in Fig. 6 and Photo 3, are widely used as convenient tools, for example, to inspect the content of fire extinguisher cylinders. For fire extinguishers installed in a ship, rapid inspection within a limited time of anchorage can surely be made only with this gauge [7]. Similar gauges are applied to routine inspection of the degree of valve opening in chemical plant [7], for instance, as is seen in Photo. 4 [8]. A total number of these kinds of gauges in use are estimated around 2000.

3.2 Unique techniques in the civil engineering and other industry

Neutron absorption tracer techniques

Instead of the use of radioactive or activable tracer in the civil engineering, Yamamoto and others developed a new tracer technique using a combination of boron compound and a neutron moisture gauge [9, 10]. The technique is based on the principle that the concentration of boron with a large absorption cross-section for thermal neutrons can be measured with the moisture gauge in water. Many kinds of applications have been made successfully [9, 10, 11, 17]. Among those, a certificate of the technique authorised by the Minister of Construction in 1984 was given to a single-well groundwater flow meter [10, 17], shown in Fig. 7 [11], measuring both the rate and direction of groundwater flow in a wide range. It is still now used

as a valuable tool that can measure a very slow groundwater flow, for example, in environmental assessment in advance of some public works [12]. A ^{252}Cf source below 3.7 MBq plays a great role also in this case.

Clark et al. in Australia proposed the application of a similar technique to an experimental coal hydrogenation plant [13]. On the basis of their proposition, actual applications are being carried out in test plants in Japan also, of which the scale is successively becoming larger under the national project [14]. Fig. 8 shows a schematic drawing of a coal liquefaction plant and a tracer experiment apparatus consisting of a gadolinium tracer injection part and a residence time measuring part by means of thermal neutron counting. A ^{252}Cf source more than 3.7 MBq is usually needed in this application.

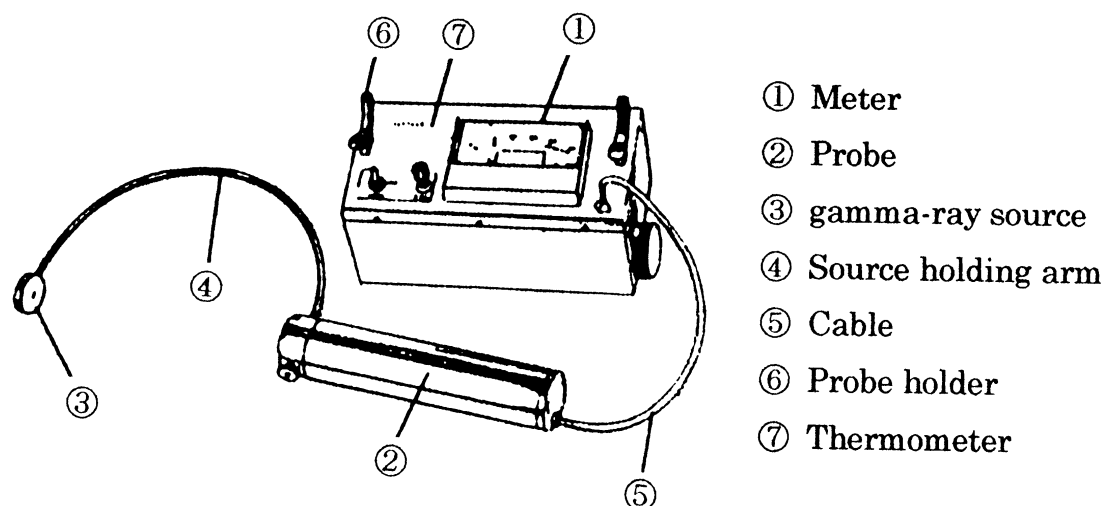


FIG. 6. A portable level guage.

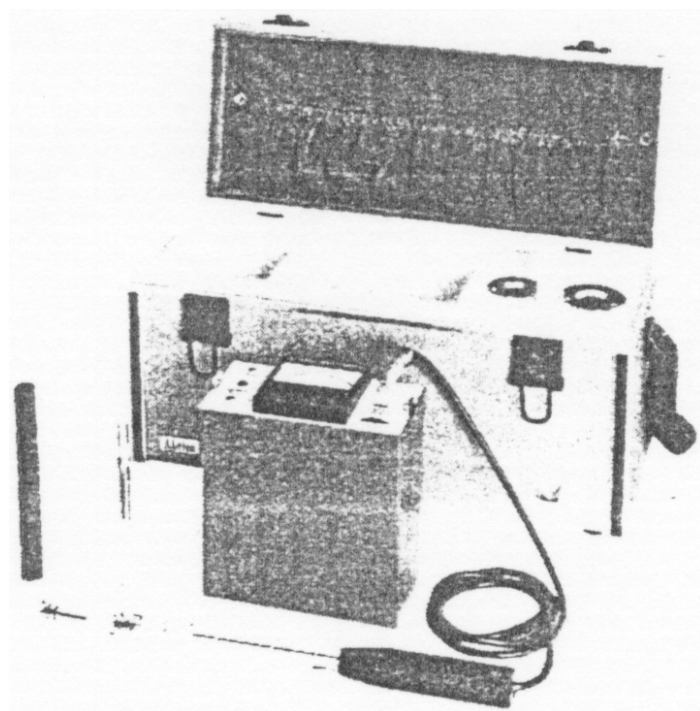


Photo 3. Another example of portable level gauge.

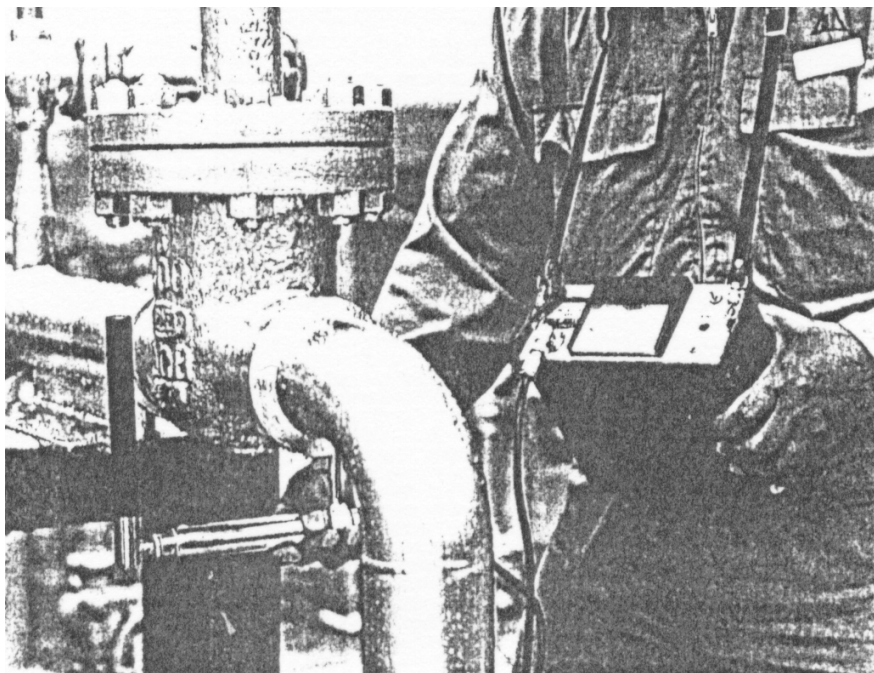


Photo 4. Inspection of valve opening degrees with a gauge similar to Photo 3.

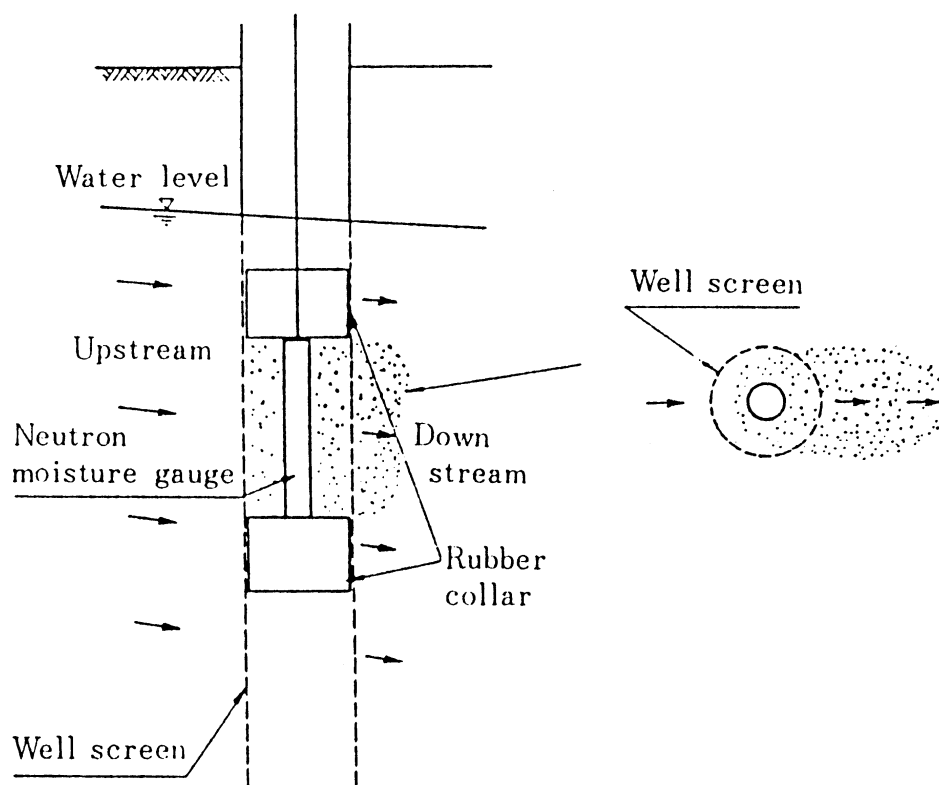


FIG. 7. Measurement of groundwater flow by the boron tracer technique.

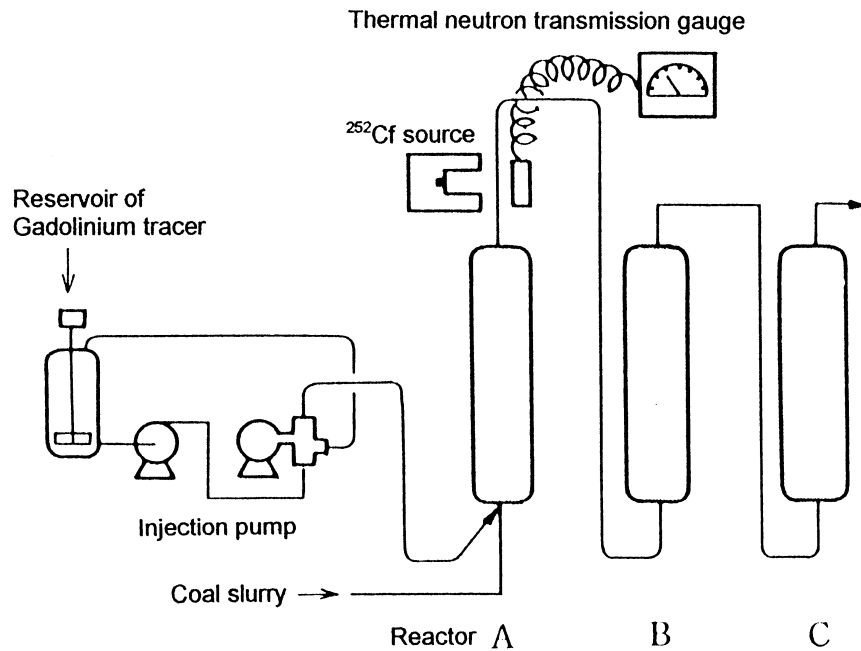


FIG. 8. Application of the neutron absorption tracer technique to a coal liquefaction test plant.

Gap meter for oil-storage tanks

Yamamoto et al. [15] developed a unique technique for surveying the foundation shape of oil-storage tanks. Since a number of oil storage tanks in Japan are placed on the soft ground near seashore, problems often occur for uneven sinking of the tank and repair of the foundation is made by material injection. Before and after the repair it is necessary to find any gap over the whole area of the bottom plate. The technique utilises back scattering of fast neutrons from a ^{252}Cf - source of less than 3.7 MBq, as shown in Fig. 9 [11, 15]. Measurement is made by putting the measuring apparatus at predetermined positions on the bottom successively, at the time when the tank is made empty for various kinds of inspections. ^3He counters covered with both a cadmium filter and moderator detect fast neutrons scattered from the foundation. The count corresponds to the distance between the bottom plate and the foundation, namely the gap. The other ^3He counters without cadmium filter measure the quantity of water or oil existing at the gap, correcting the gap measured. By combining this gap measurement with ordinary surveying of the height above the sea of each measuring point, the abnormality in shape of the foundation can be found, as shown in Fig. 10 [11]. The gap measuring technique has been applied to a large number of oil-storage tanks for more than 20 years, and the periodical measurement at the time of legal inspection is being continued up to now, for instance, in facilities of national petroleum reserves [16].

Surveying technique in tunnel construction with the shield driving method

A surveying technique using gamma ray source and detector has been recently developed to measure the amount of misalignment of the two shield tunnelling machines facing each other at a distance of less than 50 m [4, 17, 19]. Figure 11 [18] shows illustration of an example where the technique was successfully applied to construction of a tunnel road of about 5 km crossing undersea the Bay of Tokyo in 1996. A collimated gamma ray source of ^{60}Co less than 3.7 MBq was located at the top end of a boring rod which was horizontally inserted into ground from the left shield-driving machine. The position of the source was accurately

determined by measuring gamma ray intensity distribution on the inside wall of the right shield-driving machine. An axis deviation of 180 mm between the two tunnelling machines was observed in the first measurement at 50 m distance. Thereafter, adjusting in the driving direction resulted in a final deviation of only 5 mm [4, 17].

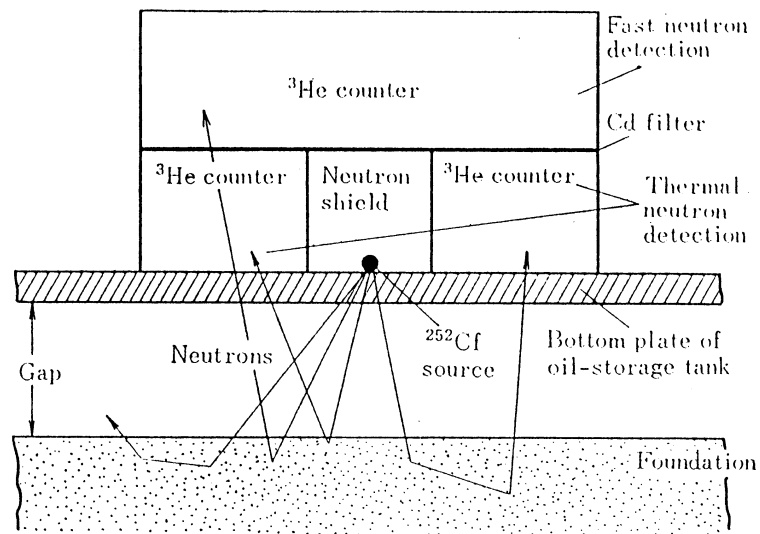


FIG. 9. Principle of measurement of the gap between the bottom plate and the foundation of an oil storage tank by neutron scattering.

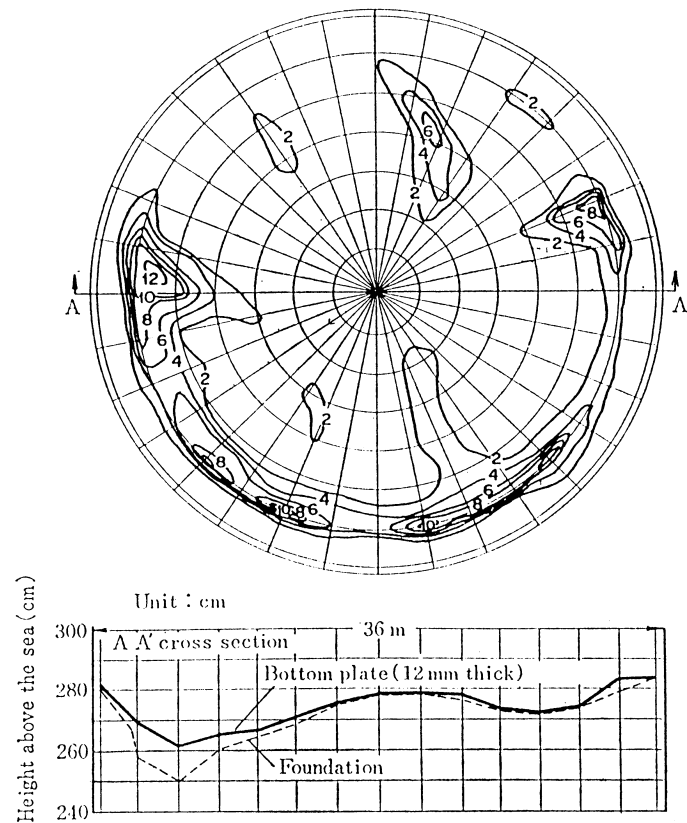


FIG. 10. Results of measurement of the gap (shown by contour in the upper figure) and the foundation shape (obtained from the gap and the level surveying, shown in the lower figure) in an oil storage tank showing remarkable depressions.

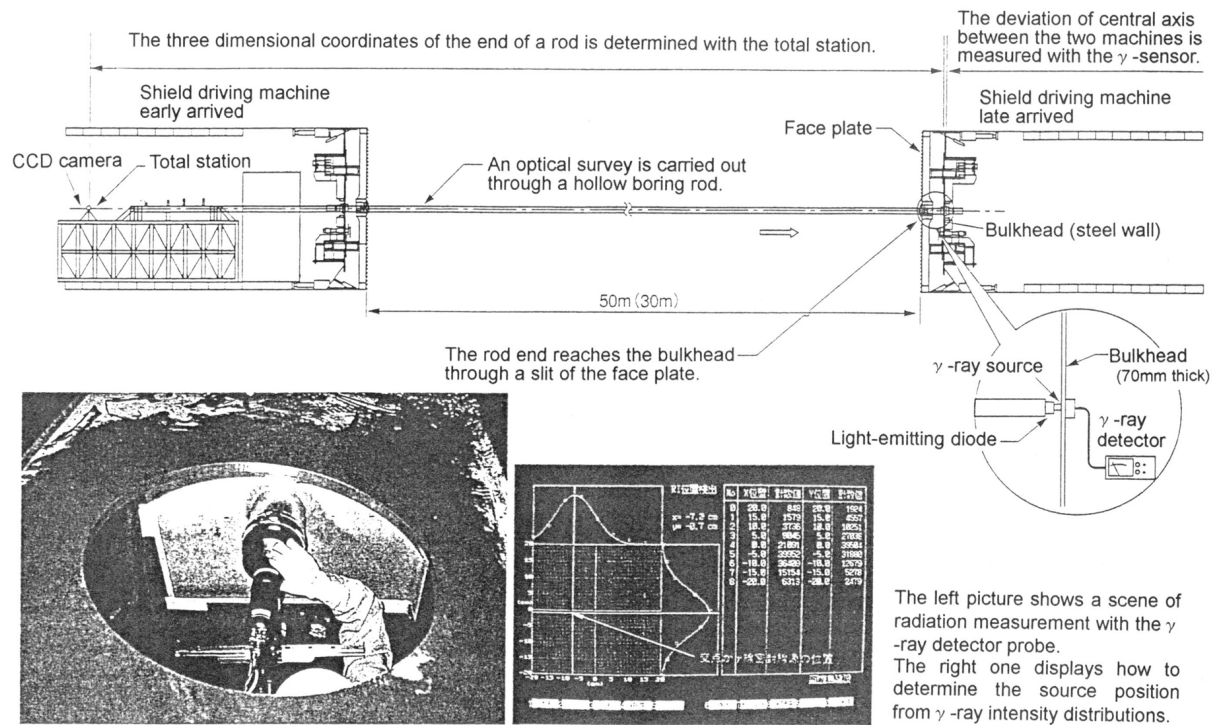


FIG. 11. Surveying with a weak gamma ray source for the position adjustment of two shield driving machines in tunnel construction.

4. NEW TECHNIQUES DEVELOPED AND UNDER DEVELOPMENT

4.1. Advanced Techniques for Measuring Multiple Variables with Simultaneous Use of Multi- Radiations or Multi- Detectors

Fast neutron and gamma ray transmission technique

A new technique by the simultaneous use of fast neutrons and gamma rays from ^{252}Cf was developed for measurement of coke moisture in iron works by Tominaga et al.[20] in cooperation of a research laboratory, an instrument manufacturer and its end user. The most remarkable features of the technique, which all were the first trial in nucleonic gauging, are:

- to use a combination of a single source and a single detector for dual radiation transmission of neutrons and gamma rays,
- to utilise gamma rays as well as neutrons from ^{252}Cf , without any additional gamma source,
- to adopt a high efficiency organic scintillation detector having the pulse shape discrimination properties for fast neutrons and gamma rays,
- to construct a highly stabilised electronic system including the pulse shape discriminator for separate counting of fast neutrons and gamma rays,
- to apply the dual radiation transmission technique to measurement of moisture and bulk density in coke falling down from a huge hopper onto a conveyor belt.

Figure 12 shows a schematic drawing of the system completed. The accuracy of moisture measurement in coke was improved several times compared with that of conventional neutron moisture gauges using scattering and thermalization. The four sets of this new moisture gauge are successfully in use at the Kimitsu Works of the Nippon Steel Corporation since 1982. For the next generation system, some improvement is now in progress employing advanced electronic techniques, etc.

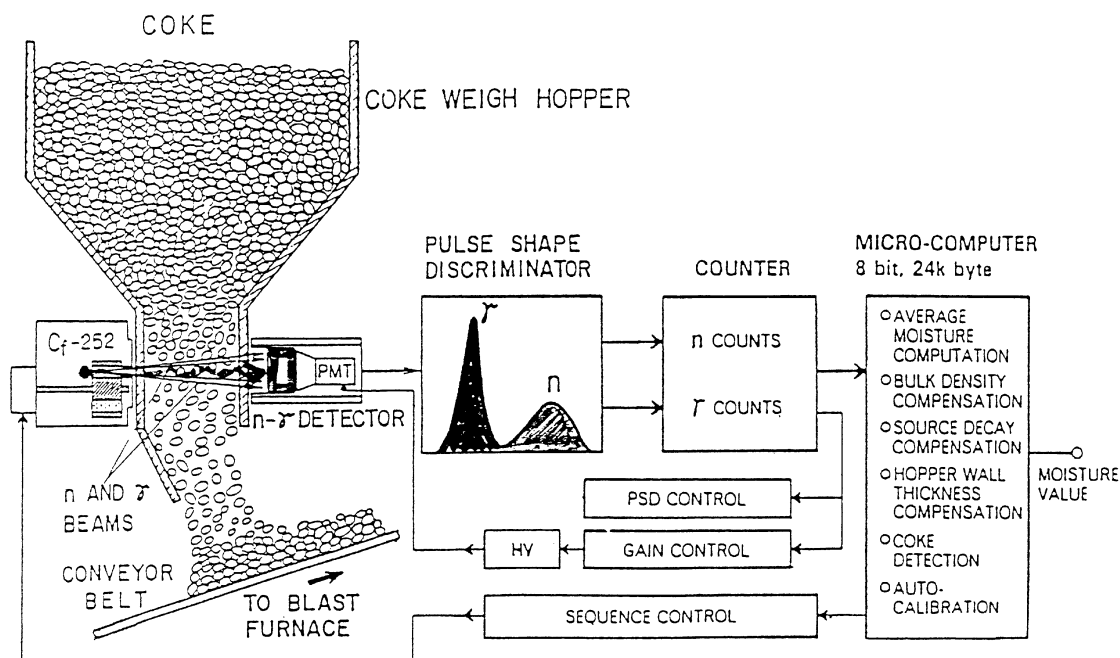


FIG. 12. High accuracy coke moisture gauge by the use of simultaneous transmission of fast neutrons and gamma rays with the aid of pulse shape discrimination technology.

This work which started at the end of the 1970's in Japan and was reported in the IAEA Conference in Grenoble (1981), and later published as a full paper [20], has attracted not a few scientists to develop various applications in several countries. The techniques of fast neutron and gamma ray transmission including some variations at present are expected to produce further new applications, in the name of "Neugat"[21] or "FNGT"[22].

Simultaneous use of neutron-capture gamma rays and scattered gamma rays

Shirakawa and Tominaga proposed a multi-function nucleonic gauge to meet the requirement for more precise and stable control of a blast furnace, by obtaining useful information on material flow and gas flow inside the furnace, as shown in Fig. 13. The proposed technique consisted of the spectrometric measurement of secondary gamma-radiation produced from materials in the furnace by radiation of ^{252}Cf [23]. Figures 14 and 15 show a sensor probe with a 3.7 MBq ^{252}Cf source and bismuth germanate (BGO) scintillator, and the spectra obtained in a laboratory experiment, respectively. The counts of neutron capture gamma rays of iron in a range of 6.5-8.5 MeV were well dependent on iron bulk density, and those of backscattered gamma rays in a lower energy region of 1.0-1.5 MeV showed a good correlation with apparent density of samples regardless of kinds of materials, as shown in Figs. 16 and 17, respectively [23]. The results suggest enough the possibility of measurement of inside conditions in a blast furnace. Similar techniques are considered to be effectively applicable also to many other objects.

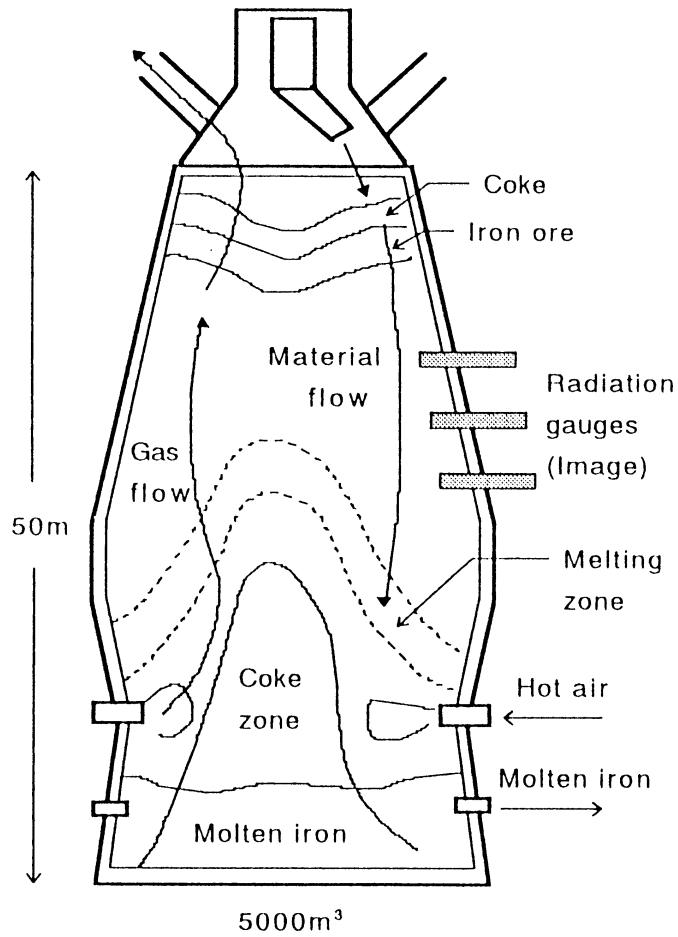


FIG. 13. General view of a blast furnace in the steel industry.

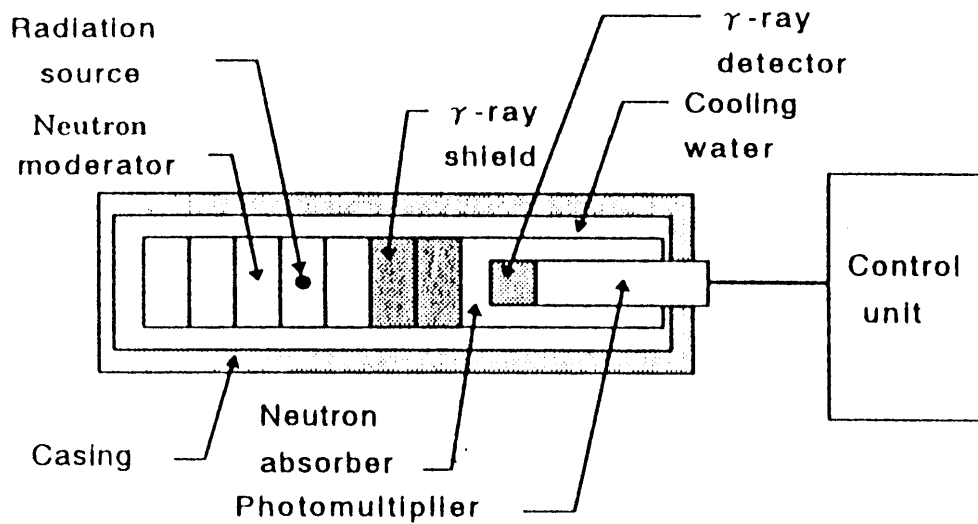


FIG. 14. Schematic drawing of a prototype sensor probe. Length: 530 mm, height: 190 mm, width: 105 mm.

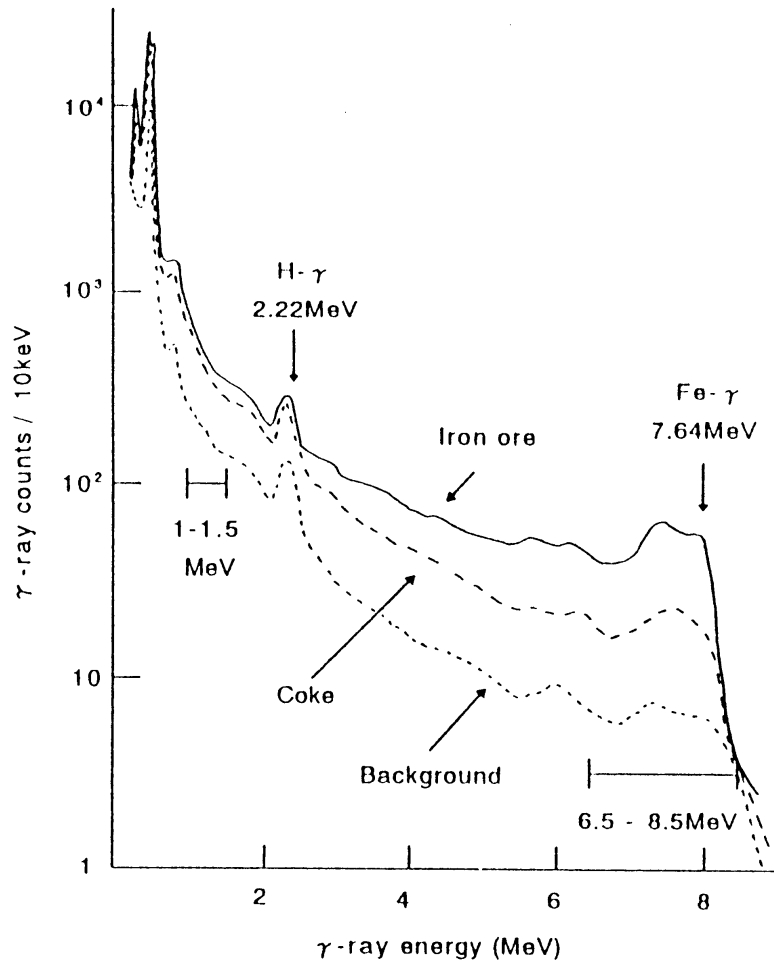


FIG. 15. γ ray pulse height spectra of iron ore and coke samples measured with a sensor probe containing a ^{252}Cf source and a BGO detector.

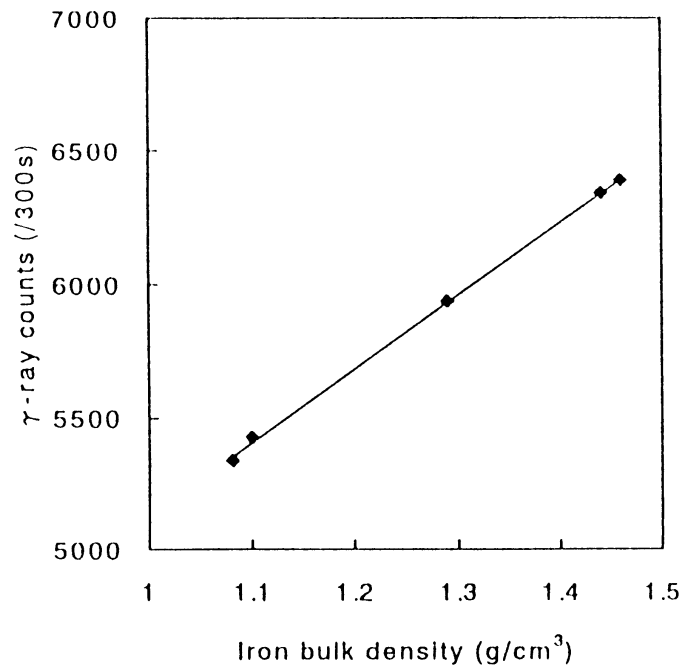


FIG. 16. Relation between iron bulk density and γ ray counts.

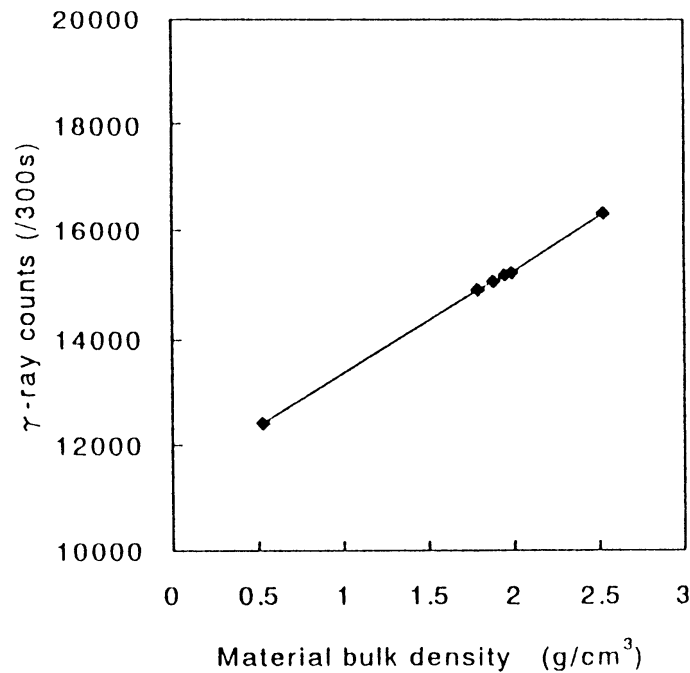


FIG. 17. Relation between material bulk density and γ ray counts.

On-stream density gauges for a sintering plant

To improve the yield of sintered ore in a sintering plant of iron works, Shirakawa et al. have developed two types of on-line density gauges, which are in routine use as shown in Fig. 18 [24]. Inserted probes [25] at the right hand of Fig. 18, which are rather conventional type using gamma ray backscattering, are used for measuring the apparent density change in the vertical direction of the raw materials immediately after loading on a conveyor from a hopper. On the other hand, a newly devised surface-type gauge [26], which is placed above the surface of raw materials and can move horizontally in the width direction of the conveyor, is employed to measure the distribution of bulk density at a surface region of the materials. The system of the new gauge, as shown in Fig. 19, is composed of a single gamma ray source of ^{137}Cs , a wolfram shield, and two bismuth germanate scintillation detectors arranged with different spacing from the source. By the use of this dual spacing technique the surface density can be measured in a sufficiently good accuracy with correction for variation of the distance between the gauge and the surface [1, 24, 26]. All of these density gauges are working with low activity ^{137}Cs sources of less than 3.7 MBq.

4.2 Challenges to difficult application with anti-conventional ideas

Description is given in this section some examples of nucleonic gauging, in which problems seemed very difficult to solve so far as conventional ideas were used, but could succeed in obtaining good results with a new idea on the opposite side to an ordinary concept.

Tominaga et al. have developed new types of high sensitivity hydrogen or moisture gauges in this several years. The basic concept common to these is to use a small sized, but appreciably large neutron moderator compared to the hydrogen content in a sample to be measured, coupled with a sufficiently big neutron reflector for the positive use of multiple reflection and efficient slowing down of neutrons [27]. The examples to which this technique were successfully applied are as follows:

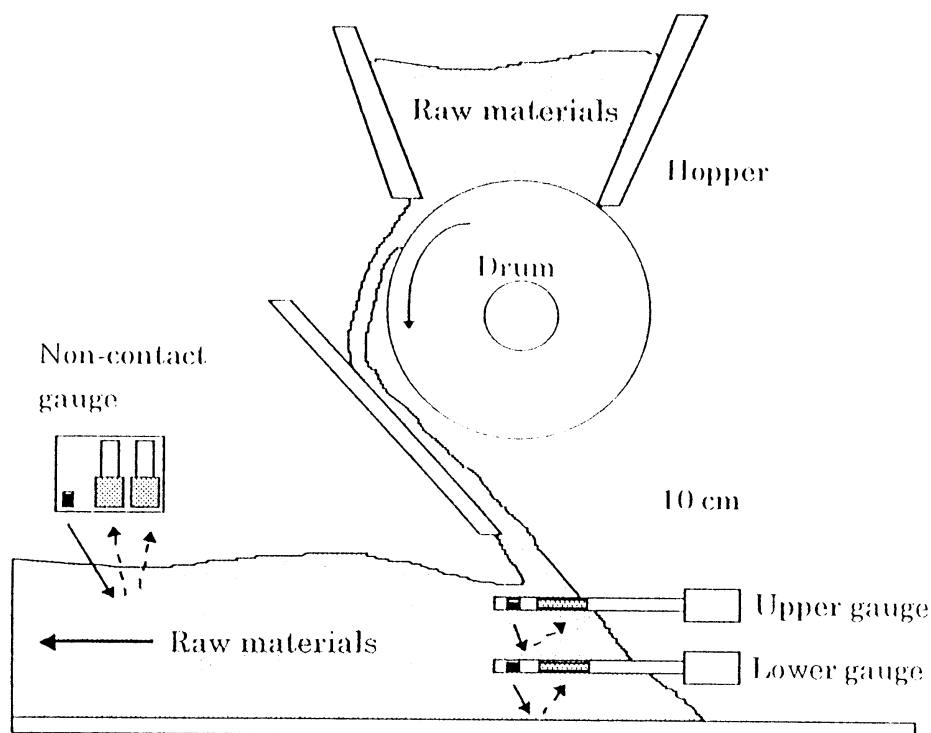


FIG. 18. On-line density gauges with low activity ^{137}Cs sources for control of density distribution at a sintering machine.

