

DEVELOPMENT OF A SLURRY MONITORING SYSTEM

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PREFACE

DECLARATION

I declare that this project report is my own, unaided work. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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Krohne Measurement and Control (Pty) Ltd for offering a full mass flow system for evaluation.

ABSTRACT

This project report can be divided into three main sections. The original objective of the project was the development of slurry monitoring instrumentation. However, during the literature survey for the project, it was found that several manufacturers had recently, or were about to, release integrated, intelligent instrumentation which met many of the project requirements. As one of the initial project requirements was, in fact, that as much commercially available instrumentation as possible should be used, with the remaining hardware only being developed if necessary, it was decided to evaluate the presently available products rather than continue with the development of further hardware.

A point which arose out of the literature survey was the increasing use of nuclear based instrumentation. Many end-users still shy away from these instruments, largely due to misunderstanding, unfamiliarity, the health hazard and the associated legal requirements for their use. It was also found that few users (and product representatives) understand the principles, operation and application of nuclear instruments. As nuclear density gauges are an integral part of the proposed solution, an investigation into the principles, operation, health hazard, legal requirements and applications of nuclear based instrumentation was undertaken. The objective of this study was to review nuclear based instrumentation and to develop an understanding of how to choose and apply such instruments. Emphasis was placed on gamma-ray based instruments which are prevalent in the mining and process control industries.

The report thus serves two purposes. Firstly, it is a survey and evaluation of instruments which satisfy the project requirements. Secondly, it is a guide to the application of magnetic flowmeters and the theory and application of nuclear density gauges in the monitoring of slurries.

The evaluation of the recommended instrumentation, was performed on a full mass flow system, which was made available by Krohne Measurement and Control (Pty) Ltd. It was found that the system met all the project requirements, but was however limited in flexibility.

The conclusion highlights the major points of the report, and discusses the success of the project. Some pointers are also given to possible future developments in instrumentation.

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1.0 BACKGROUND TO THE PROJECT

1.1 GENERAL

In deep South African gold mines, the gold bearing reef occurs as a thin sheet or table of rock which is often only 75mm to 100mm thick. Gullies are driven into the rock and the ore is then removed from stopes which cross-connect the gullies.

As the ore is mined, the stope converges under the overburden pressures (up to 100 MPa in mines of 3500m depth). A typical stope closure rate is 100mm a month.

The prevention of closure has traditionally been controlled by means of timber supports. This system has several disadvantages:

1. The handling of the timber is labour intensive.
2. The large quantities of timber underground constitutes a fire hazard.
3. Ventilation is difficult to control because of the large open spaces between the packs.

The hydraulic backfilling of stopes in deep gold mines is an attractive proposition as a means of controlling convergence of the stopes and absorbing energy released from the surrounding rock.

The advantages and benefits of using a hydraulic backfill system rather than a system of timber supports include:

1. Expensive timber need no longer be used.
2. Reduced labour requirements.
3. Reduced fire hazards.
4. Ventilation control is facilitated as a result of the elimination of open spaces.
5. Mine safety is increased. The compression of the fill absorbs energy released from the rock in the vicinity of the filled stope.
6. The problem of disposing of large quantities of mining waste can be partially alleviated by underground stowage.

The use of hydraulic stowage is not limited to gold mines. In South Africa, the large production of flyash and bottom ash in the coal-burning power stations, provides a ready source of a fill material for backfilling of the coal mines. Flyash has pozzolanic properties and it has been shown that flyash/cement mixtures can give similar shear properties to those produced by ordinary Portland cement. [Blight, 1979]

Flyash is readily available from the power stations and can normally be obtained for only the cost of its transport. As most of the power stations are located close to the coal mines, this cost is minimal. The use of flyash as a fill has several advantages :

1. Power stations need not purchase land for the formation of dumps.
2. Elimination of the dumps leads to a more aesthetic environment.
3. The ash can provide a base for further workings in thick seams and hence increase the percentage extraction, which extends the life of the power station.
4. The support to the coal pillars increases the safety factor of the mines.

A further application of high concentration paste pumping is the reclamation of unburnt flyash from slimes dams. Investigations of the chemical analysis of the flyash from one particular power plant revealed that about 45% carbon remained unburnt.

1.2 ADVANTAGES OF A HIGH DENSITY SLURRY

Hydraulic backfilling has not, despite its potential applications and advantages in gold and coal mines, been fully accepted in South Africa. The reasons for this include:

1. The fine gold tailings are slow draining. The stope could thus converge before the tailings have solidified.
2. The fill requires retaining while still in the liquid state.
3. The excess water that is introduced by conventional slurry techniques must be pumped back to the surface.

Research at the Materials Handling Research Unit (MHRU) of the University of the Witwatersrand has led to a proposed system, in which it is intended to transport the slurry in a high density 'paste' form with as little as 15% water content. On its own, this has merits, as the slurry assumes a homogeneous form and minimum use is made of a scarce resource, namely water.

Further advantages in applications to gold mines include :

1. Less drainage is required, thus less convergence takes place while the tailings solidify.

2. Retaining of the fill is not required, simplifying underground operation.

3. There is no excess water to be pumped back to the surface.

For flyash transportation the advantages are :

1. Utilization of the pozzolanic characteristic which is moisture dependant.
2. The average moisture content of the flyash as removed from the dam is about 43%. By pumping a high concentration paste back to the power plant the drying requirements can be minimized. (This is an important economic aspect as the drying plant of a short pipeline often makes the system uneconomical).

1.3 PROJECT OBJECTIVES

In order to implement a practical high density slurry pump system in coal and gold mines, instrumentation is required to enable control of the backfill process.

The project objective is the choice and/or development of suitable instrumentation to measure the mass flowrate and moisture content of the flyash/goldslime slurry. Using an inline mixer, the slurry is mixed with pneumatically conveyed dry cement, to strengthen the hydraulic fill. The cement/slurry mixing ratio is controlled by measuring the mass flowrate. The moisture content measurement is used to control the water content of the slurry.

The overall system configuration is shown in Figure 1 on page 4.

1.4 INSTRUMENTATION REQUIREMENTS

The transportation of high density slurries or "pastes" is associated with high head losses resulting from the high viscosities inherent in high concentration slurries. High pressure reciprocating pumps are used to overcome the high head losses incurred in the paste system.

The high pressure and head losses impose three important criteria on the instrumentation.

1. The instrumentation must be capable of withstanding the high pressures involved (up to 100 bar/10MPa).
2. The instrumentation must be abrasion resistive.

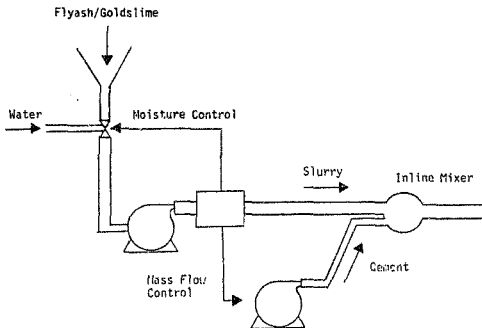


Figure 1. System Configuration

3. The instrumentation must be non-intrusive to minimize abrasion and the pressure drop.

A summary of the remaining slurry characteristics and instrumentation requirements is given in Figure 2 on page 7.

1.5 CONCLUSION

The basis of this project is the choice and/or development of instrumentation suitable for a high density slurry system. The remainder of this report outlines the procedure undertaken to choose and evaluate the necessary instrumentation. The choice/development and application of instrumentation is in many cases still much of a black art. The overriding feature of all instrumentation is the principle upon which the instrument

is based. There are many ways to obtain a measurement, but usually only one, or very few, ways suitable to a particular application. Once a suitable principle has been found, the user can survey the market for a suitable instrument based on that principle. If a commercial instrument is not available the user will then have to consider developing his own instrument.

If an analogy is sought, the principle represents the design and the instrument the implementation. No matter how good the implementation, a poor design will always lead to poor results.

Therefore, a successful instrumentation system is heavily dependant on the principles on which the instruments are based, and the users understanding of these principles. Because of the importance of the measuring principle, much of this report covers the different measuring principles, with the aim of providing a clear understanding thereof. Particular emphasis is placed on magnetic flow measurement and nuclear density measurement, which form the basis of the instrumentation suitable for a high density slurry monitoring system.

Chapters Two to Four covers the slurry monitoring instrumentation. Much of the material in these chapters was derived from instrumentation journals and manufacturers literature and as such represents the users point of view. Chapter Two consists of an extensive survey into various principles for measuring density and moisture content. Chapter Three discusses techniques for measuring mass flowrate. Chapter Four discusses techniques relating to slurry flow measurement.

Chapters Five to Eleven deals with the theoretical side of nuclear physics. The material in chapters Five to Eight was taken with slight modification from Tsoulfanidis[1983]. (This is an excellent text for an in-depth study of all aspects of nuclear physics.) The emphasis is on nuclear physics as it relates to process control instrumentation. Chapter Five reviews the concepts of atomic and nuclear physics relevant to radiation measurements. Chapter Six discusses the mechanisms by which ionizing radiation interacts and loses energy as it moves through matter. Chapter Seven discusses gas-filled detectors with scintillation detectors covered in Chapter Eight. Chapter Nine reviews statistics which are essential in any radiation measurement. Chapter Ten relates to the health hazards and legal regulations associated with the use of nuclear sources. Chapter Eleven discusses gamma ray instruments in an industrial environment. Emphasis is on their properties and design tradeoffs.

Chapter 12 discusses the evaluation of a full mass flow system which was obtained on loan from Krohne Measurement and Control (Pty) Ltd. A brief description is given of the system, followed by a detailed description of the test rig and methodology employed in evaluating the system. The test results are then evaluated in detail.

Chapter 13 concludes the report. The major points of the report are highlighted and the success of the project outlined. Some pointers to future developments in instrumentation are also given.

FLYASH and GOLDSLIME SLURRY CHARACTERISTICS.

Particle size : 0 - 3 mm
Constituency : Homogeneous Paste
pH : Alkali - acidic
Flow Profile : Flat
Temperature : Ambient
Solid Specific Gravity : 2,2 - 2,7
Slurry Specific Gravity : 1,5 - 2,0

SYSTEM PUMP and PIPING.

Pressure Range : 0 - 100 ber (10 MPa)
Flowrate Range : 0 - 1,0 m/s
Moisture Content Range : 20 - 35.%
Pipe Diameter : 125 mm
Pressure Drop : 0 - 100 bar

INSTRUMENT REQUIREMENTS.

Intruding Meters : Not allowed
Accuracy - Flow : 5 %
 - Moisture : 1 %
Output - Mass Flow : 4 - 20 mA
 - Moisture
 Content : 4 - 20 mA

Figure 2. System Characteristics and Requirements

2.0 SLURRY CONCENTRATION MEASUREMENT

2.1 INTRODUCTION

The project objectives involve the choice and/or development of instrumentation to measure the mass flowrate and moisture content of a high concentration slurry. The most important factor for a successful instrument is the measuring principle on which the instrument is based.

This chapter is an extensive literature survey into the principles for measuring the moisture content of high concentration slurries. The measurement of mass flowrate is discussed in the following two chapters. The survey consisted of reviewing instrument journals, conference papers and manufacturers literature.

2.2 MOISTURE MEASUREMENT

An important point arising from the literature survey is the confusing use of terminology surrounding moisture measurement. The terminology is relative to three areas of interest, namely moisture in a gas, moisture in a moist bulk solid, or moisture content of a slurry.

When speaking of the amount of moisture in a gas, humidity refers to the humidity. Humidity is measured using hygrometers, humidity meters or dew-point meters. In the case of bulk solids such as instant coffee, moisture or water content is the term used. In the case of slurries (where water is often simply a conveying medium and thus dominates) one is actually interested in the percent solids or concentration of the slurry. The terminology can give rise to misunderstanding and frustration.

Several techniques are available for measuring moisture content of bulk solids. These are reviewed below as they could possibly be used for measurement of concentration of slurries. These techniques either measure the amount of water directly or infer it from the physical properties of the material. The various techniques and their limitations are discussed below.

2.2.1 CAPACITANCE METHOD

This method is based on the principle that the dielectric constant of the material varies with the moisture content[Gumpert, 1981]. The major problem is that the constant also varies with the amount of material be-

tween the plates forming the capacitor. This can be compensated for by using a density meter to determine the amount of material present.

The capacitance method has a moisture measurement range of <0.01-30% with an accuracy of 0.25% and a repeatability of 0.1% depending on application. It is however affected by density, fats, protein, particle size and temperature variation.

2.2.2 CONDUCTIVITY METHOD

This method relies on the variation of conductivity of the sample material with the variation of moisture content. The conductivity is however dependent on several factors including density, temperature, dirt build-up on the container walls and constituency of the material itself. The method although often proposed has not proven reliable, gives inconsistent results and has poor accuracy.