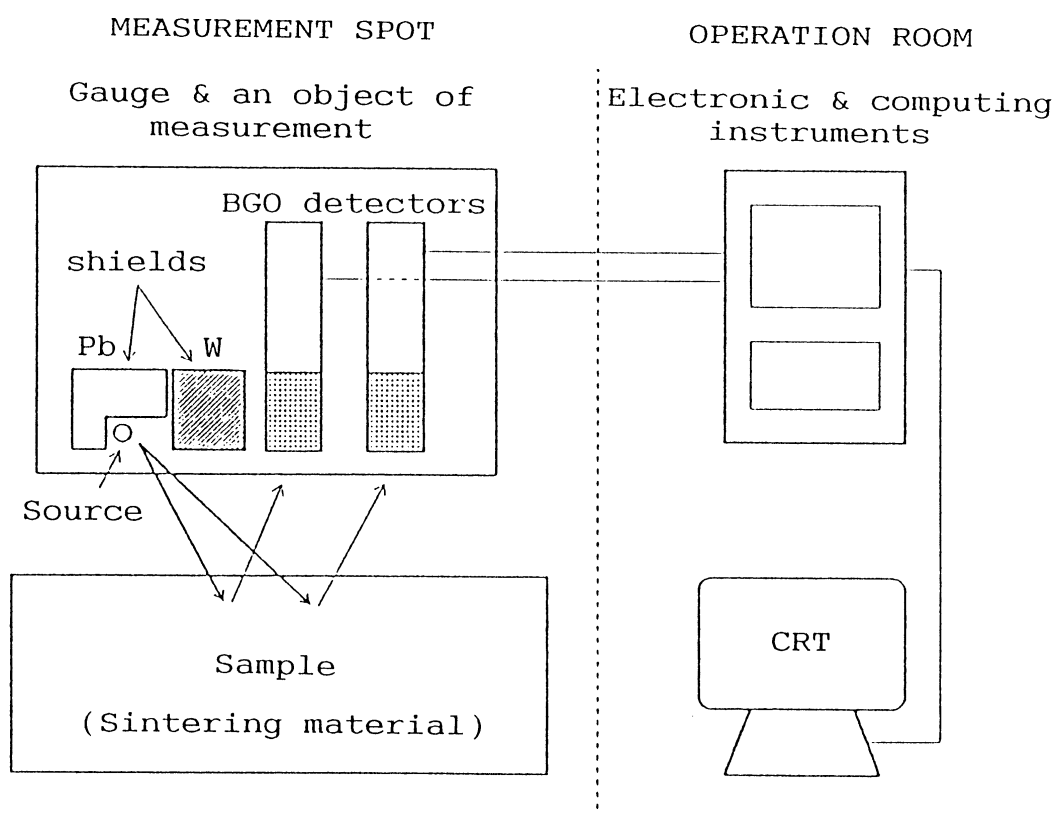


FIG. 19. Schematic diagram of the non-contact density gauge with dual source detector spacing shown in FIG. 18.

Thickness gauges for thin plastic layer sandwiched with steel plates

To measure the thickness of a thin plastic layer (30-200 μm) sandwiched with two plates of steel (0.3-32.1 mm each), a polyethylene moderator of 3 mm thickness, which was more than one order of magnitude over that of the sample plastic, was placed just close to the sample (cf. Fig. 20), resulting in a sensitivity increase of about 6 times the cases without any additional moderator. A precision of about 10 μm thickness has proved to be attained in a 1 minute measurement with a ^{252}Cf source of 40 MBq [1, 27].

High sensitivity hydrogen analysers for a trace amount of hydrogen

Because the determination of a trace amount of hydrogen in a small sample of metals or metallic oxides was a very similar case to the complex steel plate described above, the effect of an optimised polyethylene moderator (cf. Fig. 21) was clearly confirmed also in this application [27, 28]. A count increase of 0.30% per 1 mg hydrogen was recently observed in a small sample of 2 cm^3 : this means a sensitivity about 4 times higher than the best value reported by Close et al. of the Los Alamos Scientific Laboratory in 1976.

High sensitivity moisture gauges for monitoring a refractory drying process

A high sensitivity moisture gauge was requested for monitoring the decrease of residual moisture in wet refractory newly coated on the inner surface of a molten steel vessel, ladle, from its outside through a thick steel plate (32 mm thick), during the period of flame drying of the refractory. To respond to the request, a specially devised measuring probe was designed, based on experimental data, as shown in Fig. 22. Important points in this probe are 1) the distance between the source and detector, 2) the thickness of iron reflector, and 3) the size of graphite moderator. The moisture sensitivity obtained in the optimum design was about 6 times higher than that of conventional neutron moisture gauges. Figure 23 shows an example of actual measurement, which shows a typical change in the neutron count and temperature at a surface spot of a ladle [29].

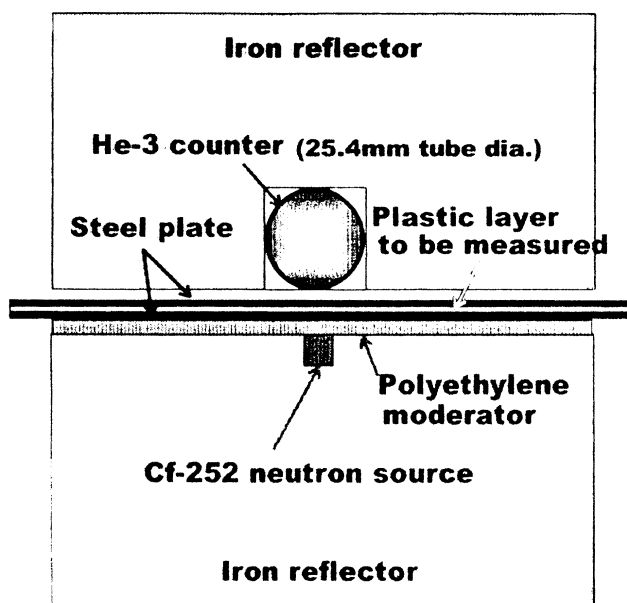


FIG. 20. Sensor head of a thickness gauge for measuring the thin plastic layer (30 ~ 200 μm) in complex steel plates (1 ~ 4 mm total thickness).

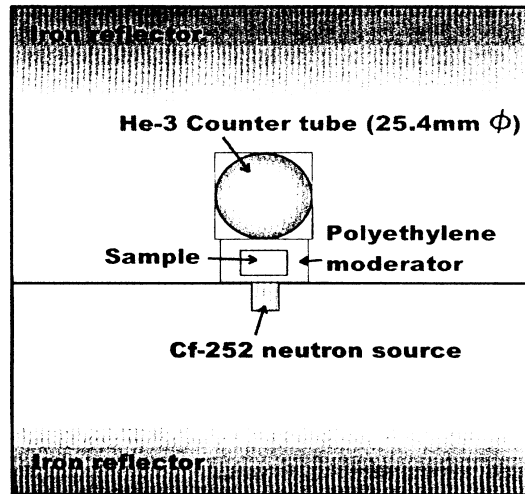


FIG. 21. A high sensitivity hydrogen analyzer for determining a trace amount of mg level hydrogen in small sized samples.

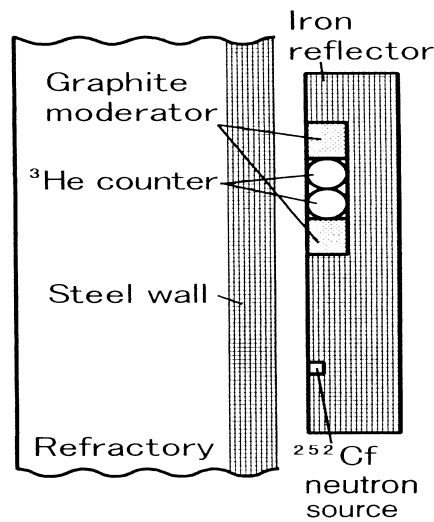


FIG. 22. A neutron gauge probe placed close on outer surface of a ladle for monitoring moisture change in relined ladle refractory under the flame drying process.

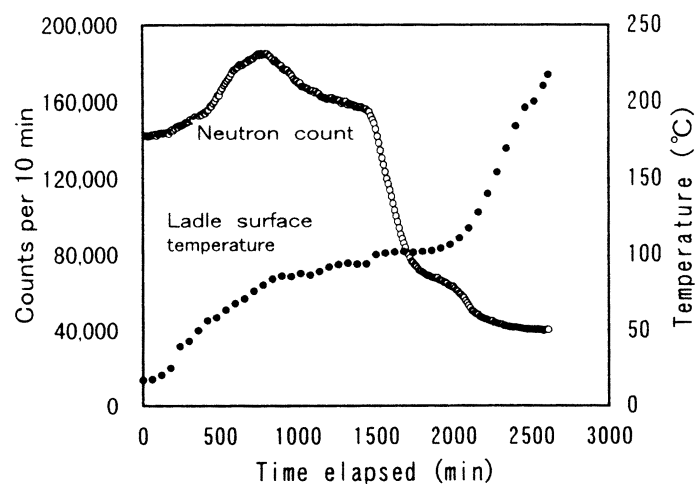


FIG. 23. An example of moisture change observed at a ladle surface spot: the count increase in the initial stage shows a movement of water from inner to outer side in ladle refractory.

4. CONCLUDING REMARKS

In developed countries, drastic changes in the number of nucleonic gauges and also in the technology can not be expected hereafter, because of the maturity in techniques and the saturation in uses, particularly in major gauges used by big industries. However, even if smaller number in diffusion, but advanced, refined, and/or sophisticated gauges are emerging still, along with the progress in many other fields of technology. A recent trend of the use of low activity radiation sources will also enlarge the new fields of application, including small industries in which nucleonic control systems have so far hardly diffused. These trends and new techniques of nucleonic gauges in developed countries must provide useful suggestions to developing countries concerning technology transfer and technical assistance. In this connection, one of the most important things never to be forgotten is to find out a really necessary point to be solved and to realise techniques just fitting to that.

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AN OIL/WATER/GAS COMPOSITION METER BASED ON MULTIPLE ENERGY GAMMA RAY ABSORPTION (MEGRA) MEASUREMENT

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Abstract

A class of multiphase flowmeters uses the principle of dual energy gamma ray absorption (DEGRA) composition measurement to determine the individual water, oil and gas fractions. Under homogenous flow conditions the ultimate uncertainty in phase fractions achievable with this technique depends strongly on the choice of component hardware. The meter presented in this paper uses unique components optimised for water, oil and gas fraction measurement, yielding theoretical uncertainties of 2% in the fractions over a 1 second measurement period. Generally composition meters are sensitive to changes in production water salinity, causing significant systematic errors in the fraction and watercut measurements. A new measurement concept based on multiple energy gamma ray absorption (MEGRA) which is insensitive to salinity variations is introduced. A multiphase flowmeter which employs the MEGRA concept does not require field calibration, a decisive advantage in subsea or marginal field developments.

1. INTRODUCTION

A multiphase flowmeter is a device, or a combination of devices, to measure the individual flow rates of water, oil and gas in a multiphase flow environment. The ultimate aim for multiphase flow meter technology is to replace the measurement function of the large, expensive, maintenance-intensive test separator. Multiphase metering should be considered as a means of providing measurements where conventional test separators would be either impractical or economically unattractive. The various measurement concepts used in multiphase meters have their specific areas of application; considerations such as flow rate, gas volume fractions (GVF), watercut (fraction of water in liquid phase), flow regime and the uncertainties achievable under all prevailing conditions must be carefully considered (Ref. 1). In addition, operational aspects (e.g., calibration, use of radioactive sources, ease of installation) and costs (both capital and operating expenditures) should be given careful thought.

Most multiphase flowmeters consist of a total fluid (water, oil and gas) flow rate measurement combined with a composition measurement (Figure 1). In homogeneous flow, these two measurements can be directly integrated resulting in individual water, oil and gas flow rates. In non-homogeneous flow, one needs either an advanced flow model, or some form of conditioning devices, such as a mixer or compact (in-line) separator upstream of the multiphase flowmeter.

Various types of multiphase composition meters are currently being developed. Most are based on either the measurement of electrical impedance or on gamma ray absorption. Use of gamma ray absorption has the advantage that it is able to cope with any oil-water ratio, in contrast to the impedance measurement. Also the non-intrusiveness of the method is an advantage.

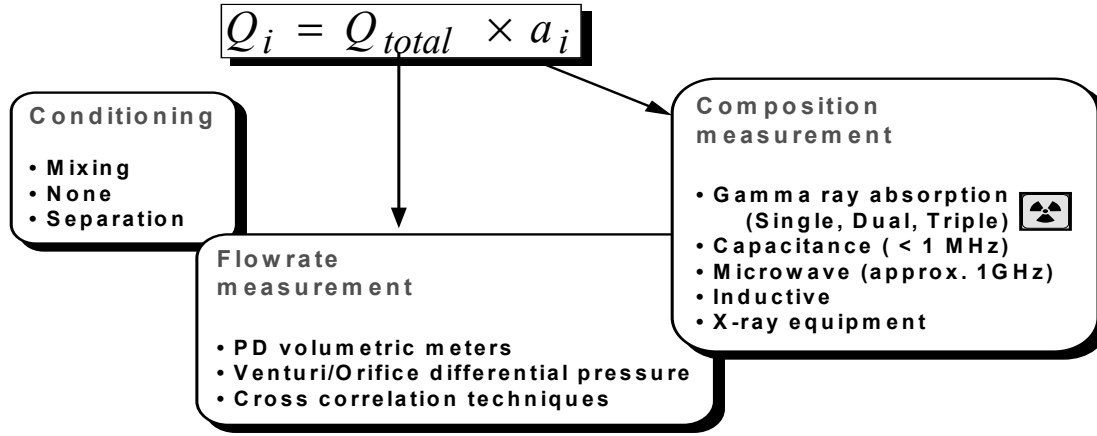


Fig. 1: Building blocks of a multiphase flowmetering system. At higher Gas Volume Fractions, conditioning devices are required to reduce velocity slip between the gas/liquid phase or to remove the bulk of the gas. Alternatively advanced flow models might be used.

2. COMPOSITION MEASUREMENT BASED ON DEGRA

As a further introduction, the basics of the dual energy gamma ray absorption (DEGRA) measurement are explained here. The principle is based on the absorption of a narrow beam of gamma- or X rays of energies e_1 and e_2 . In a pipe, with inner diameter d , containing a water, oil and gas mixture with fractions α_w , α_o , α_g , the measured count rate $I_m(e)$ is :

$$I_m(e) = I_v(e) \cdot \exp\left[-\sum_{i=1}^3 \alpha_i \cdot \mu_i(e) \cdot d\right] \dots\dots\dots (1)$$

$I_v(e)$ is the count rate when the pipe is evacuated and μ_i represents the linear absorption coefficients for the water, oil and gas phases. For two energy levels, e_1 and e_2 , provided the linear absorption coefficients between water, oil and gas are sufficiently different, two independent equations are obtained. A third equation comes from the fact that the sum of the three fractions in a closed conduit should equal 1. A full set of linear equations is given below. R_w , R_o , R_g and R_m now represents the natural logarithm of the count rates for water, oil, gas and the mixture, respectively, at energies e_1 and e_2 .

The elements in the matrix are determined in a calibration process by filling the instrument with 100% water, 100% oil and 100% gas (air). Together with the measured count rates at the two energy levels from a multiphase mixture it is then possible to calculate the unknown phase fractions (**Figure 2**).

$$\begin{bmatrix} R_w(e_1) & R_o(e_1) & R_g(e_1) \\ R_w(e_2) & R_o(e_2) & R_g(e_2) \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \alpha_w \\ \alpha_o \\ \alpha_g \end{bmatrix} = \begin{bmatrix} R_m(e_1) \\ R_m(e_2) \\ 1 \end{bmatrix} \dots\dots\dots (2)$$

In **Figure 3**, the above is graphically presented with the logarithm of the count rates of the two energy levels plotted along the axis. The corners of the triangle are the water, oil and gas calibrations, and any point inside this triangle represents a particular composition of water, oil and gas. Combining the composition measurement with a conventional venturi measurement (**Figure 4**) results in a complete three phase flow measurement for homogeneous flow regimes.

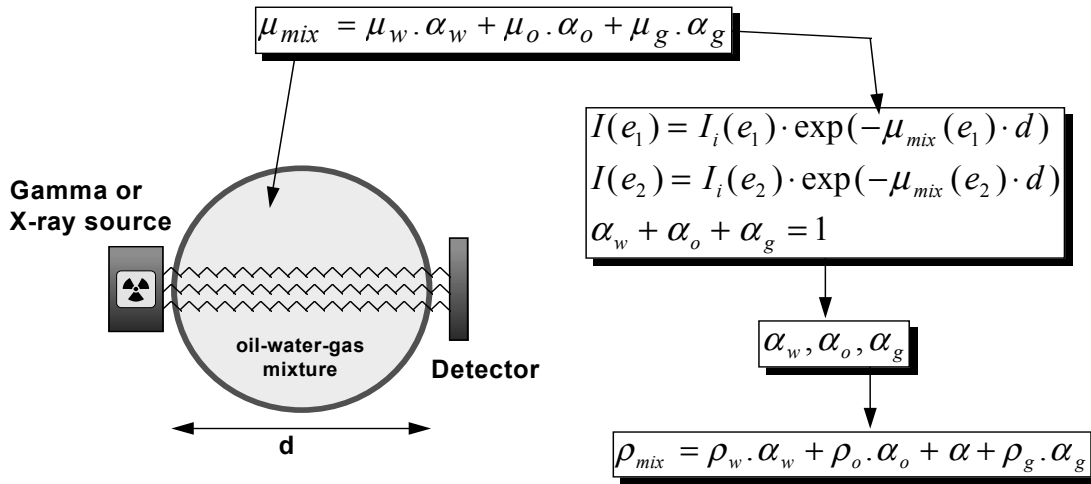


Fig. 2: Principle of the Dual Energy Gamma Ray Absorption (DEGRA) technique.

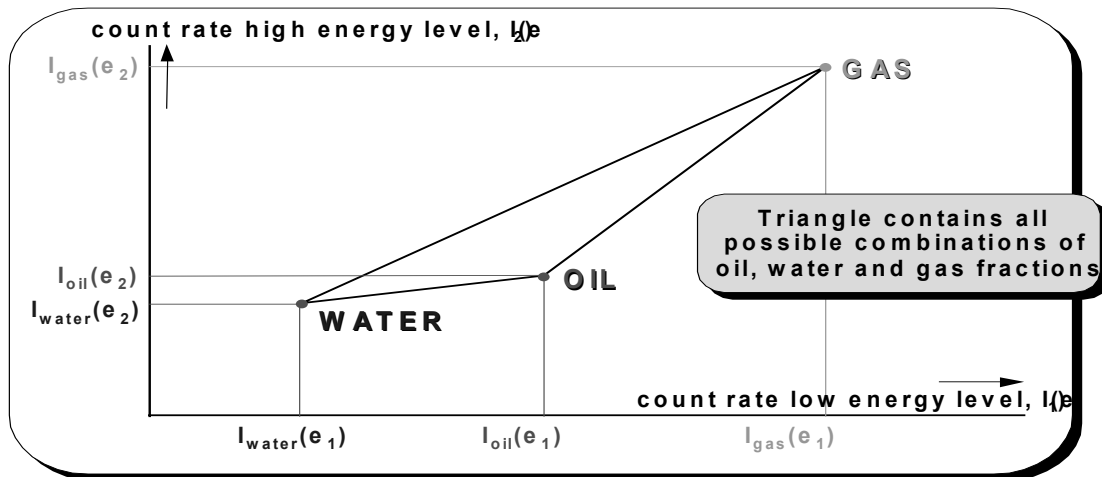


Fig. 3: Graphical presentation of the DEGRA concept. The corner points of the triangle are the water, oil and gas calibration points.

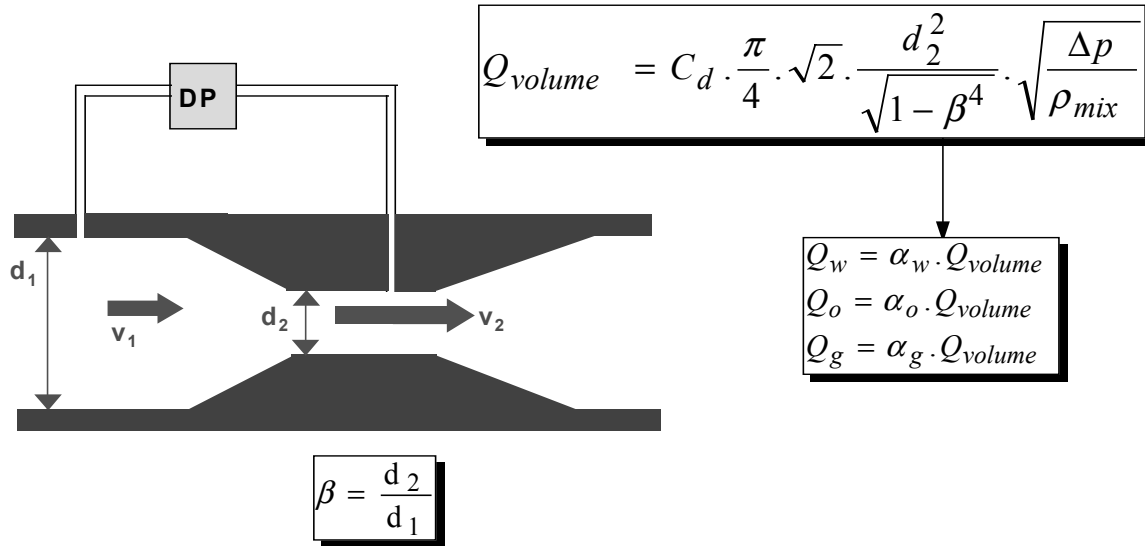


Fig. 4: Venturi application in multiphase flow measurement. Density ρ_{mix} and the fractions α_i are measured with the gamma ray absorption technique.

3. HARDWARE SELECTION AND DESIGN

Three important considerations must be addressed in the selection of hardware. These are the available energy levels (i.e. selection of radioactive source), the detection system (e.g. scintillation counters, solid state detectors, etc.), and a suitable pressure barrier (window) material.

3.1. Energy selection

The emission and absorption of g- and X rays are statistical processes, described by a Poisson distribution, therefore the measured count rate has an inherent uncertainty. For single energy g- or X ray absorption techniques, the following criterion is generally accepted (see Ref. 2).

$$\mu \cdot d = \left(\frac{\mu}{\rho} \right) \cdot \rho \cdot d = 2 \quad \dots\dots\dots (3)$$

Here μ is the linear absorption coefficient and $[\mu/\rho]$ is the mass absorption coefficient. Note that μ is temperature and pressure dependent, while $[\mu/\rho]$ is independent of both. For a dual energy γ - and X ray absorption technique the criteria for the selection of the two energies and their relative intensities have also been developed. In Ref. 3 it is demonstrated that the selection of the low energy level has a large influence on the uncertainty of the phase fraction measurement. Similar to Eq. 3, the uncertainty depends on the fluid parameters and pipe diameter. For a water, oil and gas system, the low energy level should preferably be in the range of 10-30 keV. The selection of the high energy level is not so critical, provided it is higher than 40-50 keV. Based on the above, Americium-241 (Am-241) with emissions at 13.9, 17.8, 21.5, 26.3, and 59.5 keV is a suitable source. These energy selection criteria will not be much different for the MEGRA measurement, to be introduced below.

The main disadvantages of Am-241 is that it is an alpha emitter, and has a relatively long half-life. Alternatives to Am-241 are being considered. In **Figure 5**, an example of an Am-241 spectrum measured with a Si solid state detector is presented.

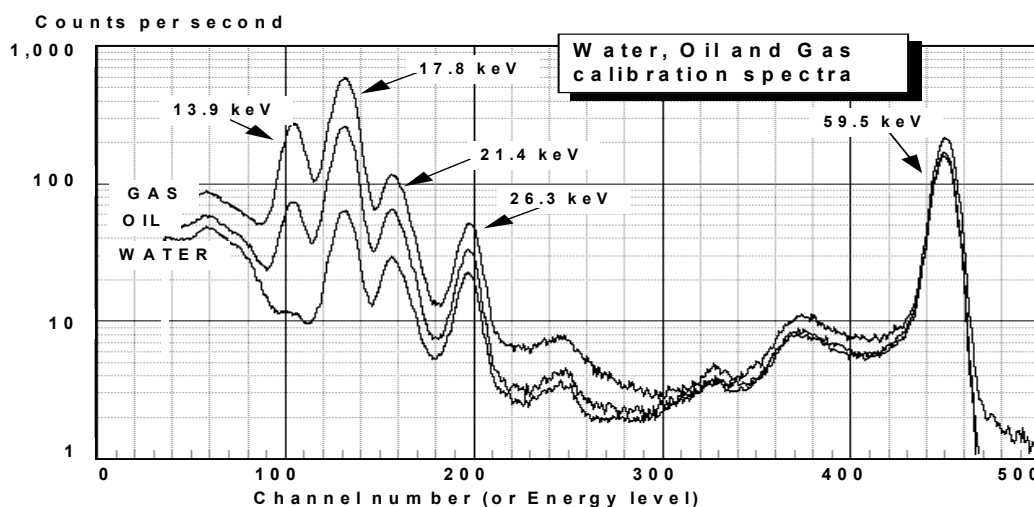


Fig. 5: Water, oil and gas calibration spectra from a 6.475 GBq (175 mCi) Am-241 source as measured with a 14 mm² Si solid state detector cooled to 5°C.

3.2. Window material

Applying low-energy gamma rays in this manner calls for strong, radiation-transparent wall material. Metal pipes are not suitable. Carbon fibre's are known to be extremely strong and are transparent to low-energy gamma rays. Held in place by an epoxy matrix, Carbon Fibre Reinforced Epoxy (CFRE) is thus an attractive window material. With an effective tensile strength of approximately 1800 to 2000 MPa, it is 4 to 5 times stronger than steel. A CFRE cylinder with an internal diameter of 44 mm and a wall thickness of 2 mm was placed in a steel housing for pressure testing. The steel housing also contained two holes (15 mm diameter) required for gamma ray transmission. This combination was pressure tested successfully up to 120 MPa (1200 bar). In the prototype composition meters, CFRE has been used as window material.

3.3. Detector selection

Two important characteristics were considered in the detector selection process :

3.3.1. Resolution

The resolution of semiconductor diodes used as solid state gamma ray detectors is much better than that of the more commonly used sodium iodide (NaI) scintillation detectors or of gas filled detectors. As an example, for a Silicon (Si) solid state detector which operates at a temperature of around 5 °C, the resolution can be on the order of 1.5-2 keV for the low energy region (14-26 keV). Detector resolution also depends on the detector area, i.e. a small area detector has a better resolution than a large area detector. Considering the Am-241 energy spectrum, with the 4 energy peaks in the 14-26 keV region and the relatively large

difference in μ in that region, a high resolution detector is required for adequate peak separation. For the fully separated energy level of 59.5 keV, the resolution is less critical.

3.3.2. Efficiency

The efficiency of NaI scintillation crystals, almost 100% for the lower gamma energy levels, is significantly better than that of Si solid state detectors, since in the latter, interactions between the photons and the detector take place in the very thin barrier (300 μm -1 mm) between the n- and the p-regions of the semiconductor. As an example, for a Si detector the efficiency is approximately 40% for the 18 keV energy level and on the order of only a few percent at 59.5 keV. In particular for the 59.5 keV peak, larger area detectors are needed to compensate for the poor efficiency and to obtain sufficiently high count rates.

3.4. Dual area solid state detector

The above considerations on resolution and efficiency resulted in the design of a “dual-area” solid state detector, consisting of one 14 mm² and one 100 mm² detector combined on a single chip. The small area detector, having a resolution of 1.7 keV, is used for the low gamma energy levels (14-26 keV). The large area detector, having a resolution of approximately 5 keV, is used for the higher gamma energy level (59.5 keV). These resolutions are for a detector temperature of 5°C, which is achieved by means of a Peltier cooling element directly attached to the detector. The total power consumption required to achieve this temperature, with an ambient temperature of 40°C and fluid temperature of 60°C, is approximately 1 watt.

The gas spectra of the two detectors with the relevant count rates for the five energy levels of Am-241 are presented in **Figure 6**. A drawback of the 100 mm² high-energy detector is that it contains a significant number of irrelevant low-energy counts. This has a negative impact on the “deadtime” of the counting electronics. By using a 100 μm -thick copper foil as a filter, this low energy radiation is almost completely absorbed with a only small effect on the 59.5 keV count rate. **Figure 7** presents a sketch of the combined 14/100 mm² detector, including the 100 μm thick copper filter and the Peltier cooling element. **Figure 8** shows the gas spectra of the 14 and 100 mm² detectors with the copper filter; the relevant count rates for the 5 energy levels are also presented. Thus, a solid state detector with both sufficient resolution for the low energies and sufficient efficiency for the high energy has been obtained.

3.5. Accuracy considerations

The uncertainty in the calculation of phase fractions is due to the statistical behaviour of the radioactive decay. It can be demonstrated that the absolute uncertainty in the oil fraction, when compared with those of water and gas, is always largest (Ref. 3). It is also obvious that the maximum absolute uncertainty in oil fraction occurs with the lowest count rate, e.g. with 100% water. In **Figure 9** this maximum absolute uncertainty in oil fraction is indicated as a function of the salinity and the fluid path over which the absorption takes place. The graph is valid for a specific configuration, i.e. a 6,475 MBq (175 mCi) Am-241 source, the 14/100 mm² dual-area Si solid state detector of 300 μm thickness, 2 mm CFRE wall thickness and a relatively short counting time of only 1 second.

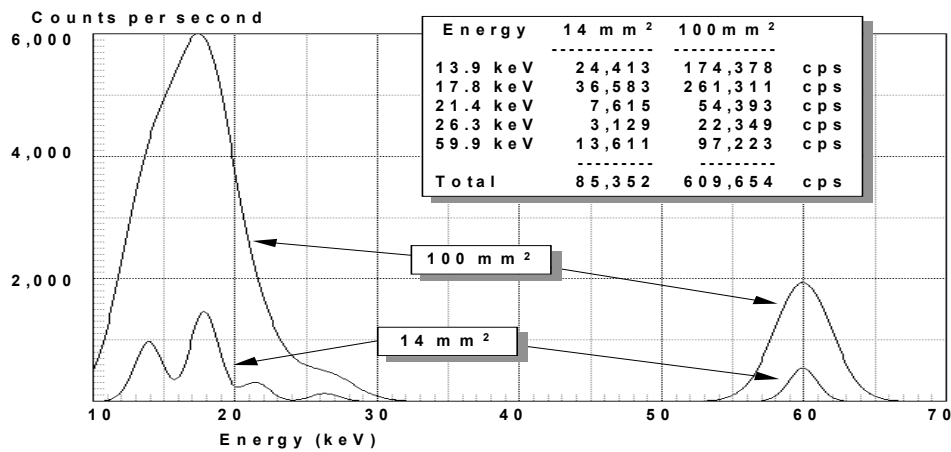


Fig. 6: Gas spectra from two separate Si solid state detectors. The 14 mm² detector provides acceptable resolution and efficiency for the 14-26 keV energy levels. The 100 mm² is used to compensate for the poor efficiency at 59.5 keV.

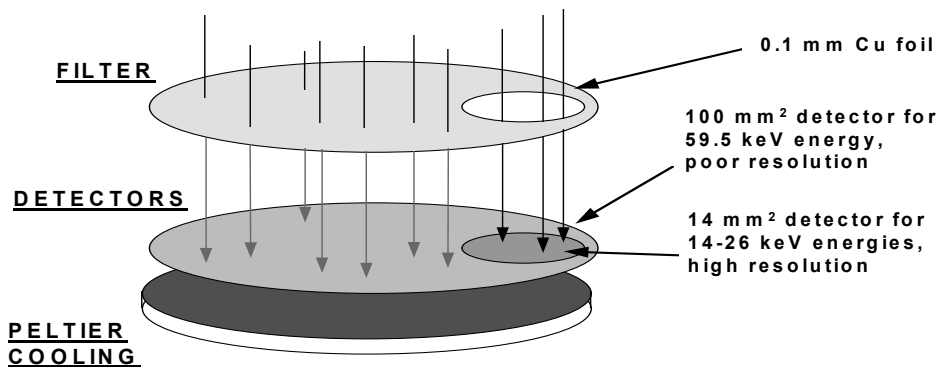


Fig. 7: The "dual area Si solid state" detector. The 100 μ m copper foil filters out the low energy gamma rays before they reach the 100 mm² detector. This large detector, having poor resolution, is dedicated to counting the 59.5 keV events.

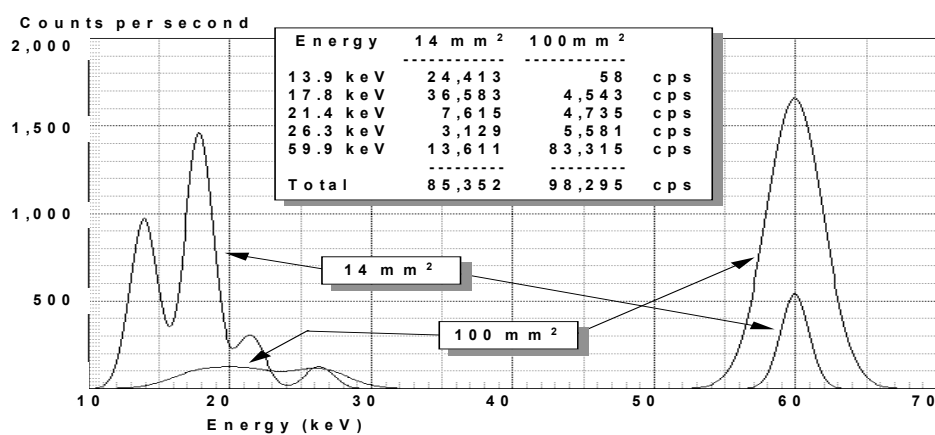


Fig. 8: Gas spectra from the "dual area solid state" detector and the 100 mm copper filter. Low energy count rates on the 100 mm² detector have been reduced significantly with this filter.

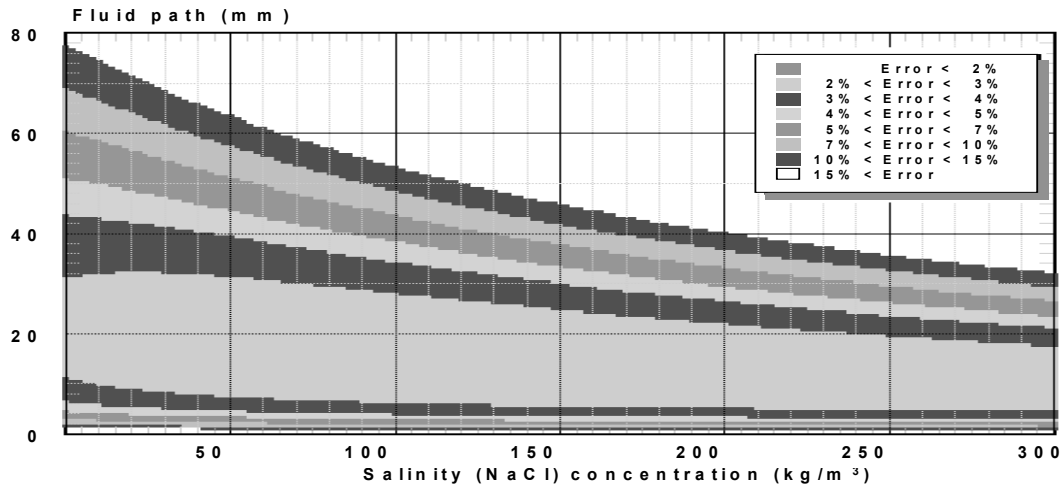


Fig. 9: Uncertainty in the fraction calculation as a function of salinity and fluid path length. The plot is valid for a 6,475 MBq (175 mCi) Am-241 source, two 2 mm Carbon Fibre Reinforced Epoxy windows, and the 14/100 mm² "dual area solid state" detector shown in Fig. 7. Above plot for 100% water is a worst case situation (lowest count rate).

The fraction uncertainty is large for a small fluid path length, as there is insufficient contrast in the absorption between the oil and the water phases, but decreases as the fluid path is extended. However, beyond a certain fluid path the uncertainty again increases because increased absorption results in count rates which are too low. The salinity also has an effect on the optimum fluid path, since with increasing salinity the optimum fluid path is reduced. For a fluid path of 15-20 mm the uncertainty in the phase fractions is not greatly influenced by salinity, hence accurate fraction measurements can be made over the full range of 0-300 kg/m³ salt (NaCl) concentration.

3.6. Concentric Venturi

The DEGRA composition meter can be used as stand-alone device only or can be integrated with any total fluid meter (e.g. a venturi plus differential pressure device) to make up a full multiphase flowmeter. With a venturi applied to homogeneous flow, the total fluid volume flow rate (Q_{tot}) can be calculated if the differential pressure (Δp) over the venturi and density of the multiphase fluid mixture (ρ_m) are known.

$$Q_{tot} = C \cdot \sqrt{\frac{\Delta p}{\rho_m}} \dots\dots\dots (4)$$

C is a geometrical constant multiplied by the discharge coefficient. Using the measured phase fractions α_w , α_o , and α_g , the base densities ρ_w , ρ_o , and ρ_g , and the measured temperature and pressure, one can calculate the actual density of the multiphase fluid mixture, ρ_m . Subsequently, the actual total fluid volume flow rate can be calculated, and with α_w , α_o , and α_g the individual water, oil and gas actual volume flow rates can be determined.

For flow rates on the order of 100 to several 1000 m³/day, a venturi throat diameter (fluid path length) of 15-20 mm is highly impractical because of the large pressure drop. However, with the introduction of a concentric venturi it is possible to achieve a fluid absorption path length of 15-20 mm and at the same time almost any desired cross sectional area for the fluid flow. In **Figure 10** a schematic drawing of a concentric configuration for very high salinity concentration (saturated brine with a concentration of 300 kg/m³) is presented. The conical body in the centre of the pipe contains the radiation source. The effective cross sectional area of the concentric throat, with inner and outer diameters of 30 and 58 mm respectively, is equivalent to that of a normal venturi with a throat diameter of 50 mm.

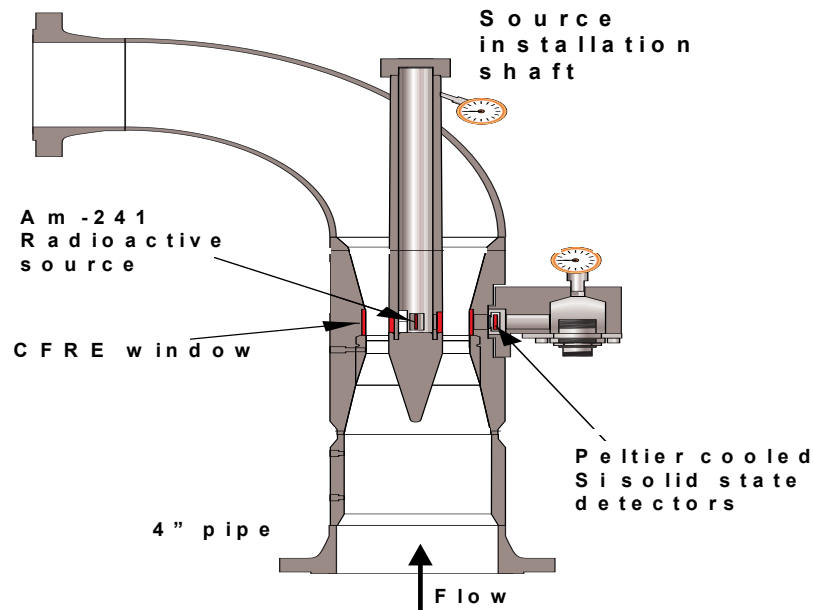


Fig. 10: Schematic drawing of the concentric MEGRA. The source is installed in the centre of the pipe and a set of concentric Carbon Fibre Reinforced Epoxy cylinders are used as window material.