2.2.3 MICROWAVE METHOD

This method is based on the use of microwaves with frequencies from 1 to 100 GHz[Meyer,1984]. The method works on the principle of comparing the effective propagation of electromagnetic waves in a specified material, to the propagation in free space. The extent of modification depends on the complex relative dielectric constant of the material. The real part of the constant determines the velocity of the propagating wave in the material while the complex part, called the loss factor, determines the attenuation of the wave amplitude as it penetrates the material. The real and complex components of the constant depend on the material density, temperature and operating frequency. The usefulness of the method, lies in the fact, that the dielectric constant for water is much greater than that of materials commonly measured. The water dielectric constant therefore largely determines the effective dielectric constant of the moist material.

A horn antennae is used to couple the microwave signals to and from the sample. The ratio of the phase shift and amplitude, which is reasonably independent of density, has a fixed relationship to the moisture content of a given material. The device can thus be calibrated to read the moisture content of the material.

The advantage of this method is that it is non-contacting, the microwaves pass right through the material, and density is automatically compensated for. The method would however be unsuitable for slurries, as it would not be feasible to mount the horn antennae onto the pipe, thus making it virtually impossible to couple the signal into the pipe. The dielectric

constant for the slurry could also be a limiting factor. The method is most suited to bulk solids.

The microwave method has a moisture measurement range of <0.01-50% with an accuracy of 0.07% and a repeatability of 0.03% depending on application. It is however slightly affected by density, fats, and particle size variation.

2.2.4 INFRARED GUAGING METHOD

The method is based on the fact that water exhibits discrete selective absorption bands in the near infrared region at 2.95 microns, 1.94 microns and 1.45 microns (decreasing sensitivity) [Crabtree, 1975]. In practise a filter wheel having two optical interference filters is rotated in front of an energy source (halogen lamp). The two beams of energy are imaged sequentially onto the surface of the material, following the same path.

The wavelengths of the beams, as determined by the filters, are selected such that one is at the chosen measuring wavelength for water, say 1.94 microns and the other at a wavelength adjacent to the absorption feature and is not absorbed by the material itself, say 1.8 microns.

A detector collects the energy bursts reflected back from the material surface, only one of which has been absorbed by the water in the material. A directly proportioned reading is obtained by forming the logarithm of the ratio of the two intensities.

The advantage of this method is that it is non-contacting and the use of a reference beam eliminates most errors resulting from time-drift, wear and dirt buildup.

The major limitation of this method is that the beams reflect off the surface of the material and do not pass through. Thus it is not suitable for any material where the water concentration within the material differs from that on the surface. Another limitation is due to strong surface reflections and thus it can not be used on shiny material. The factor which eliminates it from contention for slurry monitoring is that transparent windows would have to be provided in the pipeline for the beams to pass through (a pressure and abrasion limitation) and the fact that it is a backscatter method.

The same technique may also be applied to measurements of film thickness, in-situ gas analysis and trace element determination.

The infrared method has a moisture measurement range of <0.01-90% with an accuracy of 1% and a repeatability of 0.1% depending on application.

It is however affected by density, fats, colour, particle size and temperature variation.

2.2.5 NEUTRON MODERATION METHOD

This technique works on the principle that the speed of fast neutrons is strongly moderated by hydrogen nuclei, while the speed is barely affected by atomic nuclei of higher atomic weight [Pulse, 1983]. Thus, in the vicinity of a fast neutron source (Beryllium or Americium), a cloud of slow neutrons is formed whose density depends largely on the hydrogen content of any moisture which is present. By combining the fast neutron source with a slow neutron measuring system, a non-contact moisture measuring gauge is obtained.

Such a system is not affected by temperature, pH-value or pressure. The sensing unit can be mounted over conveyors, on bins, or on pipelines. The sample volume should be fairly large, 400mm wide by 50mm thick as a minimum for conveyors, or 200mm minimum pipe diameter.

A block diagram for a conveyor belt system is shown in Figure 3 on page 12.

The system does however have several limitations. The measurement is dependant on the number of hydrogen atoms present in the sample and thus not only water is measured, but all substances containing hydrogen (e.g. hydrocarbons). This can be compensated for if the number of non-water bonded hydrogen atoms is relatively constant. The measurement is also dependant on the density of the substance and thus density compensation is required. A possible saving can however be achieved by using the same detector for the neutrons and gamma rays. A further limitation is that the source and detector are usually combined in one housing and thus the neutrons do not pass through the sample under measurement.

2.3 CONCENTRATION OR PERCENT SOLIDS MEASUREMENT

Apart from the conductivity and capacitance methods proposed above which can be used for measuring the concentration of slurries the remainder of the methods all rely on the measurement of the specific gravity of the slurry. Density gauges can be calibrated in percent solids, only if a two-component slurry exists where one component's density (such as water SG = 1) is fixed. Some small error may be introduced if the solids' mass attenuation coefficient or density varies widely.

Using the above assumption the percent solids is calculated as follows:

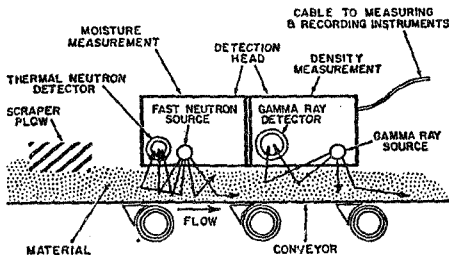


Figure 3. Neutron Moisture Measurement

$$\text{Percent Solids (by weight)} = \frac{\% \text{ Solids (SGU Slurry - 1)}}{\text{SGU Slurry (SGU Solids - 1)}}$$

The method for measuring the concentration then boils down to a method for measuring density or specific gravity. Note that this effectively excludes the above methods since density compensation is required for most of them, whereas the concentration of a slurry can be obtained simply from the density measurement alone. As will be seen later, density measurement is also required for mass flow measurement.

Note: The terms density and specific gravity are used interchangeably and this can lead to some confusion. For clarity the terms are defined below.

Density is the mass per unit volume and has units kg/m^3

Specific Gravity (SG) is the mass ratio of equal volumes of the material and water at standard conditions and is dimensionless.

The techniques for measuring density fall into three categories, namely fundamental mass measurement, nearly direct mass measurement and inferential mass measurement. The first two are likely to give the most accurate and consistent results and the discussion will centre on these categories. It is seen that all techniques measure the mass of the material. To derive the density the assumption is always made that the volume is fixed and known (full 'container').

The various techniques are discussed below:

2.3.1 GRAVIMETRIC METHOD

A diagram of this device is shown in Figure 4 on page 14. The method is very simple and consists simply of taking a section of pipe of known volume, filled with the slurry and weighing it. The method is thus one of fundamental mass measurement. The section of pipe which is weighed is usually formed into a U-tube, but there has been a proposal to use a straight section of pipe. [Baker, 1979]

Despite its simplicity the method has several limitations. Early devices were sensitive to pressure, and devices are normally limited in their working pressure. Problems can also arise with the flexible couplings. The method also does not offer high accuracies and in practical implementation is not always put in-line, but, a sample of the slurry material is tapped off and flows through the meter. It is however necessary to keep the velocity above the slurry settling velocity to prevent deposition of solids in the meter causing an error in the measurement.

2.3.2 DIFFERENTIAL PRESSURE METHOD

An example of a meter based on this principle is shown in Figure 5 on page 15. The meter has an inverted 'U'-loop in the slurry line. By measuring the pressure difference between the top and bottom of the two legs and making certain assumptions, the concentration of the slurry can be obtained [Muller, 1983; Slomians, 1979]. The method is considered to be useful but not expected to yield high accuracy. Unlike all the other meters in the literature survey, it is not known if there is a commercial meter based on this principle. The principle is one of nearly direct mass measurement.

2.3.3 NUCLEAR RADIATION METHOD

Unlike the nuclear radiation meter which uses neutron radiation for moisture measurement (discussed earlier), this method uses gamma rays and measures the density of the material in the pipe. Nuclear density meters are rapidly being accepted as the standard for density measurement, are commonly available and give accurate and consistent results. [C and I, 1982; Springer, 1979]

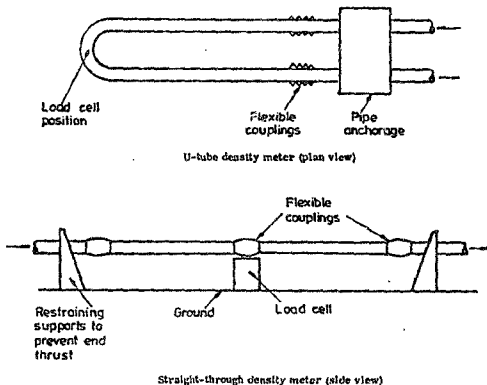


Figure 4. Gravimetric Density Meter

The measurement technique is as follows. A nuclear source (Caesium-137 with 30 yr. half life, or Cobalt-60 with 5 yr. half life) and a detector (either an ionisation chamber or scintillation counter) are placed diametrically opposite the pipe. High energy gamma rays are beamed through the pipe and onto the detector. When gamma rays pass through the material they are absorbed in proportion to the material density. An increase in the material density results in a reduced detector output.

Thus, the measurement of the absorption of the rays by the material is a direct measure of the density of the material. For acceptable stability and elimination of excessive drift, it must be ensured that at least 5% of the gamma rays are absorbed. Conversely, if pipe diameter and density are too great, not enough radiation can penetrate the detector.

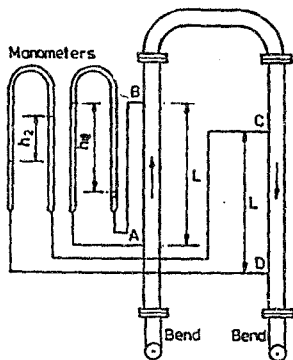


Figure 5. Differential Pressure Counterflow Meter

For the majority of density applications Caesium-137 is used as the radioisotope. Source sizes normally vary between 10 and 2000 mCi (millicuries) as a function of pipe diameter and specific gravity span. Gauge sensitivity is increased by the use of collimated beam geometry which restricts radiation in all directions except for a direct path to the detector. This minimises scatter and permits the use of larger sources with increased measuring sensitivity. Most designs are such that radiation intensity at 300mm from the gauge surface in any direction, will not exceed 5 mR/h (millirontgens per hour). This is the safe value for any process area where the operator's occupancy is less than twenty hours per week. The source holder is provided with a shutter mechanism to close the radiation beam part during installation, when the power fails or, where required, from a remote control board.

The minimum measuring full scale span is about 0.05 SG units with a corresponding accuracy of 0.0005 or better. When measuring small spans, the zero drift due to source decay becomes an important consideration. The source decay compensator unit is essential for such installations. For wider ranges, it is essential only if the source is Cobalt-60. The source decay effect with Caesium-137 is only about 3% per year. Process materials with high temperature expansion coefficients are provided with temperature compensation if variations in temperature is expected.

The disadvantage of a nuclear density gauge is that a permit is needed to operate it, and suitably qualified personnel must be employed to accept responsibility for the nuclear source. Some operators may also be reluctant to operate the gauge and extra precautions must be taken to minimize the health hazard. However, it must be stressed that the safety requirements are no more onerous than those needed for any dangerous material or chemical.

2.4 MOISTURE CONTENT/ PERCENT SOLIDS EVALUATION

It should be clear that the density meters are the best solution since not only are they often required for compensation in direct moisture measurement but are also required to calculate the solids mass flow. In choosing a density meter it is clear that the nuclear meter offers the best possibility of success. It is not affected by external effects, is accurate, commonly available and has undergone extensive development by several manufacturers.

This concludes the review of concentration and moisture content meters. The following chapter discusses the other aspect of the project, namely, techniques for measuring the mass flowrate of high concentration slurries.

3.0 MASS METERING EQUIPMENT

3.1 INTRODUCTION

To meet the project objectives instrumentation is required to measure the slurry moisture content and mass flowrate. This chapter discusses instrumentation to measure the mass flow rate of high concentration slurries.

Two basic techniques are used. The first technique uses coriolis forces to measure mass flow directly, and the second technique adopted is to calculate the mass flow. Originally this was done using analogue computers but more and more manufacturers are introducing microprocessor based systems.

3.2 MASS FLOW METER

The Mass Flow Meter measures a very small force generated by the process fluid as it moves through the sensor tube. This force results from the acceleration or deceleration of the fluid particles as the tube vibrates perpendicular to the direction of flow. The force is analogous to the coriolis force which causes air currents to circulate around the rotating earth, and to gyroscopic forces employed in navigation systems.

Meters based on this principle were initially available only in small sizes, but increasingly larger meters (up to 5 tons/hour) are becoming available. The mass flow meter is also suitable for measuring gas mass flowrates, and this has resulted in meters based on this principle becoming available from several manufacturers.

The discussion in the remainder of this section is based on the Micro Motion Mass Flow Meter [Micro Motion, 1983].

The forces induced by the fluid flow on the sensor tube are the coriolis/gyroscopic forces. Figure 6 on page 18 shows the fluid with mass (m) and velocity (V) moving through the sensor which is rotating with angular velocity (ω) about axis O-O.

Forces exerted by the fluid on each leg (F_1 and F_2) are 180 degrees out of phase. The angular velocity of the sensor tube is not required to be constant but can oscillate. The associated force is also oscillatory and is proportional to the fluid mass (m) and velocity (V). As the tube vibrates about axis O-O, the forces create an oscillating moment about the axis R-R. The total moment (M) is the integral of the moments of all the fluid particles around the sensor tube. The moment M causes an angular

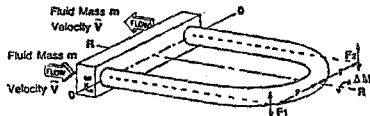
deflection or twist of the sensor about axis R-R, which is at its maximum at the midpoint of the vibrating tube travel. (see Figure 7 on page 19).

The mass flow rate can be derived by measuring the deflection angle using the two sensors shown in Figure 7 on page 19. This measurement is accomplished by measuring the relative times that each sensor detects the midpoint crossing of the respective leg. The time difference at zero flow is nulled by calibration of the signal conditioning electronics.

The mass flow rate (Q) is proportional only to the time interval and geometric constants and is independent of the vibration frequency of the sensor tube. The meter is also capable of measuring reverse flow direction.

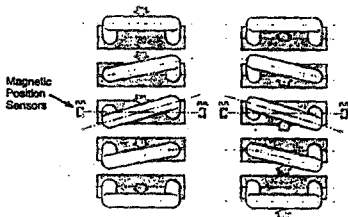
It is also possible to obtain a density output from the meter. The density output is however dependant on the spring constants and tube mass of the sensor, and thus subject to drift as metal fatigue takes place. The output is suitable only for relative density approximations.

The major limitation of using this meter in the present project is that it induces a large pressure drop which is dependant on the fluid viscosity, density and velocity.



SENSOR TUBE WITH AXES OF ROTATION
AND MOMENT ΔM

Figure 6. Micro Motion Sensor Tube



COMPLETE CYCLE OF SENSOR TUBE;
MEASUREMENT OF TWIST ANGLE θ

Figure 7. Micro Motion Operating Principle

3.3 MASS FLOW COMPUTER

The mass flow is derived from the product of the volumetric flow rate, the material density and the solids concentration. The product of the volumetric flow rate and density give the total mass flow rate. Multiplying this by the percent solids (concentration) gives the mass flow rate of the solids, i.e.

$$SF = F \cdot \rho \cdot SG$$

Where

F = volume flow of slurry in m^3/hr (from flowmeter)

PS = percent solids (concentration) by weight

SG = slurry specific gravity

The volumetric flow rate is obtained from a flowmeter, while the density is obtained from a density gauge and the percent solids from a concentration meter. It was shown in the review of concentration measurement in section "Concentration or Percent Solids Measurement" on page 11 that

a density gauge can be used to measure both the specific gravity and the concentration of a slurry.

The mass flow computer (usually a stand alone unit) has an input for volumetric flow rate, SG and percent solids, and provides signal outputs of both solids concentration and mass flow rate.

3.4 MASS FLOW EVALUATION

One of the main constraints on the instrumentation is that it must not introduce a pressure drop. Thus, it is not possible to use a Mass Flow Meter. Therefore, the mass flow is calculated by means of a mass flow computer. This has advantages as a density gauge is already required to measure the slurry concentration. In this project a nuclear density gauge is used to determine the density and slurry concentration.

To complete the mass flow calculation, the volumetric flowrate must be determined. Different flow measuring principles are discussed in the next chapter.

4.0 FLOW MEASUREMENT

4.1 INTRODUCTION

In the previous chapter it was shown that a mass flow computer can be used to calculate the mass flowrate of a slurry based on the SG, volumetric flowrate and solids concentration. This chapter discusses techniques for measuring the volumetric flowrate.

Although there are several methods for measuring flow, such as orifice plates, vortex meters and turbine meters, only two meters warrant serious consideration for the measurement of slurries. These are ultrasonic meters and magnetic flowmeters. In general, flowmeters measure the velocity of the fluid in a pipe. The volumetric flowrate is determined from the pipe dimensions and the assumption that the pipe is full.

4.2 ULTRASONIC METERS

Ultrasonic meters (Meritt, 1982; Mintek, 1983;) are usually based on one of two principles, measurement of transit time or measurement of doppler frequency shift. Of the two, doppler is the most commonly used and only doppler meters will be discussed.

When doppler meters were introduced, they were heralded as the first ideal and universal flowmeters. The meters were non-intrusive and could in fact be simply clamped onto the pipe conveying the material. The meters did, however, not live up to their promise, largely due to poor quality and, possibly, incorrect application.

More recently the quality of the meters has improved, and the meters are being recommended in instrumentation journals for measuring the flowrate of slurries.

The prime advantage of such instruments, are, that they are non-intrusive, - they can also be fixed onto pipework without interrupting the process. Their cost does not rise with pipe diameter and they can also measure slurries with magnetic properties. It is further claimed that they are inexpensive, accurate and when properly applied, give reproducible results.

The meter operates by transmitting an ultrasonic beam through the wall of the pipe. The beam is backscattered, or reflected from particles in the slurry or ore, or from air bubbles. If these particles are moving their velocities are added to (or subtracted from) the velocity of the reflected ultrasonic beam in the medium. The resulting change in frequency between the incident and reflected beam is known as the Doppler shift, and is directly proportional to the velocity of the particles. A combi-

nation of the doppler equation and Snell's law shows that the change in frequency is :

$$\text{Frequency change} = f_1 - f_2 = (2V \cdot \cos x) / C$$

Where:

f_1 and f_2 are the transmitted and reflected beams respective frequencies;

x is the angle between the axis of the pipe and the incident ultrasonic beam;

C is the velocity of sound in the medium; and

V is the velocity of the reflecting particles, and is much smaller than C .

The mode of operation is shown in Figure 8.

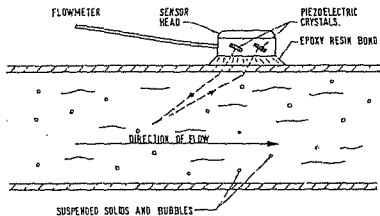


Figure 8. Doppler Flowmeter Schematic

For transmission of the ultrasonic beam, there must be an acoustic bond between the transducer and the pipe, and the wall of the pipe must transmit the ultrasound into the slurry. Further, since Rayleigh back-scattering depends on the size of the particles (a relation to the third power) the slurry must contain particles of a certain size and in a certain concentration.

In order to evaluate doppler meters, investigations were undertaken by the Council for Mineral Technology (Mintek) using six different doppler meters. The tests were conducted on mine-sand slurry at three relative densities : 1,040, 1,167 and 1,271 with flow rates over the range 1,5 m/s to 6 m/s.

The major results of the tests revealed that all flowmeters responded well to changes in flow and gave linear outputs to within 2 % of the maximum. The time constants for doppler meters is longer than that of magnetic flowmeters and that the slope of the response decreases as the density of the slurry increases (thought to be due to the velocity profile). [Mintek,1984]

4.3 MAGNETIC FLOWMETERS

Magnetic flowmeters were specifically designed for the measurement of flowrates in slurries [Marks, 1977; Springer, 1980]. The magnetic flowmeter is based on Faraday's law of electromagnetic induction. As the material flows through the magnetic field, which is set up by exciting the meter's electromagnets, an electric voltage, which is directly proportional to the liquid's velocity, is induced in the liquid which acts as the electrical conductor i.e.

$$U = B.D.v.$$

Where:

U = The induced voltage (V)

B = The magnetic field strength (Tesla)

D = The distance between the electrodes (m)

v = The velocity of the material (m/s)

The operation is shown in Figure 9 on page 24.

The induced voltage is perpendicular to both the conductive liquid and the magnetic field set up by the meter's coils. The voltage is measured for subsequent transmission to an applicable converter. The flux density of the magnetic field and the distance between the electrodes are constant; therefore the induced voltage is solely a function of the material's velocity. The induced voltage is not affected by temperature, viscosity, or conductivity - as long as the conductivity of the measured liquid is above a minimum threshold level (min. 0,05 microSiemens/cm). For reliable measurements, the pipe must be completely full of liquid. This is necessary as the electrode voltage is a weighted function of the induced voltage throughout the cross-section of the pipe. Secondly, the

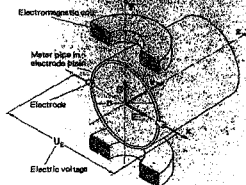


Figure 9. Magnetic Flowmeter Schematic

meter output is often taken as a volumetric flowrate which is only valid if the pipe is full.

To prevent the voltage being shorted out through the meter walls, the meter must be lined with an insulating lining. The magnetic flowmeter is available with different linings, different electrodes (including capacitive pick-up) and with either AC or DC excitation.

4.3.1 CHARACTERISTICS

The magnetic flowmeter has the following advantages:

1. Linear indication of average flow velocity, thus ensuring superior accuracy to differential pressure meters.
2. The meter is non-intrusive, therefore wear and pressure loss in the meter are the same as an equivalent length of straight pipe.
3. The metering is independent of the nature of the flow (turbulent or laminar).
4. The measurement is independent of temperature, pressure, viscosity, density, concentration, and direction of flow.

5. There is no preferred flow direction and even pulsating flows can be measured.
6. The primary head (detector) can be mounted in any position.
7. The method is independent of undissolved solids in the medium.
8. The method can be used to measure chemically corrosive liquids by suitable choice of tube liners and electrodes.
9. The output signal is a voltage which is readily converted to any desired electrical quantity.
10. Accuracy of up to 0.5% of rate down to 10% of full scale and thereafter an accuracy of 0.5% of full scale. The percent-of-rate accuracy means the meter remains accurate at low flow rates.
11. A turn-down ratio (i.e. maximum to minimum flowrate) of 10 to 1 in a span of 40 to 1.

The disadvantages of the meter are:

1. Pressure and temperature limitations imposed by the liner and electrode material.
2. The fluid must have sufficient conductivity, i.e. typically greater than 20 $\mu\text{S}/\text{cm}$.
3. The fluid must not contain magnetic materials.
4. The cost of the meter is high.

4.3.2 SINEWAVE OR PULSED DC EXCITATION

In order for a magnetic flowmeter to operate, a magnetic field must be established. The field is established by coils mounted on the meter body. An AC or pulsed DC voltage is used to excite the coils.

Sinewave or AC excitation of magnetic flowmeters has been in use for more than twenty years. This method was originally used because of its manufacturing simplicity. The method however has several disadvantages: [Marks, 1977; Springer, 1980]

1. AC meters have a high power consumption which results from the reactance of the magnetic field coils. The meters are thus large and bulky.
2. AC meters have a quadrature voltage component induced onto the electrodes as a result of transformer coupling between the excitation coils and the path formed by a line joining the electrodes and the signal cables emanating from the electrodes. This voltage is 90 degrees out of phase with the velocity induced voltage. The measured

signal is thus the vector sum of the desired signal and the quadrature component. Elimination of this signal is required.

3. If the conductivity of the fluid is not constant along the cross-section and along the length of the primary head, eddy currents result which vary with time. Therefore, interference voltages arise which cannot be fully suppressed in the meter.
4. Fouling of the electrodes increases the internal resistance of the signal circuit and the capacitive coupling between the magnetic coils and the signal circuitry. Furthermore, the signal circuitry becomes more sensitive to capacitive transmission by interference from nearby power lines.
5. Interference voltages may be coupled into the signal circuit from nearby cables carrying high currents.
6. Occasionally, such as in buried pipelines near railway networks, stray currents of unknown phase orientation are carried by the liquid flowing in the pipe and by the pipe itself. These currents can give rise to interference voltages.
7. Interference voltages can be produced as a result of inadequate earthing which allows stray currents to induce voltages in the meter body.
8. In AC magnetic-inductive flow measurement, interference voltages can only be eliminated with great difficulty if at all.
9. The AC meter requires zero point setting which is done during calibration.

The pulsed DC magnetic flowmeter was developed to overcome the limitations of the AC excited meter. A close examination will reveal that almost every source of error in the AC meter is a result of magnetic (transformer) or capacitive coupling resulting from the use of AC fields. To eliminate the AC sources of error the DC flowmeter was developed. The use of pulsed DC has two advantages apart from eliminating problems resulting from AC excitation:

1. The periodic reversal of the field (typically 6 to 11 times a second) prevents polarization of the material in the pipe and reduces buildup on the electrodes.
2. Every time the field is reversed, the signal voltage is measured at the zero crossing point, thus automatic zero compensation takes place at twice the pulse rate.

A further advantage of the pulsed DC meter, is that many meters now incorporate a microprocessor, which allows for simple setting of span, range and output scaling, usually by means of BCD switches. This results from the fact that all signal conditioning is performed mathematically by the microprocessor. To change the range only the constants in the scaling formulae has to be changed. A meter using an analogue computer (operational amplifiers) would require recalibration of the scaling potentiometers.