3.7. Influence of fluid parameters

The 100% water reference count rates for the lower energies required in the DEGRA calibration are strongly dependent on the salinity of the production water, since salt has a high absorption coefficient compared to water. Systematic errors in the measured water, oil and gas fractions will occur if the salinity of the production water changes and the 100% water reference count rate is not corrected. In many potential multiphase metering applications, the salinity of the production water will indeed vary in time, and could be different for each well drilled in the same reservoir. In water injection reservoirs, for example, the salinity will vary between that of formation water and that of injection water. In **Figure 11** the production water salinity for the wells of a North Sea reservoir are shown as measured in January and June 1993. It not only shows that salinity is different for each well in the same reservoir, but also that in a 6 month period the salinity for some wells has changed by more than 10 kg/m³. Also horizontal and/or vertical gradients in formation water salinity across the reservoir may occur. Ref. 4 presents an example where such gradients can lead to salinity variations much larger than 10 kg/m³. In **Figure 12** the relative change in watercut ($\Delta\text{watercut}/\text{watercut}$) is

indicated for a change in salinity of 10 kg/m^3 from the calibration salinity. In this example, at a 50 kg/m^3 salinity and a salinity change of 10 kg/m^3 results in a $(\Delta \text{watercut}/\text{watercut})$ of 8%. At a watercut level of 50% this equals a 4% absolute error in watercut and an 8% relative error in net-oil production.

The curve in **Figure 12** is almost independent of the energy levels used. Multiphase meters using a Barium-133 source (30 and 360 keV) or a combination of Am-241 and Caesium-137 sources (60 keV and 660 keV) will suffer from the same errors in watercut due to a change in salinity. It should be noted that the problem of salinity changes is not unique to the gamma ray absorption technique. Conductivity measurement techniques, often used in situations of water external emulsions, are also influenced by salinity changes (Ref. 5).

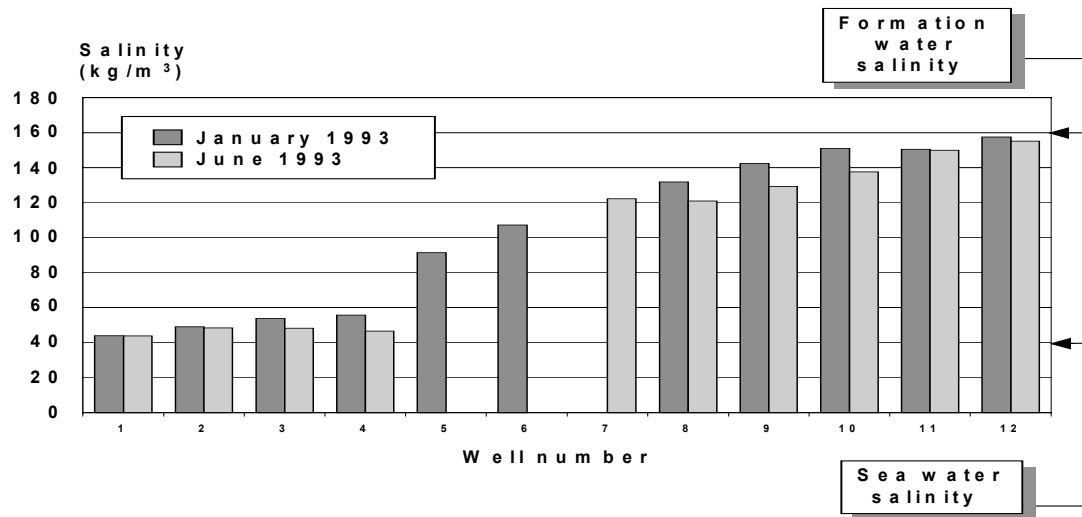


Fig. 11: The salinity's of various wells from one North Sea field as measured in January and June 1993. The formation water salinity is 160 kg/m^3 while the sea water salinity is 35 kg/m^3 . The salinity measured changes gradually from that of the formation water to that of the sea water.

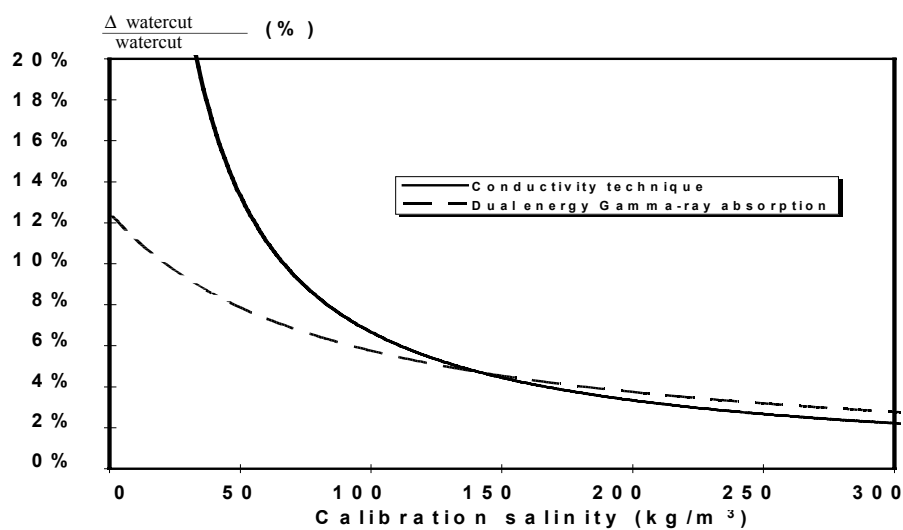


Fig. 12: The relative error in watercut as function of salinity for a change in salinity of 10 kg/m^3 .

4. COMPOSITION MEASUREMENT BASED ON TEGRA

When two energy levels are used it is possible to calculate the three phase fractions in a mixture. When three energy levels are applied (TEGRA, or Triple Energy Gamma Ray Absorption), it is possible to calculate one additional parameter; in the case presented here, the parameter of interest is salinity. In the measured water, oil and gas calibration spectra (**Figure 5**), it can be seen that 13.9, 21.5 and 26.3 keV energy levels are also available. The 26.3 keV level was chosen for the calculation.

4.1. Exact solution of TEGRA

It will be shown that the new set of equations is very sensitive to small measurement errors or to the statistical uncertainty in the measured count rates. The 4x4 matrix, similar to the 3x3 matrix of Eq. 2, is very poorly conditioned and small variations in the measured count rates will lead to large fluctuations in estimates of phase fractions and salinity. In a computer simulation, with $a_W=a_O=0.15$, $a_g=0.70$, $S=100 \text{ kg/m}^3$ and applying the Poisson-type of statistical fluctuations, the exact solution of the set of equations for each measurement shows enormous fluctuations in the calculated a_W , a_O , a_g and S . In **Figure 13** it is shown that the calculated fractions are even outside the region of 0 to 1, and salinity estimates vary from -600 to +600 kg/m^3 . Hence, solving the equations for each measurement (one calculation per second) will not result in an acceptable composition measurement.

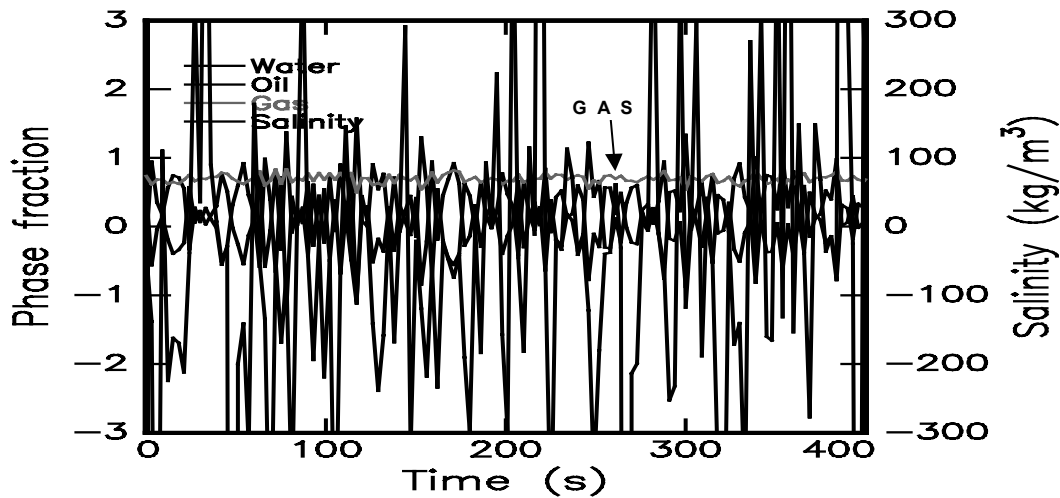


Fig. 13: Phase fractions and salinity obtained from the computer simulated count rates by directly solving the matrix equations. The left hand scale is valid for the phase fractions and the right hand for salinity. Input values are $\alpha_W=0.15$, $\alpha_O=0.15$, $\alpha_g=0.70$ and $S=100 \text{ kg/m}^3$. While the gas fraction calculation is acceptable, the oil and water fractions calculations and the salinity estimate are not acceptable.

4.2. Constant salinity approach

As indicated above, salinity typically changes either on a time scale of months (gradual change from formation water to injected water) or perhaps on a time scales of days (sudden injection water breakthrough). In the time span of a few hours the salinity can be assumed constant; an improved calculation scheme based on this assumption has been developed. After imposing this constraint to the algorithms, it is no longer possible to solve the set of 4 equations exactly, but instead a solution can be found which is optimal in a chi-square minimisation sense. The outcome of this minimisation process is a set of individual phase fractions for each measurement, and one salinity figure for all measurements. The previous simulation was repeated with this new algorithm and the results are presented in **Figure 14**. The calculated phase fractions demonstrate acceptable variations, and the calculated salinity equals the input value.

The chi-square minimisation algorithm is not limited to 3 energy levels. When more energy levels are added to the algorithm, e.g., 13.9 and 21.5 keV, the minimum acquisition time is reduced and the accuracy of the composition measurement is further improved. Hence, a composition measurement based on Multiple Energy Gamma Ray Absorption (MEGRA) has been created.

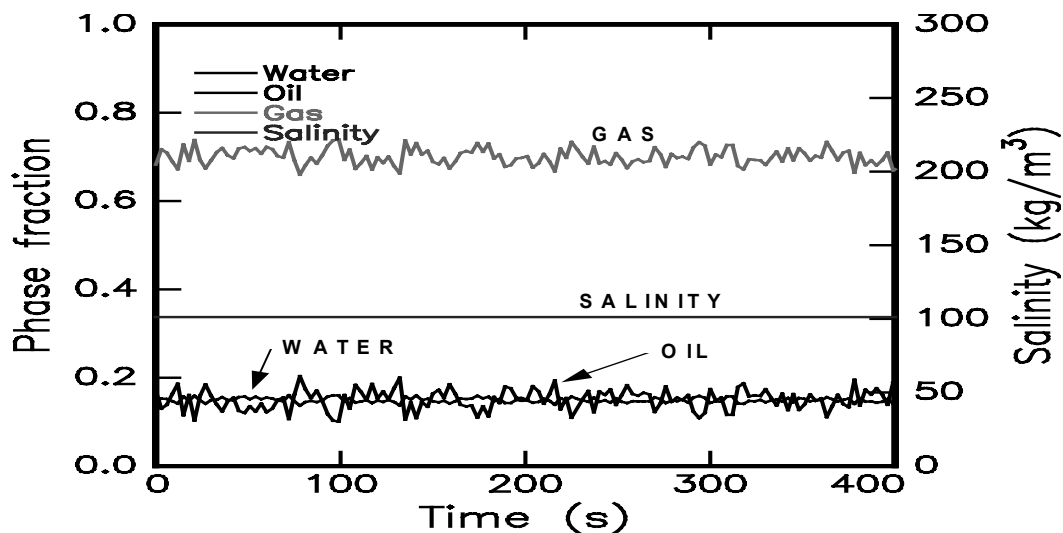


Fig. 14: Phase fractions and salinity obtained from the chi-square minimisation algorithm, where the same computer simulated count rates as in the previous figure were used as input. The left hand scale is valid for the phase fractions, that on the right for salinity. Input values are $\alpha_w=0.15$, $\alpha_o=0.15$, $\alpha_g=0.70$ and $S=100 \text{ kg/m}^3$. This new algorithm results in a statistically acceptable composition measurement and a proper estimation of the salinity.

4.3. Salt composition changes

The TEGRA or MEGRA algorithms cannot distinguish between salinity changes or salt composition changes. Heavier salt components, e.g. potassium or calcium based salts, have higher absorption coefficients than the more commonly occurring NaCl. However, a sensitivity analysis showed that salt composition changes affect only the calculated salinity, and that the errors in the calculated phase fractions are negligible — less than 1% absolute

error in phase fraction for a worst case of 100% water with a salinity concentration of 100 kg/m^3 .

5. CALIBRATION FREE OPERATION USING MEGRA

The entire purpose of the **DEGRA** calibration is to determine the matrix elements of Eq. 2, i.e. to measure the reference count rates of (saline) water, oil and gas at two gamma energy levels. With **TEGRA** it is possible to measure the salinity concentration in-situ. The absorption coefficients of fresh water are well known (Ref. 6) so it is possible to calculate the reference saline water count rate from the empty-pipe count rate. A similar procedure can be followed for the oil reference count rates, for which the density and composition of the oil needs to be known. A sensitivity analysis shows that the errors in phase fractions resulting from density and composition changes are small. For example, a relatively large change of 10 kg/m^3 in oil density results in a maximum absolute error of approximately 1% in any phase fraction. Hence, all the reference rates can be calculated from the empty-pipe count rates, assumed oil composition and density, and tabulated absorption coefficients. The measured spectra, the empty-pipe spectrum, and the mixture spectrum are each a linear combination of the peaks occurring in Am-241, fluorescence peaks for materials in the vicinity of the detector, sum peaks, Compton scattering and build-up contributions.

This approach of calibration free operation (**Figure 15**) has been verified with a prototype meter, which was evaluated in the Shell test loop and subsequently transported to an oil field. In **Figure 16**, the phase fractions from the meter as measured for a particular well are presented. These fractions have been calculated with on-site calibration, i.e. the DEGRA concept and filling the meter first with saline production water and then with oil. The average watercut in the period between 1600-4000 seconds was measured to be 78%.

All the measured spectra over the above period were then re-processed, but this time the MEGRA algorithm, the empty-pipe count rate from the earlier testloop evaluation, and the tabulated, known, absorption coefficients were used. The resulting phase fractions are presented in **Figure 17** and the average watercut estimate over the same period used above was 76%. It is concluded that calibration free composition is practically possible if correction of the various distorting effects on the measured spectra is under control.

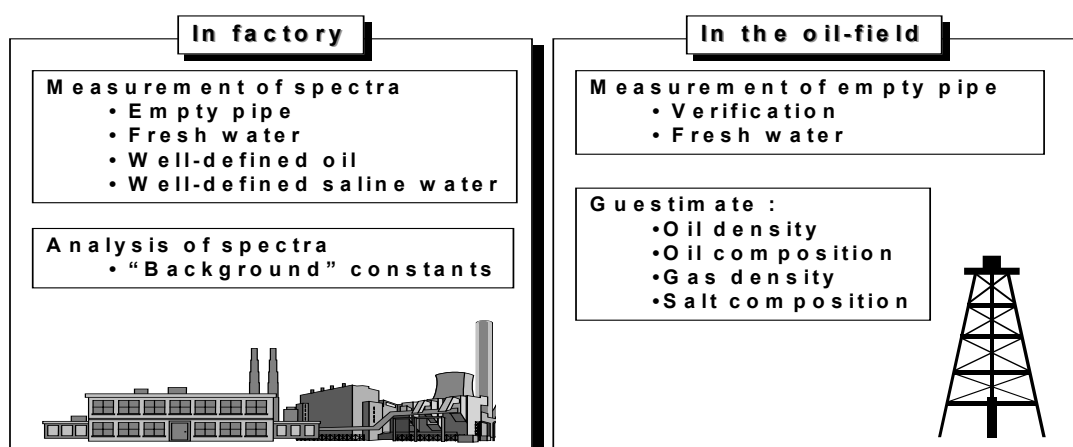


Fig. 15: Principle of calibration free operation. No water, oil and gas calibration is required in the field.

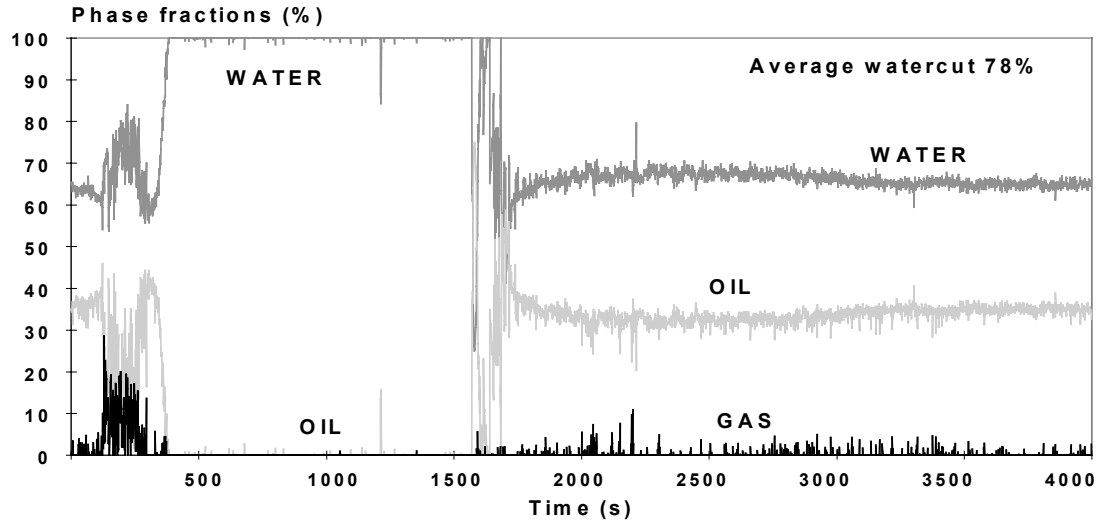


Fig. 16: Fractions obtained using conventional calibration and the DEGRA calculation method. Saline water and oil reference count rates as measured in the oil field are used.

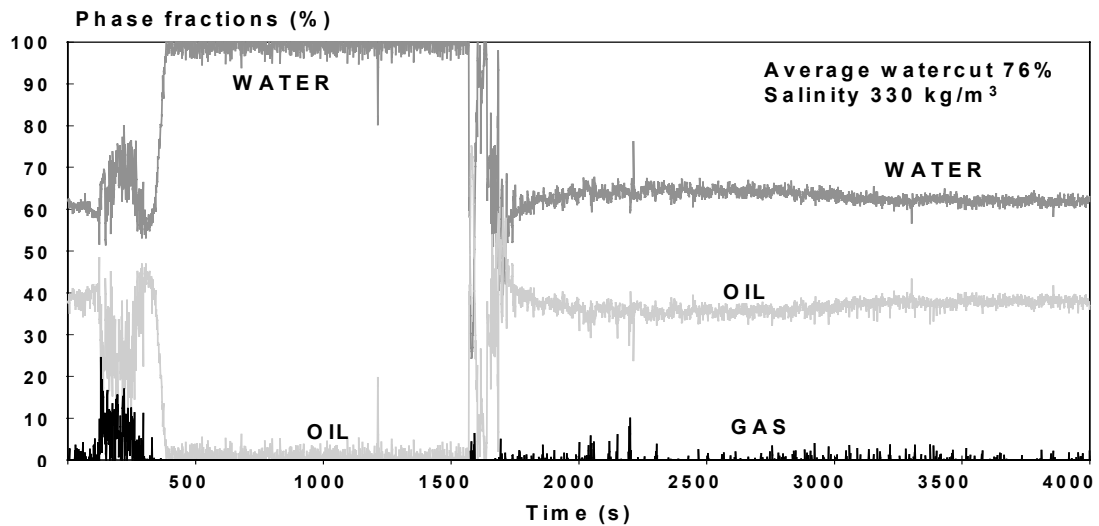


Fig. 17: Fractions obtained using the calibration free concept plus the MEGRA algorithm. No reference spectra from the field are used, only spectra from the testloop evaluation.

6. AREAS OF APPLICATION

A composition meter which uses MEGRA without flow models is only applicable to homogeneous flows, i.e. when (1) there is no velocity difference between the individual phases, (2) the individual phases are homogeneous, and (3) there are no variations in composition during a measurement period (for the MEGRA, within the 1 second measurement time). Equation 2 contains the mean logarithm of the count rate, but the actual measurement gives the logarithm of the mean count rate; these two are not equal in the case of non-homogenous or varying compositions. In **Figure 18** a worst case situation of this phenomenon is schematically presented. Theoretically it can be demonstrated that in such a

situation, or in any slug flow regime, the composition measurement always yields an under-reading of the watercut. This was further demonstrated in a testloop evaluation in which mixing intensity could be controlled (**Figure 19**). The higher the mixing intensity, the better was the watercut measurement.

An overview of the various MEGRA applications in a multiphase flow measurement and classified by Gas Volume Fraction (GVF) is treated here.

6.1. Gassy liquid streams

Gas might be present in drainlines of separators because of excessive pressure loss causing gas breakout in the drainline or insufficient gas/liquid separation. Both phenomena result in fairly homogeneous “gassy liquid” streams (low GVF multiphase flows). **Figure 20** is an example which presents the watercut reading of a prototype MEGRA. The GVF of the mixture during these measurements was between 0 and 30%.

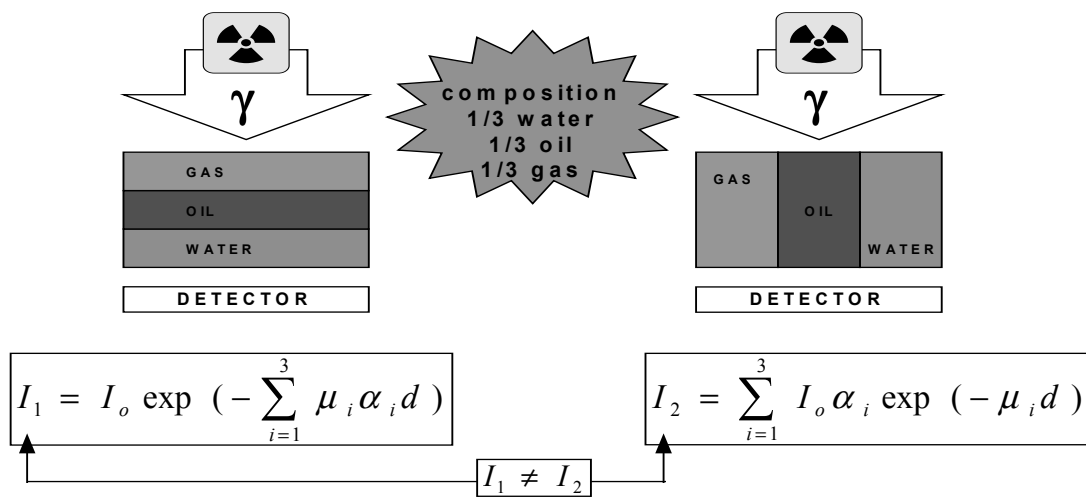
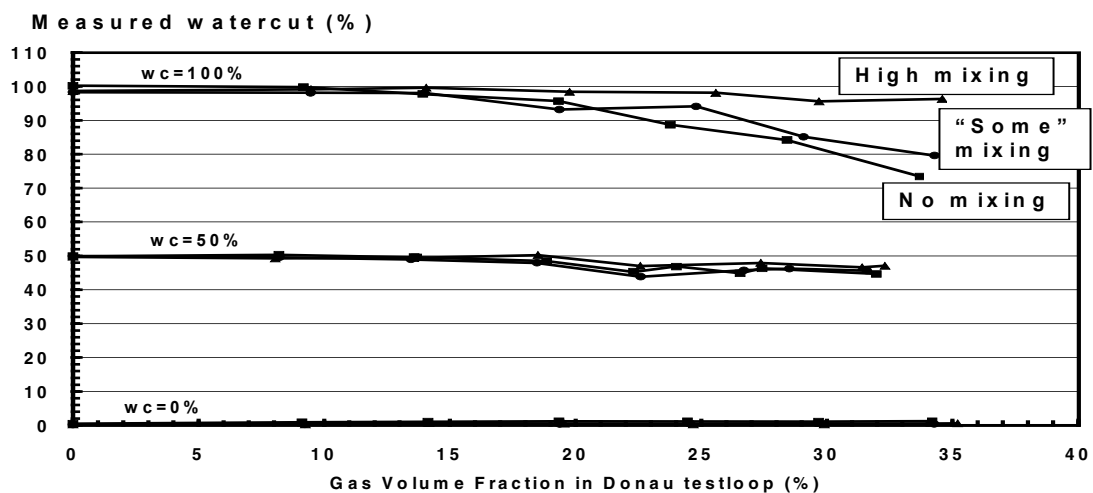


Fig. 18: Count rates measured in these two situations are not equal, although the fractions in both are the same. If variations in time occur (second situation), the result is systematic under-reading of the watercut.



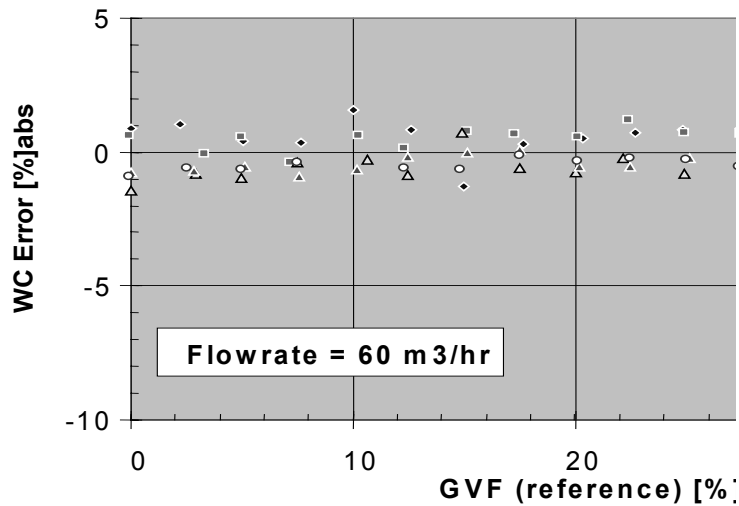


Fig. 19: Watercut reading as a function of Gas Volume Fraction. Mixing is required above 20% GVF to avoid systematic errors in the composition measurement.

Fig. 20: Absolute errors in watercut reading of the Daniel prototype MEGRA versus the test loop Gas Volume fraction.

6.2. Moderate Gas Volume Fraction streams

Naturally occurring flow streams with GVF's between 20% and 80%. are ordinarily not homogeneous. Mixing of the multiphase flow is required upstream of the MEGRA to eliminate the velocity slip and reduce the variations in composition. This approach is already commercially available (Ref. 7-8).

6.3. High Gas Volume Fraction streams

At very high GVF's, i.e. GVF's higher than approximately 80%, it is difficult to achieve a slip-free and homogeneous mixture. Here the liquid and gas might be roughly separated using a small and simple separator followed by a measurement of the “gassy liquid” and “wet-gas” streams (**Figure 21**). The “gassy liquid” stream can be measured with a MEGRA/venturi combination. This approach has been tested in the field recently; the well test package is commercially available.

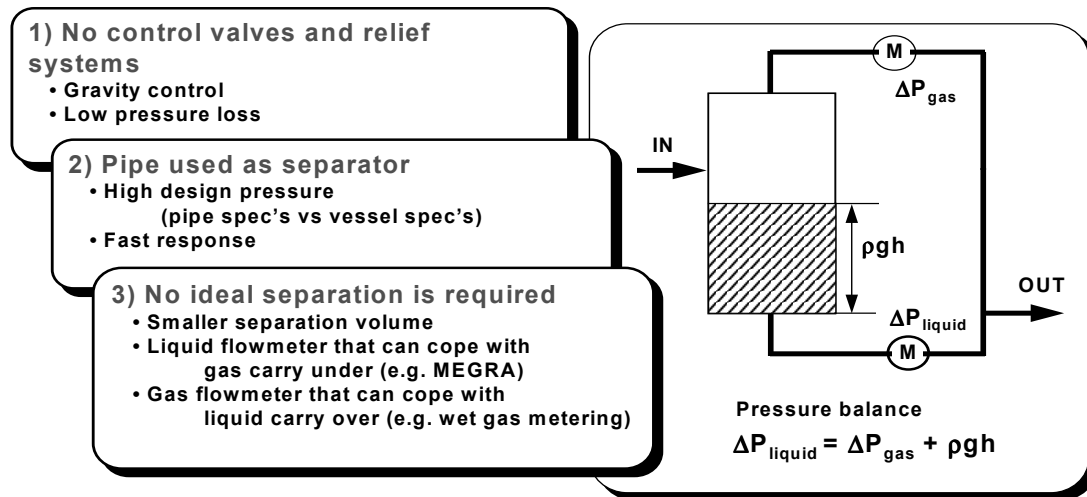


Fig. 21: A simple In-Line Conditioner (ILC) to remove the bulk of the gas from a high GVF multi-phase flow. MEGRA can be applied in the "gassy liquid" drainline, a "wet gas" meter in the gas line.

7. FURTHER DEVELOPMENT OF MEGRA

In May of 1995, Shell awarded an exclusive License to Daniel Industries, Inc. to commercialise the MEGRA technology world-wide. As an initial step in the development of this product, Daniel designed and built several prototype meters, the first of which are currently located at an offshore platform in the South China Sea, onshore production location in Borneo and in a oil field installation in Rotterdam. These units produced the results shown in **Figure 20** from measurements made in the Shell multiphase flow loop.

Recent improvements in the MEGRA algorithms, mainly because of better spectra modelling and interpretation, have resulted in salinity calculations with an uncertainty of approx. 1 kg/m³ while errors in watercut are in the order of 2-3% (absolute).

8. CONCLUSIONS

Accuracy considerations showed that the lower gamma energy levels of a composition meter based on DEGRA (TEGRA or MEGRA) should be in the range of 10-30 keV, and that the high energy level is not so critical provided it is above 40-50 keV. Am-241 proved to be a very attractive source from a measurement point of view.

The introduction of a unique dual-area solid state detector, with a small area detector providing good resolution for the various low energy levels (14-26 keV), and a large area detector with reduced resolution for the isolated high energy level (59.5 keV) of Am-241, is ideal for the MEGRA concept.

A sensitivity analysis for a combination of Am-241 and the dual-area solid state detector showed that with a fluid path length of 20 mm, the uncertainty of the measurement becomes almost independent of the salinity. Uncertainty in phase fractions are of the order of 2% if counting periods of 1 second are applied.

With a concentric configuration, having the Am-241 source in the centre of the pipe, the optimum 20 mm fluid path length can be selected without serious restriction in the fluid flow throughput.

Salinity changes, more than density and molecular composition changes, have a significant impact on the calculated phase fraction and watercut. With the introduction of a third energy level and an advanced calculation method, it is possible to calculate phase fractions and production water salinity with acceptable accuracy.

Calibration free composition measurement, which does not require field calibration with reference fluids, is feasible. For this only spectra for an empty-pipe, fresh water, and a "well defined" oil need be measured, and these only once. A subsequent analysis of the various background contributions will then result in instrument constants. All this can be done in the factory, and once installed in the field only a rough estimate of the salt composition and of the densities and molecular compositions of the oil and gas are required.

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PORTABLE NUCLEONICS INSTRUMENT DESIGN — THE PORTACAT EXAMPLE

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Abstract

Portable nucleonic gauges prototypes are designed and manufactured in New Zealand for niche applications. Considerable development in hardware and software provide new opportunity in design of relatively low cost portable nucleonic gauges. In this paper are illustrated principles, and specific factors to be consider when designing portable nucleonic instrumentation, using an example called PortaCAT, which is a portable computed tomography scanner designed for imaging wooden power poles.

1. INTRODUCTION

The penetrating properties of radiation present unique opportunities for measurement applications in industry. However, in addition to the high costs associated with the sources and radiation detectors, there is general public concern with safety issues. While much of this concern is irrational, there are three principles by which potential radiation applications should be judged: justification, optimisation, and limitation. Clearly, if alternative techniques are available, then the continued use of radiation must be justified by the unique benefits it delivers. Safety must be assured. Given that justification, the particular form of radiation to be used must be selected to enhance measurement of the required property. For instance, with a density measurement using attenuation of gamma or X rays, this means choosing the energy which gives the necessary penetration, but which also has sufficient loss to be sensitive to density changes. The third principle is to limit the amount of radiation necessary to make the measurement. Obviously, the last two principles are not necessarily independent.

The high costs of nucleonic instrumentation also partly arise from safety considerations. For instance, radioisotopic sources should be in *special form*, and encapsulated in appropriate safety enclosures. Design and use are subject to regulatory authority approval. Considerable development has occurred in radiation detectors, providing new opportunities in applications. However, these are not consumer items, and the combination of development and production costs means that they are relatively expensive.

In general, the principles underpinning nucleonic gauge applications have been long-established. It is the new detectors coupled with modern electronics and computers that continue to make new applications feasible. Although feasibility may be assured, unless industrial end-users are prepared to pay for the final product, there is little point in investing further development costs. It is increasingly important that the relevance of the research is established from the outset, and a way of showing this is through market analysis, and demonstration of the potential cost-benefits that would evolve through adoption of the new instrumentation.

2. THE POLE INDUSTRY

2.1. Cost benefits

Many countries have extensive overhead power distribution, and the supporting poles represent a large capital investment made by an electrical supply authority. In New Zealand, total replacement costs currently average about \$US750 per pole. Throughout Australia, there are about eight million wooden poles in service. The expected lifetime of each is about 30 years. There are considerable savings to be made by lifetime extension. If, through better techniques, pole replacement can be delayed, and average lifetime extended by 5 years, there are potential annual savings of \$US29 million in Australia. The other aspect is sudden pole failure. This can be as a result of various means, particularly fungal or termite attack in the critical zone (about ground level). Although infrequent, consequences can be dire, and linesmen have been fatally injured carrying out maintenance on defective poles. The collapse of a pole can also lead to unexpected power outages.

2.2 Required performance for an NDE pole technique

A pole must withstand the forces applied to it by the power lines it supports. A successful technique for pole NDE needs to provide an accurate estimation of the available bending moment of the pole about the critical zone. This depends on the type of timber, and its distribution within the cross section of the pole. Defects, such as rot or cracks, may not necessarily detract from the strength of pole provided that they remain central or limited. Clearly, cross sectional imaging is to be preferred over spot measurements obtained by drilling. However, the imaging device would have to be quick, cost-effective and reliable in pole assessment; it should be non-destructive; be able to be used safely on public streets, as well as cross country; require only one person to operate; and not need a graduate engineer to use, and interpret the results.

3. COMPUTED TOMOGRAPHY

3.1. Principles

Computed tomography (CT) is a standard technique developed in the 1970s for body imaging in the medical field. It is a combination of numerous radiation (normally X ray) transmission measurements from which a cross sectional image can be reconstructed. If the object to be scanned is fixed, then the source and detector must translate and revolve around the object. The geometry applicable to first generation CT scanners is illustrated in fig. 2 which shows parallel line integrals of X ray attenuation ("ray sums") at three different angular steps ("projections"). Standard methods are available for image reconstruction from this data [9,11,12,13,14].

A variety of applications of CT to industrial inspections have been reported, but these have mostly been done on borrowed medical scanners, or laboratory set-ups, as demonstrations [1-7]. The inverse procedure, meaning that the scanner visits the "patient" at an industrial site, has proved difficult to implement. The very few exceptions to this have generally required a vehicle to transport the scanner and ancillary equipment, and cannot be regarded as truly portable. An understanding of the difficulties in applying industrial CT scanning can be gained by consideration of the CT triangle (Fig. 1). CT is governed by three interdependent factors: spatial resolution, contrast or density discrimination, and scanning time. Any gain in one or two of the factors results in a loss in the others. Hence a performance trade-off always applies. Medical CT scanners maintain good image resolutions and short scan times by using multiple detectors and high X ray fluxes. They are large, fixed instruments. To achieve similar performance with a

transportable instrument would grossly limit its utility and cost-effectiveness. Furthermore, plant engineers ever conscious of costs, and can generally fall back on traditional “maintenance by replacement” practices.

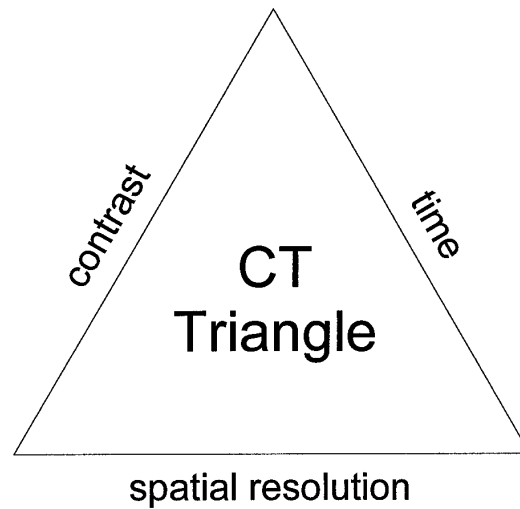


Figure 1: The CT triangle.

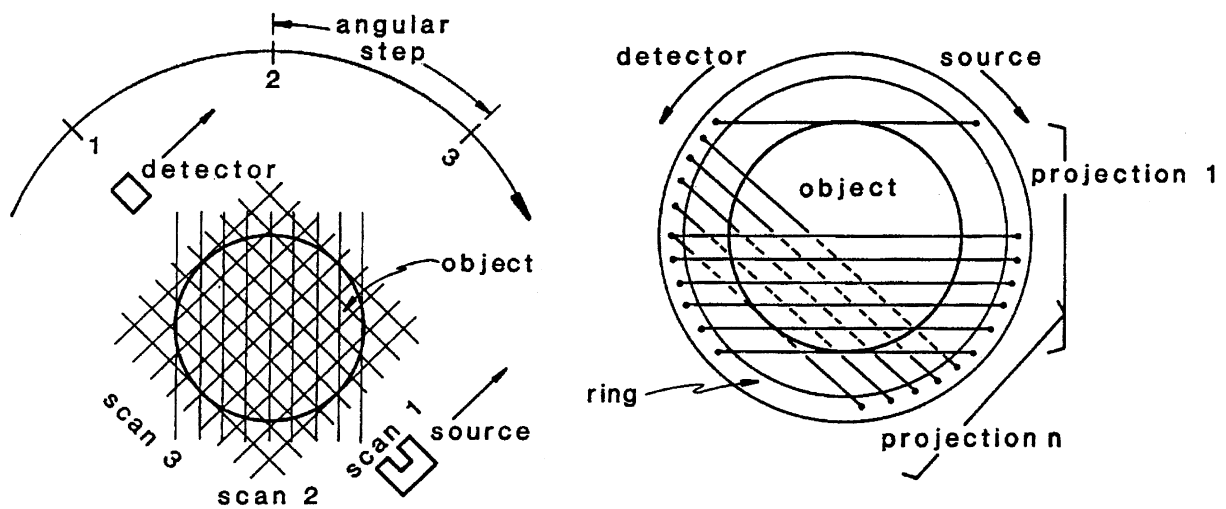


FIGURE 2: Conventional, first generation CT scanning (left) and portaCAT scanning (right).

3.2. PortaCAT CT

A prototype portable CT scanner for poles was first reported by Miller [8], and PortaCAT is a development from this. To minimise the space required around the pole, a circular scanning motion is used. While similar to the fan-beam geometry used by medical scanners, it differs in that the source and detector rotate about the centre of the object, rather than the detector moving at a constant radius about the source.

In practical terms, an X ray tube and power supplies are too bulky to satisfy the requirement for a truly portable scanner. Therefore, a radioisotopic source of X rays is indicated. Although the 60 keV is somewhat lower energy than optimum [10], the ^{241}Am emission has sufficient penetration through 300mm dry wood to be suitable. Because the source output is greatly inferior to a tube, the resolution was compromised to maintain a reasonable data acquisition time. A minimum image pixel size of 10mm for 300mm pole diameter (15mm for 450mm) was decided upon. The number of ray sums required for each projection is $n = 31$. As the image region is circular, a total of $\pi n^2/4$ or 755 non-zero density values are required. This implies 755 independent measurements, so that the number of projections necessary is $m = \pi n/4$ or 25. The projections must cover 180° , giving a separation of 7.2° . Clearly, automated data acquisition was essential for acceptable performance.

4. PORTACAT DESIGN

Portability places additional demands on nucleonic equipment design. Radiation shielding must be adequate for the environment in which the instrument is expected to work. Intrinsic safety features must be adopted if working in hazardous areas. If equipment is exposed to marine or other corrosive environments, fabrication materials should be selected for compatible electrochemical properties. Battery operation of electronics demands low power consumption. Both internal and external electronics plugs/sockets should be minimised for reliable field operation. Ergonomics should be incorporated in equipment design — ease of use aids efficiency and eliminates potential human errors. And with routine operations, data processing and presentation should be sufficiently advanced to allow ordinary inspection staff to make correct judgements on site. Most of these factors have been incorporated in the design of PortaCAT. It is packaged as two handheld units, scanner and electronics, powered by a 12 V, 7 Ah battery. A schematic of its components is shown in Figure 3.

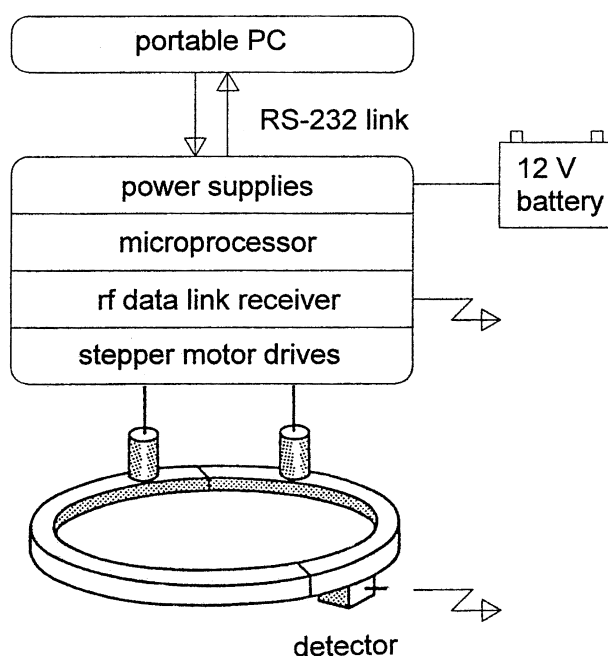


Figure 3: Schematic of the PortaCAT components.

4.1. Mechanical design of the scanner

Concern for the ease of operator action in using the instrument pervades the design of the scanner component parts. Source and detector are mounted on separate split rings, individually driven by

sprocket wheels meshing onto gear chains. Movement of the rings is obtained by step motors, geared to give a positioning accuracy of 0.1° . The ends of the rings engage through ball-socket joints, and the outer surfaces are automatically thrust against idler bushings. Precision fabrication is required for reliable operation. Minimising the moving masses of source and detector is important for speed, and well as power consumption. Up to half of the time scanning is spent simply repositioning to take the next measurement. The aluminium housing containing the rings is split and hinged to allow the scanner to be quickly wrapped around the pole. Source and detector rings have physical home positions enabling accurate repositioning. A scanner for 300mm diameter objects needs an external clearance of 440 mm; 450 mm diameter needs 680mm clear. Neglecting motors and clamps, the thickness of the scanner is about 100mm

A key time saving factor is in the attachment of the scanner to a pole (Fig. 4). The split housing is held together by one clasp, and the housing is automatically centred on the pole using pairs of geared arms. These are held to the centre of the scanner by spring-tensioned 50mm fabric belts, and are spread as the housing envelops the pole. A ratchet engages when the housing is closed up, and the belts are then tensioned by hand to stop the scanner slipping down the pole. The result of this design is that PortaCAT can be attached to a pole by one person, and be ready to start in seconds. The alignment of the image in relation to scanning is marked on the housing. This is important for correlating line load with later calculation of bending moments.

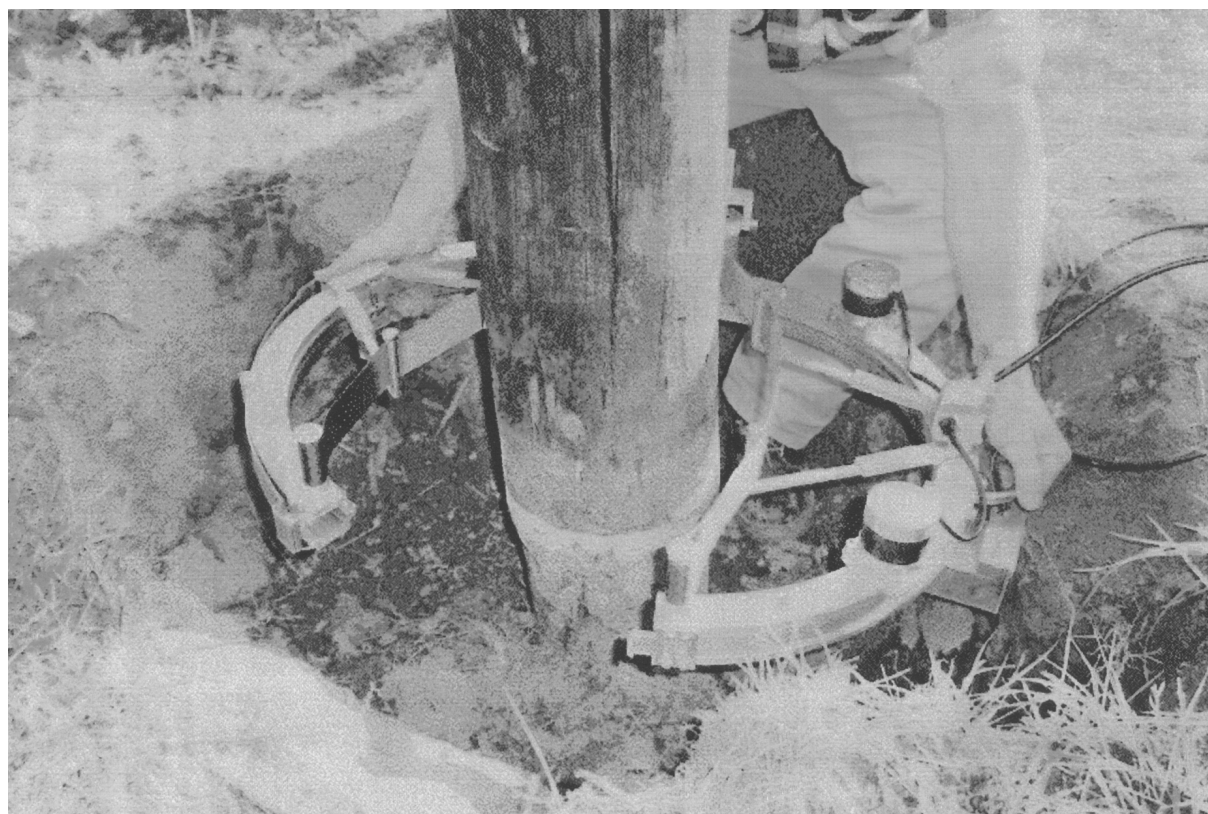


Figure 4: PortaCAT scanner being attached to a pole.

4.2. Source Enclosure

The source used is 11.1 GBq (300 mCi) ^{241}Am ; Amersham AMC17, type X92/0, IAEA special form GB/39/S. The adherence to *special form* sources is important for transport of the instrument.

The source has an active area of 12mm diameter, and is contained in a stainless steel enclosure, with a shutter which springs open when it is moved from its home position on the scanner. This protects the operator when attaching the scanner to a pole. A manual override can be used to lock the shutter in the closed position. Because the source and detector are rarely diametrically opposite each other when taking data, the radiation beam is deliberately wide angle. The varying distance between the pair compensates for the changes in solid angle through each projection. Figure 4 shows the dose rates adjacent to the 410mm diameter housing (300mm object size). With nothing in the scanner, a 25 $\mu\text{Sv/hr}$ boundary would be a circle of 1.5m diameter centred on the scanner. However, when wrapped around a pole, this 25 $\mu\text{Sv/hr}$ boundary is reduced to a circle of 0.8 m diameter. Based on this, the scanner can be judged as safe for use in public areas.

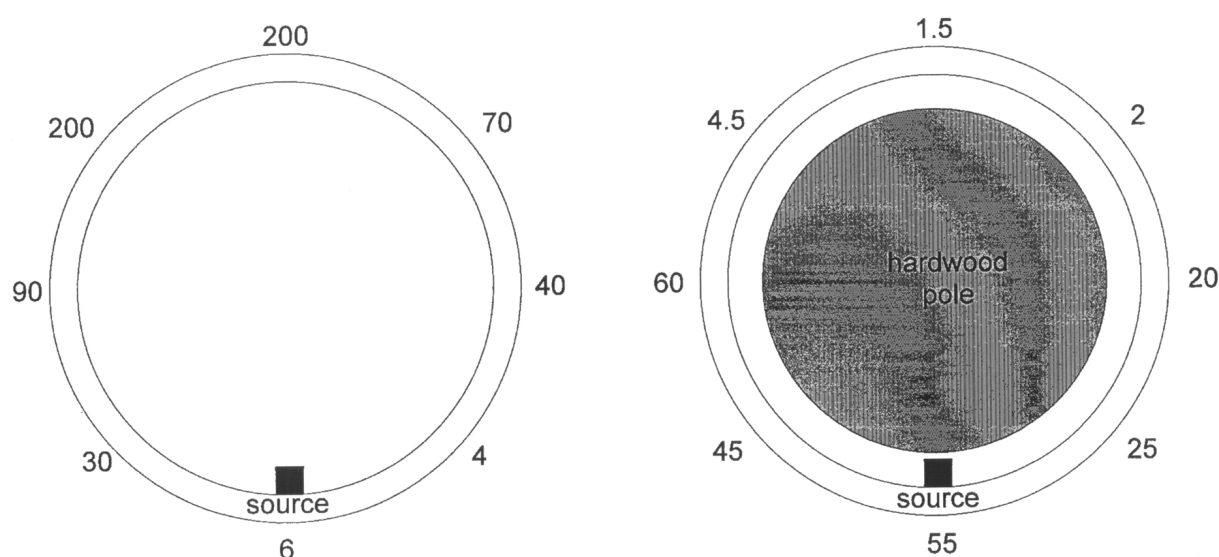


Figure 5: Ambient radiation ($\mu\text{Sv/hr}$) around PortaCAT scanner.

4.3. Detector

As with the source, a physically small detector was indicated. Two CdTe semiconductor counters, 2 mm thick, were mounted in a sealed enclosure butted together to give a sensitive area of 10 x 20 mm. The two counters are simply paralleled, feeding into a hybrid charge sensitive preamp. This is followed by a two stage amplifier-shaper, using low power opamps, and output fed into a low level discriminator set just above the noise level to produce logic pulses. Initially, the detector was connected by cable to the microprocessor electronics. Tracking inconvenience arising from rotation of this cable was later overcome by replacing it with a digital VHF radio link. To achieve this, the detector electronics had to be extended to include onboard counting, an rf transmitter and a self-contained power supply. The counting is done by a low power I²C counter which is controlled by a programmable interface controller (PIC16C71). Counting is done in intervals of 100 msec, after which the counter is read by the PIC, and the value is encoded into a data packet suitable for direct on/off-keying of the transmitter hybrid. The rf frequency used is 303 MHz at a power level lower than one milliwatt. Each packet is sequentially numbered, contains its own, and the two previous interval's, count data, and is appended with a 16 bit CRC (cyclic redundancy check) code. The transmitter hybrid is one

that is often used for consumer remote controls, such as garage door openers. However, the PortaCAT application is rather more demanding than opening garage doors! The CRC code ensures that any doubtful data is discarded. The aerial is merely a short wire (~15cm) as the distance to the receiver in the base instrument is at most 4 metres.

Power for the detector is supplied by two AA size alkaline cells giving an endurance of about 8 hours continuous operation. Two micropower switchers provide some hundred volts of detector bias as well as analogue and digital low voltage rails. Efficient circuit design resulted in a compact package measuring 90x80x40 mm, and this was achieved without resorting to surface mount electronics. Noise was the largest problem. Switching supplies are inherently noisy and separate shielding was not practical in the very confined space available. Careful mechanical layout of the pcbs and orientation of high current switching conductors away from the detector input section was imperative. Use of magnetically shielded inductors was essential in the power supplies. Microphonic detector noise was substantially reduced by rigid counter mounting in a milled aluminium block, and by using a quasi-bipolar signal to drive the discriminator.

4.4. Step motor drives

The step motors are 5V, 1A per phase, with 1.8° step size. Given the amount of movement required for CT data acquisition, they are the major drain on battery power for PortaCAT. In this application, they are required to make a great many small movements accurately. Good torque is required, as well as fast acceleration/deceleration. The inductance of a winding means that the current takes a finite time to build up and to die away as the winding is switched on and off. To achieve a rapid step rate, the windings of a step motor are generally switched in series with resistors. With a series resistor, a higher voltage than the rated value for the motor can be used across the resistor and winding. When the winding is first switched on, the current will rise more quickly than with the case of the rated voltage just across the winding; however, the resistor dissipates power. For instance, running a 5V, 1A motor at 12V requires a resistor of 7 ohms, which will then waste 7 W of power when the rated current is achieved.

Switched mode power supplies are used for PortaCAT step motors. With switched mode operation, the resistor is eliminated. When a step motor winding is energised, it is switched on at regular intervals, and switched off each time the winding current exceeds a set value (in this case 1A). Properly set up, this results in a reasonably constant current through the winding, and no power wastage. Each motor for full stepping mode requires two of four windings energised at any time. Running 5V rated motors at 12V and 0.8A/winding with no mechanical load using resistors theoretically requires about 20W; of this, only 8W is dissipated in the motors. With the switching mode drivers, the power requirement is reduced to about 12W. The driver produces fast maximum step rates, high torque, and good efficiency. A PIC16C71 is used to generate the switched mode interval, and to switch the motor windings in the correct sequence to step the motor. Step timing and direction is controlled by external inputs. In most PortaCAT applications, it is only necessary to energise the winding when the motor is moving, and rely on mechanical friction to hold the source and detector in place.

4.5. System data acquisition and control

A laptop personal computer (PC) in conjunction with a 8-bit 80C552 microprocessor controls the movement of motors and the acquisition of data. The two are connected by a serial line. To save time, motor movements are precalculated according to the particular image and pixel sizes, and

stored in tabular form for quick access. Scanning steps are passed to the 80C552, along with the required dwell time. To maintain constant measurement accuracy, each position is held until a preset number of x rays have been counted. Hence, scanner movement is slower at the centre of a projection than at the ends. Acquired data is passed back to the PC only at the completion of each projection. This enables progressive image reconstruction to proceed in parallel with data acquisition, and the final image is available within 10 seconds following completion of scanning. The operator, through the PC, can abort operation at any time. The 80C552 can also be used to report battery voltage.

Because of the need to drive step motors, the drain on the battery from the control electronics is not significant for PortaCAT. However, this is not the case in many other portable instruments. Microcontrollers and peripheral devices need to be low power devices, and preferably have standby or disabled modes that can be used to reduce power use when not in use. For instance, the 80C552 can be put in an "idle" mode when it stops processing, but can be "woken up" by various events. This saves power. Limiting clock speeds of microcontrollers also reduces power consumption — some versions can even programmatically alter their clock speed, allowing fast processing when needed, and lower power use at other times without completely stopping processing. In cases where the internal ROM and RAM of a microcontroller are insufficient, and external memory is added, this generally only needs to be enabled when the microcontroller accesses them e.g. for the 80C552, by tying the code read signal PSEN to both the output enable and chip enable pins of an EPROM. It is a case of "horses for courses" in selecting microcontrollers. Very simple tasks can be performed by "chicken brains". For instance, a PIC16C71 can use significantly less power than a 80C552 but it can not be used for as complex tasks. Finally, some sensors that have significant power use, but are only measured periodically, can be depowered in between measurements by using a FET or IC analogue switch.

4.6. Image processing and presentation

The software on the PC is written in Pascal, and runs under MS-DOS. The system is complete in that it incorporates data acquisition and control through to calibration, image reconstruction, archiving and final analysis of images. Routine calibration involves running with an empty scanner to record null rates. These are angularly dependent, and can be averaged over several projections. The images produced by PortaCAT are maps of x ray attenuation. These are converted to density pictures by a simple multiplicative factor which should be determined by measurement of attenuation through a known density of similar wood.

As a result of previous experience, it had been found useful to alter the succession of projections so that the second one is at right angles to the first. Image reconstruction of just these two projections then provides a very early indication of any anomalies that might be present within the cross section of the pole. This 'quick' image is however square and, while other reconstruction techniques could produce a rounded image, filtered back projection has the advantage of emphasizing defects to provide early indication of loss of pole integrity. An example is given in Figure 6. As expected for the pixel size, the images produced are crude in resolution. However, these are adequate for determination of power pole integrity. The corresponding full image is also given in Figure 6. This has been enhanced in resolution by a factor of two; while the data is unchanged, enhancement aids eye interpretation. 3D density plots are also available. As only raw image data is stored, each only takes 1.7 kB storage.

On the basis of the 'quick' image, the software informs the operator as to whether the pole is suspect or sound. This has been found to be a conservative judgement [1]. If sound, scanning can

be aborted, and inspection shifted onto the next pole. This overcomes the necessity of having highly trained operators. Full engineering analysis can be applied to the pole image using the same software. This reports the available maximum and minimum bending moments, and those at 0° and 90° to the image. An example of this is shown in Figure 7.

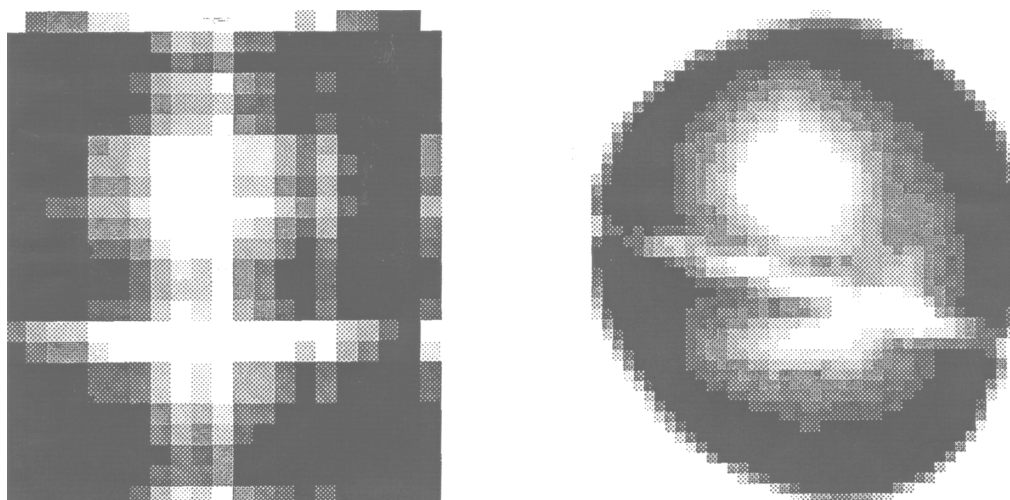


Figure 6: Quick image (left) and full image (right) of cracked pole with interior decay.

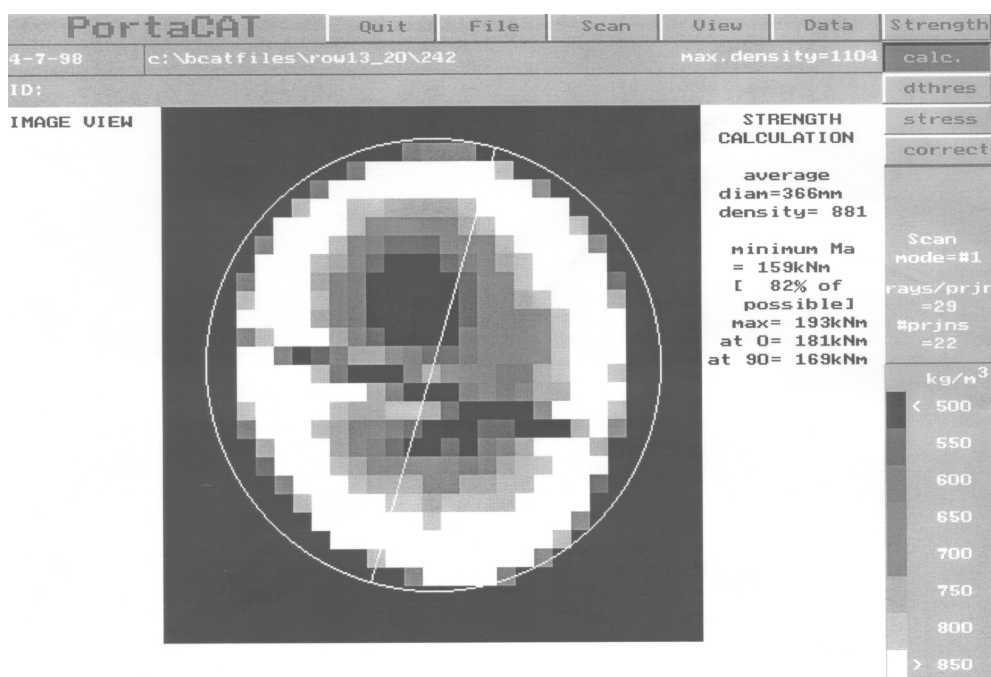


Figure 7: Screen dump of PortaCAT programme showing bending moments calculations.

5. CLOSING REMARKS

In terms of computed tomography, PortaCAT is not a particularly sophisticated imaging device. However, in terms of portable nucleonic instrumentation, it is a successful example of the use of precision engineering, modern electronics and computing power to produce a complex device

tailored to a specific need. The following features make it suitable for the detection of internal defects arising from rot or termite activity in wooden power poles:

- two handheld packages: scanner (6.2 kg) and electronics (9.2 kg)
- battery operated; battery lasts 3 hours, quick replacement
- uses compact semiconductor X ray detectors
- compact, long-life, low output radioisotopic source of X rays
- includes unmodified laptop computer running under MS-DOS
- user friendly software, staff easily trained
- simple performance check and calibration
- rapid attachment of scanner to pole, self centring
- scans virtually at ground level, minimum excavation to scan below
- non-destructive and non-invasive examination
- verification of good poles every 3.3 minutes on average
- full images (450 mm, 15 mm pixel) every 11.2 minutes
- move between poles without shut-down: check 5–20 poles each hour
- archival of images for later retrieval and hard-copy
- calculation of available bending moments conforms to accepted engineering requirements
- uncertainty therefore removed on need for replacement of defective poles
- cost-effective because of potential for life extension of distribution networks.

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NUCLEONIC GAUGES IN POLAND AND NEW APPROACH TO THEIR CALIBRATION

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Abstract

The current status of manufacturing and application of radioisotope gauges in Poland is presented. Metrological performance of the gauges is briefly described and their expected future prospects on the market of the industrial measuring instruments are discussed. Progress in electronic engineering and common use of the microprocessor systems in the radioisotope gauges made possible application of the sophisticated methods of signal processing and data treatment, as for example statistical multivariate analysis. Some examples of the multivariate calibration of nucleonic gauges are presented. Application of the partial least square regression (PLS) and artificial neural network (ANN) for calibration of the gauges has been shown.

1. INTRODUCTION

First application of nuclear techniques, including nucleonic gauges in Poland were reported nearly 45 years ago, and in 1961, about 200 radioisotope gauges were already installed in Polish industry [1]. During the next thirty years, manufacturing, installation and servicing facilities have been built enabling application of the nucleonic gauges in the industry on the relatively large scale. Since the beginning of the 90's decade, profound reconstruction of the Polish economy has started. Introduction of the market economy rules caused, sometimes temporary, reduction of the demand from the industry on the measuring and automatic control devices. Such situation influenced manufacturers of that instrumentation and their production capacity had to be considerably reduced. Moreover, competition of the foreign firms offering their products to the industry had also some impact on the position of domestic manufacturers of radioisotope gauges.

All those factors determined the scope of the market for the radioisotope gauges in Poland. According to data of the National Atomic Energy Agency, the following numbers of licenses for using radioisotope and radiation sources were issued till the end of 1997 [2]:

Medical sources and accelerators	110
Industrial and geological field research	200
Radioisotope gauges	1280
Firms installing gauges and smoke detectors	410
Industrial and research laboratories (open sources)	260
Industrial and research laboratories (sealed sources)	280
Production, transport and sales of radioactive materials	110

Total, more than 2800 enterprises have got licenses for using radioactive sources. Only in 1997, NAEA has issued about 600 licenses (including annexes to existing ones) for activities connected with radiation sources. Medical and industrial instrumental X ray sources are not included in the above data.

Number of issued licenses for using gauges containing a radioisotope source is not always the same as the number of installed or operating devices in industry. However, they show an image of the scale of the production and application of the nucleonic gauges in Poland. Practically there are three main manufacturers of those instruments: Polon-ZOT Ltd, Institute

of Nuclear Chemistry and Technology (INCT) and Center for Electrical Engineering and Automation in Mining (EMAG) where the gauges for coal mines were developed and are produced. There are also a few firms providing installation and service facilities.

Beside manufacturing, some research is conducted directed towards development of new gauges, as well as introduction new technologies into the designed gauges to expand their scope of applications. They resulted for example, in development of a system for continuous ash content measurement based on natural radioactivity or design radioisotope instruments where multivariate calibration procedures have been applied.

The aim of this presentation is to portray the present status of the manufacturing and installation of the radioisotope gauges in Poland and to point out on benefits which can be gained when the multivariate approach is to be used in calibration of some types of radiometric instruments.

Production and application of radioisotope gauges in Poland

At the end of 1997 more than 1200 radioisotope gauges were operating in Polish industry. Generally, they are used for measurements and/or automatic control of such quantities as level, density, thickness, coating thickness, massflow, ash content, acid concentration and airborne dust. There are some specific branches of industry where „traditionally” nucleonic gauges are readily installed, such as sugar-factories (density), sulphuric acid production lines (concentration gauges) or coal mines (ash). Short specification of the nucleonic gauges already installed and operating in industry is presented in Table 1:

Level gauges

The most of the level gauges installations are single point measurements based on the gamma-relay type UPR, which has been produced in Poland for more than 20 years. More than 650 gamma relays were installed in Poland and about 430 abroad. Continuous on-line level gauges are based on application of the 2 m long ionisation chambers.

The prospect of future application of the single point level gauges seems to be quite good, because up to now there are no alternative method capable to perform contactless measurements of the level in such vessels as storage tanks, hot product bunkers, etc.

Density gauges

Radioisotope density gauges maintain their predominant position, compared with instruments operating on other principles. Their main advantage is contactless measurement in the toughest process environment including hazardous areas. About 50% of the radioisotope density gauges are installed in sugar producing plants where they are used mainly for the automatic control of the production process. The gauges produced by Polon- ZOT can measure density within the range 0.6–3 g/cm³ with accuracy better than 0.3%. They can operate with high temperature of the measured medium — up to 200 °C, and are designed for the pipe diameters from 50 to 400 mm and pipe walls thickness up to 12 mm. They can also be constructed in anti-explosive housing. The prospect for their production in future looks well and the expected area of the application are chemical, food and mineral processing industries.

TABLE 1: SOME NUCLEONIC GAUGES MANUFACTURED IN POLAND AND APPROXIMATE NUMBER OF THEIR INSTALLATIONS (1998)

Measured quantity	Range and accuracy	Principle of operation/ Source and detector	Manufacturer/ Units installed
LEVEL Single point	-	γ — absorption, Cs-137, Co-60 G-M counter	POLON 650
On- line	1–6 m	γ — absorption, Co-60 Ionisation chamber	2
DENSITY	$0.6\text{--}3.5\text{g/cm}^3 \pm 0.3\%$	γ -absorption, Am-241, Cs-137 Ionisation chamber	POLON-ZOT 325
THICKNESS Steel sheets	$0.1\text{--}4\text{mm} \pm 1\mu\text{m}$ $0.8\text{--}8\text{mm} \pm 5\mu\text{m}$	γ — absorption, Am-241, Sr-90 Ionisation chamber	POLON-ZOT 38
foils (Al, plastic)	$20\text{--}100\mu\text{m} \pm 0.5\mu\text{m}$ $100\text{--}800\mu\text{m} \pm 1\mu\text{m}$	β — absorption, Kr-85, Pm-147 Ionisation chamber	11
Basic weights	$250\text{--}950\text{ g/m}^2 \pm 1\%$	β — absorption, Sr-90 Ionisation chamber	3
pipe walls	$2\text{--}20\text{ mm} \pm 1\%$ $10\text{--}50\text{ mm} \pm 1\%$	γ — absorption, Am-241 Ionisation chamber	12
COATING THICKNESS laboratory	$0.2\text{--}2\mu\text{m} \pm 5\%$ Au/Cu (example)	β — backscattering Pm-147, Tl-204, G-M counter	INCT 60
on line	Zn/Fe	XRF, Am-241. Proportional counter	POLON-ZOT 2
MASSFLOW	Belt width-up to 1 m Accuracy $< \pm 1\%$	γ — absorption, Am-241, Cs-137 Ionisation chamber.	POLON-ZOT 230
SULPHURIC ACID CONCENTRATION	$90\text{--}99\% \pm 0.2\%$ H_2SO_4	n — scattering. Pu/Be, He — 3 prop. counter	INCT 45
ASH IN COAL on-line	$3\text{--}50\% \pm 1\%$ ash $2\text{--}20\% \pm 1\%$ moist.	γ — scattering, Am-241 microwaves	EMAG 30
on-line	$\pm 1.5\%$ ash	γ — absorption, scint. counter Am-241, Cs-137.	3
laboratory	$\pm 1\%$ ash	XRF, Pu-238 Proportional counter	
AIRBORNE DUST	$5\text{--}5000\mu\text{g/m}^3 \pm 2\%$ $2\mu\text{g/m}^3$	β — absorption Pm-147, G-M counter	INCT 20
COMPOSITION	-	XRF, Fe-55, Cd-109, Am-241 Proportional counter	POLON/INCT 20

Thickness gauges

There are several types of radioisotope thickness gauges produced in Poland by Polon-ZOT:

- 38 gauges designed for the fast measurements and control of steel sheets are installed in six steel making and rolling plants. They exhibit very good accuracy — 1 μm within the range 0.1–4 mm. The measurements are performed using γ — source Am-241, or β -X converter with Sr-90.
- Thickness meters for thin Al or plastic foils, paper and cardboard are also offered with traversing device. Scanning traverses of length up to 3300 mm consist of frame with driving motors and movable measuring head. Hence, the gauges can be used for the profile determination and mapping. This group of thickness meters use β rays (Pm-147, Kr-85 and Sr-90) absorption method with ionisation chamber used for detection of transmitted radiation. Measurement range covered by the gauges is from 20 to 800 μm and 250-950 g/m^2 with accuracy better than 1%.
- Pipe walls thickness gauges are designed for on-line measurements of plastic pipes during the production process. Principle of operation is based on absorption of γ rays from Am-241. The instrument can be used for measurements of wall thickness from 2 to 50 mm for the plastic pipes diameters within 50 -630 mm. During the measurements, profile of the pipe is shown on the computer display.

For the last years increasing demand for on-line thickness gauges from the industry has been observed. It can be explained by the pressure which is beared on the industry to maintain high quality of the final product. The contactless radiation thickness gauges are accurate, reliable and capable to operate in heavy industrial environment, hence their position on the industrial sensor market is very high.

Coating thickness gauges

Laboratory coating thickness gauges operating on the principle of β rays backscattering were designed for fast, non-destructive measurements of metallic and non-metallic coatings. The ranges of measured thickness depend on the energy of primary β -radiation, and in the case of determination Au thickness on Cu substrate are up to 2 μm for Pm-147, 10 μm for Tl-204 and 20 μm for Sr-90. Their use is limited to such cases when the difference in atomic numbers between coating and substrate material is higher than 5. Ten, fifteen years ago there were many such instruments used in industrial laboratories. Competition of the much cheaper devices based on other physical principles (electromagnetic, eddy- currents, etc.) caused considerable decrease of demands on the β -backscattering coating thickness gauges. However, on-line XRF coating thickness gauges (e.g. for Zn or Sn coatings measurements) are still unrivalled. But instead of radioisotope sources, the X ray tubes are commonly used in such installations. Unfortunately, Polish manufactures of industrial gauges do not yet use X ray tubes for XRF analysis and coating thickness measurements.

Nucleonic weighers

Nucleonic belt weighers are designed for the non-contact on-line measurements of bulk materials transported on the conveyors of belt width from 300 to 1000 mm. They were intended for application in heavy industrial environment. The belt weighers operate on the principle of γ -absorption (Am-241, Cs-137) and the weighing accuracy is claimed to be about

1%. In 80's producer of the nucleonic belt weighers has got a certificate of the Polish Committee of Standards and Measurements. However, in spite of relatively high number of the current installations it seems that industry is less interested in further application of nucleonic weighers. Progress made in design and development of electronic weighers caused, that in many cases nucleonic gauges are replaced by the cheaper and more accurate electronic devices. The prospect of future application of the nucleonic belt weighers is rather gloom.

Sulphuric acid concentration gauge.

Designed and produced in Institute of Nuclear Chemistry and Technology these gauges are intended for the continuous, non-contact measurement of sulphuric acid concentration through the pipe-line (Table 2). The measure of the acid concentration is hydrogen content in the solution, which can be determined using slowing-down neutrons from Pu-238/Be source. The most suitable concentration range for the instrument is 90-99% H₂SO₄. In this range of concentration conductometric devices, as well as methods based on density measurements have much worse performance. This gauge can properly operate with temperature of the acid flowing in the pipeline up to 140°C. More than 40 gauges were installed and are used mainly for the automatic control in sulphuric acid production plants. One can say that for now all demands for such gauges from the Polish industry are fulfilled.

TABLE 2: NEUTRON GAUGES OF ACIDS CONCENTRATION

Acid	Concentration %	Pipe-diameter mm	Sensitivity % /%	Accuracy % abs
H ₂ SO ₄	95-100	108/100	5.1	0.2
	93-98	108/100	4.4	0.2
	70-80	60/54	2.2	0.5
	65-75	57/50	1.7	0.6
HF	65-75	57/50	1.2	0.8
HNO ₃	55-65	57/50	2.0	
H ₃ PO ₄	70-80	57/50	1.1	
H ₂ SiF ₆	30-40	66/47	approx. 1	

Ash in coal monitors

Measurement methods of the ash content in coals, continuous quality monitoring systems (ash and moisture content, calorific value determination) for coals transported on belt conveyors have been elaborated and modernised by the EMAG Centre for almost 30 years. The two on-line systems have found the widest application:

- A system consisting of the radiometric ash monitor based on measurements of γ rays from Am-241 backscattered from the coal layer, and the microwave moisture meter based on measurements of the intensity of 9 GHz microwaves reflected from the coal surface. The ash content can be measured within the range 3-50% and moisture content from 2 to 20%. Accuracy of the both measurements is better than 1%. Having determined values of the ash and moisture it is possible to compute the calorific value of the coal transported on the conveyor. About 30 such — measuring systems have been installed in the Polish coal mines and coal processing plants.

- A system based on the two-source γ rays (Cs-137, Am-241) absorption method. The main advantage of this system is that results do not depend on the varying mass and layer depth of the coal. Till now three such systems have been implemented for raw coal quality inspection.

Laboratory radiometric ash monitor can also be used for determination of sulphur. The X ray fluorescence method is applied with Pu-238 source and proportional counter. Accuracy of ash determination in powdered samples of coal is about 1%.

Coal production in Poland is relatively high — about 120 million tons in 1997 and huge majority of the electric power production is based on the coal. Hence, it can be expected that in the future demands for the industrial gauges designed for inspection of the coal quality will be at least on the same level as today. Since nucleonic gauges are practically unrivalled for the on-line ash measurements their future prospects look quite well.

Airborne dust monitors

The instruments were developed in INCT in 80's and later modernised and are still produced and installed. Principle of operation is based on measurement of the dust mass collected on the fibre glass filter. The dust is collected when the air sample of known volume is pumped through the filter. The mass of the dust is measured using absorption of β rays from Pm-147 source. The instrument operates automatically and needs no attendance for months. Results are stored in the memory and/or can be transmitted through modem and public telephone line. The range of the measurements is from 5 to 5000 $\mu\text{g}/\text{m}^3$ and reproducibility about 2% but not less than 2 $\mu\text{g}/\text{m}^3$. Optionally, the monitor can be fitted with a set of meteorological sensors for measurement of speed and direction of wind, temperature, humidity and pressure of the air.

The dust monitor is not an industrial gauge, but is intended to measure degree of pollution caused by industry. Instruments for the current monitoring of the environment pollution designed for operation in the monitoring networks are of great importance Beta absorption airborne dust monitor proved its usefulness for this purpose, therefore its future prospect looks rather good.

Analysers

This group of instruments consists of analysers designed for on-line application in industry and laboratory devices. Their principle of operation is based on X ray fluorescence excited by such radioisotope sources as Fe-55, Cd-109 or Am-241. Proportional counters are used for detection of secondary radiation. The industrial analyser designed by Polon -ZOT consists of the immersing XRF probe for „in-stream” measurements of Fe, Zn and Pb in zinc ore processing plant. The laboratory XRF instruments are offered by Polon-ZOT and INCT and are very useful for the fast, non-destructive analysis and coating thickness measurements in industrial laboratories.