Normally, given the development of the pulsed DC meter, this meter should always be chosen above that of the AC meter. Its advantages, simplicity and ease of use, make it the overriding choice wherever applicable.

NOTE Despite their advantages, pulsed DC meters are no longer specified for slurry applications! After, their introduction users noted inadequate performance in slurry applications. The reason most often cited is, that as the slurry particles collide with the electrodes they induce noise which results in incorrect readings. This has been attributed to poor electrode design and at least one manufacturer will still specify pulsed DC meters for slurry applications. The induced noise is not a problem in AC meters because of the higher effective sampling rate.

4.3.3 SELECTION OF INSULATING LINER

An important point in the selection of magnetic flowmeters is the selection of the liner. This naturally varies with every application and determines the temperature and pressure rating of the meter as well as its resistance to corrosion and abrasion. These ratings result from the characteristics of the liner material. As a general guideline the characteristics shown in Figure 10 apply. [Springer, 1980]

Liner Type	Corrosion Characteristic	Abrasion Characteristic	Temperature Max.(Celsius)	Pressure Max.(MPa)
Hard Rubber	Fair - Excellent	Fair	90	10
Soft Rubber	Varies	Very Good	40	6,4
Neoprene	Varies	Excellent	80	25
Polyurethane	Varies	Excellent	40	25
Teflon (PTFE)	Excellent	Fair	180	4

Figure 10. Magnetic Flowmeter Liner Characteristics

4.3.4 SELECTION OF ELECTRODES

Several types of electrodes are available, differing mainly in abrasion resistance. Many of the electrodes are a natural evolution of manufacturers development. In normal circumstances the standard electrodes supplied with the meter will be sufficient. For extreme circumstances of

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Soft Rubber	Varies	Very Good	40	6,4
Neoprene	Varies	Excellent	60	25
Polyurethane	Varies	Excellent	40	25
Teflon (PTFE)	Excellent	Fair	180	4

Figure 10. Magnetic Flowmeter Liner Characteristics

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Several types of electrodes are available, differing mainly in abrasion resistance. Many of the electrodes are a natural evolution of manufacturers development. In normal circumstances the standard electrodes supplied with the meter will be sufficient. For extreme circumstances of

electrode fouling, ultrasonic cleaning of electrodes is available as an option, or removable electrodes can be obtained. A recent development is the use of capacitive pickup, where the electrodes forming the capacitor plates are imbedded behind the liner and thus cannot be fouled. Capacitive electrodes also allow operation with liquids of conductivities as low as 5 $\mu\text{S}/\text{cm}$. This is possible as a result of a larger electrode area. Capacitive electrodes are however expensive and the situation must warrant their use. Available electrode materials include Hastelloy C, Stainless Steel, Titanium and Platinum-Iridium.

4.3.5 INSTALLATION RECOMMENDATIONS

In order for a magnetic flowmeter to operate correctly it must be correctly installed. Incorrect installation can lead to inaccurate readings and/or unreliable operation. When installing magnetic flowmeters the following guidelines should be followed to ensure reliable operation.

1. The flowmeter can be installed in any position (electrode axis approximately horizontal).
2. The pipe must be filled at all times as the output, is often taken to be the volumetric flowrate (velocity times cross-sectional area), which assumes a constant cross-sectional area.
 - Inlet/outlet section must be greater than or equal to 5 times (for inlet) or 2 times (for outlet) the diameter of the meter measured from the electrode axis.
4. Slide valves or control flaps must not be mounted directly on the primary head. (See point 3)
5. Shut-off and control valves should be fitted downstream of the primary head.
6. For AC meters a shut-valve must be installed for zero-point setting.
7. Signal transmission cables must be as short as possible and should not run alongside heavy-current lines so as to minimise interference.
8. The meter must be correctly and adequately grounded to prevent interference of the signals. (See manufacturers specifications).

4.4 FLOWMETER EVALUATION

The doppler and the magnetic flowmeter both have their respective advantages. The main advantage of the doppler meter is that it is a clamp-on device and thus is easy to install and use. However, the magnetic flowmeter is a proven device and is widely used. The main argument against the doppler meter is its high probability of failure in this application.

Despite the Mintex study the suitability of the doppler meter to high density (paste) slurries and their associated low velocities (a system characteristic) is still unknown. The major disadvantage of the magnetic flowmeter is that the required pressure rating makes it a non-stock item, thus increasing both its cost and availability. Despite this, the magnetic flowmeter is considered to be the most suitable meter for the project. An AC flowmeter must be used until pulsed DC meters have proved to be reliable in slurry application.

This concludes the review of instrumentation which meets the requirements for mass flowrate and concentration measurement of high concentration paste slurries.

The instrumentation can be summarised as follows:

Mass Flow Measurement

Magnetic Flowmeter - For measuring volumetric flowrate

Nuclear Density Gauge - For measuring SG

Mass Flow Calculator - For calculating mass flow

Moisture Content Measurement

Nuclear Density Gauge - For measuring concentration

The same nuclear density gauge is used for both mass flow and concentration measurement. However, many end-users still shy away from nuclear instruments, largely due to misunderstanding, unfamiliarity, the health hazard and the associated legal requirements for their use. It was also found that few users (and product representatives) understand the principles, operation and application of nuclear instruments. As nuclear density gauges are a integral part of the proposed solution, an investigation into the principles, operation, health hazards, legal requirements and applications of nuclear based instrumentation was undertaken.

The objective of this study, which is presented in the following chapters, was to review nuclear based instrumentation and to develop an understanding of how to choose and apply such instruments.

5.0 NUCLEAR RADIATION APPLICABLE TO DENSITY MEASUREMENT

5.1 INTRODUCTION

This chapter reviews the concepts of atomic and nuclear physics relevant to radiation measurements. The field is however a very broad one and the emphasis is on the concepts relating to process control applications. The intention of this chapter is not to present a detailed discussion of the subjects, but rather to outline the principles inherent in nuclear process control instrumentation. The emphasis is on the nuclear behaviour and theory relevant to level, moisture and density measurement. For an in-depth discussion of the theory, principles and spectrum of nuclear physics the reader is referred to the Tsoulfanidis[1983].

5.2 ATOMS

To the best of our knowledge today, every atom consists of a central positively charged nucleus around which negative electrons revolve in stable orbits. Considered as a sphere, the atom has a radius of the order of 0.1 nm and the nucleus a radius of the order of 10 fm. The number of electrons is equal to the number of positive charges of the nucleus; thus the atom is electrically neutral in the normal state.

The number of positive elementary charges in the nucleus is called the atomic number and is indicated by Z . The atomic number identifies the chemical element. All atoms of an element have the same chemical properties.

The atomic electrons move around the nucleus as a result of the attractive electrostatic Coulomb force between the positive nucleus and the negative charge of the electron. According to classical electrodynamics, the revolving electrons ought to continuously radiate part of their energy, follow a spiral orbit, and eventually be captured by the nucleus. Obviously, this does not happen: atoms exist and are stable. Therefore, a new theory governing orbital mechanics and called quantum mechanics was developed.

The available experimental evidence points toward the following facts regarding the motion of atomic electrons:

1. Bound atomic electrons revolve around the nucleus in stable orbits without radiating energy. Every orbit corresponds to a certain electron energy and is called an energy state.
2. Only certain orbits (only certain energies) are allowed. That is, the energy states of the bound electrons form a discrete spectrum. This phenomenon is called quantization.
3. If an electron moves from an orbit (state) of energy E_i to a state of lower energy E_f , then (and only then) electromagnetic radiation, an x-ray, is emitted with frequency ν such that

$$\nu = (E_i - E_f)/h \quad (5.1)$$

where h is Planck's constant.

The energy of the x-ray depends on the atomic number:

$$E_x = h\nu = E_i - E_f = k(Z-a)^2 \quad (5.2)$$

where k and a are constants. Every atom emits characteristic x-rays with discrete energies that identify the atom like fingerprints. X-ray energies range from a few eV for the light elements to a few hundreds of keV for the heaviest elements.

4. A bound electron may receive energy and move from a state of energy E_1 to a state of higher energy E_2 . This phenomenon is called excitation of the atom. An excited atom moves preferentially to the lowest possible energy state, therefore in times of the order of 10 ns, the electron will return to E_1 and an x-ray will be emitted.
5. An atomic electron may receive enough energy to leave the atom and become a free particle. This phenomenon is called ionization, and the positive entity left behind is called an ion. The energy necessary to cause ionization is called the ionization potential. The ionization potential is not the same for all electrons of the same atom because the electrons move at different distances from the nucleus. The closer the electron is to the nucleus, the more tightly bound it is and the greater its ionization potential becomes.
6. When two or more atoms join together to form a molecule, their common electrons are bound to the molecule. The energy spectrum of a molecule is also discrete but more complicated than that of an atom. The discrete and unique spectrum of molecules and atoms is used in X-ray Fluorescence to identify the substance.

5.3 NUCLEI

At the present time, all experimental evidence indicates that nuclei consist of neutrons and protons, which are particles collectively known as nucleons. Some of the properties of a neutron, proton and an electron are listed in Figure 11 on page 32 for comparison.

	Electron	Neutron	Proton	
Rest mass	9.109558×10^{-31}	1.674919×10^{-27}	1.672614×10^{-27}	
	≈ 0.511	$= 939.549$	$= 938.256$	MeV
	$= 0.000549$	$= 1.008665$	$= 1.007276$	u
Charge	-e	0	+e	

Figure 11. Neutron-Proton Properties.

A Nucleus consists of A particles,

$$A = N + Z$$

where

A = mass number

N = number of neutrons

Z = number of protons = element atomic number

A nuclear species X is indicated as



where X = chemical symbol of the element.

The following definitions apply:

1. Isobars are nuclides that have the same A.
2. Isotopes are nuclides that have the same Z. They are nuclides of the same chemical element. They have the same chemical but slightly different physical properties, due to their difference in mass. The nuclear properties change drastically from isotope to isotope.
3. Isotones are nuclides that have the same N, i.e. same number of neutrons.
4. Isomers are two different energy states of the same nucleus.

The different atomic species are the result of different combinations of one type of particle - the electron. There are 92 natural elements. Since 1940, 15 more have been artificially produced for a total of 107. The different nuclides, on the other hand, are the result of different combinations of two kinds of particles, neutrons and protons, and so there are many more possibilities. There are more than 700 known nuclides.

Experiments have determined that nuclei are almost spherical, with a volume proportional to the mass number (A), thus all nuclei have similar densities, and an average radius approximately equal to

$$R = 1.3 \times 10^{-15} A^{1/3} \text{ in meters.} \quad (5.3)$$

The mass of the nucleus with mass number A and atomic number Z, indicated as $M_n(A, Z)$, is equal to

$$M_n(A, Z) = Z \cdot m_p + N \cdot m_n - B(A, Z) c^2 \quad (5.4)$$

where m_p = proton mass

m_n = neutron mass

$B(A, Z)$ = binding energy

The unit used for the measurement of nuclear mass is equal to 1/12 th of the mass of the Carbon-12 isotope. Its symbol is u (formerly amu for atomic mass unit):

$$1u = (1/12)(\text{mass of } ^{12}\text{C}) = 1.660531 \times 10^{-27} \text{ kg} = 931.478 \text{ MeV}$$

In many experiments, what is normally measured is the atomic mass and not the nuclear mass. The atomic mass is obtained by adding the mass of all the atomic electrons. The mass may be given in one of the following three ways:

1. Units of u.
2. Kilograms.
3. Energy units (MeV or J, in view of the equivalence of mass and energy).

The meaning of $B(A, Z)$ may be expressed in two equivalent ways:

1. The binding energy $B(A, Z)$ of a nucleus is equal to the mass transformed into energy when the Z protons and the $N=A-Z$ neutrons combined to form the nucleus. An amount of energy equal to the binding energy was released when the nucleus was formed. Or
2. The binding energy $B(A, Z)$ is equal to the energy necessary to break the nucleus apart into its constituents, Z free protons and N free neutrons.

The energy necessary to remove one particle from the nucleus is the separation or binding energy for that particle for that particular nuclide. A "particle" may be a neutron, proton, an alpha particle, a deuteron, etc. The separation or binding energy of a nuclear particle is analogous to the ionization potential of an electron. If a particle enters the nucleus, an amount of energy equal to its separation energy is released. The separation or binding energy is equal to the difference in binding energies of the original nucleus and the resulting nucleus after the "particle" has been removed.

5.4 NUCLEAR ENERGY LEVELS

Neutrons and protons are held together in the nucleus by nuclear forces. Although the exact nature of nuclear forces is not known, scientists have successfully predicted many characteristics of nuclear behaviour by assuming a certain form for the force and constructing nuclear models based on that form. The success of these models is measured by how well their predicted results agree with the experiment. Many nuclear models have been proposed, each of them explaining certain features of the nucleus; but as of today, no model exists that explains all the facts about all the known nuclides.