There are several places, where simple analysers could be applied. It seems, that in future the number of applications will considerably increase when the radioisotope sources will be replaced by an X ray tube. Analysers employing radioisotope sources will be preferable in field applications.

All the radioisotope gauges presented above belong to the new generation of measuring devices. They are computerised and are fitted with data processing and archivization software. An interesting feature of the gauges produced by Polon-ZOT is using ionisation chamber for majority of applications. They are very suitable detectors for industrial application due to their robust construction and stability. However, successful using of ionisation chambers was possible thanks to precise I/f (current/frequency) converter of sensitivity about $820 \text{ cps}/10^{-12} \text{ A}$. The pressurised β and γ ionisation chambers and He-3 proportional counters are produced by the Institute of the Nuclear Studies. The new producer of the X ray proportional counters DETRON claims resolution of its products for Mn K X ray below 15%. Radioisotope sealed sources for industrial gauges practically are not produced in Poland. Similarly, as it was said above, the X ray tubes applicable for industrial gauges are neither produced.

Trends in development of radioisotope gauges

First applications of the radioisotope instruments in industry were reported about 50 years ago. As early as in 1957 number of the radioisotope thickness and density gauges installed in United States was 4000 and increased to 9000 in 1964. In 1961 there were 1465 radioisotope gauges installed in France, 1347 in Germany and 2000 in United Kingdom [1]. However, it can be supposed that since that time an increase in the number of new installations of nucleonic gauges in industry is much slower.

An interesting question is, how to compare radioisotope gauges developed, say 40 years ago with recently produced in developed countries? Which components of the gauges remained unchanged and where the most substantial progress is being observed? It seems, that generally, the measuring heads, or measuring probes, are those components of the radioisotope gauge which remained almost in the same shape as forty years ago. Progress in the radiation detectors used in the industrial gauges is not very impressive. Practically, during the last fifty years no new detector applicable in the industrial instruments has appeared on the market. The hopes for non-cooled semiconductor detectors designed for operation in heavy industrial conditions were not realized. The choice of detectors used in the industrial gauges is the same as forty years ago: ionisation chambers, gas filled and scintillation counters. Naturally, the progress in technology caused that performance of the modern detectors is in some cases considerably better than those produced in the past, but physical principle of their operation is still the same.

The similar situation can be observed in the field of the radioisotope sources. The choice of the radioactive nuclides applicable in the industrial instruments is limited to a few β , γ and X ray sources (see e.g. Table 1). However, during the last decade, in some industrial applications the radioisotope sources are superseded by X ray tubes, which are considered as more safe and their price become comparable with the radioisotope source.

The domain, where the most dramatic progress has been observed and which have had crucial impact on performance of the radioisotope gauges is electronics. The modern electronics creates almost unlimited possibilities of signal processing. Microprocessor systems or microcomputers, which are included in practically every modern gauge enable application of sophisticated computational methods to extract useful information from the measured signal or collected data. It may be supposed, that in the near future progress in the design and application of the nucleonic gauges will be mainly based on development and implementation of those methods into the measuring practice.

A good example of such methodology could be multivariate analysis. It consists of a collection of methods that can be used when several measurements are made on each object in one or more samples. Historically, the bulk of applications of multivariate techniques have been in the behavioural and biological sciences. However, recently interest in multivariate analysis has spread to numerous other fields of investigation [3].

An attempt of using of some multivariate techniques in radioisotope gauges was undertaken few years ago [4]. Application of such multivariate techniques as partial least squares regression (PLS) and artificial neural networks for calibration of some nucleonic gauges will be presented in the next chapters.

Calibration of nucleonic gauges

To calibrate an measuring instrument, is to use empirical data and prior knowledge for determining how to predict unknown quantitative information y from available measurements x via some transfer function [5]. Correct identification of this function, called also calibration model, is very important, since any incorrectness in the model which is later used for prediction, directly influences the measurement error.

One of the specific feature of nucleonic gauges is sophisticated process of radiation interaction with matter, as well as the physical effects connected with conversion of the radiation intensity into electrical signals. Those effects can not be satisfactorily described by the simple physical models which could be applicable in metrology. It seems, that the calibration models of nucleonic gauges should be identified experimentally and a convenient way of their identification is regression analysis. Examples of the calibration models of some nucleonic gauges are presented in Figure 1 [6]. It can be seen from the above examples, that for the most of nucleonic gauges, their calibration models are linear or non-linear, but can be considered as univariate, since generally they use a single variable to determine measured quantity. However, in some cases identification of a model using univariate methodology fails, and then methods of multivariate calibration should be tried.

Figure 2 shows a response from the immersing XRF probe used for „in-stream” measurements of iron, zinc and lead content in slurry. The device is actually operating in lead-zinc ore processing plant. The peaks of characteristic radiation of Fe, Zn, and Pb excited with Cd-109 and measured with proportional counter are strongly overlapped. It is not possible to use detectors of better resolution in the severe industrial conditions. But even having all the peaks resolved, some procedures should be developed to cope with the interelement effect.

Other example is calibration of the XRF gauge designed for simultaneous determination of the thickness and composition of the Sn-Pb deposits plated on the printed boards [4, 7]. The measured sample was irradiated with the γ rays of Am-241. Spectra of the secondary radiation detected by an argon filled proportional counter is shown in the Fig.4. Four interesting area can be observed in the presented spectrum: Sn L peak of energy 3.5 keV, Cu K peak of energy 8 keV, Sn K peak at 25 keV and area between 9 and 14 keV where Pb L peaks should be present. The Cu K peak overlaps the Pb peaks and determination of the net intensity of the Pb L peaks is very difficult. The attempt of the application of any quantitative method relying on the net peak area and least square fitting to the layer thickness and/or tin content in the layer has failed. In the both mentioned gauges calibration problem was solved using multivariate approach.

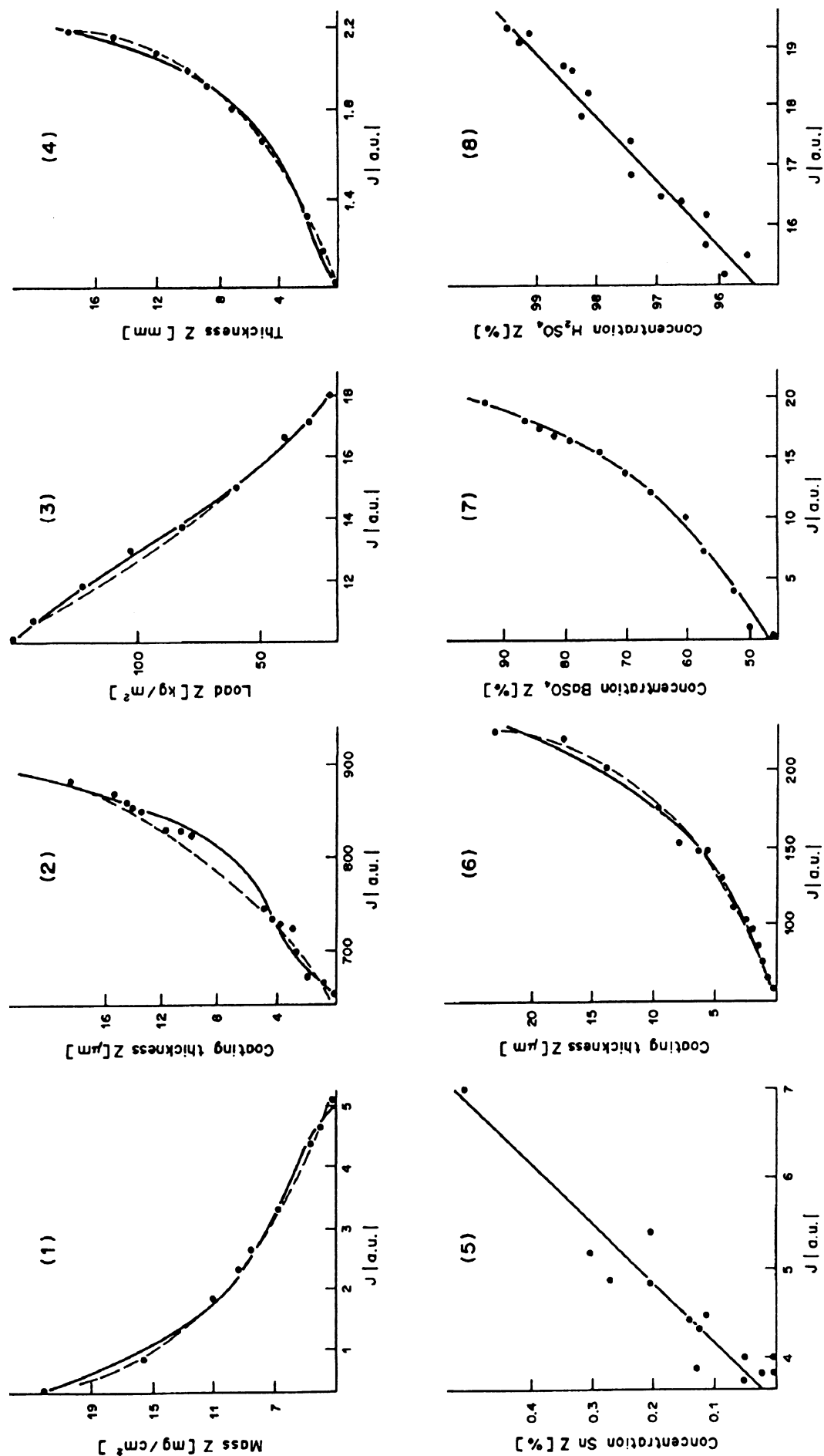


FIG. 1. Models of calibration procedures of some radioisotope gauges.

(1) β transmission (2) β scattering, (3) β backscattering, (4) β XRF (analysis), (6) XRF (coating thickness), (7) γ selective absorption (reverse scale), (8) n scattering (reversed scale).

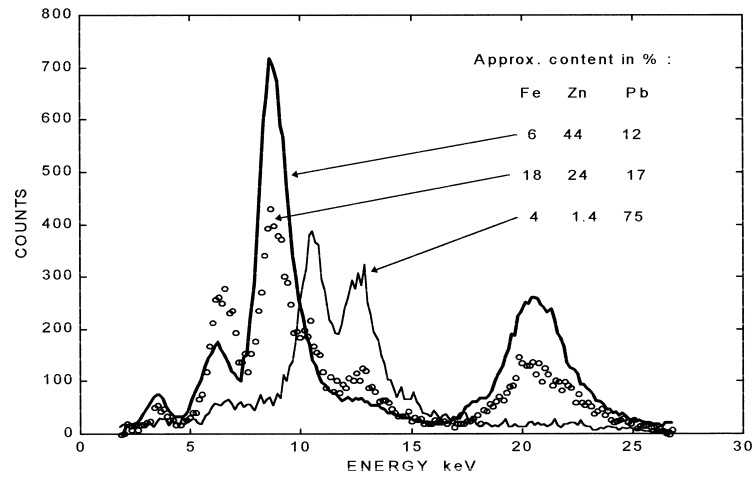


FIG. 2. Secondary X-ray spectra from three samples measured by the immersion probe installed in the zinc-lead ore processing plant (Source: Cd-109, detector: Ar proportional counter). (By courtesy of POLON-ZOT.)

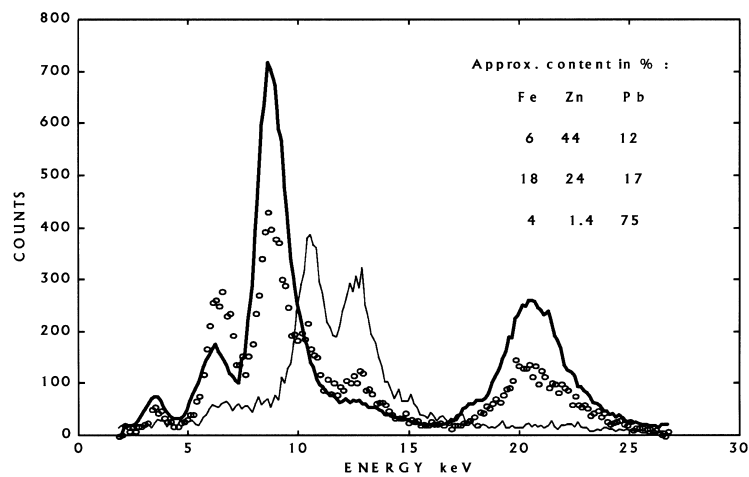


FIG. 3. Secondary X-ray spectra from three samples measured by the immersion probe installed in the zinc-lead ore processing plant (Source: Cd-109, detector: Ar proportional counter). (By courtesy of POLON-ZOT.)

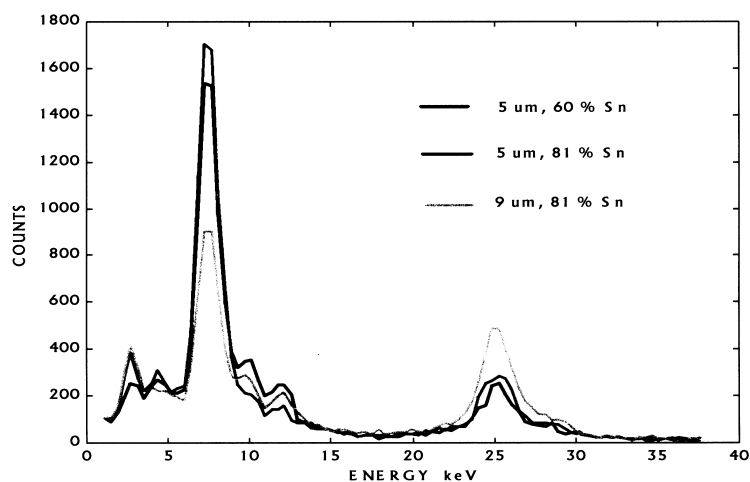


FIG. 4. Secondary X-ray spectra from three samples of different thickness and composition of SN-Pb layers plated on printed board.

Multivariate approach

Multivariate calibration means determining how to use many measured variables $x_1, x_2, \dots, x_m = \mathbf{x}$ simultaneously for quantifying some target variable y [5]. For instance, variable \mathbf{x} could be a vector corresponding to the entire spectrum of measured radiation (Fig .2, 3) and the target variable could be measured quantity (e.g. thickness or concentration of an analyte). In the multivariate calibration, if \mathbf{y} is a vector of dependent variable from n observations and \mathbf{X} is a matrix of m variables from n observations (n spectra of m channels), the linear regression model looks like:

$$\mathbf{y} = \mathbf{X}\mathbf{b}_k + \mathbf{f} \quad (1)$$

where: \mathbf{b}_k — vector of m regression coefficients \mathbf{f} — vector of residuals.

Least squares solution of the above equation (by the multiple linear regression — MLR) is equal:

$$\mathbf{b}_k = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y} \quad (2)$$

The MLR model when used for the whole spectrum variables presents two main problems:

- Estimation of \mathbf{b} can be accomplished if the number of observation n is sufficiently higher than the number of the variables (channels) m .
- Matrix $\mathbf{X}^T \mathbf{X}$ is being inverted, so the columns of \mathbf{X} should not be intercorrelated.

To solve equation (2) and avoid problems connected with MLR approach, the biased regression methods such as principal component (PLS) could be used. Their principle is to compress the matrix data

$$\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_m\} \quad (3)$$

into a set of a latent variables, called also components or factor scores:

$$\mathbf{T} = \{\mathbf{t}_1, \mathbf{t}_2, \dots, \mathbf{t}_a\} \quad (4)$$

where $a \ll m$. In other words, the matrix \mathbf{X} is decomposed into the sum of outer products of vectors called loadings (\mathbf{p}) and scores (\mathbf{t}):

$$\begin{aligned} \mathbf{X} &= \mathbf{t}_1 \mathbf{p}_1^T + \mathbf{t}_2 \mathbf{p}_2^T + \dots + \mathbf{E} \\ &= \mathbf{T} \mathbf{P}^T + \mathbf{E} \end{aligned} \quad (5)$$

Where \mathbf{E} is the matrix of residuals not explained by the above model..

The score vector (\mathbf{t}) represents the correlation between the objects (samples) whereas the loading vector (\mathbf{p}) represents the correlation between the variables [8].

Having matrix \mathbf{X} decomposed into a few (a) components \mathbf{t} it is easy to find a relationship between vector of the dependent variable \mathbf{y} and score matrix \mathbf{T} and after then to compute \mathbf{b} being used to predict the value of y_p from the measured spectrum \mathbf{x}_p .

$$y_p = \mathbf{x}_p \cdot \mathbf{b} \quad (6)$$

Selection of the optimal number of components (a) included into the calibration model is very important since it determines prediction ability of the model. As more dimensions are included, the model may be overfitted owing to the addition of higher rank components containing more noise. The overfitted models fit well to the calibration data but have worse predictive abilities [5]. Selection of the optimum number of components can be accomplished by internal cross-validation. The principle of leave-one-out cross-validation is such, that from a given set of n reference samples calibration is performed using n-1 samples and the $y_{i, cv}$ value for the object not included into the calibration set is predicted. This process is repeated a total of n- times until each sample has been left once. The sum of squared differences between the reference y_i and predicted $\hat{y}_{i, cv}$ values, called RMSECV (root mean squared

error of cross-validation) is a measure of predictive ability of the model. A reasonable choice for the optimum number of components would be that which gives the minimum RMSECV.

$$\text{RMSECV} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_{i, cv})^2} \quad (7)$$

Formal tests for predictive ability of a PLS model with a given number of dimensions can be found in the literature. [9]

Another method of model validation is using an independent set of k reference samples (not participating in calibration) and compute the root mean square error of prediction (MSEPr)

$$\text{RMSEPr} = \sqrt{\frac{1}{k} \sum_{i=1}^k (y_i - \hat{y}_{i, pr})^2} \quad 8)$$

where:

- k - number of samples in the prediction set
- y_i — reference value
- $\hat{y}_{i, pr}$ -value predicted from the model

A quantity showing how well a chosen model for a particular set of calibration samples fits the reference data is called RMSEE (root mean square error of estimation).

$$\text{RMSEE} = \sqrt{\frac{1}{n-a-1} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (9)$$

Multivariate calibration can also be used for identification of non-linear models. [10]. In such cases, the inner relation between the dependent variable y and latent variable t for each component is approximated by a non-linear function, such as a polynomial or a spline [11].

Since the middle of the last decade an increasing drive towards the application of the artificial neural network (ANN) has been observed. One of the fields when ANN offer a powerful set of tools is multivariate calibration of sophisticated measuring systems [12]. Sometime the both multivariate calibration methods as combined: PLS loadings are used as weights of the neurones in the hidden layer of the ANN.

Computation leading to identification and validation of the multivariate model can be performed using available software packages, e. g. [13]. However, it seems that one of the important problems emerging in the multivariate calibration of nucleonic gauges is to find physical interpretation of the computed results. It should be always kept in mind, that multivariate data analysis which is the base of multivariate calibration, tells about calibration data structures and correlation patterns but it does not tell the name of the processes that generated then [8].

Application

Application of the multivariate calibration will be presented on the three following examples: measurements of thickness and composition of the Sn-Pb layers, determination of ash in black coal, and measurement of the coating thickness of nickel on iron substrate. In the all considered examples X ray fluorescence was used as the measurement methodology.

Thickness and composition of Sn-Pb layers

A set of 24 reference samples of Sn-Pb coating thickness ranging from 2 to 9.5 μm and Sn content in the layer within the range 60-81% was used for calibration and prediction testing. X ray spectra (Figure 4) from 16 samples were used to construct calibration model and 8 to test prediction ability of the model being developed.

Spectra of the first two PLS loadings \mathbf{p} and predictors \mathbf{b} computed for the coating thickness measurement and determination of the Sn content in the layer are presented in Figures 5-6. They show contribution of the individual parts of the X ray spectrum (Figure 4) in the value of the predictor \mathbf{b} used for determination of the thickness and composition from the calibration model.

It can be seen, that for the coating thickness the most important part of the spectrum is Cu K peak, whereas for the Sn content its contribution is negligible. On the other hand, Sn and Pb L peaks as well as Sn K play the most important role in Sn content determination. It is in good agreement with the qualitative examination of the spectra presented in Figure 4. However, using multivariate decomposition of the calibration matrix one gets a quantitative relationship between radiation intensity collected in the individual channels and measured parameters (thickness and composition of Sn-Pb layer).

The score plot presented in Figure 7 reveals that the first component represents variability of the responses from the calibration samples, caused by the changes of the Sn-Pb coating thickness whereas the second PC is responsible for the variability of Sn content in the layer. It also agrees well with the pattern shown in Figure 4 where it can be seen, that changes in the coating thickness much more influence intensity of the registered radiation than variability of the Sn content in the layer.

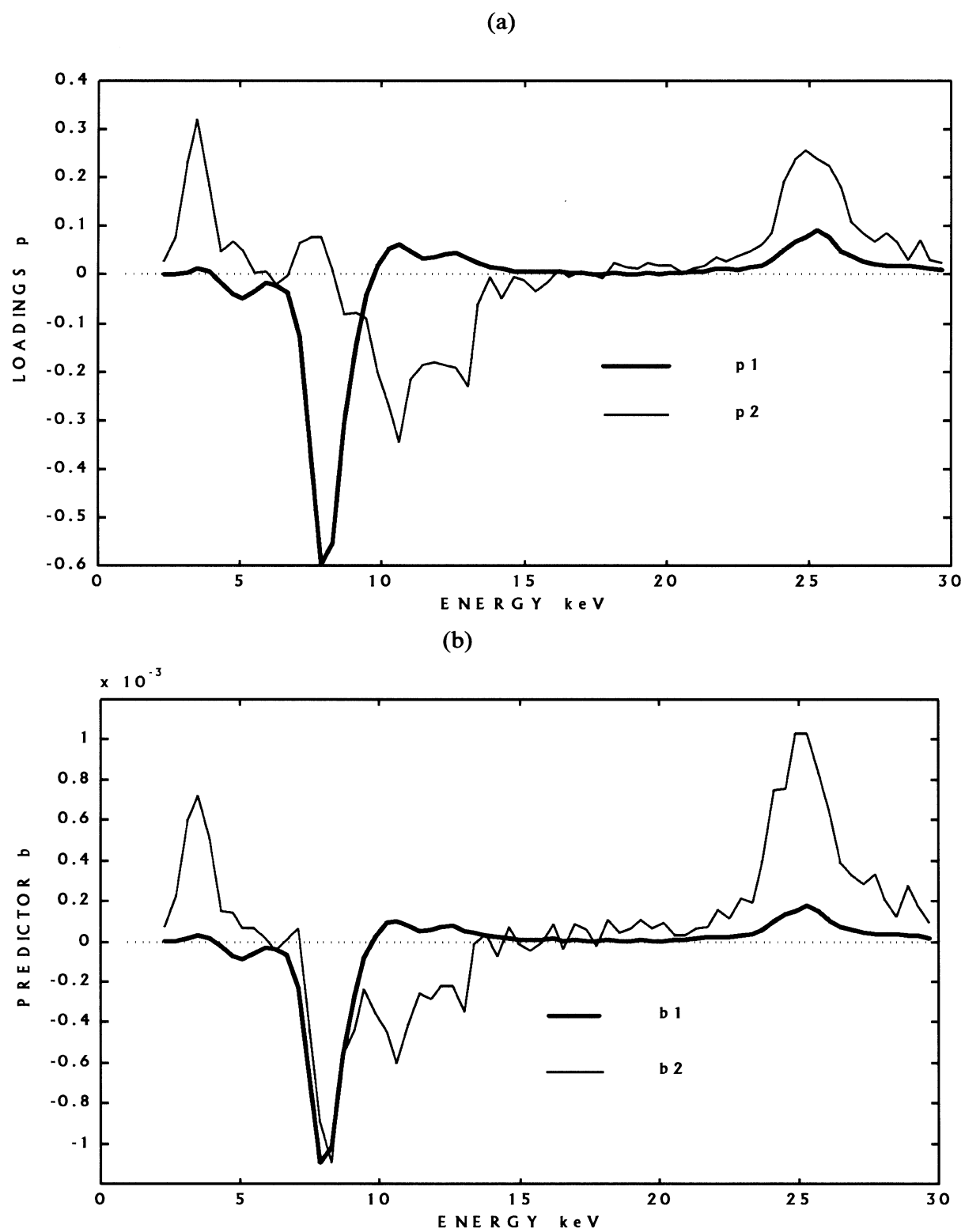


FIG. 5. PLS loadings (a) and predictors (b) for the first two principal components. Calibration of SN-Pb coating thickness.

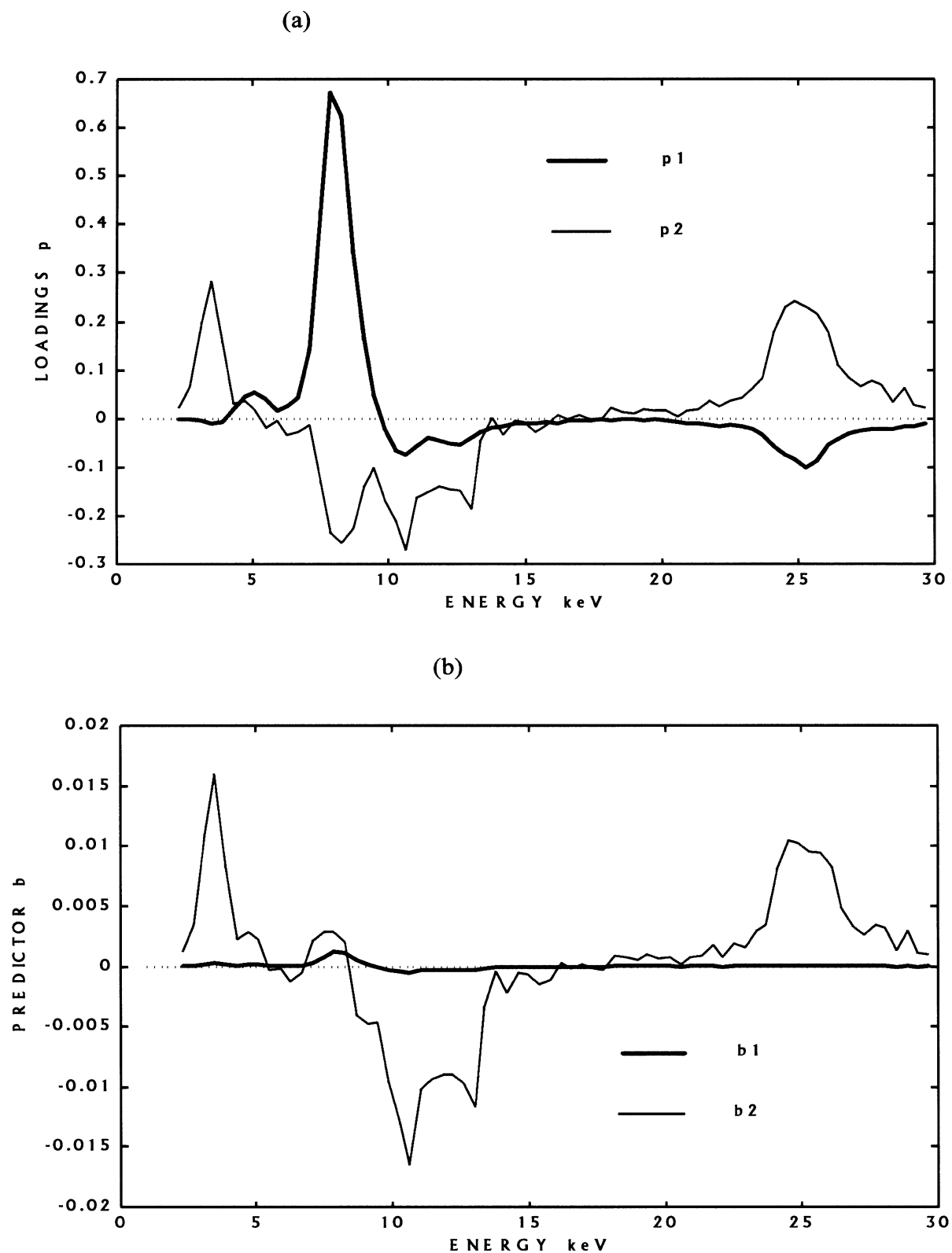


FIG. 6. PLS loadings (a) and predictors (b) for the first two principal components. Calibration of Sn content in layer.

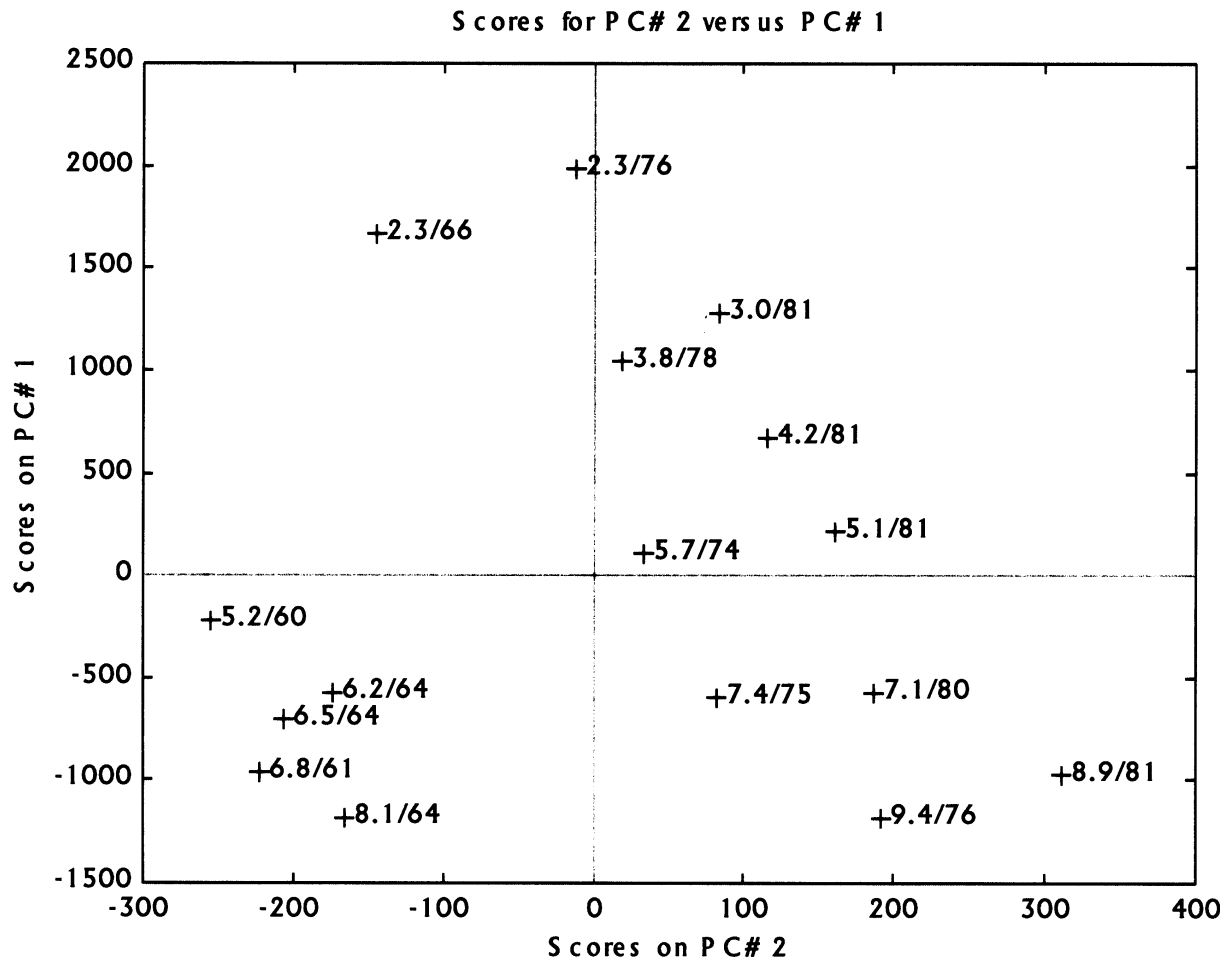


FIG. 7. Scatter plot of the two first scores for the set of calibration samples. First number left of the cross shows the coating thickness in μm and the second number Sn content in the layer in %.

The same data were used to develop ANN calibration model [14]. The network was learnt successively for each of the parameters (thickness and Sn content). Number of neurons in the hidden layer varied from 1 to 4. Two ways of NN training were applied:

- (1) preset weights and thresholds of neurons in the hidden layer were random variables ranging from -1 to 1.
- (2) weights of the hidden layer neurons were chosen as the loadings computed for the PLS regression for the same set of the calibration samples.

Prediction abilities of both the ANN and PLS models have been computed and results are presented in Tables 3 and 4. The models were tested using a set of samples (not included into the calibration set) but for the PLS model cross-validation technique was also applied. It is seen that in the case of coating thickness measurements the RMSEPr value is considerably lower for the ANN model than for the PLS but for determination of Sn content the ANN model gives generally poorer results. However, when the PLS loadings are used as weights of the neurons in the hidden layer, RMSEPr for Sn content improves and learning process in this case becomes much faster.

TABLE 3: ROOT MEAN SQUARE ERRORS OF ESTIMATION, CROSS-VALIDATION AND PREDICTION FOR PLS REGRESSION

		a = 1	A = 2	a = 3	a = 4	a = 5
Thickness	RMSEE μm	0.63	0.42	0.21	0.10	0.05
	RMSECv μm	0.61	0.46	0.36	0.41	0.41
	RMSEPr μm	0.65	0.52	0.35	0.40	0.41
Tin content	RMSEE %Sn	8.82	2.05	1.20	0.72	0.43
	RMSECv %Sn	8.29	2.40	2.42	2.59	2.63
	RMSEPr % Sn	5.20	1.31	0.83	0.90	1.10

TABLE 4: ROOT MEAN SQUARE ERRORS OF PREDICTION (RMSEPR) FOR DIFFERENT NUMBER NEURONS (S1) IN THE FIRST LAYER. ANN MODEL

		S1 = 1	S1 = 2	S1 = 3	S1 = 4
Random weights	Thickness μm	0.41 0.45	0.31 0.27	0.33 0.27	0.35
	Tin content %Sn	3.14	2.28	1.81 2.06	3.26
Weights of the first layer as loadings from PLS	Thickness μm	-	0.25 0.28	0.27 0.28	-
	Tin content %Sn	-	1.20 1.27	1.10 0.82	-

It seems that better results of the coating thickness measurement obtained for the ANN calibration model can be explained by the fact, that the relationship between the intensity of registered radiation and coating thickness is non-linear. It can be expected that ANN calibration model computed for the tansigmoid transfer function should exhibit better prediction ability than the linear PLS model.

Cross-validation of the PLS model yields a local minimum at three latent variables (Table 3) whereas no more, than two would be expected, because there are only two processes influencing calibration data system — variable coating thickness and Sn content. It can also be explained by the fact, that an extra latent variable is required to model the non-lineanties existing in the data set.

One can observe also, that number of neurons (S1) in the first layer of the ANN corresponds to the number of components in the PLS. model. For S1 = 4 some overfitting can be seen, and the same effect can be noticed for the number of PLS factors higher than 4.

Possibility of using X ray fluorescence and scattering of the low energy X ray for measurement of ash concentration in coal was reported in the literature many years ago [15]. The weakness of this method is influence of the variable iron content in the measured sample on the intensity of backscattered radiation. This effect can be observed on Fig 8. where the spectra of 28 coal samples with ash content ranging from 2 to 30% are presented. It is seen, that for samples with high iron content (peak at 6.4 keV) a „valey” in backscattered radiation (15–20 keV) can be observed. It is possible to overcome this effect using multivariate calibration.

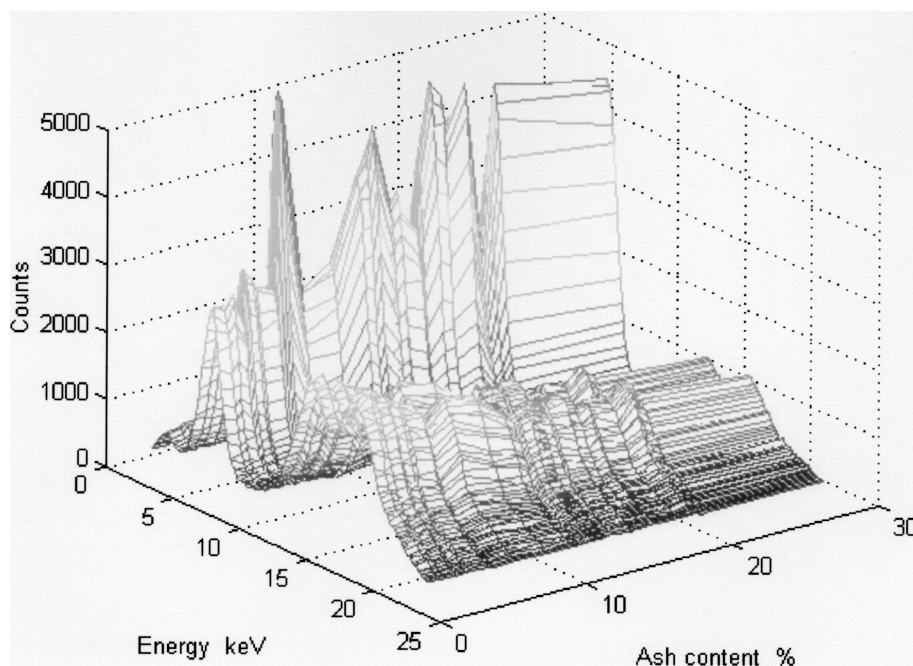


FIG. 8. Spectra of the secondary X-rays from 28 powdered samples of black coal. Source: Pu-238, detector: Ar proportional counter.

The spectra from Figure 8 were used as the calibration data set to compute PLS models. Two models were computed: first using original spectra and second using corrected spectra, where in the area of backscattered radiation, instead of count-rates in the individual channels their reciprocal values were taken to the model. The spectra of the PLS predictors **b** for the first and second component, for the original and corrected spectra are shown in Figure 9a and 9b, respectively. It is seen that in the both cases intensity of Fe K radiation has significant contribution to the model.

Mean square errors of estimation and cross-validation are presented in Table 5 [14]. Local minimum of the RMSECV is observed for the models consisting of four components. However minimal RMSECV value for the corrected spectra (1.1%) is about 50% lower than that for the original spectra (1.7%), which confirms advisability of applied correction.

The same data sets (original and corrected) were used for computation of the ANN calibration, but no significant improvement compared with PLS model was observed.