All nuclear models assume that the nucleus like the atom, can exist only in certain discrete energy states. Depending on the model, the energy states may be assigned to the nucleons - neutrons and protons - or the nucleus as a whole. The present discussion of nuclear energy levels will be based on the second approach.

The lowest possible energy state of a nucleus is called the ground state, in Figure 12 on page 35, the ground state is shown as having negative energy to indicate a bound state. The ground state and all the excited states below the zero energy level are called the bound states. If the nucleus finds itself in any of the bound states, it de-excites after a time of the order of 1 to 100 ps by dropping to a lower state. De-excitation is accompanied by the emission of a photon with energy equal to the difference between the initial and final states. Energy states located above the zero energy level are called virtual energy levels. If the nucleus obtains enough energy to be raised to a virtual level, it may de-excite either by falling to one of the bound levels or by emitting a nucleon.

Studies of the energy levels of all the known nuclides reveal the following:

1. The distance between nuclear energy levels is of the order of keV to Mev. By contrast, the distance between atomic energy levels is of the order of eV. Thus photon emission from atomic de-excitation (X-rays) are of a much lower frequency than that of nuclear de-excitation (gamma-rays).
2. The distance between energy levels decreases as the excitation energy decreases. For very high excitation energies, the density of the levels becomes so high that it is difficult to distinguish individual energy levels.
3. As the mass number A increases, the number of levels increases; i.e. heavier nuclei have more energy levels than lighter nuclei (in general - there may be exceptions).
4. As A increases, the energy of the first excited state decreases (again, in general - exceptions exist).

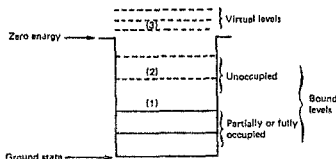


Figure 13. Bound and virtual nuclear energy levels

5.5 NUCLEAR DISINTEGRATIONS

This section outlines the three main modes of decay: alpha, beta and gamma, and the variations which can occur. The type of decay of relevance in process control instruments is gamma decay and the emphasis will be on this mode. Some naturally radioactive elements have more than one decay mode as shown in Figure 13 on page 36 [PBI, 1983]. The most commonly used elements in process control are Cobalt-60, Americium-241, and Caesium-137. The thickness gauge applications are prevalent in the paper and pulp industry.

5.5.1 GAMMA DECAY

In gamma decay, a nucleus goes from an excited state to a state of lower energy and the energy difference between the two states is released in the form of a photon (an electromagnetic wave). Gamma decay is represented by



where the * indicates an excited nucleus.

Radioisotope	radiation type	radiation energy (MeV)	Half life (years)	Application	Typical source activities (millicuries)
Iron 55	X-ray	0.006	27	thickness gauges	50 - 100
Nickel 63	Beta	0.066	100	thickness gauges	100
Krypton 85	Beta	0.158	10.73	thickness gauges	10 - 2000
		0.672			
Promethium 147	beta	0.103	2.62	thickness gauges	50 - 400
		0.225			
Strontium 90	Beta	2.274	28.6	thickness gauges	10 - 100
Thallium 204	Beta	0.763	3.78	thickness gauges	20 - 200
Americium 241	Alpha	5.5	433	smoke detectors	few micro
	Gamma	0.060		thickness gauges	500
Cesium 137	Gamma	0.662	30.17	density gauges	50 - 100
Cobalt 60	Gamma	(1.17	5.27	level gauges	100
		1.33)			
Polonium 210	Alpha	5.305	138 days	static eliminator	Up to 1000
Carbon 14	Beta	0.15	5760	radiography	200
Radium 226	Beta	0.227		thickness gauges	10 micro
	Gamma	4.781	1600	thickness gauges	100
	Alpha	4.598		smoke detectors	0.5 micro

Figure 13. Radioactive Isotopes.

Sometimes the excitation energy of the nucleus is given to an atomic electron instead of being released in the form of a photon. This type of nuclear transition is called an internal conversion (IC), and the ejected atomic electron is called an internal conversion electron.

When internal conversion occurs, there is a probability that an electron from the K shell, L shell, or another shell, may be emitted. Therefore, a nucleus that undergoes internal conversion is a source of groups of mono-energetic electrons.

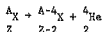
The total probability for gamma decay is the sum of the probability for internal conversion decay (λ_e) and the probability a photon will be emitted (λ_γ).

For most nuclei $\lambda_e=0$, but there is no gamma-decaying nucleus for which $\lambda_\gamma=0$. This means radioisotopes that internally convert, emit gammas, electrons and x-rays. The x-rays result from an electron from a higher shell that "falls into" the shell vacated by the internal conversion electron.

Three frequently used isotopes that undergo internal conversion are Sn-113, Cs-137 and Bi-207. These isotopes are very useful for instrument calibration.

5.5.2 ALPHA DECAY

Alpha particles are Helium nuclei, i.e. Helium atoms stripped of their electrons. Alpha decay is represented by the equation



Note that after the alpha particle is emitted, the parent nucleus is transformed into a new element (daughter nucleus). In many cases, the daughter nucleus is left in an excited state and alpha decay is thus often accompanied by gamma decay.

5.5.3 BETA DECAY

In beta decay, a nucleus emits an electron or a positron and is transformed into a new element. In addition to the electron or positron, a neutral particle with rest mass zero (neutrino) is also emitted. There are two types of beta decay, β^- and β^+ . In β^- an electron is emitted while in β^+ a positron is emitted. A free positron will eventually combine with an atomic electron, the two annihilate and two 0.511 MeV annihilation gammas are emitted.

Beta particles are emitted with a continuous range of velocities, from zero up to a maximum which depends on the nucleus. The decay spectrum for beta decay is thus continuous.

In some cases it is possible for the nucleus to capture an electron and in this case a neutrino is emitted. This transformation is known as Electron Capture. When an electron is captured a vacancy is left which may be filled by an electron from a higher energy state and a x-ray will be emitted.

5.5.4 COMPLEX DECAY SCHEMES

In many nuclei more than one mode of decay is possible. For information about particles emitted, energies and probabilities of emission a comprehensive collection of data is given in Table of Isotopes by Lederer and Shirley[1978]. The user involved in process control instrumentation however need only be concerned with gamma decay and the source is usually specified by the supplier.

5.6 THE RADIOACTIVE DECAY LAW

Radioactive decay is the spontaneous change of a nucleus. The change may result in a new nuclide or simply a change in the energy of the nuclide. If there is a certain amount of radioisotopes on hand, there is no certainty that in the next second "so many nuclei will decay" or "none will decay". One can talk of the probability that a nucleus will decay in a certain time.

The probability that a given nucleus will decay per unit time is called the decay constant and is indicated by the letter λ . For a certain species, λ is

1. The same for all nuclei.
2. Constant, independent of the number of nuclei present.
3. Independent of the age of the nucleus.

Consider a certain mass m of a certain radioisotope with decay constant λ . The number of atoms (or nuclei) in the mass m is equal to

$$N = m \cdot N_A / A \quad (5.5)$$

Where $N_A = 6.023 \times 10^{23}$ = Avogadro's number
 A = atomic weight of the isotope

This number of atoms decreases with time, due to the decay according to

Decrease per unit time = decay per unit time

or mathematically

$$\frac{-dN(t)}{dt} = \lambda N(t) \quad (5.6)$$

The solution of this equation is

$$N(t) = N(0)e^{-\lambda t} \quad (5.7)$$

where $N(0)$ = number of atoms at $t=0$.

The average lifetime τ of the nucleus is given by

$$\tau = 1/\lambda \quad (5.8)$$

One concept used extensively with radioisotopes is the half life T , defined as the time it takes for half of a certain number of nuclei to decay. Thus,

$$\frac{N(t)}{N(0)} = \frac{1}{2} = e^{-\lambda T} \quad (5.9)$$

which then gives the relationship between λ and T

$$T = \ln 2 / \lambda \quad (5.10)$$

For a sample of $N(t)$ nuclei at time t , each having decay constant λ , the expected number of nuclei decaying per unit time is

$$A(t) = \lambda N(t) \quad (5.11)$$

where $A(t)$ = activity of the sample at time t .

The units of activity are the Becquerel (Bq), equal to 1 decay/s, or the Curie (Ci) equal to 3.7×10^{10} Bq. The Becquerel is the SI unit defined in 1977.

The term specific activity is used frequently. It may have one of the two following meanings.

1. For solids:

$$SA = \frac{\text{activity}}{\text{mass}} \text{ (Bq/kg or Ci/g)}$$

2. For gases or liquids:

$$SA = \frac{\text{activity}}{\text{volume}} \text{ (Bq/m}^3 \text{ or Ci/cm}^3 \text{)}$$

There are isotopes that decay in more than one mode. The total probability of decay is then the sum of the individual probabilities of decay for each mode. The term partial half-life is sometimes used to indicate a different decay mode.

Sometimes the daughter of a radioactive nucleus may also be radioactive and decay to a third radioactive nucleus. Thus a radioactive chain is generated. A well known example is that of Uranium-238, which through combined alpha and beta⁻ decays ends up as an isotope of lead. The general equation giving the number of atoms of the i th isotope at time t in terms of the decay constants of all the other isotopes in the chain was developed by Bateman [1910]. This equation is not important in this discussion as the isotopes encountered in process control do not form a series.

5.7 CONCLUSION

This chapter discussed the basic theory of nuclear physics and the different types of radiation. In order to fully understand how radiation can be utilised, the following chapter discusses energy loss and penetration of radiation. A knowledge of how different materials absorb radiation allows certain properties of that material to be deduced.

6.0 ENERGY LOSS AND PENETRATION OF RADIATION THROUGH MATTER

6.1 INTRODUCTION

This chapter discusses the mechanisms by which ionizing radiation interacts, and hence loses energy, as it moves through matter. The study of this subject is extremely important for radiation measurements, because the detection of radiation is based on its interactions with, and energy deposited in, the material of which the detector is made. Therefore in order to build (or understand and choose) detectors and interpret the results of the measurement, it is important to know how radiation interacts and what the consequences are of the various interactions. The topics presented here should only be considered an introduction to this extensive subject. The range of energies considered is shown in Figure 14 [Tsoulfanidis, 1984].

Particle	Energy (MeV)
alpha (α)	20
beta (β)	10
gamma (γ)	20
neutrons (n)	15
Heavy ions	100

Figure 14. Maximum Energy Calculated

For the discussion that follows, ionizing radiation is divided into three groups:

1. Charged particles: electrons (e^-), positrons (e^+), protons (p), deuterons (d), alphas (α) and heavy ions ($A \geq 4$).
2. Photons: Gammas (γ) or x-rays.
3. Neutrons.

The division is convenient because each group has its own characteristics and can be studied separately. Emphasis will be given to the last two as these are the most important in instrumentation. The discussion on charged particles will centre on explaining why these have limited applicability in instrumentation applications.

6.2 MECHANISMS OF CHARGED-PARTICLE ENERGY LOSS

Charged particles travelling through matter lose energy as a result of:

1. Coulomb interactions with electrons and nuclei.
2. Emission of electromagnetic radiation (bremsstrahlung).
3. Nuclear interactions
4. Emission of Cerenkov radiation.

When a charged particle travels through a certain material it may interact with either the electrons, or the nucleus, of the atoms of the material. Since the cross-sectional area of the atom is approximately 10^8 times the cross-sectional area of the nucleus, interaction with the electrons is much more likely. Therefore, for the charged particles with kinetic energies considered here, nuclear interactions may be neglected.

Cerenkov radiation constitutes a very small fraction of the energy loss, and is visible electromagnetic radiation emitted by particles travelling in a medium, with speed larger than the speed of light.

As a result of energy losses, the particle finally stops after travelling a finite distance, called the range. The probability of a charged particle going through a piece of material without interaction is practically zero. It is this fact that limits the application of charged particle radiation in process instrumentation.

6.2.1 COULOMB INTERACTIONS

A coulomb force F is exerted on an electron by a charged particle at a distance r from it. The action of the force over a period of time, may result in the transfer of energy from the moving charged particle to the bound electron. Ionization or excitation of the electron may then occur. Ionization occurs when the electron obtains enough energy to leave the atom and it then behaves like any other charged particle. Excitation occurs when the electron moves to a higher energy level. In a short period of time the electron will move to a lower energy level, if there is one available, and an x-ray will be emitted.

6.2.2 EMISSION OF ELECTROMAGNETIC RADIATION

Every free charged particle that accelerates or decelerates loses part of its kinetic energy by emitting electromagnetic radiation. This radi-

ation is called bremsstrahlung, which in German means braking radiation. Bremsstrahlung is not monoenergetic, but consists of photons of energies from zero up to a maximum equal to the kinetic energy of the particle.

It can be shown that:

1. For two particles travelling in the same medium, the lighter particle will emit a much greater amount of bremsstrahlung than the heavier particle (other things being equal).
2. More bremsstrahlung is emitted if a particle travels in a medium with higher atomic number Z than in one with a lower atomic number.

For low energy radiation, bremsstrahlung might be important for electrons only in high- Z materials like lead ($Z=82$).

6.2.3 STOPPING POWER DUE TO IONIZATION AND EXCITATION

A charged particle moving through a material exerts Coulomb forces on many atoms simultaneously. Every atom has many electrons with different ionization and excitation potentials. As a result of this, the moving charged particle interacts with millions of electrons. Each interaction has a certain probability of occurrence and energy loss. It is thus only possible to calculate an average energy loss per unit travelled (dE/dx). Owing to their different masses the calculation differs slightly for electrons and positrons than that for the heavier charged particles like protons, deuterons and alpha particles.

This is because an incoming electron or positron may lose all its energy in a single collision with an atomic electron as they are of similar mass. They may also be easily scattered, and as a result their trajectory is a zig-zag one. Heavier particles on the other hand lose smaller amounts of energy and their trajectory is almost a straight one. For the derivation of the average energy loss per unit distance travelled (dE/dx). (see Evans[1972], Segre[1968] or Roy et. al.[1968]).

Many different names have been used for the quantity dE/dx : names like energy loss, differential energy loss, or stopping power. In this text the term stopping power will be used.

It should be noted that the stopping power [Tsoulfanadis, 1984]

1. Is independent of the particle,
2. Is proportional to the square of the particle charge,

3. Depends on the speed of the particle,
4. is proportional to the density of the material.

6.2.4 RANGE OF CHARGED PARTICLES

A charged particle moving through a certain material loses its kinetic energy through interactions with the electrons and nuclei of the material. Eventually the particle will stop, pick up the necessary number of electrons and become neutral.

The pathlength S , is the total distance travelled by the particle (zig zag path). The thickness of material that just stops a particle of kinetic energy T , mass M and charge z is called the range of the particle in the material. The range is equal to the displacement of the particle and is an average quantity.

Range can be measured in meters, or, if normalised by the material density in kg/m^3 . The range measured in kg/m^2 is independent of the state (density) of the matter, i.e. it is the same whether it moves in ice, steam or water.

Examples of particle ranges are:

1. 3 MeV alpha particle in gold = $4\mu\text{m}$.
2. 5 MeV deuteron in air = 0.21m .
3. 1 MeV electron in gold = $113\mu\text{m}$.

6.3 INTERACTIONS OF GAMMA AND X-RAYS WITH MATTER

X-rays and gamma rays are electromagnetic radiation. Considered as particles, when they travel with the velocity of light c , their rest mass is zero and so is their charge. A common name for x-rays and gamma (γ) rays as particles is photons. The relationship between energy, frequency and wavelength is:

$$E = h\nu = hc/\lambda \quad (6.1)$$

There is no clear distinction between x-rays and gamma rays. The term x-rays is applied generally to photons with $E < 1 \text{ MeV}$. Gammas are photons with $E > 1 \text{ MeV}$. In what follows, the terms photons, gamma and x-rays will be used interchangeably.

X-rays are generally produced by atomic transitions such as excitation and ionization. Gamma rays are emitted in nuclear transitions. Photons are also produced as bremsstrahlung, by accelerating or decelerating charged particles. X-rays and gamma rays emitted by atoms and nuclei are monoenergetic. Bremsstrahlung has a continuous energy spectrum.

Both x-rays and gamma rays are used in the process control industry. X-rays are used in x-ray fluorescence to identify various substances and to examine process material (e.g. pipes) for defects. Gamma rays are widely used in instrumentation and are the centre of discussion here. Gamma rays are used for level, density, thickness and weight measurement.

There is a long list of possible interaction of photons with matter, but only the three most important ones will be discussed here: the photoelectric effect, Compton scattering and pair production.

6.3.1 THE PHOTOELECTRIC EFFECT

The photoelectric effect is an interaction between a photon and a bound atomic electron. As a result of the interaction, the photon disappears and one of the atomic electrons is ejected as a free electron called a photoelectron.

The probability of this interaction occurring is called the photoelectric cross section or photoelectric coefficient and is designated $\tau(\text{m}^{-1})$,

where

τ = probability for photoelectric effect to occur per unit distance travelled by the photon.

The photoelectric effect decreases as E_γ increases and increases as Z increases. Thus it is more important, i.e. more probable for high Z materials. It is also more important for $E_\gamma=10$ keV than $E_\gamma=500$ keV for the same material.

6.3.2 COMPTON SCATTERING OR COMPTON EFFECT

The Compton effect is a collision between a photon and a free electron. Of course, under normal circumstances, all the electrons in a medium are not free but bound, however, if the energy of the photon is of the order of keV, while the electron binding energy is of the order of eV, the electron may be considered free.

The photon does not disappear after Compton scattering, only its direction and energy change. The photon energy is reduced by the amount given to the electron. The minimum energy of the scattered photon is greater than zero. Therefore, in Compton scattering, it is impossible for all the energy of the photon to be given to the electron. The energy of the electron will be dissipated in the material in a distance equal to the range of the electron. The scattered photon may escape.

The probability that Compton scattering will occur is called the Compton coefficient or the Compton cross section and is designated $\sigma(\text{m}^{-1})$,

where σ = probability for Compton scattering to occur per unit distance.

The probability for Compton scattering to occur is almost independent of the atomic number of the material. σ decreases as E_γ increases and is almost constant as Z increases but does decrease slightly for high Z .

6.3.3 PAIR

N

Pair production is an interaction between a photon and a nucleus. As a result of the interaction, the photon disappears and an electron-positron pair results. Although the nucleus does not undergo any change as a result of the interaction, its presence is necessary for pair production to occur.

The kinetic energy of the electron-positron is equal to the photon energy minus 1.022 MeV, which is necessary for the production of the two rest masses. Note that this means only gamma rays of energy greater than 1.022 MeV are capable of pair production. The electron and positron share, for all practical purposes, the available kinetic energy. Pair production eliminates the original photon, but two photons are created when the positron annihilates. The annihilation photons are important in constructing shielding against them as well as for the detection of gammas.

The probability for pair production to occur is called the pair production coefficient or cross section and is designated $k(\text{m}^{-1})$,

where k = the probability for pair production to occur per unit distance travelled.

k has a threshold at 1.022 MeV and increases with E_γ and Z . Of the three coefficients discussed, k is the only one increasing with the energy of the photon.

6.3.4 TOTAL ATTENUATION COEFFICIENT

When a photon travels through matter, it may interact through any of the three interactions discussed earlier. (For pair production, $E_\gamma > 1.022$ MeV). There are other interactions, but they are not mentioned here as they are not important in the detection of gammas.

Figure 15 (from Evans[1972]) shows the relative importance of the three interactions as E_γ and Z change. Consider a photon with $E = 0.1$ MeV. If this particle travels in carbon ($Z=6$), the Compton effect is the predominant effect by which this photon interacts. If the same photon travels in iodine ($Z=53$), the photoelectric effect dominates.

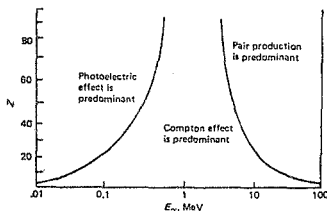


Figure 15. The relative importance of the three major gamma interactions

The total probability for interaction μ called the total linear attenuation coefficient, is equal to the sum of the three probabilities.

$$\mu(\text{m}^{-1}) = \tau + \sigma + \kappa \quad (6.2)$$

Physically μ is the probability of interaction per distance. There are tables that give μ for all the elements for many photon energies. Most of the tables provide μ in units of m^2/kg . (or cm^2/g), because in these units the density of the material does not have to be specified. If μ is given in m^2/kg (or cm^2/g) it is called the total mass attenuation coefficient. The relationship between linear and mass coefficients is

$$\mu(\text{m}^2/\text{kg}) = \mu(\text{m}^{-1})/\rho(\text{kg}/\text{m}^3) \quad (6.3)$$

The total mass attenuation coefficient shows a minimum because as E_γ increases, τ decreases, k increases and σ does not change appreciably. However, the minimum of μ does not fall at the same energy for all elements. For lead, μ is minimized at $E_\gamma \sim 3.5$ MeV; for aluminum at 20 MeV and for NaI at 5 MeV.

If a parallel beam of monoenergetic gamma rays goes through a material of thickness t , the fraction of the beam that traverses the medium without any interaction is equal to $e^{-\mu t}$. The probability that a photon will go through thickness t without an interaction is:

$$\begin{aligned} \text{Probability of} \\ \text{traversing} &= \frac{\text{number transmitted}}{\text{number incident}} = e^{-\mu t} \end{aligned} \quad (6.4)$$

The average distance between two successive interactions, called the mean free path (λ), is the inverse of the total linear attenuation coefficient.

The total mass attenuation coefficient for a compound or a mixture is:

$$\mu_c (\text{m}^2/\text{kg}) = \sum W_i \mu_i (\text{m}^2/\text{kg}) \quad (6.5)$$

where

μ_c = total mass attenuation coefficient for a compound or mixture

W_i = weight fraction of i th element in compound

μ_i = total mass attenuation coefficient for i th element.

6.3.5 PHOTON ENERGY ABSORPTION COEFFICIENT

When a photon has an interaction, only part of its energy is absorbed by the medium at the point where the interaction took place. Energy given by the photon to electrons and positrons is considered absorbed at the point of interaction because the range of these charged particles is short. However, x-rays, Compton scattered photons or annihilation gammas may escape. The fraction of photon energy that escapes is important when one wants to calculate heat generated due to gamma absorption in shielding materials or gamma radiation dose to humans. The gamma energy deposited in any material is calculated with the help of energy absorption coefficient defined in the following way.

The gamma energy absorption coefficient is in general that part of the total attenuation coefficient that when multiplied by the gamma energy, will give the energy deposited at the point of interaction. The energy absorption coefficient μ_a is:

$$\mu_a = \tau + T_{av} \sigma / E_\gamma + k \quad (6.6)$$

The total mass attenuation coefficient shows a minimum because as E_γ increases, τ decreases, k increases and σ does not change appreciably. However, the minimum of μ does not fall at the same energy for all elements. For lead, μ is minimized at $E_\gamma \sim 3.5$ MeV; for aluminum at 20 MeV and for NaI at 5 MeV.

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The gamma energy absorption coefficient is in general that part of the total attenuation coefficient that when multiplied by the gamma energy, will give the energy deposited at the point of interaction. The energy absorption coefficient μ_a is:

$$\mu_a = \tau + \tau_{av} \cdot a/E_\gamma + k \quad (6.6)$$

where T_{av} is the average energy of the Compton electron and μ_a may be a linear or mass energy absorption coefficient depending on the units.

In writing Eq. 6.6 it is assumed that:

1. If photoelectric effect or pair production takes place, all the energy of the gamma is deposited there.
2. If Compton scattering occurs, only the energy of the electron is absorbed. The Compton scattered gamma escapes.

In the case of photoelectric effect, assumption (1) is good. For pair production, however, it is questionable because only the energy $E - 1.022$ MeV is given to the electron-positron pair. The rest of the energy, equal to 1.022 MeV, is taken by the two annihilation gammas and is not deposited in the medium. There are cases when Eq. 6.21 is modified to account for this effect [Hubbell, 1969].

6.4 INTERACTIONS OF NEUTRONS WITH MATTER

Neutrons with protons, are the constituents of nuclei. Since a neutron has no charge, it interacts with nuclei only through nuclear forces. When it approaches a nucleus, it does not have to go through a Coulomb barrier, as a charged particle does. As a result, the probability (cross section) for nuclear interactions is higher for neutrons than for charged particles. This section discusses the important characteristics of neutron interactions, with emphasis given to neutron cross sections and calculation of interaction rates. Neutron radiation is commonly used in process instrumentation to determine the moisture content of bulk solids. (See Chapter 2).

6.4.1 TYPES OF NEUTRON INTERACTIONS

The interactions of neutrons with nuclei are divided into two categories.

SCATTERING

In this type of interaction, the neutron interacts with a nucleus, but both particles reappear after the reaction. Scattering may be elastic or inelastic. In elastic scattering, the total kinetic energy of the two particles is conserved and simply distributed between the particles. In inelastic scattering, part of the kinetic energy of the neutron is given to the nucleus as excitation energy. After the collision, the excited nucleus will decay by emitting one or more gamma rays.

ABSORPTION

If the interaction is an absorption, the neutron disappears, but one or more particles appear after the reaction takes place.