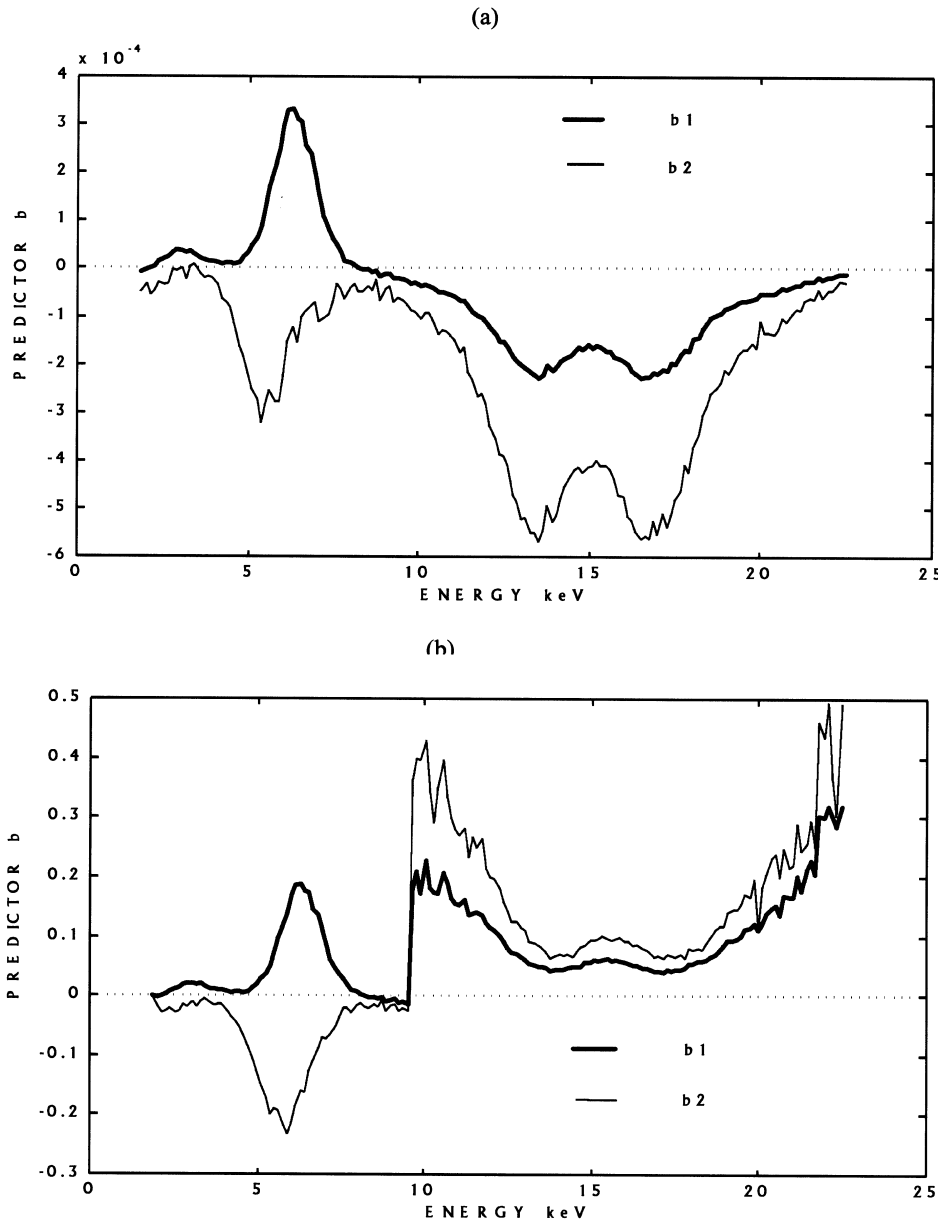


FIG. 9. Predictors b for the first and second principal components for the original (a) and corrected (b) X-ray spectra of the coal samples from Fig. 7. In corrected spectra, reciprocal value of counts corresponding to the scattered radiation is taken to the model.

TABLE 5: ROOT MEAN SQUARE ERRORS OF ESTIMATION (RMSEE) AND CROSS-VALIDATION FOR PLS MODELS. MEASUREMENT OF ASH CONTENT IN COAL.

		a = 1	a = 2	a = 3	a = 4	a = 5
Original Spectra	RMSEE %	4.48	1.99	1.64	0.89	0.57
	RMSECV%	4.55	2.09	1.89	1.70	1.78
Corrected Spectra	RMSEE %	6.00	1.31	1.11	0.97	0.54
	RMSECV%	6.16	1.49	1.29	1.10	1.16

Measurement of Ni thickness on Fe substrate.

The spectra of 13 reference samples of Ni coating deposited on Fe base are shown in the Figure 10. Thickness of the Ni layer varied from 1 to 14 μm and their XRF spectra were collected in 70 channels. The measurements were performed using a Cd-109 X ray source and an argon-filled proportional counter. It can be seen that the Fe K and Ni K peaks are strongly overlapped. Moreover, the relationship between the intensity of the registered Ni K or Fe K peaks and the coating thickness is non-linear.

Both the linear and non-linear PLS regression were used for the calibration and the obtained results are presented in the Table 6 [16]. In the non-linear PLS the second and third degree of polynomial regression spline was used as inner relation [11]. It can be seen that linear models give rather poor results. The results obtained for non-linear models are considerably better, however, increasing the degree of polynom and/or the number of knots of the used regression spline causes increase of RMSECV value, whereas RMSEE remains on the same level. It is typical overfitting effect [5] and possibility of its occurrence should always be taken into consideration, especially in the non-linear PLS and ANN models [17].

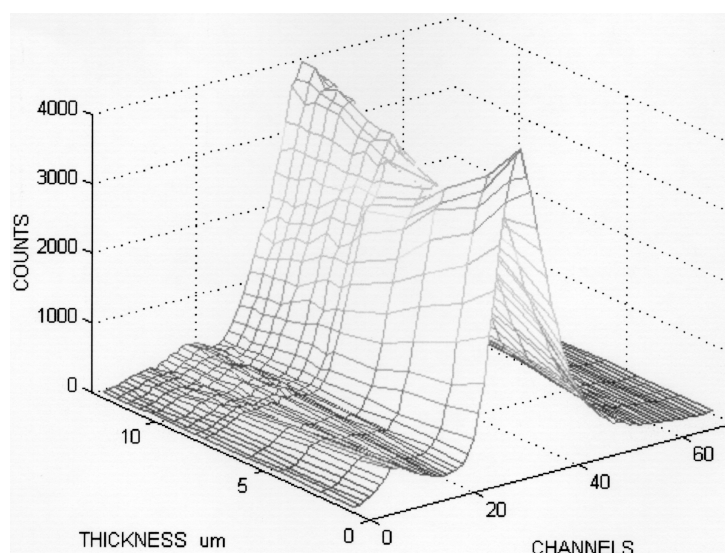


FIG. 10. XRF spectra of a set of Ni/Fe reference samples. Source: Cd-109, detector: Ar proportional counter.

TABLE 6: RESULTS OF MEASUREMENTS OF NI COATING ON STEEL SUBSTRATE OBTAINED WITH LINEAR AND NON-LINEAR PLS CALIBRATION.

RMSEE μm	RMSECV μm	Number of components	Degree of polynom/Number of knots in spline
0.65	0.85	1	Linear model
0.34	0.68	2	Linear model
0.29	0.35	1	2/0
0.27	0.55	1	3/0
0.27	0.36	1	2/1
0.27	0.57	1	3/1

Discussion of the calibration results

Multivariate calibration can be used in gauges giving response in the form of a vector. In other words, it can be applied in such cases, when spectrometric signal is used, or signals from many sensors or detectors are collected. Being used in spectrometric radiometric gauges is advantageous especially in those cases, where the useful information is not sufficiently selective and is distributed over the whole spectrum. It means that it may be successfully used even when peaks in the spectrum overlap. Moreover, this calibration procedure allows also to compensate interelement effect, when used in XRF analyzers.

Physical interpretation of some PLS parameters is important, since it can provide a new insight into the methodology used, thus allowing a better understanding of measuring process. It is dangerous to apply a statistical predictor if the user do not understand what it means.

Non-linearity between the measured quantity and the intensity of registered radiation can be included in the calibration model either by increasing the number of PLS components or by applying non-linear models. Also artificial neural networks have proved their applicability for development of the multivariate calibration models. However, using ANN method for calibration, possibility of finding physical interpretation of computed parameters is lost.

Multivariate, compared with univariate calibration method exhibits also an important feature — creates possibility of detecting a sample as an outlier. One of the methods of outliers detection is analyzing the score plots (Figure 7) for first two or higher rank components.

In the PLS calibration model, variation in the data matrix (\mathbf{X}) is approximated by \mathbf{TP} , where \mathbf{T} , spans all possible types of systematic factors: e.g. concentrations, coating thickness, interferences and non-linearities. Hence, the measuring system can be calibrated for a single factor, assuming other factors influencing data matrix as interferences. It has been shown, that in the case of the Sn-Pb layers, the system can be calibrated for the Sn content without knowledge of the layer thickness, providing that the thickness is properly spanned in the calibration set. Generally it should be noted, that all phenomena that vary in the target population, must be spanned in the calibration set and described in the calibration model [5].

Application of the methods of multivariate analysis is not limited only to the calibration. These methods can be also used for interpretation of the results obtained from the measuring devices, as well as for the pattern recognition or image processing [18].

CONCLUSIONS

There are more than thousand radioisotope gauges installed in Polish industry. They belong to the new generation of measuring devices and their performance fully satisfy industrial users. It seems that in the near future, the number of installed level, thickness and density gauges, as well as airborne dust monitors together with industrial analyzers will be kept at least on the similar level as today. Number of installed nucleonic belt weighers and laboratory coating thickness gauges rapidly decreases.

One of the direction of development on the field radioisotope gauges is application of the multivariate analysis for calibration and data treatment. Some studies of this subject showed, that multivariate calibration gives very promising results and can create new application of

the radioisotope gauges, particularly in those cases where spectrometric methods of X and γ ray are employed.

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CURRENT STATUS OF NUCLEONIC GAUGES IN PORTUGAL

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Abstract

The nucleonic gauges are largely used in Portugal industry, despite the fact that design and manufacturing of prototypes of nucleonic gauges is rather limited. The modernization of some industrial sectors (cement, paper and civil engineering) has enhanced applications of nucleonic gauges and has created local capability but new legislation tends to restrict further spread of them. The Institute of Nuclear Technology is the only applied research institution developing nucleonic gauges for moisture, thickness and density, and elemental analysis, as well as providing assistance in calibration, safe operation and maintenance of them.

1. INTRODUCTION

In 1961, the Nuclear Physics and Engineering Laboratory (LFEN) was founded which became the main laboratory of the Portuguese Atomic Energy Commission (Junta de Energia Nuclear). LFEN originated the present-day Institute of Nuclear Technology (ITN) under the Minister of Science and Technology. Some theoretical and laboratory work on radiation attenuation in materials was reported during this period.

In 1975, a joint team of physicists and engineers initiated a programme of development of nuclear methods and nucleonic gauge prototypes. The intention was to develop national capability in design and fabrication of nucleonic gauge prototypes to serve local end users. The first difficulty to overcome was, naturally, the mistrust of national capability from end users, which preferred purchasing them abroad.

The first contract came from the Portuguese Steelworks to develop a neutron surface moisture gauge to be mounted on the side-wall of a hopper to monitor the moisture of the coke charged into the blast furnace. The system was installed in 1977 upgraded a few years later and is still in operation. Many other gauges were designed and produced later on.

2. NUCLEONIC GAUGES INSTALLED IN PORTUGAL

Operational nucleonic gauges can be found in Portugal in a broad range of industrial and other activities. The most important are: cement fabrication, chemical industry, basic metal industry, petrol, paper, plastics, textile, wood and food industries, civil engineering, mining and agriculture. The main gauge types used are level monitors (including package monitors), thickness, density and moisture gauges, X ray fluorescence systems and X-or gamma ray radiographic equipment. Most units are imported but some were designed and made locally .

Figure 1 shows the number of gamma level monitors installed in different industries in the indicated time-intervals. Since 1964 415 gauges (100 of ITN design) were installed. Most of them are in factories of the cement and chemical industries.

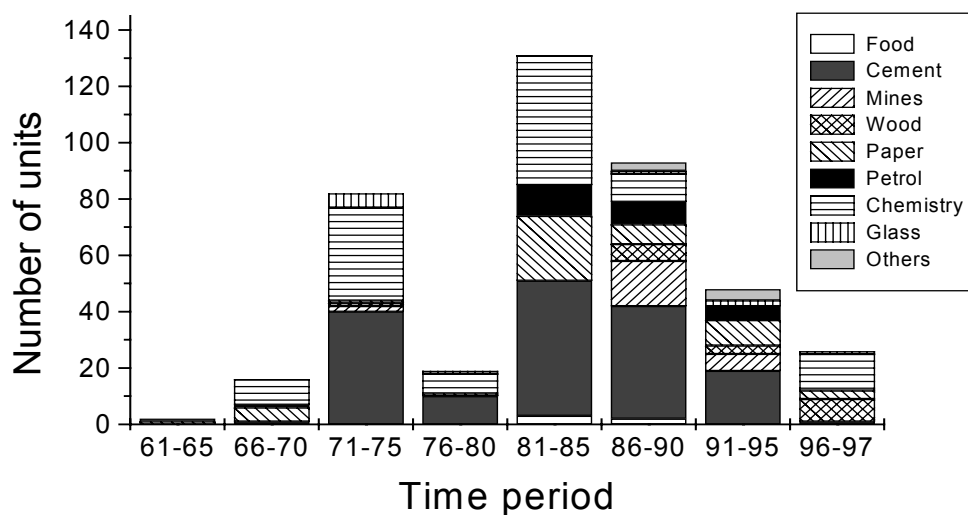


Figure 1: Gamma level monitors installed in Portugal

Also surveyed were 54 package monitors to control the fill-level (mainly of beverages) in tins, cartons and bottles. Figure 2 shows the overall distribution of these package monitors by different activities. The main users are in the field of food and beverages.

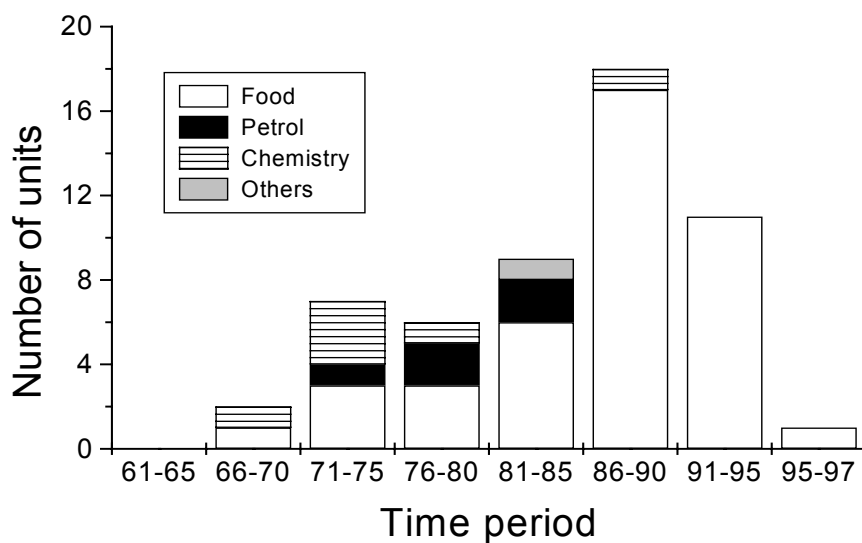


Figure 2: Package monitors installed in Portugal

Density and thickness gauges have a widespread application. The first gauge was installed in 1964 in the plastics industry. Since then 228 gauges were installed. The number and the time-rate of installation of new gauges have steadily increased (Figure 3), except in the last time period. The main users of thickness gauges are the paper and textile industries.

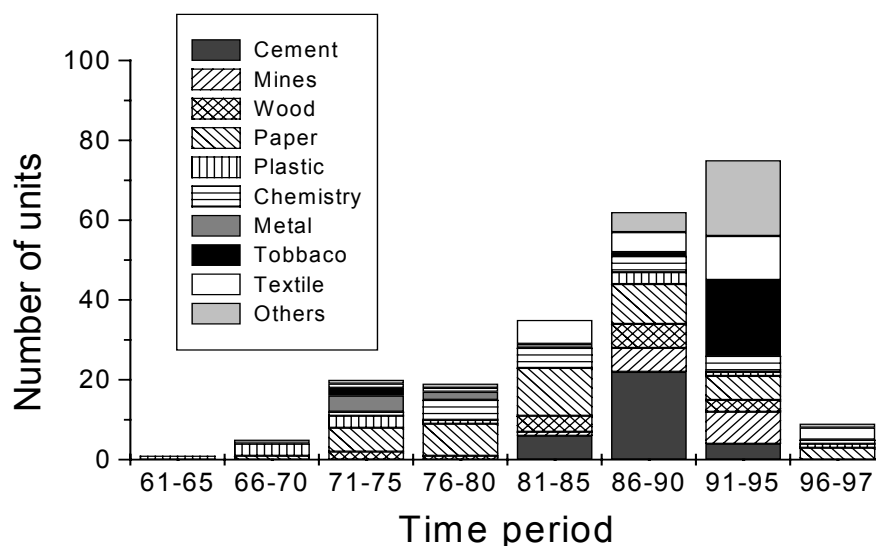


Figure 3: Density and thickness gauges installed in Portugal

The main users of surface and depth density–moisture gauges are in civil engineering (mainly for real-time monitoring of the compactness of pavement layers during road construction) and in agriculture (density and moisture profiles of soils) (see Figure 4). Surface moisture gauges are also being used for controlling coke moisture content (2 units). In total 66 units have been surveyed, 15 of them of ITN design.

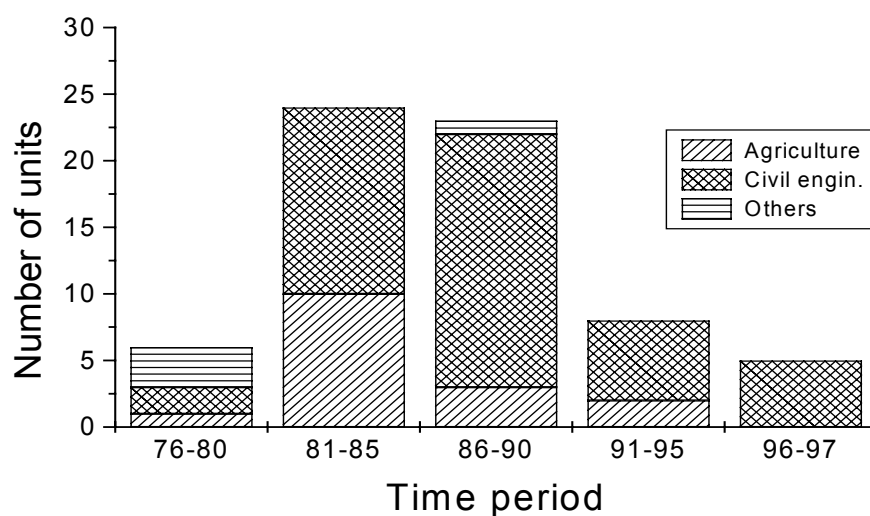


Figure 4: Density-moisture gauges in use in Portugal

Ore processing plants are the principal users of X ray fluorescence techniques, as is shown in Figure 5. Forty-two systems have been installed.

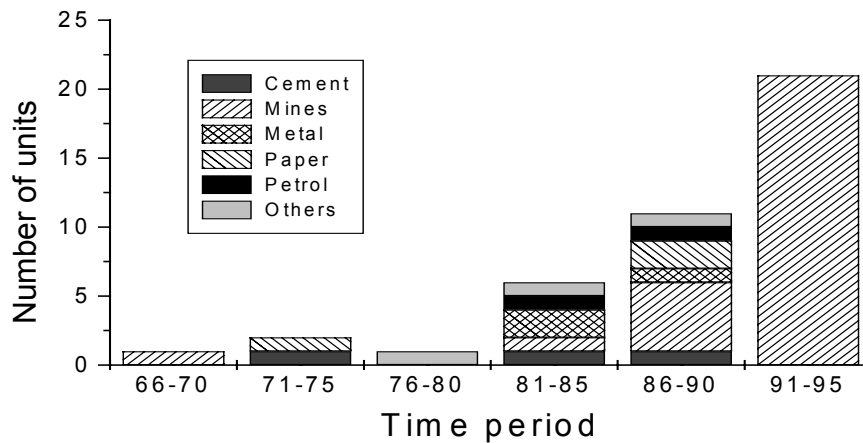


Figure 5: XRF instruments in operation in Portugal

The number of companies that are applying industrial radiographic techniques, using X ray tubes or gamma ray sources, has also increased, attaining at present 60 (Figure 6). The histogram represents the number of new units acquired in the indicated time interval. Excluding the abrupt jump in the period 1971 to 1975, the average annual increase in the number of companies engaged in the radiographic techniques appears to have stayed relatively constant for several decades.

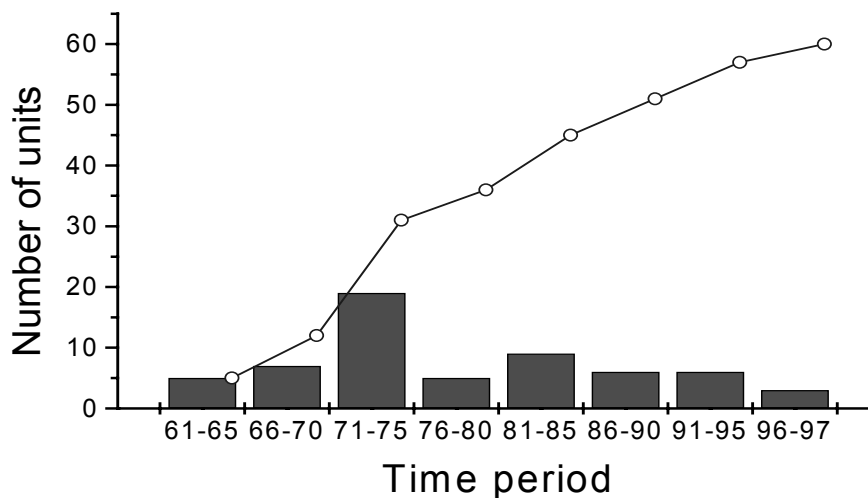


Figure 6: Industrial radiographic systems used in Portugal

Other applications of nuclear gauges are continuous mass measurement on conveyor belts (5 radioisotopic balances surveyed) and X ray control of parcels and luggage (9 units).

It is difficult to explain the evolution of the use of nuclear systems in our country. Along the years, several factors have contributed in opposite ways to this situation. The modernisation of some industrial sectors (cement industry, in the 80s) and the construction of highways (in the 80s and 90s) have contributed to an increment in the application of specific types of nucleonic gauges. On the other hand, the coming in force of a new law in 1996 may

objectively counter the growth of the number of new equipment making use of radioactive sources. In fact, this law imposes on the owner of the installation an obligation of insuring civil liabilities in the amount of ca. \$US 100,000 for source activities greater than 1 GBq and at the same time requires the deposit of a guarantee in the amount of 10% of the price of the radioactive source to be freed only after the source is disposed away.

3. DEVELOPMENT OF NUCLEONIC GAUGES AND NUCLEAR INSTRUMENTATION

Since the 70s, our laboratory has invested a considerable effort in the development of nucleonic gauges and nuclear instrumentation. Normally, the specifications of the instruments or of the techniques were discussed with the end-users and the hardware and software were designed and tested taking into account the required specifications. In general, instruments and systems were customised and a prototype were supplied. Only in a few cases small equipment series were fabricated. In the following, a short description is given of the nuclear instrumentation developed through the years with a brief reference to application.

Industrial neutron moisture gauge: Neutron moisture gauges have been in operation for 20 years at factories of the steel and chemical industries, for the determination of the water content of coke. A noticeable improvement in furnace control and, consequently, in iron quality was achieved (Salgado *et al.*, 1981).

Nuclear moisture and density depth-gauges for soil studies: The gauges for soil studies are designed to measure soil moisture and bulk density profiles down to several meters below the surface. The gauges are mainly used for irrigation studies and the determination of water consumption by plants (Salgado *et al.*, 1983, Salgado *et al.*, 1987, Pacheco, 1989).

Gamma ray transmission density probe: The gamma ray transmission probe is designed for high spatial resolution measurements of arable soil porosity and bulk density (Pacheco, 1989).

Gamma ray level indicator: The gamma ray level indicator has found application in several industrial branches, such as cement factories, paper pulp plants, oil refineries, glass making.

Spark counter: The jumping spark counter is designed for fast and reliable automatic counting of nuclear tracks in thin plastic foils. Indoor radon measurements have been performed in dwellings, caves and spas (Faísca and Bettencourt, 1987, Faísca *et al.*, 1991, Faísca *et al.*, 1991, Faísca and Teixeira, 1995). Radon exhalation measurements in soils and building materials have also been carried out (Faísca *et al.*, 1995a and Faísca *et al.*, 1997).

Gamma ray spectrometer for nuclear monitoring of refractory lining wear: The instrument is a dual-channel analyser designed for the simultaneous measurement of gamma rays emitted by ^{192}Ir and ^{60}Co sources. Measurements of lining wear rates in a steel convertor were carried out during several campaigns at the Portuguese Steelworks (Salgado *et al.*, 1988). The technique is currently used to control the lining wear of the company's convertors.

Liquid or slurry density gauge: Following a request of the National Civil Engineering Laboratory, in Lisbon, a system was developed for measuring solids in suspension in water for sedimentation studies in rivers and estuaries.

Moisture transmission gauge: A transmission gamma ray gauge was designed for measuring the moisture content of building materials with given composition and geometry. The equipment fulfils the specifications required by the Dept. of Civil Engineering, of the Faculty of Engineering, Porto.

Electrodeposition set for the determination of radioactive element traces: A standard electrodeposition set was developed for the determination of radioactive element traces. This unit has been supplied to Algeria, Bulgaria, Romania and Turkey through the IAEA TC. The same standard of the electrodeposition set have been supplied also to the IAEA Maritime Environment Laboratory (MEL) in Monaco, to the EC Joint Research Centre, in ISPRA, Italy, and to Environmental Physics, Inc, USA.

Personal radiation dosimeter: Two models of a pocket size radiation dosimeter for monitoring personnel subject to X-and gamma ray exposure hazards have been developed and are available commercially.

4. OPTIMISATION OF NUCLEONIC GAUGES, PROGRESS IN CALIBRATION

Nuclear measurement methods are, normally, indirect methods. A calibration is required to relate the detector count rates to the physical quantities to be determined. The calibration curves depend on the nature, size and relative position of gauge components, as well as on the bulk density, moisture and dry composition of the material. Bench experimental methods are very time consuming in the case the calibration has to yield results applicable to a wide range of situations and they require handling large amounts of samples with known compositions. Non-experimental methods based on calculations are currently used. Among these methods, the Monte Carlo simulation technique has proved to be particularly useful in handling calibration problems, namely in complicated geometries such as those normally found in nuclear gauge applications. By means of this technique, radiation interaction and transport are simulated and the desired quantities are recorded for each geometry or set of parameters defining the measuring arrangement. Although a Monte Carlo simulation study does not replace the experimental calibration work, it reduces the number of experimental points, references or standards necessary.

On the other hand, as the system response is a multi-variable function of several parameters (composition, moisture, bulk density, source radiation energy, and system geometry), a design optimisation of the system is desirable. The purpose of this optimisation is to reduce the complexity of the functional dependence of the system response relative to the calibration parameters and thus to simplify the calibration work or to increase the sensitivity and/or accuracy of the method. This can be achieved, for instance, by acting on the system geometry, sample dimensions or on the radiation source spectrum. Monte Carlo methods can also be used for this objective.

Since the early 80s, Monte Carlo method for optimisation and calibration of nucleonic gauges was introduced. In the beginning we have used self-developed computer codes. Oliveira (1982) carried out the first simulation. The objective of the work was the simulation of a surface density probe using a ^{137}Cs gamma-source, and a GM tube. The code used the principle of similitude (Christensen, 1972) in order to increase the calculation efficiency. The results showed the influence of the density, equivalent atomic number and distance source–detector on the photon energy and count rate as well as the depth reached by 95% of the photons that are counted, which is a measure of the importance layer. Figure 7 reproduces this quantity. For densities greater than 1.5 g.cm^{-3} the importance layer attains about 10 cm.

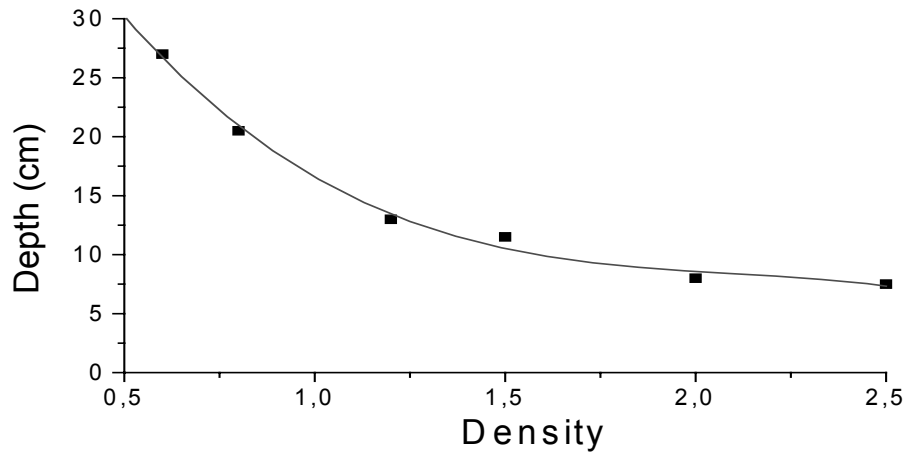


Figure 7: Dependence of the importance layer of a surface density gauge on the density

Another study was the design and calibration of a gamma ray transmission density probe (Oliveira and Salgado, 1987). The distance between source and detector can be mechanically set at either 20 or 30 cm; two gamma sources (^{137}Cs and ^{60}Co) were considered. The work established the dependence of important parameters (build-up factor, sensitivity, relative statistical error, spatial resolution, calibration curves) on density, gamma ray energy and source-detector distance. Figure 8 shows the spatial resolution – defined as the layer thickness, which contributes 95% to the total count rate. The curves show that the resolution becomes worse as (a) the source detector distance increases and (b) the source photon energies decrease.

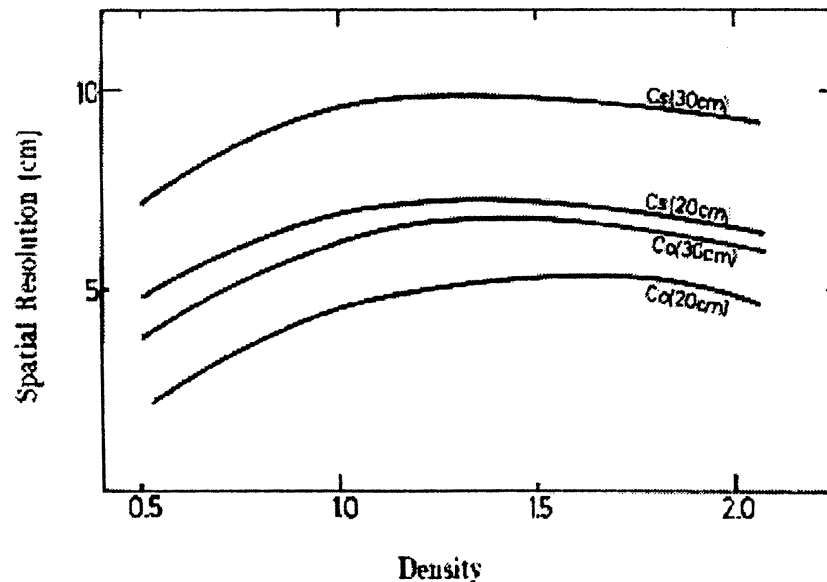


Figure 8: Variation of the spatial resolution with density

Figure 9 shows the experimental and simulated calibration curves. The full lines are the fit obtained by using a quadratic regression on the experimental points while the dash lines are

the simulated calibration curves. There is a good agreement between simulated and experimental calibration curves.

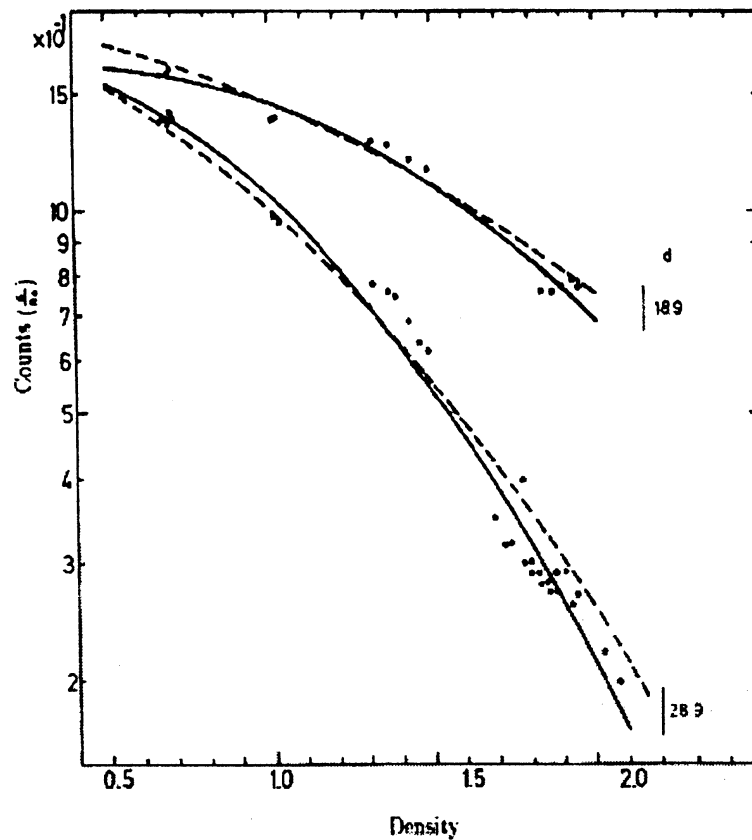


Figure 9: Calibration curves (experimental points; experimental curve and simulated curve).

The next Monte Carlo simulations were performed using the MCNP code (Briesmeister, 1989 — version 3A and updated versions) running successively on VAX-780, VAX 8700, CONVEX, UNIX and PC's.

Calibration of a neutron moisture depth-gauge: The geometry simulated was that of a neutron moisture depth-gauge designed by ITN. Energy splitting was used in order to improve the accuracy in thermal region. The code used also the scattering law to handle the scattering from bound hydrogen at energies below 4 eV. At higher energies the free-gas model was used (Gonçalves *et al.*, 1992). The simulation was prepared so as to yield a number representing a relative count rate, defined as the ratio of the soil count rate to that when the gauge was directly immersed in water. The simulation revealed the effects of the bulk density, detector active length and access tube and probe casing material on the calibration curve. The results suggest that dependence of the relative count rate, C_n on bulk density and moisture volume fraction, H_v can be described by the expression:

$$C_n = (\alpha + \beta \rho_d) + \gamma H_v,$$

where the parameters α , β and γ depend on the soil composition.

A test of the reliability of the calibration based on the Monte Carlo calculation was carried out using the experimental results of Pacheco (1989), in a reference soil with density of 1.5. The experimental, C_n^{exp} and the simulated, C_n^{sim} calibration curves are, respectively:

$$C_n^{\text{exp}} = 0.0034 + 0.0097H_v$$

$$C_n^{\text{sim}} = 0.0043 + 0.0093H_v$$

Comparison of computed and experimental results indicates that reliable calibration curves can be obtained by simulation with a considerable saving of time and effort. Although computed calibration curves require experimental confirmation this can be done by carrying out a small number of test measurements.

Calibration of a moisture-density surface — gauge: This simulation was carried out using the MCNP-4A code. The simulated arrangement was chosen to reproduce that of a dual neutron-gamma ray gauge (Gonçalves, *et al.*, 1994). A variance reduction technique based on geometry splitting was used. For density measurements two modes were studied: (a) the backscatter mode (BS mode) and (b) the transmission mode. Calibration points were obtained for a soil with the composition of limestone, for different penetration depths, h , of the source and for densities ranging from 1.2 to 2.7 g.cm⁻³. The results are shown in Figure 10 together with the experimental points obtained by Neves using a set of reference limestone blocks with different densities (Neves, 1993). Figure 11 shows a measure of the softening of the average gamma ray energy at the detector, for different densities and depths. The lowest energies correspond to the BS mode.

An optimisation of the gamma ray density gauge can be achieved by studying the effects on the response of the device caused by appropriate changes in gauge parameters, namely, the relative position of source and detector, position of the lead shielding blocks and use of absorbing material to cover the detectors. The count rates of the different configurations showed significant differences.

The chemical composition of the test medium affects also the detector count rate. It is possible, however, to reduce this dependence by shielding the detectors with an appropriate material that predominantly absorbs photons in the low energy region of the spectrum.

The fitting between experimental and simulation results was also satisfactory in the case of the neutron moisture gauge.

Elemental composition of raw materials by PGNA: The determination of the elemental composition of a raw material by means of conventional analytical techniques requires, as a rule, the careful preparation of small representative samples in a process that is costly and time-consuming. PGNA uses large samples, thus making it easy to ensure that the samples are representative of the bulk material. Sample preparation is not necessary. On the other hand, the technique simultaneously yields information on a broad range of elements. The data is automatically handled and results are available in real time, as is required for continuous flow operation. The crucial part of design and calibration of a PGNA system is that of ensuring a well-defined correspondence between the output of the system and the content of the relevant elements. This correspondence is determined in a complex manner by the system parameters – the geometry, source activity, neutron energy spectrum, detector efficiency – and by certain properties of the analysed material, namely, bulk density and per cent weight of hydrogen, normally as part of water.