6.4.2 NEUTRON CROSS SECTIONS

Consider a monoenergetic parallel beam of neutrons hitting a thin target (i.e. one that does not appreciably attenuate the beam). The number of reactions per second, R , may be written as:

$$R = I(n/m^2s)[N(\text{nuclei}/m^2)] [a(m^2)][v(m)][\sigma(m^2)] \quad (6.7)$$

The parameter σ , called the cross section, has the following meaning:

$\sigma(m^2)$ = probability that an interaction will occur per target nucleus per neutron per m hitting the target

The unit of σ is the barn (b).

$$1 \text{ b} = 10^{-24} \text{ cm}^2 = 10^{-28} \text{ m}^2$$

Neutron cross sections depend strongly on the energy of the neutron as well as the atomic weight and number of the target nucleus. The cross section $\sigma(b)$ is called the microscopic cross section. Another form of cross section frequently applied is the macroscopic cross section $\Sigma(m^{-1})$ and is analogous to the linear attenuation coefficient of gamma rays.

6.4.3 THE NEUTRON FLUX

In most cases the neutron source consists of neutrons that travel in all directions and not in the same direction as assumed till now. It is thus necessary to modify Eq. 6.7. Assume that at some point in space the neutron density is $n(\text{neutrons}/m^3)$. If a target is placed at that point, the interaction rate R (reactions/ m^3s) will be:

$$R = n(\text{neutrons}/m^3)[v(m/s)][\Sigma(m^{-1})] \quad (6.8)$$

The product nv , represents the total pathlength travelled per second by all the neutrons in 1 m^{-3} , and is called the neutron flux ϕ .

Another quantity related to the flux and used in radiation exposure calculations is the neutron fluence F , defined by

If the interaction is an absorption, the neutron disappears, but one or more particles appear after the reaction takes place.

6.4.2 NEUTRON CROSS SECTIONS

Consider a monoenergetic parallel beam of neutrons hitting a thin target (i.e. one that does not appreciably attenuate the beam). The number of reactions per second, R , may be written as:

$$R = I(n/m^2s)[N(\text{nuclei}/m^3)] [a(m^2)][t(m)][\sigma(m^2)] \quad (6.7)$$

The parameter σ , called the cross section, has the following meaning:

$$\sigma(m^2) = \text{probability that an interaction will occur per target nucleus per neutron per m hitting the target}$$

The unit of σ is the barn (b).

$$1 \text{ b} = 10^{-24} \text{ cm}^2 = 10^{-28} \text{ m}^2$$

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Another quantity related to the flux and used in radiation exposure calculations is the neutron fluence F , defined by

$$F(n/\pi^2) = \phi t$$

where t is the exposure time to flux ϕ .

6.5 CONCLUSION

This chapter discussed energy loss and penetration of radiation in matter. It was shown that charged particles have a finite range and are quickly absorbed by the material. Photons, however, have only a statistical probability of absorption. The probability depends on the properties of the material. An important property affecting absorption is the density of the material. By determining the number of photons absorbed, a measure of the density of the material can be obtained. The density of the material is also important when building detectors. The higher the density of the detector material, the more photons will be absorbed and the higher the detection efficiency.

In order to detect the number of photons passing through a material, and hence infer some of the material properties, a detector is required. Two common detector families are discussed in the following two chapters.

7.0 GAS-FILLED DETECTORS

7.1 INTRODUCTION

In this section the basic operation of gas-filled detectors is outlined. Although, gas-filled detectors have, until now been the mainstay of nuclear based process instrumentation, they are being replaced by scintillation detectors.

Gas-filled detectors can be either gas-filled or gas-flowing, however, only gas-filled detectors will be discussed, as only these are used in process instrumentation.

Gas-filled detectors operate by utilizing the ionization produced by radiation as it passes through a gas. Typically, such a detector consists of two electrodes with a certain potential applied across them. The space between the electrodes is filled with a gas. Ionizing radiation passing through the gas generates electron-ion pairs. These charge carriers move under the influence of the electric field, inducing a current on the electrodes which may be measured (Figure 16 on page 53).

Either the current is measured directly, in which case the detector is called a current or integrating chamber, or alternatively, the charge may be transformed into a pulse by inserting a resistor into the circuit. The voltage pulse developed across the resistor is then measured and amplified. In this case the detector is called a pulse chamber.

For most gases, the average energy to produce an electron-ion pair is about 30 eV. If a 3 MeV alpha or beta particle deposits its energy in the counter, it will produce, on average

$$(3 \text{ MeV}) / (30 \text{ eV}) = 100\,000 \text{ electron-ion pairs [Tsoulfanidis, 1983]}$$

A typical gas-filled detector has a capacitance of about 50 pF, and the charge will be collected in a time of the order of 1 μ s. If all the charge is collected, the voltage and current expected are of the order

$$V = Q/C \sim (10^5 \times 1.6 \times 10^{-19} \text{ C/e}) / (50 \text{ pF}) = 0.5 \text{ mV}$$

$$i = Q/t \sim (10^5 \times 1.6 \times 10^{-19} \text{ A}) / 10^{-6} = 1.6 \times 10^{-8} \text{ A}$$

Electrons move to the positive plate and ions to the negative plate under the same force $F=Eq$, where E = the electric field intensity. The acceleration, $a=F/m$, is however quite different as the ion mass is approximately 1000 times the electron mass. Thus the time to collect the electron is about $1\mu s$ and the time to collect the ion about $1ms$.

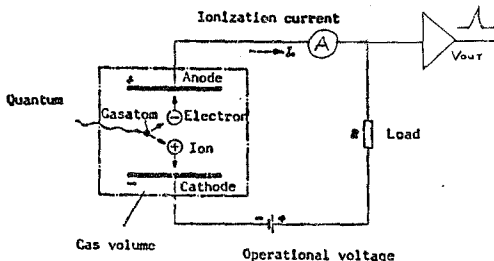


Figure 16. A typical gas-filled detector

7.2 RELATIONSHIP BETWEEN HIGH VOLTAGE AND CHARGE COLLECTED

If, in an experiment, the HV applied to the counter is steadily increased, the charge collected per unit time changes as shown in Figure 17 on page 54. The curve is divided into 5 regions. [Tsoulfanidis, 1983]

REGION I

When the voltage is very low, the electric field is weak, electrons and ions move relatively slowly, and have a considerable recombination rate. As V increases, the field becomes stronger, the carriers move faster and the recombination rate decreases until it becomes zero. Then, all the

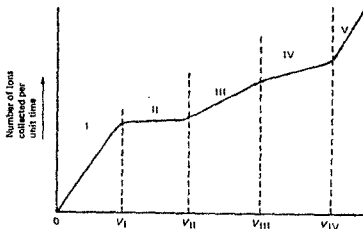


Figure 17. The relationship between applied voltage and charge

charge created is being collected ($V=V_I$). Region I is called the recombination region.

REGION II

In region II, the charge collected stays constant despite a change in the voltage because the recombination rate is zero and no new charge is produced. No charge multiplication takes place. The output signal is proportional to the energy dissipated in the detector; therefore measurement of particle energy is possible. Conversely, low energy particles will produce small output signals. Thus ionization counters can be used for particle identification. This region is called the ionization region and is the region in which the ionization chamber, used for density measurement, is operated. The applied voltage is usually less than a 1000 V.

REGION III

In this region, the collected charge starts increasing because the electrons produce secondary ionization that results in charge multiplication. The electric field is so strong, in a certain fraction of the volume, that electrons from primary ionization acquire enough energy between collisions to produce additional ionization. The gas multiplication factor (i.e. the ratio of the total ionization divided by the primary

ionization) is for a given voltage, independent of the primary ionization. The counter output is thus proportional to the energy dissipated in the counter; therefore particle identification and energy measurement is possible. The higher the energy of the particle the higher the output signal. This region is called the proportional region, but is not important in process instrumentation. Proportional counters may be used for the detection of any charged signal. The applied voltage ranges between 800 and 2000 V.

REGION IV

In this region, the electric field in the counter is so strong that a single electron-ion pair generated in the chamber is enough to initiate an avalanche of electron-ion pairs. This avalanche will produce a strong signal with shape and height independent of the primary ionization and the type of the particle. Region IV is called the Geiger-Müller (GM) region. Detectors operating in this region are called Geiger-Müller counters and are used for detection of radiation thus making them ideal for point level measurement. The advantage of GM counters is that their signal is so strong that a preamplifier is not needed. A disadvantage is their relatively long dead time (200 to 300 μ s). The applied voltage ranges between 1000 to 3000 V.

REGION V

If the applied voltage is raised beyond the value V_{IV} , a single ionizing event initiates a continuous discharge in the gas and the device is not a counter anymore. A commercial counter operating in this region will probably be destroyed.

In operation as a detector in a density gauge the gas-filled detector must operate in either region II or in region IV. Operation in region II is however preferable, as the long dead times characteristic of region IV will lead to many photons not being detected. Operation in region IV is preferable for on/off type measurements i.e. in determining if radiation is present or not.

7.3 DIFFERENT TYPES OF GAS-FILLED COUNTERS

7.3.1 CONSTRUCTION

Gas counters may be constructed in any of three basic geometries [Tsoulfanidis, 1983]: parallel plate, cylindrical or spherical. In a parallel-plate chamber the electric field is uniform, with strength equal to

$$E = V_0/d$$

where d is the plate separation.

In the cylindrical chamber, the voltage is applied to a very thin wire, stretched axially at the centre of the cylinder. The cylinder wall is usually grounded. The electric field in this case is:

$$E(r) = V_0 / (\ln(b/a) \cdot r)$$

where

a = central wire radius

b = counter radius

r = distance from the centre of the counter

Thus, very strong fields can be maintained inside a cylindrical counter close to the central wire. This is the usual construction for gas-filled detectors.

In a spherical counter, the voltage is applied to a small sphere located at the centre of the counter. The counter wall is usually grounded. The electric field is:

$$E(r) = V_0 \cdot ab / ((b - a)r^2)$$

where a , b and r have the same meaning as in the cylindrical case. Strong fields may be produced in the spherical counter but this geometry is not favoured because of construction difficulties.

A counter filled with a gas at a certain pressure may operate in any of the regions discussed previously, depending on the following parameters:

1. Counter size.
2. Size of wire in cylindrical counters.
3. Gas type.
4. Gas pressure.
5. Level of high voltage.

Normally gas counters are manufactured to operate in one region only. The manufacturer has selected a combination of the above variables that results in a ionization, proportional or GM counter. It is nowadays usual for manufacturers of process instrumentation to include the high voltage supply in the detector casing and it is thus not variable as would be the case for counters for general use.

7.3.2 IONIZATION CHAMBERS

Ionization chambers are used in process instrumentation to count the number of particles reaching the detector. From a knowledge of the source strength the density of the material can then be obtained. Although it is possible to obtain the energy of the particles using a ionization chamber, for density measurement one is only interested in the number of particles reaching the detector.

The ionization chamber may be used to produce either pulses or current. To produce a pulse a resistance is connected across the chamber which forms a capacitor. The electron-ion pairs created by the ionization of the gas, produce a small time-varying voltage superimposed on the HV of the applied field. However, because of the low drift velocity of the ions, the length of the period of the resulting pulse, (of the order of ms) can result in incoming photons not being detected. Thus, to ensure discrimination between various particles, the pulse period is truncated via a RC circuit after a time equal to the time it takes an electron to reach the anode (of the order of μ s). Isoufanidis[1983] gives calculations of pulse formation for a parallel plate geometry while Franzen and Cochran[1962], and Kowalski[1970] give detailed calculations of the pulse shapes for the three geometries of gas-filled chambers.

An ionization chamber of the current type measures the average ionization produced by incoming particles. This is achieved by measuring directly the current generated in the chamber. The proper operating voltage of a current ionization chamber is that for which all the ionization produced by the incoming radiation is measured. If this is the case, a slight increase in the voltage will have a negligible effect on the current. This voltage is called the saturation voltage and the corresponding current, the saturation current. The value of the saturation current depends on the intensity and the type of source.

It should be noted that the ionization chamber has an inherent RC time constant. For the pulse chamber the C corresponds to the chamber and the R to the resistor connected across the chamber. For the current type chamber the R results from the input resistance of the measuring instrument or amplifier. Thus the ionization chamber has a limited response time.

The advantages of the ionization chamber are its:

1. Mechanical stability
2. Simplicity in construction and
3. High reliability.

The disadvantages of the ionization chamber are:

1. The detection efficiency (i.e. the ratio of incoming photons detected to the total number of incoming photons) is low (about 1%). Consequently large radiation sources have to be employed which automatically increases the health hazard. The detection efficiency can be raised by increasing the gas pressure (hence its density) or adding extra capacitor plates. Both alternatives however increase the price of the chamber considerably. Another consequence of the low detection efficiency is the necessity of a wide radiation beam in order to detect as many gamma quanta as possible.
2. The ionization chamber does not discriminate between types of radiation, and is therefore sensitive to background radiation, which can be alleviated by careful and efficient screening.
3. The ion current is directly proportional to the gas pressure which is temperature dependant. The high ohmic resistors required as a result of the low ionization currents (in the picoamp range) are also highly temperature dependant. Consequently to maintain accuracy it is often necessary to mount the chamber and/or the resistor in a temperature controlled oven.