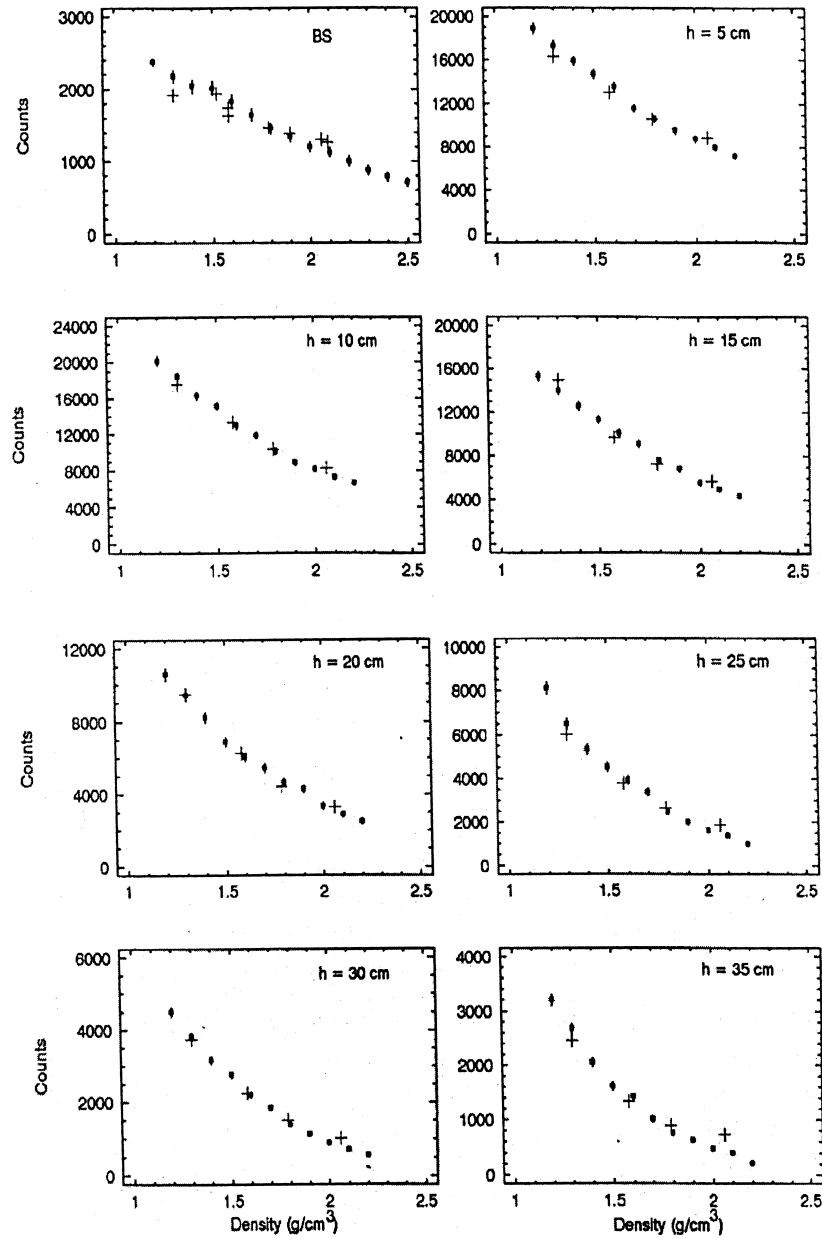


Figure 10: Simulated (•) and experimental (+) calibration points for backscatter (BS) and transmission ($h > 5$ cm) modes

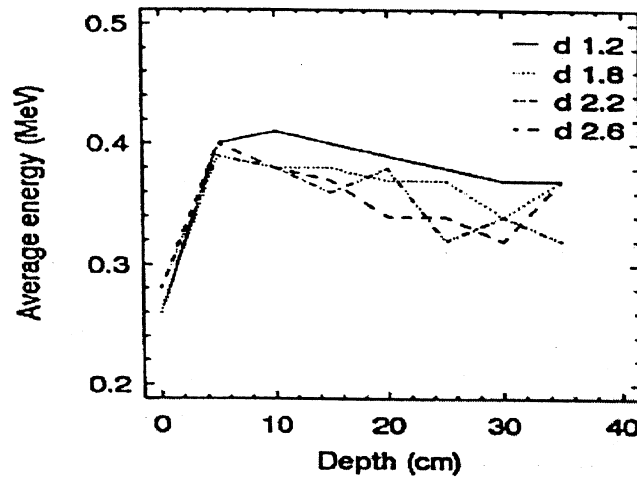


Figure 11: Average gamma ray energy for different soil densities and source depths

When a fast neutron source is used, as is the case in systems designed for on-line operation, the thermal flux in the sample is strongly dependent on the number of hydrogen atoms per unit volume of the sample. This effect can be attenuated by supplying thermalized neutrons to the sample instead of relying on the intrinsic neutron moderation and thermalization properties of the material. On the other hand, the average length of the path of gamma rays generated in the sample between emission point and detector strongly depends on the sample bulk density and dimensions.

The optimisation of a PGNA system design can be achieved in a certain range of material parameters by changing sample geometry. The optimisation of the performances of PGNA systems to control coal and cement raw materials was investigated.

PGNA of bulk coal samples — A simulation study using a ^{241}Am -Be source has shown that the bulk coal density bears an important influence on the fast neutron flux distribution inside the sample and on the detected gamma ray intensity from (n, n'gamma) reactions inside the sample. The dependence of the detected gamma ray intensity on coal density can be accounted for by correction factors calculated for a given configuration. The results show also that, for the configuration used, most of the detected photons originate in a layer 15 cm thick next or around the neutron source.

Hydrogen is an important component of coal. Therefore fast neutrons can be easily moderated in coals, thus increasing the probability of (n,gamma) reactions. Monte Carlo simulations performed in bulk coals of different compositions for a given sample size and geometry have shown that the gamma-count rate due to (n,gamma) reactions for an arbitrary element depends on the sample's hydrogen content and bulk density. The total count under a gamma peak should be corrected for the volume hydrogen content. This correction can be done using the area under the hydrogen peak. Moreover, the 2615 keV gamma-line due to (n, n'gamma) reactions in a lead shield surrounding the neutron source can be used to measure the density and normalise the spectra to the neutron source intensity.

In spite of the good moderating properties of coal, a comparison study of the performances of PGNA systems using ^{241}Am -Be and ^{252}Cf neutron sources showed remarkable differences. For a given volume hydrogen content, the hydrogen gamma ray count rate is, to a first approximation, independent of the bulk density for the ^{241}Am -Be source while this dependence cannot be ignored for the ^{252}Cf source. On the other hand, the gamma ray count rate per weight percent of an arbitrary element is a monotonically increasing function of H_v for the ^{241}Am -Be source in the range considered, while it shows a saturation effect for $H_v > 0.06 \text{ g.cm}^{-3}$ for the ^{252}Cf source. The rather more pronounced effect of the bulk density on the response function in the case of ^{252}Cf source is explained by the softer ^{252}Cf energy spectrum leading to a higher degree of thermalization in sample regions closer to the source. This effect implies a higher gamma ray attenuation in the sample volume. A suitable choice of neutron source and sample thickness can cancel or minimise the dependence of the count rate on H_v .

Sets of simulations were carried out for given coal compositions, in order to investigate the effect of variable thickness and of the modification of the effective neutron source energy by using an external thermalization. For this purpose the source was placed at the centre of a moderating sphere of polyethylene with variable radius. In the case of not shielded ^{252}Cf source, the results showed that for thick and medium-thick samples it is necessary to determine two sets of curves representing the functional dependence of, respectively, the

hydrogen gamma-count rate and the gamma-count rate per wt% of an arbitrary element in the coal, on the volume hydrogen content, with the bulk density as a parameter.

For thin samples ($<25\text{ cm}$) and $H_v < 0.07\text{ g.cm}^{-3}$, the effect of density splitting can be neglected and two straight lines can be used instead of two set of curves. The indicated upper limit of H_v range will probably be adequate for most industrial applications.

For an arrangement with external thermalization, the results showed that a suitable choice of the sample thickness, L and of the radius of the external moderating sphere can be made so that the system response is univocally determined by the wt% of hydrogen, H_p , at least in the range studied. In this case the system calibration will require the experimental determination of two curves (the hydrogen gamma-count rate and the gamma-count rate per wt% of an arbitrary element). This situation is attained at the cost of a reduction of the system response in comparison with the arrangement without external moderation.

By using a moderating sphere with small radius (less than 5 cm) the system response can be enhanced, probably without losing the advantage of the absence of the density splitting effect that occurs in thick samples (more than 25 cm).

Furthermore it has been shown (Oliveira *et al.*, 1995) that the dependence of the gamma-count rate per wt% on H_v is progressively weakened as the radius of the moderator sphere increases. This is true for each coal composition taken separately. For small radii, i.e., for a poorly thermalized incident neutron spectra, and small H_v , the dependence is almost linear. As the sample thickness increases, the region where this linear dependence manifests itself becomes progressively smaller. For sufficient large thicknesses (25 or 30 cm) there is a region of flat dependence or of a very broad maximum for radius between 5 and 10 cm.

PGNAA in cement raw materials: In co-operation with the largest Portuguese cement producer a conveyor belt system for the on-line analysis of cement raw materials was simulated. The purpose of the system was the determination of the calcium, silicon, iron and aluminium contents. The influence of different system and sample parameters (overall system geometry, neutron moderator/reflector composition and thickness, sample bulk density, dry composition, water content and thickness) on the background count rate originating from structural material and on the count rate from the raw material was studied. The simulated system is described below. In the first phase of the study the influence of the structural materials was studied.

The conveyor belt is made of rubber with embedded iron wires. The belt glides on a polyethylene stand, which acts as an external neutron moderator. The ^{252}Cf source is enclosed in a sphere, with a radius of 2 cm, made of gamma ray absorbing material (lead, zirconium or bismuth). Around the sphere, two hemispherical bodies are placed, each, also 2 cm thick. The material used in these two bodies can be either polyethylene, for neutron moderation, or lead, zirconium or bismuth, for neutron reflection. The neutron source is located below the conveyor belt at a variable distance from the polyethylene stand.

Two detector banks are used: a lower bank formed by four detectors positioned symmetrically around the source, to detect gamma rays emitted downwards; an upper bank, with a central detector and eight other detectors symmetrically arranged around the first. The upper detector bank sits on a plate made of a moderating or reflecting material. Polyethylene is used as moderator and lead, bismuth and zirconium as neutron reflectors.

The influence on the count rate of sample density, water content and thickness was investigated. The variation of a given parameter can affect the gamma count rate of a given element, although its concentration has not changed. A formalism was developed which enables one to obtain the calibration curves by adjusting analytical expressions to data from the simulation. Once the simulated calibration curves are obtained together with experimental

results from a few selected standards, a regression analysis can convert the simulated curves into experimental calibration curves.

The study has shown also that both detector sets (upper and lower) can be used separately to obtain PGNA results. As their responses have different behaviours, two independent systems for composition measurements are in fact available.

5. CONCLUDING REMARKS

One important aspect of nucleonic gauge design is Monte Carlo simulation, which is used in many cases for optimal design of various prototypes. The physical bench calibration is also important for optimal performance of nucleonic gauge prototypes. Keeping consultant and technical expertise to assist end users to select the proper nucleonic gauge and to perform in safe and optimal conditions is quite important and beneficial activity for many groups and countries that can not compete in nucleonic gauge industrial manufacturing.

The most important consultant activities are currently:

- organisation of training courses for nucleonic gauge users and operators, with special emphasis on calibration, safety and maintenance of nucleonic gauges and protection against ionising radiation;
- collaboration in re-calibration of nucleonic gauges;
- collaboration in data interpretation;
- selection of the most appropriate technique to solve a given measurement/control problem.

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SOME NEW APPLICATIONS OF NUCLEONIC GAUGES IN RUSSIA

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Abstract

Russia has been a big producer of nucleonic gauges for many years. There are still some institutions that design and manufacture nucleonic gauges for industry, like level gauges, density gauges and thickness gauges. Industrial demands for NCS (especially after the Chernobyl accident) have been decreasing. Examples of recent development are given in this paper. Substantial improvements in the hardware, source and detectors system, are being undertaken. The potential for new applications is large, also, there is a good capability of local researchers for increasing the quality and quantity of nucleonic gauges in industry to meet local needs and to compete better in the international scale and market.

Introduction

The Institute in Physical-Technical Problems (IPTP) in Dubna, develops and fabricates a number of the most mass-produced radioisotope instruments for industry, namely, level gauges for liquids and other media in the large volume vessels, density meters for liquids and pulps, thickness gauges for paper, films and plastics, ash coal meters, and high-sensitive fire detection systems.

It should be noted that, unfortunately, after the tragedy of Chernobyl, in Russia, due to the total radiofobia, the total number of radioisotope instruments, applied in the industry, began quickly decreasing. Nevertheless, there are some industries where it would be impossible to avoid the application of NCS and, thus, further improvement of the methods and instruments takes place.

The beta-albedo-absorption (BAA) method

An original method for high-precision thickness measurement of thin films, paper, and other materials in industry, was developed recently in the IPTP. This method is called a BAA method (beta-albedo-absorption method). In Figure 1, the principle of thickness measurement of this method is given. The measured material (1) is snug against the working (measurement) surface of the gauge (2). The beta-radiation from the beta-source (3) passes through the measured material and is registered by the beta-detector (4).

Due to double passing of beta-radiation through the measured material and to the considerable decreasing of the average energy of beta-radiation, the sensitivity of the BAA method is 5-6 times higher than for the classical beta-absorption thickness measurement method. In Figure 1, the mass absorption factors are given for the BAA method and for the beta-absorption method for the beta-sources based on isotopes (promethium-147, thallium-204, and strontium-90). In addition, the BAA method has its major advantage at thickness measurement in comparison with the classical beta-albedo method. Due to the effect of the "double passing of beta-particles through the material" and not to their "reflection" from the material, the measurement results practically do not depend on the atomic number Z of the measured material.

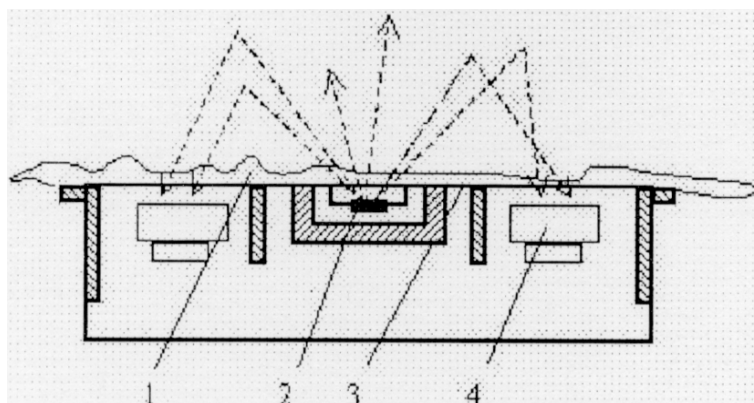


FIG. 1. Measurement procedure of thickness by the BAA method (1: material, 2: beta radiation source, 3: operation (measurement) surface of the gauge, 4: beta radiation detector).

The other advantage of the BAA method is the possibility to measure the thickness of the material by placing the gauge from only one side of the material. The BAA method should be applied when measuring the thickness of super-thin materials (from 1 to 50 μm) and the precision of the measurement can be not worse than $\pm 0.1 \mu\text{m}$.

In Figure 2, a real design is given of the BAA thickness gauge for polyethylene films with a ring-shape scanning device.

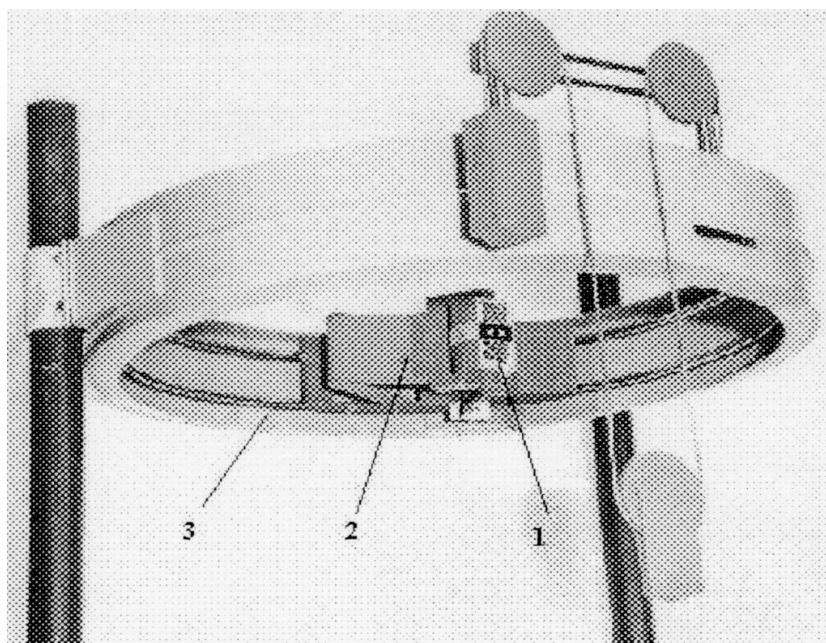


FIG. 2. Thickness gauge for polyethylene films with a ring shape scanning device of the RTRP-1 type (1: gauge, 2: lever, 3: ring shape scanning device)

In Figure 3, the designs of thickness gauges for thin paper materials are given. In Figure 4, the design of the BAA gauge is given for concentration measurement of aerosols in air which precipitate on the horizontal working (measurement) surface of the gauge in the process of natural sedimentation. The gauge has the protective cover which is automatically opened when the measurements begin

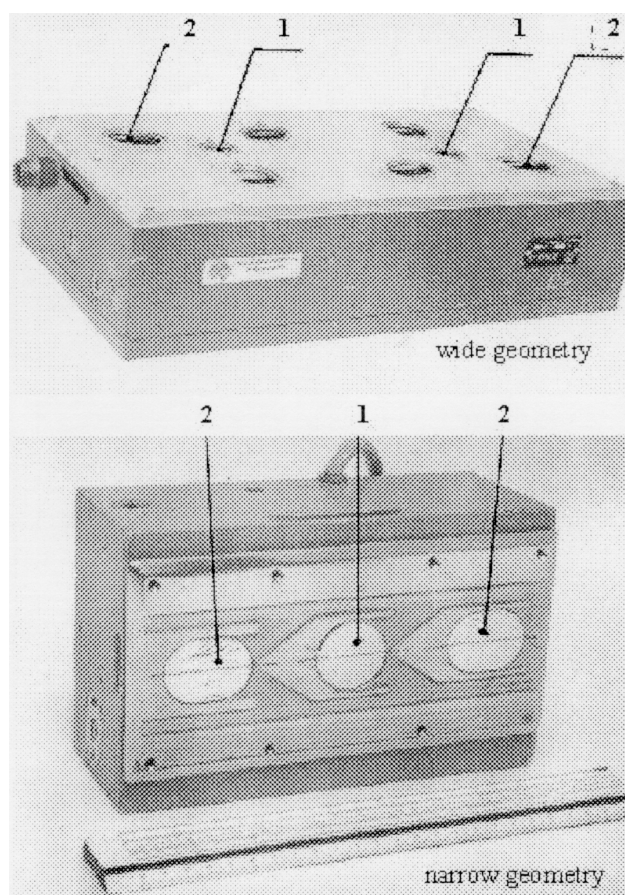


FIG. 3. Thickness gauges for thin paper materials (1: beta radiation source, 2: beta radiation detector).

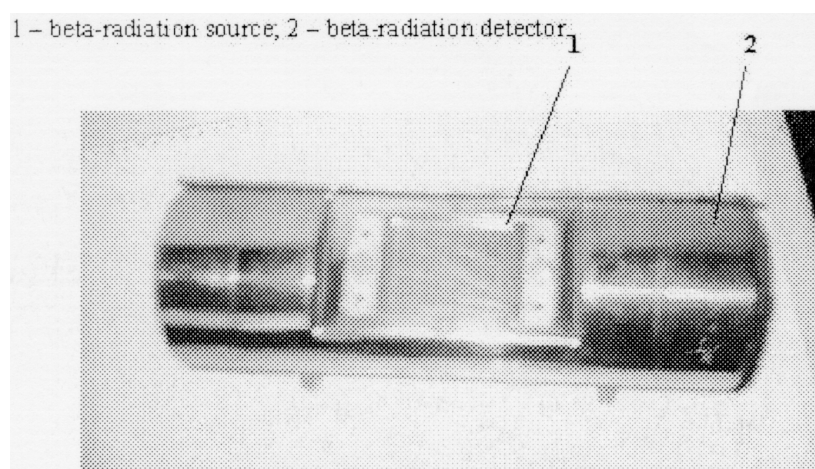


FIG. 4. Gauge for measurement of dust concentration in the air of the IPPF-1 type (1: measurement surface, 2: protective cover of the measurement surface).

Dustmeter

A new ionisation-flow method was developed for the detection of the ejection (leakage) of the extra-low concentrations of harmful (toxic) aerosols in production of different materials. The threshold for detecting the volume concentration for this method lies within the limits of 0.1–1.0 mg/m³.

The measurement technique of volume concentration of aerosols is shown in Figure 5. Pure air passing along the body of the gauge is ionised by the alpha-source (1). The positive are-ions are quickly recombined in the area of the source and the negative aero-ions fly along the body and are neutralised on special electrodes-neutralisers (2) and on the output electrode (3) the signal is absent.

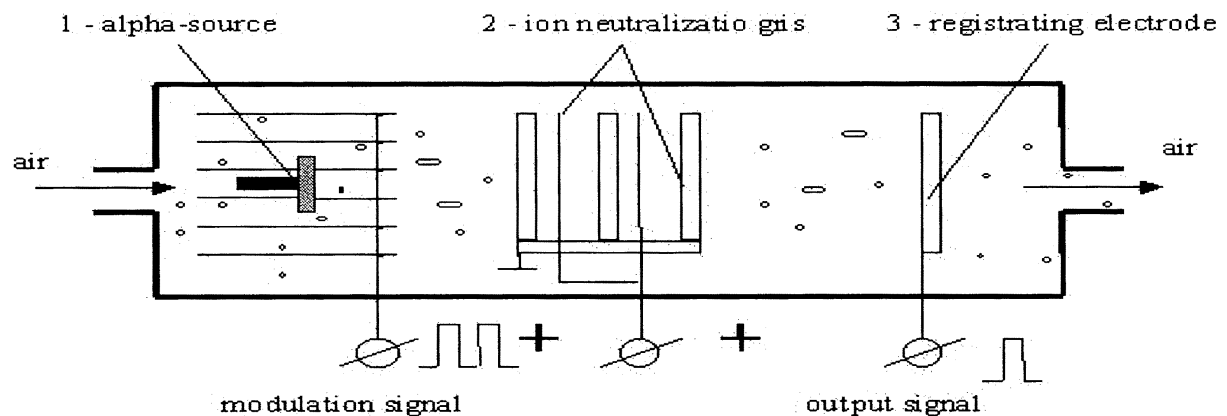


FIG.5. Measurement procedure of volume concentration of aerosols for the flow ionization.

If there is aerosol in the air, then the charged aerosol particles, because of their large mass, fly through the neutralisation grids (2) without discharging and fly further along the body of the gauge to the electrode (3), where they create the inductive emf. The gauge detects the separate aerosol particles which explains the fact that the detection sensitivity is so high (0.1 mg/m³).

In Figure 6, a real design of the ionisation-flow gauge is given. High sensitivity and the possibility to change the registration threshold permit one to use this gauge as a highly-sensitive smoke fire detector.

In Figure 7, the schematic drawing is given of the application of these gauges as fire detectors as well as other possible applications.

The other interesting instrument developed in the IPTP is a beta-absorption detector of mass concentration of dust in the air, the measurement principle of which is shown in Figure 8. The measured air (1) is pumped with the air pump (2) and a special tube (3) through the disk filter (4). Before the air pump is on, the surface density (mass) of the clean filter (m_0) is measured by measuring the beta-particle absorption rate from the beta-sources (5) placed in the head of the device. The registration of the beta-particles is performed with the miniature beta-detector (6). After the pumping of a certain air volume (V_1) through the filter, the dust remains on filter. The mass of the dust (m_1) is continuously measured by the beta-detector. The mass concentration of the dust (c) is calculated with the computer by the formula (1).

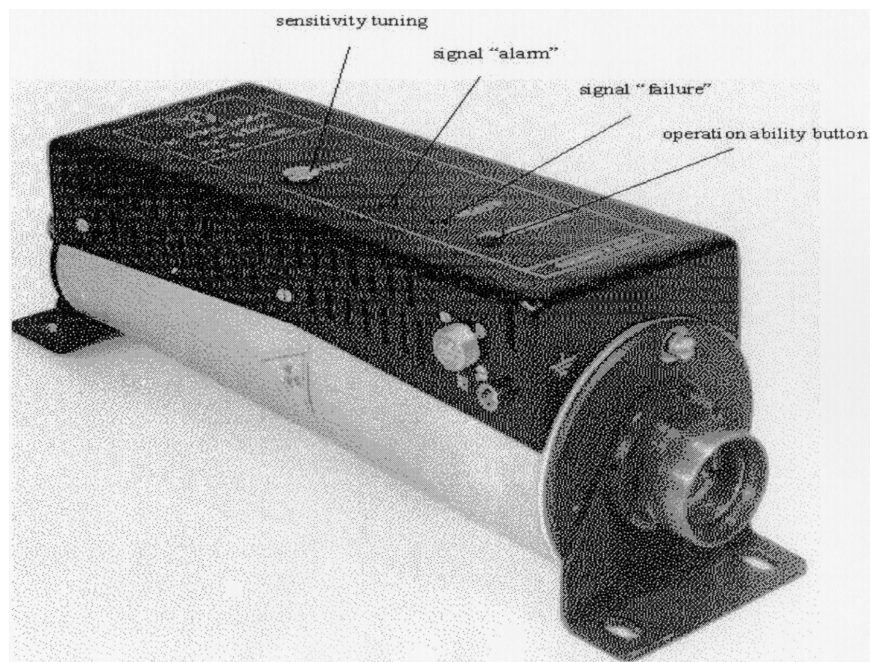


FIG. 6. Flow-ionization gauge (indicator) for mass concentration of aerosols in the RPI-D-2 (IP-211-2) type.

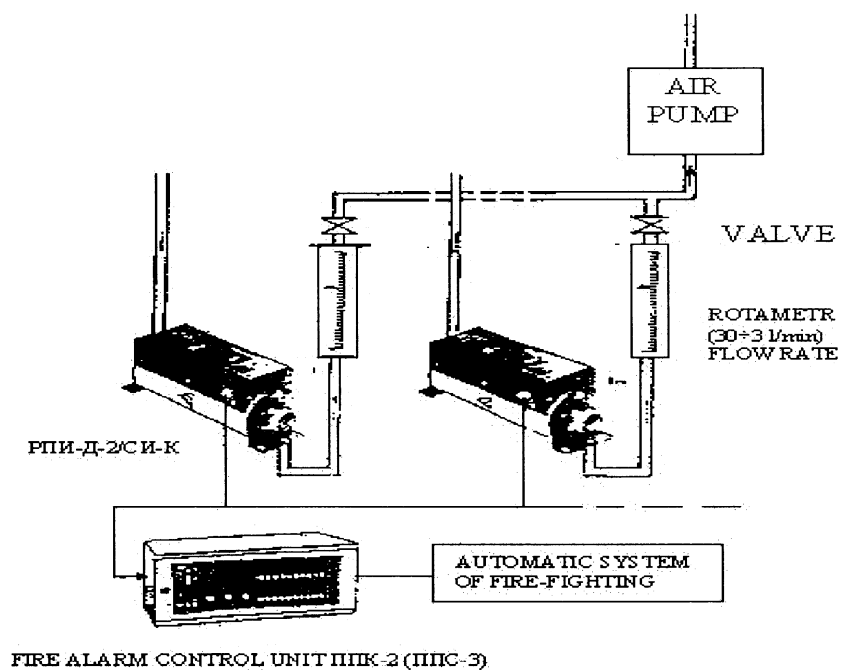


FIG. 7. Circuit connection of the radioisotope fire detector.

Possible monitored objects:

- cable canals and mines
- areas of nuclear power plants
- computing centres, equipment communications
- television and radio centres
- seagoing ships, riverboats, submarines,
- libraries and book depositories
- chemistry and Electrotechnical plants

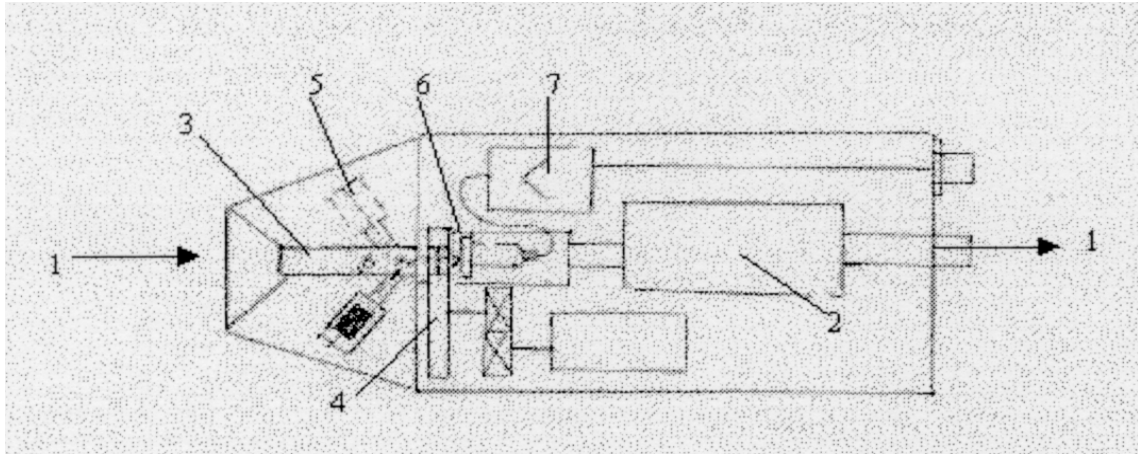


FIG. 8. Constructive functional scheme beta absorption dustmeter (1: air, 2: air pump 2-20 L/min, 3: air intake tube, 4: disk filter, 5: beta sources, 6: beta detector, 7: amplifier former).

$$c = K \frac{m_1 - m_0}{V} \quad (1)$$

where K is a constant coefficient.

In Figures 9 and 10, the photographs of the dustmeter are given.

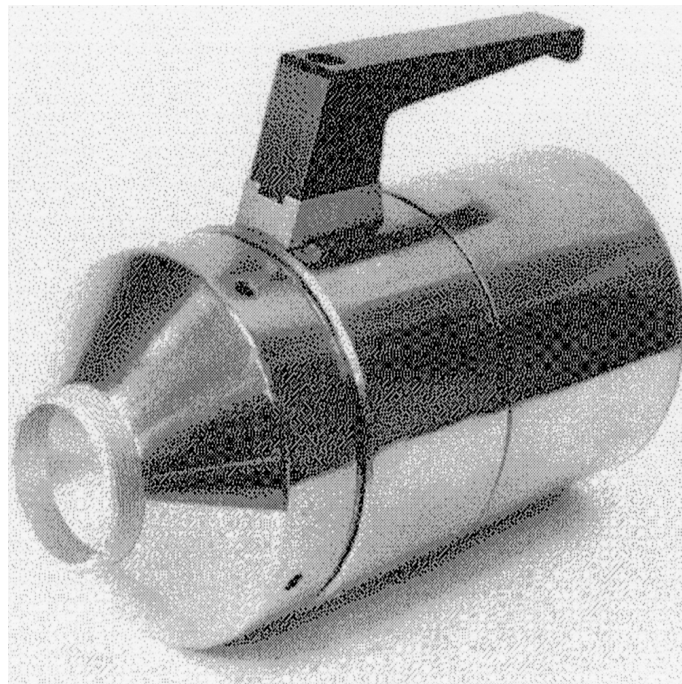


FIG. 9. General view of the dust meter KPI-1.

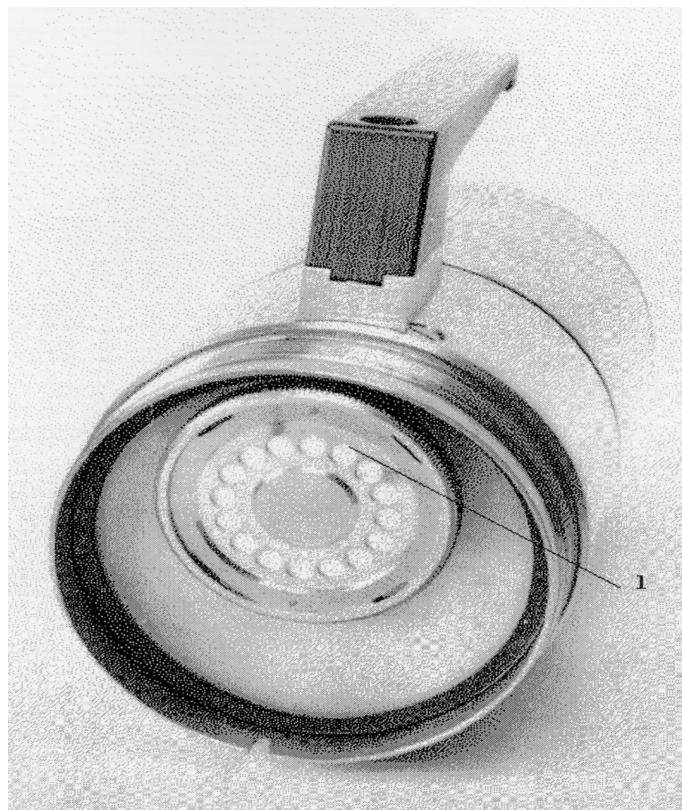


FIG. 10. General view of the dust meter KPI-1 without the end with the beta sources (1: accessory disk filter for 16 frames).

The advantage of this gauge in comparison to the design of other dustmeters, is the possibility of the continuous measurement of the build up of the dust in the filter, i.e., the possibility of the dust content dynamics study. The gauge has a strong construction suitable for operation in an emergency (or under field conditions). There is a possibility of remote control of detector operation from the computer, which means it can be operated as a stationary device in a system of automated air monitoring, for example, in the dust-dangerous factories. The gauge is designed for the 16 measurement cycles without the disk filter change.

Another interesting possibility is the application of this gauge for gamma-active radionuclide specific activity measurement in the air such as cesium-137, cobalt-60, europium-152, and iodine-131. This is attained by registration of beta-particles which accompany gamma decay. In this case, of course, the beta sources must be removed from the head of the gauge. The experiments show that the gauge can be successfully applied for the specific radionuclide activity control. In Figure 11, the measurement results of the gauge tests are given. It can be clearly seen in the Table of the Figure 11 that the threshold sensitivity of the Amin detector is two orders of magnitude higher than the admissible levels of volume activity of radionuclides. The measurement time is $T_{mes}=10\text{min}$, the volume capacity of the air pump is $V=15\text{ l/min}$, and the total volume of the pumped air is $V=150\text{ litres}$.

At present the gauge is being redesigned in order to make it possible to measure the aerosols of harmful metals in the air using the XRF method. For this purpose, instead of the beta-source a miniature silicon-lithium semiconductor X ray detector with a small-size Peltier-thermo-refrigerator is mounted. The range of the registered energies is from 1 to 30 keV. Energy resolution for energy of 5.9 keV is not more than 300 eV. The sensitive area is 5 mm^2 .

Instead of beta-sources, into the head of the gauge radioisotope sources Fe-55, Pu-238, and Cd-109 are inserted.

Nuclide	AVA(Bk/m ³)	A_{min} (Bk/m ³)	
Cs-137		$1.7 \cdot 10^3$	2.32
Co-60		$8.2 \cdot 10^2$	4.6
Eu-152		$2.1 \cdot 10^2$	2.4
I-137		$1.1 \cdot 10^2$	50

$$T_{meas} = 10 \text{ min}$$

$$U=15 \text{ l/min}$$

$$V=150 \text{ l}$$

FIG. 11. Test results of the KPA-1 gauge at radionuclide specific activity measurement in the air, where AVA is admissible volume activity of radionuclides in Bq/m³. At A_{min} is the minimal measured by the gauge concentration in Bq/m³.

Coal ash meter

The radioisotope coal ash meter for measurements on the conveyor belt was developed in the IPTP and successfully applied in the coal industry. The general view of the instrument is given in Fig.12.

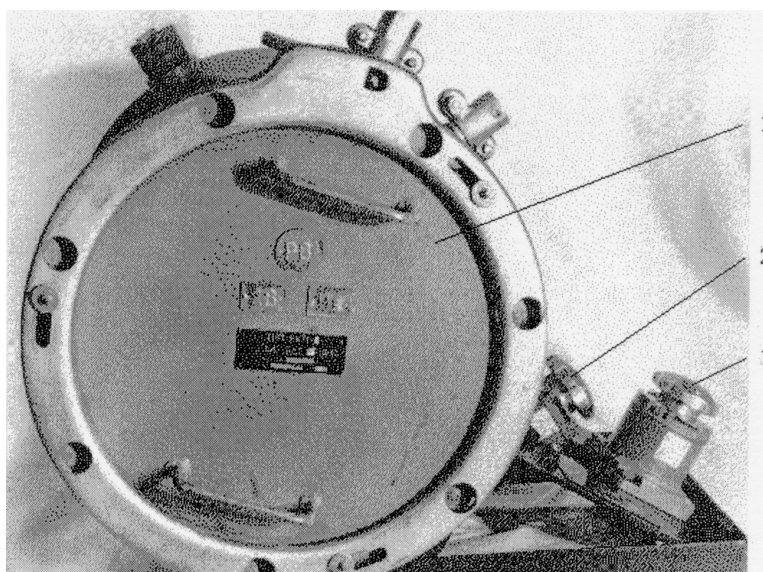


FIG. 12. General view of the radioisotope ash coal meter on the conveyor belt (1: compensation source, 2: main source, 3: the case with the scintillating detector).

The gauge is a rigid metallic construction which comprises:

- two gamma-radiation sources: the main source and the controlling one;
- the scintillating detection unit in an explosion-proof case.

The control source compensates the influence of the changing distance between the main source and the controlled material on the reading of the gauge.

The scintillating detection unit registers gamma-radiation scattered by the coal and produces the electrical pulses with frequency functionally connected with the ash content.

The BI-16 unit located in the frame is placed above the belt at a distance of 25-30 mm from the surface of the coal. Minimum thickness of the coal layer in the measurement zone must be not less than 100 mm and the maximum is not limited.

The gauge specifications are the following:

Range of measured ash content	4--40
Basic measurement error, with the confidence level of 0.95, %:	
-at ash content less than 10%	± 1.0 abs.
-at ash content more than 10%	± 10 rel., but not more than ± 2.0 abs
Coal size, mm, not more	150
Operating temperature range, $^{\circ}\text{C}$	-10...+50

The test of the gauge (calibration) was performed according to the specially elaborated technique using the standards which are large plastic vessels with the solution of salts permitting to imitate the changes of the average atomic number Z , equivalent to the change of Z when using the coal ash content from 4 to 40%. In Figure 13, the system for ash-meter calibration is shown. The calibration technique was developed together with the Central IPTP of the Coal Industry (CICI, Lubertsy, Moscow region).

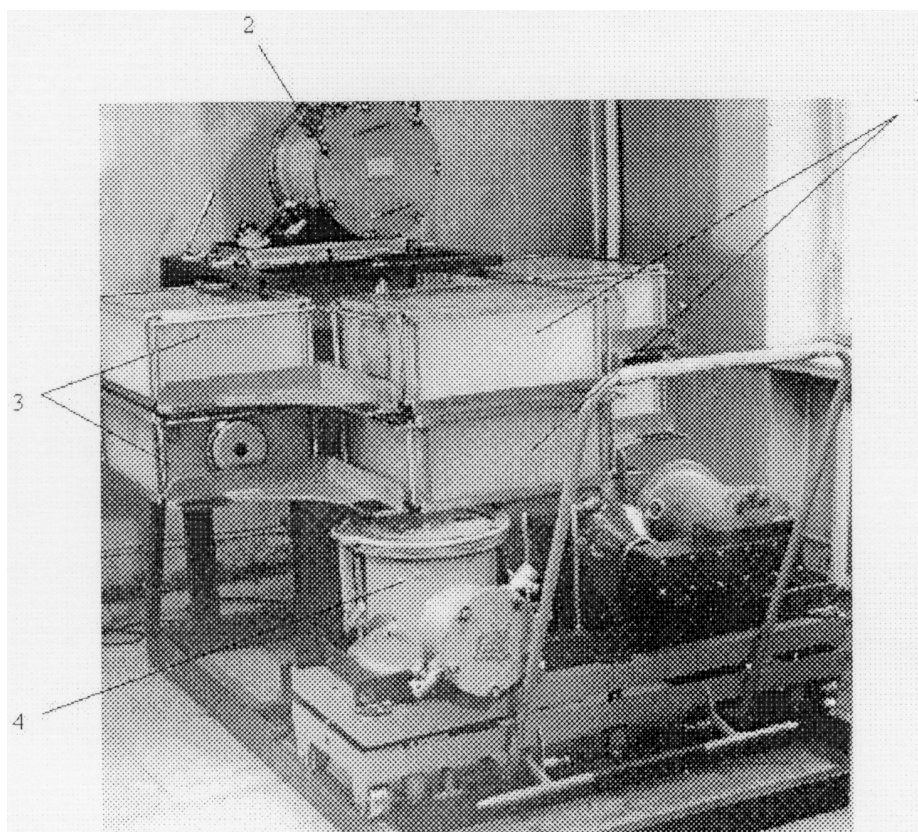


FIG. 13. Measurement system for ash coal meter calibration (1: equivalent absorber, 2: graduated instrument mounted over the conveyor, 3: standard measure, 4: graduated instrument mounted under the conveyor).

Density meter

The successful joint development of the IPTP and the firm "Sredazenergotsvetmet" (Tashkent, Uzbekistan) is also a radioisotope densimeter of the PR-1026 type. The densimeter has a high stability operation in the temperature range of $+5^{\circ}\text{C}$ to $+40^{\circ}\text{C}$ because it is equipped with the scintillating detection unit with the thermostat. The schematic of the densimeter is given in Fig. 14. A standard single crystal NaI(Tl) and a photomultiplier FEU-93 are used in the scintillating detection unit. The characteristics of the densimeter are the following:

- measurement range is $500\text{--}3000\text{kg/m}^3$;
- measurement base, i.e., the distance from the source unit to the detection unit is from 0.1 to 0.3 m;
- when the measurement base is 0.5 m, the measurement range is from 500 to 1500 kg/m^3 ;
- the measurement precision is from 0.1 to 1.0% according to the real difference of the measured densities and to the pipe-line diameter.

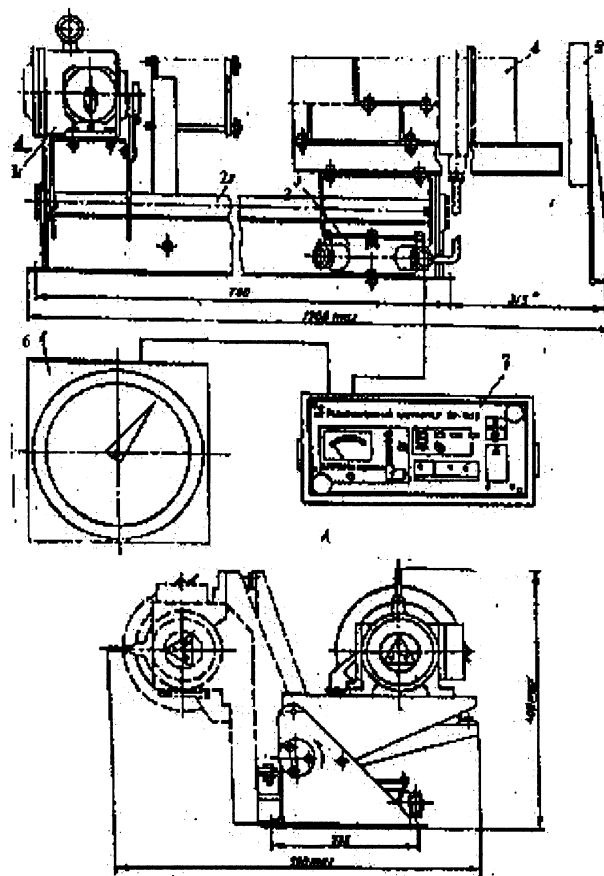


FIG. 14. Radioisotope densimeter PR-1026 (1: gamma radiation source unit, 2: stand, 3: connection box, 4: detection unit, 5: protection, 6: registration device, 7: processing unit).

The principal advantage of this gauge is the fact that it is mounted on a special turning frame and can be easily moved away from the measured pipe-line and in a measurement gap special metallic density standards are located. Changing the density standards, the operator can easily calibrate the density meter or check its stability. The gauge testing technique and the attestation method of the surface density measure are agreed with the Central Certification Agency of Russia (State Standard of Russian Federation).

Most of radioisotope instruments in Russia are equipped with the standard protected gamma-radiation units for transportation. The container types BGI-45A (0.02 Ci), BGI-60A (0.17 Ci), BGI-75A (1.7 Ci), and BGI-90A (6.5 Ci) are used for sealed cesium-137 sources with various activity. The collimation angle (the cone of the beam divergence) of the units BGI-45A and 60A is 8.00, and of the units BGI-75A and 90A is 6.00. The BGI units are produced with a narrow (slit) beam with the divergence angle from 00 to 450 for tracing level gauges, or for the level gauges with long detectors.

At present, the BGI-A units are the only gamma-radiation containers in Russia approved by the State Atomic Supervision of Russian Federation for utilization in industry. The certificate-licenses Ru/017N/T and Ru/027N/S are issued respectively for container and gamma-sources. The safety of these units comply with the international standards and they are permitted for exportation from Russia. The only producer of these units in Russia is the IPTP.

The photographs of the units are given in Figure 15.

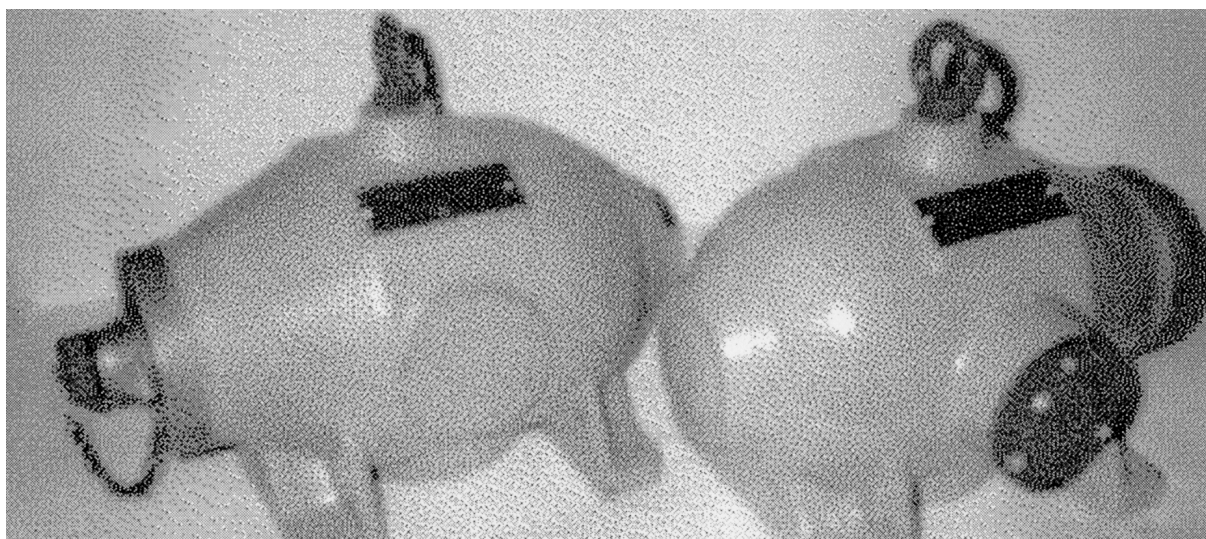


FIG. 15. Standard protected gamma-radiation units for transportation of the BGI-75 A type (RU/017N/T) with caesium-137 gamma sources (RU/027N/S).

The BGI-A units have an advantage over many units produced in other countries, for example, over the LB74440, 42, 44 type designed by the firm "BERTHOLD". According to the requirements of the National Standard of Russia GOST 18324-73 "Units of gamma-radiation sources for radioisotope gauges", these containers have a gate of special design which can instantly close the source in case of emergency. The gate is designed on the principle of the "catch" or the "trigger". The source can be opened only with a special key. Moreover, the unit is supplied with a set of special accessory lead plugs which are inserted into the collimation hole during transportation. Choosing the thickness of the plugs, the user can easily decrease the dose rate of the beam.

The radioisotope level gauges for industrial use are reliable instruments widely used in Russian industry. The most used is level gauge RRP-3 type which operates stably within temperatures from -50°C to $+50^{\circ}\text{C}$.

In the last 15-20 years there were produced about 100 thousand gauges and they are still working in many industries. The system comprises the spark-proof and explosion-proof designs. The gauges are equipped with the gamma-radiation sources of the BGI-A type mentioned above.

CURRENT AND EVOLVING STATUS OF NUCLEONIC GAUGING IN THE UNITED STATES OF AMERICA

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Abstract

This paper discusses the present status of applications of nucleonic gauges for control in present commercial use. Then the use of Monte Carlo simulation is briefly discussed for providing accurate models of the various nucleonic gauges for purposes of calibration (or interpretation), error analysis, and design. The use of dual-gauge methods with the Measurement Chi-Square (MCS) approach for minimising or eliminating measurement interferences is described with particular reference to the measurement of aluminium sheet thickness independent of alloy composition. Finally, the future evolution of nucleonic gauges for control in the USA is discussed.

1. INTRODUCTION

The nucleonic control system (NCS) industry in the USA is a very mature one that has evolved from the availability of radioisotopes produced initially in governmental nuclear reactors used in either the atomic bomb or nuclear power development programs. In the USA this industry has evolved with very little association with either university or government laboratory research and development support — except for the latter's support in producing radioisotope sources. Perhaps partially for this reason this industry is very proprietary in nature and very few technical articles with technical details have been published by USA industries on NCS. For this reason it is difficult to assess the capability of the USA NCS industry.

The author has tried in several ways to change the emphasis on this proprietary philosophy in the USA NCS industry. Working with Dr. C.L. Dobbs (1997) of Alcoa, special technical sessions, workshops, and panels have been organised for NCS in the aluminium thickness measurement area. This has been done both at American Nuclear Society meetings and in the three Topical Meetings on "Industrial radiation and radioisotope measurement applications" (1988, 1992, 1996).

The present paper is the author's attempt to evaluate the present and evolving status of NCS in the USA. It is largely based and prejudiced by personal experiences. Two recent publications by the author are pertinent to the present paper. They are "Black Box Radiation Gauges and Analyzers: Dream or Reality?" (Gardner, Guo, Ao, and Dobbs, 1997) which was given as a plenary lecture at the third topical meeting on Industrial Radiation and Radioisotope Measurement Applications in Raleigh October 6-9, 1996 and "Nuclear Radiation Gages and Analyzers" (Gardner and Dobbs, 1998) which was an invited talk at ASNT's Advanced School on Sensors for Process Monitoring and Quality Control in Banff June 26-30, 1995. This latter talk will be published as a Chapter in an ASNT monograph which should be out soon.

2. GENERAL COMMENTS: CURRENT STATUS

The nucleonic control system (NCS) industry in the USA is apparently in good economic health as ascertained simply by sales figures for sealed radioisotope sources. This is in spite of increased regulation costs and poorer public relations that have probably been triggered primarily by public concerns. Regulation costs will probably continue to increase — a recent announcement (No. 98-53 of April 15, 1998) by the Nuclear Regulatory Commission details additional regulatory measures for devices that contain radioactive material. We must hope and work for a decrease in regulatory costs and a corresponding increase in regulatory effectiveness so that this industry will maintain the position that its technical superiority demands.

To provide background for a discussion of the current status of the NCS industry some historical perspective is in order. In the USA a prime mover in the development of NCS was the Isotopes and Radiation Division (IRD) of the U.S. Atomic Energy Commission. IRD disappeared many years ago (more than 20), but was very influential for some time. A number of industrial and not-for-profit companies (20 to 30) obtained research and development contracts from IRD that contributed to the present status of the NCS industry.

Unfortunately (in the author's opinion), a large fraction of the research and development contracts sponsored by IRD stressed application ideas that promised very novel or even revolutionary end products that had very low probability of success. Very few projects were funded that were involved with the orderly development of established application areas that were known to be useful. This latter type of high success probability research would probably have led to a greater confidence in these measurement techniques and, perhaps, to a different type of researcher in this area.

At present in the USA NCS is controlled by an industry that is very proprietary in nature. Good technical papers written by this industry that give technical details in an expository style are very rare. The word "proprietary" appears to be used often by personnel of this industry in answer to questions about how certain measurement interference problems are being or have been solved. Because of this philosophy it is very difficult to assess just how good NCS products are in the USA. It does appear to this author that the NCS hardware is quite good in the USA. For the most part it is rugged and durable.

Other countries where the research and development on NCS products has been shared with industry by either universities or government laboratories or both seem to have a healthier atmosphere for NCS. Perhaps that is why public opinion in those countries is not as critical as that in the USA. Association in the USA of public opinion with the nuclear power industry — particularly in the waste disposal area — has probably also been detrimental.

One other criticism of the USA NCS industry is that it tends to produce only one-of-a-kind devices which are to be applied to a wide range of applications. If that device will not work for a particular application it is very difficult and expensive to develop an alternative device that will. A company interested in such a device will probably have to pay almost all of the developmental costs to an NCS company.

In spite of these criticisms the USA NCS industry appears to be healthy and strong. Nuclear gauges are consistently being used for level and fill level control, for sheet thickness measurement and control, for density and basis weight measurement and control, and for binary composition measurement and control. All cigarette machines are controlled with beta-

particle gauges, all paper machines are controlled with nuclear gauges, almost all metal sheet thickness rolling mills are controlled with nuclear gauges, and fluid density nuclear gauges are still very common in chemical, petrochemical, and mineral processing.

3. MONTE CARLO SIMULATION

Monte Carlo simulation of nuclear radiation measurement applications for design and calibration purposes is fast emerging as standard procedure. This is personally gratifying to the author since he has been a proponent of this for some time (Lippold, Carnesale, and Gardner, 1969, Gardner and Verghese, 1983). A number of things have recently contributed to this increased use including: (1) the general availability of excellent general purpose Monte Carlo codes such as MCNP4B (Briesmeister, 1997) and ITS (Halbleib et al., 1992) that are becoming more and more user friendly; (2) the recent availability of low-cost, high-performance computers; and (3) the recent reported successes of Monte Carlo simulation in such diverse fields as medical and industrial applications. It is likely that this trend will continue as more and more researchers become aware of the benefits of this approach.

In the design of nuclear gauges Mickael et al. (1994) have demonstrated that the complete design of a new oil well logging tool can be accomplished by Monte Carlo simulation — thereby avoiding the excessive cost and time demands of an experimental program to accomplish the same thing. It is likely that in the near future this will become relatively common. Another area of general usefulness is in error analysis which is illustrated in the work of Dobbs, et al. (1992) for the effect of position (passline) on sheet thickness measurement with beta gauges.

Monte Carlo simulation in its simplest form (called analog Monte Carlo) consists of simulating the actual paths of individual nuclear radiations by using random numbers generated within the computer (these are actually pseud-random numbers) to make the choices for the various stochastic processes that are involved. This includes: (1) directions of emission or scatter; (2) distances to the next interaction site; and (3) type of interaction (scatter or absorption). The usual final answer of such a simulation is the yield or number of 'successes' divided by the total number of histories (actual paths). For example, in a nuclear radiation gauge simulation the yield will be the number of radiations detected divided by the total number considered. When the yield is multiplied by the radiation source intensity, one obtains the actual gauge response.

In most cases of practical interest the yield is very small- say 1 in 10^4 to 10^8 . In this case analog Monte Carlo is impractical even on the fastest computers because to obtain an answer to within a 1% standard deviation at least 10^4 successes are required. Note that the statistics of analog Monte Carlo predictions are Poisson distributed like radiation counting experiments. Therefore, the standard deviation of the mean of a number of successes or counts is just the square root of that number. So to obtain a standard deviation of 1% when the yield is 1 in 10^4 one must generate at least 10^8 histories within the computer when analog Monte Carlo is used. This has led to the use of efficient variance reduction techniques in Monte Carlo simulation which require fewer histories for adequate accuracy and allow one to solve the many low yield problems that are encountered in a practical amount of computation time.

There are many types of variance reduction methods, but all involve changing the weight of the nuclear radiation history in an appropriate way to compensate for doing something that is

non-analog. The general purpose code MCNP is equipped with a very good general variance reduction technique called 'weight windows'. In this approach an importance map is generated and nuclear radiations are split when the nuclear radiation history weight is larger than the upper window weight limit and Russian roulette is played when the weight is smaller than the lower window weight limit. Splitting involves making the weight of the resulting split radiations proportional to the reciprocal of the number of splits. Russian roulette involves either killing the radiation entirely or increasing the weight of the radiation to the lower weight window limit. This approach can lead to larger Figures of Merit (FOM) for the Monte Carlo simulation by several orders of magnitude as compared to the analog case. The FOM is the reciprocal of the relative standard deviation squared times the computer time required. So a computation would take several orders of magnitude less computation time than that of the analog case if the FOM is several orders of magnitude larger. This allows many of the problems that are impractical for analog computation to be treated easily when appropriate variance reduction is used. Recent papers by Liu and Gardner (1997a, 1997b) describe a modification of MCNP4B that allows the use of a simpler and finer mesh importance map. This approach increases the FOM by factors of four for a neutron oil well logging tool simulation and a factor of six for a gamma ray tool. In addition the approach makes MCNP4B much more user-friendly.

Another important aspect of Monte Carlo simulation is that it is intrinsically parallel. That is, one can simultaneously run the same Monte Carlo simulation on any number of computers by simply arranging to use a different set of random numbers on each computer. In that way the total amount of required computation time for obtaining a given accuracy for a particular problem is reduced directly by the number of computers of the same kind that are used in this manner. This allows one to use the new PVM technique (Geist et al., 1994) for accessing a number of computers. For example, many companies connect all their workstations in this manner and then use them in parallel at night (when they are normally not used) for this type of problem. One can easily pick up another order of magnitude in efficiency by using this approach.

Unfortunately, there is no ideal introductory literature on Monte Carlo simulation that allows one to begin using it with minimal effort. However, a number of references have introductory chapters (Schaeffer, 1974; Manin, 1988; Jenkins et al., 1988) that are useful in this regard. The MCNP manual (Briesmeister, 1997) can be used, but it is extensive and primarily written for intermediate or expert Monte Carlo practitioners. The XTM Division of Los Alamos National Laboratory, which is responsible for MCNP, often gives short courses for beginning users and this is probably an optimum way to get started when viable for the individual. To obtain information on these courses, contact Judith Briesmeister (Briesmeister, 1996).

There are still special cases where specific purpose Monte Carlo codes are best. This is true when the code is to be used often for the same problem and one can be written that is more efficient than a general purpose code or that can be run on an available computer with less memory. This might occur when the problem of interest is one in which a great deal of forcing variance reduction (Gardner et al., 1996) can be used or when the expected value is an optimum variance reduction technique (Mickael et al., 1988) as it is in X ray or gamma ray gauging or tomography problems that involve a lot of collimation. One of the additional advantages of writing your own specific purpose Monte Carlo code is the increased fundamental understanding that is obtained when this is done.

4. DUAL-GAUGE APPROACHES

Probably the most important problem encountered in nuclear gauging is that of measurement interferences. Assuming that a radiation gauge has a single response and is designed to measure a single sample parameter such as thickness or density, the response of the radiation gauge can be expressed as a function of the sample parameter to be measured. In general, radiation gauge response depends not only on the sample parameter of interest, but also on other sample and environmental parameters (such as sample composition and position) that represent measurement interferences. So in reality we have a function that mathematically represents a radiation gauge as:

$$R = f(x, u, v, w, \dots)$$

where R is the gauge response (usually counting rate in counts/s), x is the parameter to be measured (usually mass thickness in g/cm^2), and u, v, w, \dots represent variables that characterise the measurement interferences. However, problems in the use of radiation gauges are inverse in the sense that parameters of interest are being determined from measured responses:

$$x = F(R, u, v, w, \dots)$$

where F is the inverse function of f . Most gauge response models are very complex and it is often necessary to simulate them by using numerical methods or the Monte Carlo approach. In any case it is good practice to simulate the raw response directly since the appropriate error analysis is straightforward when this approach is used.

It is important to express radiation gauge accuracy in terms of the measured variable. Using the usual Taylor series approximation for uncorrelated, independently determined variables, the variance (the square of the standard deviation) of the measured variable x is given by:

$$\sigma^2(x) = (\partial F / \partial R)^2 \sigma^2(R) + (\partial F / \partial u)^2 \sigma^2(u) + \dots$$

It is assumed here that this standard deviation is identical to the gauge error. There are two components to this standard deviation; one is the reciprocal of the gauge sensitivity as represented by the partial derivative term and the other is the standard deviation of the gauge response. Large sensitivities and small gauge response standard deviations yield small gauge errors. The variance of the radiation gauge response consists of statistical counting rate fluctuation variances that are normally Poisson distributed and electronic instability variances that are normally taken as Gaussian distributed. The latter requires that one use the general estimator to determine it. To design a radiation gauge that is less sensitive to measurement interferences, the optimum design parameters should be chosen in such a way that the variance given by the previous equation is minimised with respect to both the gauge response variance and the variances of each measurement interference.

To use a radiation gauge that is subject to measurement interferences for measuring the parameter of interest, there are several possible approaches, including: (1) keeping the measurement interferences constant at fixed values during calibration and subsequent measurement; (2) making independent measurements of the measurement interferences and calibrating for all possible interferences that might be encountered; (3) using a dual or multiple radiation gauge in which the individual gauge responses are modelled and these models are solved simultaneously for the sample parameter of interest independent of the measurement interferences; and (4) combinations of these.

As mentioned before one method of eliminating or at least minimising measurement interferences is the dual- or multiple-gauge approach in which the individual gauge responses are modelled and these models are solved simultaneously for the sample parameter of interest independent of the measurement interferences. This assumes that the individual gauges have different relative sensitivities to the sample parameter of interest and the variable or variables that characterise the measurement interference or interferences and that there are as many individual gauges plus one as measurement interferences.

Although dual nuclear gauge techniques have been in use since at least 1960, a unified approach to their use was only put forward recently by the authors (Gardner, Dobbs, Szalanski, and Verghese, 1993). In that paper a fairly extensive review is given first of nuclear radiation dual-gauge techniques in the literature, then a detailed description of the measurement chi-square (χ_M^2) approach is given, and finally, an example application involving X ray transmission and backscatter gauges for measuring aluminium sheet thickness is treated. The reader is referred to that paper for more details — only a brief review is given here.

A number of dual-gauge techniques have been developed over the years. The earliest application identified by the authors was that of Gray, Clarey, and Beamer (1960) in which beta-particle transmission and backscatter gauges were used simultaneously to measure the hydrogen content of hydrocarbon liquids independent of their composition (other than hydrogen). Soon after this, dual-gauge techniques were apparently independently developed for gamma-radiation backscatter gauges for road bed density and formation density in oil wells and for neutron moderation gauges for hydrogen (or water) content in road beds and formation porosity in oil wells. The oil well logging dual-gauge applications have been routinely used while the road bed applications have not. Recently, the application of X ray transmission and backscatter gauges for measuring aluminium sheet thickness has become of considerable commercial interest. Each of these applications used different approaches to modeling the gauge responses and solving them for the measurement parameters of interest.

The measurement chi-square (χ_M^2) approach is an attempt to unify dual- or multiple-gauge techniques. The basic idea was adapted from the usual χ^2 approach that is used in the weighted least-squares analysis for determining model parameters (like the coefficients of polynomials). In this case the measurement chi-square is defined as:

$$\chi_M^2 = \frac{(R_{1E} - R_{1M})^2}{\sigma_1^2} + \frac{(R_{2E} - R_{2M})^2}{\sigma_2^2} + \dots$$

where the R_{1E} , R_{1M} , R_{2E} , and R_{2M} are the first gauge experimental response, the first gauge model response, the second gauge experimental response, the second gauge model response, ... and the σ_1^2 , σ_2^2 , ... are the expected variances of the experimental responses for the individual gauges, respectively. The responses are all functions of the parameter to be measured and the measurement interferences. The variances are functions of both the counting rate statistical fluctuations and the gauge instabilities, as previously mentioned.

One uses the χ_M^2 approach by varying the measurement parameter of interest and a parameter (or parameters) that is representative of the measurement interference until either a minimum or zero is obtained. Since nuclear radiation gauge models are often transcendental and, therefore, the explicit solution for the measurement parameter of interest is the solution to another transcendental equation, there is usually no disadvantage to using this trial-and-error iterative approach insofar as the mathematical solution for the measurement parameter of

interest is concerned. However, there are major advantages in using this approach for other aspects of the problem. First of all, the nuclear radiation gauge models required are "forward" models and, therefore, are expressed in their most natural way. This means that one can continue to develop and improve the models essentially independent of their solution or solution difficulty. It also means that the models treat the actual responses of the nuclear radiation gauges directly and, therefore, their experimental error structure is applicable directly to the model responses. Finally, the actual X^2_M values, particularly the ratio of the individual gauge contributions, can be used for on-line "detective" work in that one can determine when the measurement interference significantly changes.

There are a number of ways (three are discussed here) that the X^2_M approach can be used. The first of these (Use 1) is for a single measurement in which both the measurement parameter of interest and the measurement interference or interferences are varied simultaneously until a zero X^2_M is obtained. This use assumes that one can represent all the measurement interferences adequately by a single parameter for each and that simultaneous values of the measurement parameter of interest and the measurement interference (or interferences) exist that yield model values of the gauge responses that are exactly equal to the experimental values obtained. This use is probably the most difficult to implement since there are a number of problems that can be encountered. One problem is that the experimental responses may statistically fluctuate to higher or lower values than the models allow. Another is that the X^2_M values do not usually approach zero with changes in the searched parameters in a manner conducive to easy solution. They often approach zero in a steepening manner that is difficult to follow by ordinary means. The authors have investigated the use of a modified version of a multi-variable Newton-Raphson search for this use that appears to work quite well. Another problem with this use is that it can be shown that the solution in this case is independent of the variances of each measurement — so both model responses always have equal weight in this case. Considering all these problems it is best to avoid this use whenever possible.

The second (Use 2) is for a sequential set of measurements which can all be assumed to have the same known fixed measurement interference or interferences. In this case the measurement parameter of interest is varied for the known fixed measurement interference(s) until a minimum X^2_M is obtained. This may seem to be a trivial case at first look since when the measurement interferences are known and fixed a dual-gauge approach is not necessary. However, use of the X^2_M approach in this case provides one very important feature — the individual gauges are used in an optimum way for best accuracy over the entire range of the measurement parameter of interest. The search technique is a simple Newton-Raphson search since the X^2_M hypersurface behaves very well in this case.

The third (Use 3) is for a sequential set of measurements which can all be assumed to have the same fixed but unknown measurement interferences. In this case one searches on individual values of the measurement parameter of interest for each measurement and a fixed value of the measurement interference or interferences for the entire set to obtain a minimum average chi-square (X^2_M) value. Note that this case uses the previous case as an inner loop search on the measurement parameter of interest while an additional outer loop search is made on the measurement interference values. This case is the most common and, fortunately, the X^2_M hypersurface is quite well behaved in this case. The search technique developed by the authors involves a combined model linearization and steepest gradient method. Other specialized uses exist in which the measurement interference or interferences are of primary interest and Uses 2 and 3 are actually reversed. These are discussed in more detail in the reference by Gardner, Dobbs, Szalanski, and Verghese (1993).

The application of this approach of primary interest to the authors has been the combined X ray transmission and backscatter measurement of aluminium alloy sheet thickness in the presence of unknown variations in alloy composition. This is the application that was treated in detail in the paper by Gardner, Dobbs, Szalanski, and Verghese (1993). This interest originated from a desire to improve the thickness measurement accuracy from about 1 or 2% to 0.1%. It was found that unknown variations in alloy composition as small as 0.15% magnesium, 0.64% silicon, 0.024% titanium, 0.017% chromium, 0.015% manganese, 0.013% iron, 0.010% copper, and 0.009% zinc individually introduce thickness error measurements as large as 0.1% when a single X ray transmission gauge is used for thickness measurement.

The measurement chi-square (χ^2_M) approach was applied to this problem based on experimental data provided by Gouel, Outhwaite, and Burnett (1992) who pursued the commercial development of this device along with Alcoa. The plan pursued by Gardner, Dobbs, Szalanski, and Verghese (1993) was to use "nominal" compositions of the alloys and assume that changes in the copper content would adequately approximate all the composition variation. First, fairly elaborate and universal semi-empirical models were developed for both the transmission and backscatter X ray gauges. For the transmission gauge the model was:

$$R_T(t) = \sum_{i=1}^n A_i \exp(-\mu_i t)$$

where $R_T(t)$ is the normalised response given by:

$$R_T(t) = \frac{1000[\hat{R}_T(t) - \hat{R}_T(\infty)]}{\hat{R}_T(0) - \hat{R}_T(\infty)}$$

with the "hat" responses referring to raw counting rate data and the A_i and μ_i being the exponential coefficients and total linear coefficients for the i th X ray energy, respectively. The A_i implicitly contain the total X ray intensity, the relative abundance of the i th X ray energy, the detection efficiency for the i th X ray energy, and the geometrical yield of the gauge. The μ_i are the total linear attenuation coefficients for the i th X ray energy for the sample composition and density of interest. It is obtained from:

$$\rho = 1 / \sum_{j=1}^m w_j f_j$$

where ρ is the sample density in g/cm^3 , w_j is the weight fraction in the sample of element j , and $(\mu/\rho)_{ij}$ is the j th elemental cross section in cm^2/g of the i th X ray energy. Tables of $(\mu/\rho)_{ij}$ as a function of X ray energy are readily available. The density ρ can be obtained for aluminium alloys from the relationship:

$$\mu_i = \rho \sum_{j=1}^m w_j (\mu/\rho)_{ij} f_j$$

where the f_j is an empirical factor for the j th element.

The authors found that the optimum number of X ray energies for representing the transmission model for an X ray machine operating at 36 kV was five for the method of determining the A_i that was used. The energies used were 15, 20, 25, 30, and 35 keV. Experimental results were available for 19 alloys including the 1100, 1145, 1199, 2024, 2036, 3003, 3004, 3105, 5005, 5082, 5182, 6009, 6010, 7021, 7046, 7072, 7146, and 7178 alloys. The reduced chi-square (χ^2_v) value for all 19 alloys for a range of thicknesses from zero to 0.5 cm was 6.02 when a standard deviation on each data point of 1% was used. When the worst six alloys were removed from consideration the reduced chi-square became 0.206. They were Alloys 1199, 2024, 7021, 7046, 7146, and 7178. Table 1 lists all results. It should be noted that as one would expect very small changes in the alloy compositions make a big difference in how well they fit. Therefore, it is believed that the model is quite good and that the six alloys that fit poorly probably do so because their composition is not known well enough.

TABLE 1: MODEL COEFFICIENTS A_i , THEIR STANDARD DEVIATIONS $\sigma(A_i)$, EXPONENTIAL TERM LINEAR CORRELATION COEFFICIENTS R , AND THE REDUCED CHI-SQUARE (χ^2_v) FOR THE 19 AND 13 ALLOY CASES FOR THE X RAY TRANSMISSION THICKNESS GAUGE.

Case	i	A_i	$\sigma(A_i)$	R	χ^2_v
19 Alloys	1	0.017029	0.00695	0.303	6.02
	2	0.148415	0.01100	0.652	
	3	0.559469	0.00800	0.972	
	4	0.211402	0.00408	0.979	
	5	0.063441	0.00105	0.923	
13 Alloys	1	0.018418	0.00990	0.437	0.206
	2	0.159540	0.02090	0.798	
	3	0.525616	0.02420	0.995	
	4	0.253523	0.01880	0.979	
	5	0.042957	0.00643	0.945	

The general model proposed by the authors for the backscatter X ray gauge was:

$$R_B(t) = \sum_{i=1}^n B_i(\sigma_i/\hat{\mu}_i)[1 - \exp(-\hat{\mu}_i t)]$$

where $R_B(t)$ is the normalised response given by:

$$R_B(t) = \frac{1000[\hat{R}_B(t) - \hat{R}_B(0)]}{\hat{R}_B(\infty) - \hat{R}_B(0)}$$

with the "hat" responses referring to raw counting rate data and the B_i , σ_i , and μ_i being the exponential term coefficients, the scatter coefficient, and the "effective" total linear attenuation (for the original and scattered radiation) coefficients.

The authors found that the optimum number of X ray energies for representing the backscatter model for an X ray machine operating at 36 kV was three for the method of determining the B_i that was used. The energies used were 25, 30, and 35 keV. Experimental results were

available for the same 19 alloys as for the transmission gauge results. The reduced chi-square (χ^2_v) value for all 19 alloys for a range of thicknesses from zero to 0.8 cm was 0.561 when a standard deviation on each data point of 1% was used. Five of the worst six alloys were found to be the same as those for the transmission gauge results. They were Alloys 2024, 7021, 7046, 7146, and 7178. When these alloys and Alloy 2036 were removed from consideration the reduced chi-square became 0.0961. Table 2 lists all results. As in the transmission gauge case very small changes in the alloy compositions make a big difference in how well they fit. Therefore, it is believed that the backscatter model is also quite good and that the six alloys that fit poorly probably do so because their composition is not known well enough.

TABLE 2: MODEL COEFFICIENTS B_i , THEIR STANDARD DEVIATIONS $\sigma(B_i)$, EXPONENTIAL TERM LINEAR CORRELATION COEFFICIENTS R , AND THE REDUCED CHI-SQUARE (χ^2_v) FOR THE 19 AND 13 ALLOY CASES FOR THE X RAY TRANSMISSION THICKNESS GAUGE.

Case	i	B_i	$\sigma(B_i)$	R	χ^2_v
19 Alloys	1	6.11064	0.646	0.964	0.561
	2	9.30779	0.820	0.999	
	3	2.14238	0.301	0.957	
13 Alloys	1	7.89274	0.806	0.937	0.0961
	2	6.72458	1.070	0.999	
	3	3.21424	0.409	0.980	

When the X^2_M approach was applied for the unadjusted nominal compositions of the 19 alloys (Use 2) with the model parameters given in Tables 1 and 2, it was found that the average relative error in the thickness measurement was 0.174% for the range of thicknesses from 0 to 0.8 cm. All alloy individual results were above 0.1% except Alloys 3004, 3105, and 6061. When the X^2_M approach was applied using the parameters for the 13 alloys while adjusting the copper weight fraction to simulate all composition variation (Use 3) the average relative error in thickness improved to 0.078% with only three alloys (1199, 5082, and 7072) having values greater than 0.1%.

Typical results for the model parameters obtained with a set of calibration standards for Alloy 3004 are shown in Table 3. This shows that this approach yields quite good results throughout the entire range of thickness, but the best results are at the smaller thicknesses. The ratio shown is for the transmission gauge contribution to the X^2_M value divided by the backscatter gauge contribution. With the exception of the first two or three thicknesses, the X^2_M value is dominated by the backscatter gauge contribution. This is true because the backscatter gauge responses are essentially independent of thickness above a thickness of about 0.2 cm.

These results are very promising. It appears that slight improvements in the models and composition analyses would yield the desired 0.1% accuracy. This could be done now by simply using A_i and B_i coefficients determined for each individual alloy — which is practical, but not as satisfactory as the use of the *universal* models. It appears that the optimum design of many of the dual-gauge applications will involve a transmission and a backscatter gauge since they complement each other extremely well. Dual transmission or dual backscatter gauges do not generally provide such complementary responses — they are too much alike.

This is particularly true if the measurement interference is composition — not so true for sample position.

TABLE 3: TYPICAL RESULTS USING THE X_M^2 APPROACH FOR THE 3004 ALLOY WITH THE CALIBRATION PARAMETERS OBTAINED FROM 13 ALLOYS

Actual Thickness (cm)	Measured Thickness (cm)	Transmission to Backscatter X_M^2 Contribution	X_M^2
0.0000	0.0000	0.0000	0.0000
0.1218	0.1215	0.8919	0.0002
0.1637	0.1636	0.3406	0.0166
0.2044	0.2045	0.1498	0.0116
0.2448	0.2450	0.0722	0.0263
0.2855	0.2857	0.0365	0.0234
0.3096	0.3098	0.0249	0.0167
0.3500	0.3501	0.0133	0.0097
0.3907	0.3906	0.0073	0.0251
0.4326	0.4324	0.0042	0.0188
0.4733	0.4729	0.0026	0.0117
0.5138	0.5133	0.0016	0.0129
0.5544	0.5540	0.0079	0.0432
0.5768	0.5763	0.0006	0.0322
0.6172	0.6169	0.0004	0.0354
0.6579	0.6577	0.0002	0.0350
0.6998	0.6996	0.0001	0.0412
0.7405	0.7406	0.0001	0.0504
0.7880	0.7816	0.0001	0.0318

It is likely that the use of the X_M^2 approach would benefit many of the previous dual-gauge applications. In particular, previous treatments such as using the ratios of two gauge responses may be improved upon with this approach. Many other applications should be amenable to this approach and triple or even quadruple gauges may find useful application in the future.

5. GENERAL COMMENTS: EVOLVING STATUS

As it is difficult to assess the present status of the NCS industry in the USA, it is even more difficult to assess the future or evolution of this industry. Therefore, it may be appropriate to concentrate more on the author's desired evolution rather than speculate on what will actually happen.

First of all the positive evolution of this industry — even its survival — depends on the success of making regulatory costs less expensive while at the same time more effective. This must be the number one goal of everyone that desires a healthy growing NCS industry in the USA. All other goals are an order of magnitude less important.

One of the lesser goals is removing or at least minimising the proprietary philosophy of the USA NCS industry. The author believes that this will make for a much healthier industry and,

ironically, would probably help public perception and, indirectly, regulatory costs. Even if the industry resists this change it can partly be brought about from outside sources. If University and Government Laboratory personnel become more involved in the research and development of NCS devices, their publications in the open literature will force the industry to respond in a positive way.

Another lesser goal is removing the one-device-fits-all philosophy that now pervades the USA NCS industry. The author sees that inroads are already being made in this case. In some cases this is being done by the NCS user industries. For example, Alcoa initiated the work on the combined X ray transmission and backscatter gauges for eliminating or minimising the composition dependence of X ray sheet thickness gauges. However, if the USA NCS industry would initiate a policy of pursuing new and different applications on their own with their own resources, the author believes that there would be many benefits. By building up a research and development group that is capable of devising new application designs, these companies would have a more versatile and perhaps more competent staff that could improve on their primary product as well as better identify and capitalise on new markets. A part of this problem appears to be the present popular short-term financial gain philosophy that is pervading much of USA industry and causing drastic reductions in pure and even applied research.

In the author's opinion other desirable goals would naturally follow if the three already discussed are met. This would include: (1) a greater reliance on mathematical simulation (including Monte Carlo simulation) and modeling and (2) increased use of the dual- or multi-gauge approach for eliminating or minimising measurement interferences.

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