7.3.3 GEIGER-MULLER (GM) COUNTERS

7.3.3.1 Operation and Quenching of the Discharge

The GM counter is usually cylindrical in shape. The electric field close to the very thin central wire is so strong that the gas multiplication factor M is extremely high. In a GM counter, a single primary electron-ion pair triggers a great number of successive avalanches. Therefore the output signal is independent of the primary ionization.

The operation of the GM counter is as follows. When the electrons are accelerated in the strong field surrounding the wire, they produce, in addition to a new avalanche of electrons, considerable excitation of the atoms and molecules of the gas. These excited atoms and molecules produce photons when they deexcite. The photons, in turn, produce photoelectrons in other parts of the counter. Thus, the avalanche, which was originally located close to the wire, spreads quickly to the counter volume. During all this time the electrons are continuously collected by the anode wire, while the much slower moving positive ions are still in the counter and form a positive sheath around the anode. When the electrons have been collected, this positive sheath, acting as an electrostatic screen, reduces the field to such an extent that the discharge should stop. However, this is not the case because the positive ions eject electrons when they strike the cathode, and since by that time the field has been restored to its original high value, a new avalanche starts and the process just described is repeated. Clearly some means is needed by which the discharge is permanently stopped or "quenched". There are two methods of quenching the discharge.

In external quenching, the operating voltage of the counter is decreased after the start of the discharge until the ions reach the cathode, to a value for which the gas multiplication factor is negligible. The decrease is achieved by a properly chosen RC circuit as shown in Figure 18. The resistance R is so high that the voltage drop across it due to the current generated by the discharge (i_d) reduces the voltage of the counter below the threshold needed for the discharge to start. The net voltage is $V_0 - i_d R$. The time constant RC , where C represents the capacitance between anode and cathode, is much longer than the time needed for the collection of ions. As a result, the counter is inoperative for an unacceptably long period of time, i.e. the dead time is too long.

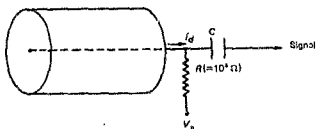


Figure 18. External quenching circuit for GM counter

The self-quenching method is accomplished by adding to the main gas of the counter a small amount of a polyatomic organic gas or a halogen gas. The organic gas molecules, when ionized, lose their energy by dissociation rather than by photoelectric processes. Thus, the number of photoelectrons is greatly reduced. In addition to that, when the organic ions strike the surface of the cathode, they dissociate instead of causing the ejection of new ions. Therefore, new avalanches do not start.

GM counters using an inorganic gas as a quenching agent have a finite lifetime because of the dissociation of organic molecules. Usually, the GM counters last for a 10^6 to 10^7 counts. The lifetime can be considerably increased if a halogen gas is used as a quenching agent. The halogen molecules also dissociate but there is a certain degree of regeneration of the molecules which greatly extends the lifetime.

7.3.3.2 The Pulse Shape and the Dead Time of a GM Counter

For GM counters the output signal is a result of the sum of all the contributions from all the positive ion avalanches produced throughout the volume of the counter. The pulse however rises very slowly. The shape and height of GM counter pulses are not very important because the pulse is only used to signal the presence of the particle and nothing else. However, how one pulse effects the formation of another is important.

During the formation of a pulse the electric field in the counter is greatly reduced because of the presence of positive ions around the anode. If a particle arrives during that period, no pulse will be formed because the counter is insensitive. The insensitivity lasts for a time called the dead time of the counter. Then the detector slowly recovers with the pulse height growing exponentially during the recovery period. This is illustrated in Figure 19 on page 61 which shows the change of voltage and pulse for a typical GM counter. Typical values of dead time are from 100 to 300 μ s. If the dead time is 100 μ s and the counting rate is 500 counts/s, there is going to be a 5% loss of counts due to dead time.

Because of the dead time, GM counters are used as comparators in level switches, i.e. they are only used to indicate the presence of radiation. GM counters are not employed for counting purposes in process instrumentation.

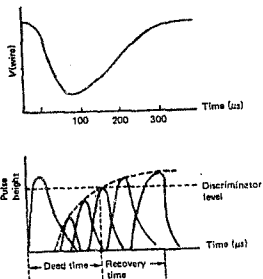


Figure 19. Dead time and recovery time for a GM counter

7.4 CONCLUSION

In order to perform any sort of measurement of nuclear radiation a detector is required. This chapter discussed gas-filled detectors. Two types of gas-filled detectors are available: the Geiger-Muller counter and the Ionization chamber.

The GM counter has a long dead time and is thus inappropriate in accurate counting applications. GM counters are applied to situations such as level measurement, where it is only necessary to detect the absence or presence of radiation. When the material in the bunker is below the level of the measuring path, a high amount of radiation will reach the detector and a high count rate will be detected. When the material reaches the measuring level, the radiation beam will be strongly attenuated and a much lower count rate will result. It is usual for manufacturers to include the discrimination logic into the detector housing and only to provide a single binary output. Geiger-Muller detectors are thus not suitable for slurry density measurement.

The ionization chamber has been the predominant detector in industrial applications but is gradually being superseded by the scintillation counter. Its main advantages are its simplicity and reliability. However, because it is based on a gas, which has a low density, it has a low efficiency (typically 1%). This results in a much larger source than would be required for a more efficient detector. In order to compensate for the low efficiency and raise the number of photons reaching the detector a divergent radiation beam is used. This compounds the increased health hazard already presented by the larger source.

The other family of detectors suitable for slurry density measurement are scintillator based detectors. These are discussed in the following chapter.

8.0 SCINTILLATION DETECTORS

8.1 INTRODUCTION

Scintillators are materials -solids, liquids, gases- that produce sparks or scintillations of light when ionizing radiation passes through them. The first solid material to be used as a particle detector was a scintillator. It was used by Rutherford, in 1910, in his alpha scattering experiments. In his setup, alpha particles hit a zinc sulphide screen, which were counted with the aid of a microscope. This was a very inefficient, inaccurate and time consuming process, which resulted in the method being abandoned for about 30 years. It was renewed when the advent of electronics made possible amplification of the light produced in the scintillator. Despite this, and despite their advantage over ionization chambers, (40% versus 1% typical conversion efficiency and insensitivity to background radiation), it was only recently that they became robust and reliable enough to be employed in an industrial environment. [Springer, 1979]

The amount of light produced in the scintillator is very small. It must be amplified before it can be recorded as a pulse or in any other way. The amplification or multiplication of the scintillator's light is achieved with a device known as a photomultiplier tube (or phototube). Its name denotes its function: it accepts a small amount of light, amplifies it many times and delivers a strong pulse at the output. Amplifications of the order of 10^6 are common.

The operation of the scintillation counter may be divided into two broad steps:

1. Absorption of incident radiation energy by the scintillator and production of photons in the visible part of the electromagnetic spectrum.
2. Amplification of the light by the photomultiplier tube and production of the output pulse.

The different types of scintillators may be divided into three groups [Tsoulfanidis, 1983]:

1. Inorganic scintillators
2. Organic scintillators
3. Gaseous scintillators

However only inorganic scintillators (crystal scintillators) are used for detectors in industrial instruments and only these will be discussed.

8.2 INORGANIC (CRYSTAL) SCINTILLATORS

Most of the inorganic scintillators are crystals of the alkali iodides, that contain a small concentration of an impurity. Examples are NaI(Tl), CsI(Tl), CsI(Na), LiI(Eu) and $\text{CaF}_2(\text{Eu})$. The element in parentheses is the impurity or activator. Although the activator has a relatively small concentration it is the agent responsible for the luminescence of the crystal.

8.2.1 THE MECHANISM OF THE SCINTILLATION PROCESS

The luminescence of inorganic scintillators can be understood in terms of the allowed and forbidden energy bands of a crystal. The electronic energy states of an atom are discrete energy levels, which in an energy level diagram are represented as discrete lines. In a crystal, the allowed energy states widen into bands (Figure 20 on page 65). In the ground state of the crystal, the uppermost allowed band that contains electrons is completely filled. This is called the valence band. The next allowed band is empty (in the ground state) and is called the conduction band. An electron may obtain enough energy from incident radiation to move from the valence to the conduction band. Once there, the electron is free to move anywhere in the lattice. The removed electron leaves behind a hole in the valence band which can also move. Sometimes, the energy given to an electron is not enough to raise it to the conduction band, instead it remains bound to the hole in the valence band. The electron hole pair is then called an exciton. The exciton states form a thin band with the upper level coinciding with the lower level of the conduction band.

In addition to the exciton band, energy states may be created between valence and conduction bands because of crystal impurities or imperfections. Particularly important are the states created by the activator atoms such as thallium. The activator atom may exist in the ground state or one of its excited states. Elevation to an excited state may be the result of photon absorption, or the capture of an exciton, or the successive capture of an electron and a hole. The transition of an impurity atom from an excited to a ground state (if allowed), results in the emission of a photon. If this photon has a wavelength in the visible part of the electromagnetic spectrum it contributes to a scintillation. Thus, production of a scintillation is the result of the occurrence of these events:

1. Ionizing radiation passes through the crystal.
2. Electrons are raised to the conduction band.
3. Holes are created in the valence band.

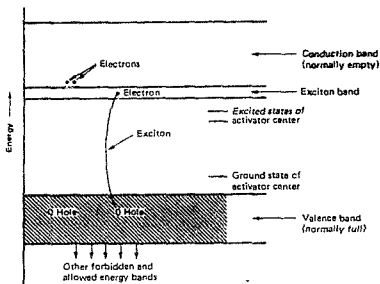


Figure 20. Allowed and forbidden energy of a crystal

4. Excitons are formed.
5. Activation centers are raised to the excited states by absorbing electrons, holes and excitons.
6. De-excitation is followed by emission of a photon.

The light emitted by a scintillator is primarily the result of transitions of the activator atoms and not of the crystal. Since most of the incident energy goes to the lattice of the crystal (eventually becoming heat), the appearance of luminescence produced by the activator atoms means that energy is transferred from the host crystal to the impurity.

The magnitude of the light output and the wavelength of the emitted light are two of the most important properties of any scintillator. The light output affects the number of photoelectrons generated at the input of the phototube, which in turn affects the pulse height produced at the counting system. Information about the wavelength is necessary in order to match the scintillator with the proper photomultiplier tube. The light output also depends on the temperature of the crystal. Emission spectra and temperature response are given in Tsoulfanidis[1983].

8.2.2 TIME DEPENDANCE OF PHOTON EMISSION

Since the photons are emitted as a result of decays of excited states, the time of their emission depends on the decay constants of the different states involved. Experiments show that the emission of light follows an exponential decay law of the form

$$N(t) = N_0 e^{-t/T} \quad (8.1)$$

where $N(t)$ = number of photons emitted at time t
 T = decay time of the scintillator

Most of the excited states of the scintillator have essentially the same lifetime T . There are however some states with longer lifetimes contributing a slow component in the decay of the scintillator known as afterglow, which may be important in certain measurements where the phototube output is integrated.

In a counting system using a scintillator, the light produced by the crystal is amplified by a photomultiplier tube and is transformed into an electric current having an exponential behaviour given by Eq. 8.1. The current is fed into a parallel RC circuit and a voltage pulse is produced of the form

$$V(t) = V_0 (e^{-t/RC} - e^{-t/T}) \quad (8.2)$$

In practice, The value of RC is chosen much greater than T . Thus for short times - i.e. $T \ll RC$, which is the timespan of interest- Eq. 8.2 becomes

$$V(t) = V_0 (1 - e^{-t/T}) \quad (8.2a)$$

Thus the rate at which the pulse rises is determined by the decay time T .

8.2.3 IMPORTANT PROPERTIES OF CERTAIN INORGANIC SCINTILLATORS

NaI(Tl)

This is the most commonly used scintillator for gamma rays and is the basis for almost all scintillation detectors in industrial density gauges. Its relatively high density ($3.67 \times 10^3 \text{ kg/m}^3$) and high atomic number combined with its large volume make it a gamma ray detector with a very high efficiency (40 to 80%). Although semiconductor detectors have better energy resolution, they cannot replace NaI(Tl) in experiments where large detector volumes are needed.

The emission spectrum of NaI(Tl) peaks at 410 nm and the light conversion efficiency is the highest of all the inorganic scintillators. It does however have many undesirable properties. It is brittle and sensitive to temperature gradients and thermal shocks. It is also so hygroscopic that it must be kept encapsulated at all times. NaI(Tl) always contains a small amount of potassium, which creates a certain background because of its radioactive ^{40}K .

CsI(Tl)

CsI(Tl) has a higher density ($4.51 \times 10^3 \text{ kg/m}^3$) and higher atomic number than NaI(Tl); therefore its efficiency for gamma detection is higher. The light conversion efficiency is however only about 45% of NaI(Tl) at room temperature. At liquid nitrogen temperatures (77K), pure CsI(Tl) has a light output equal to that of NaI(Tl) at room temperature. The emission spectrum extends from 420 nm to about 600 nm.

CsI(Tl) is not hygroscopic. Being softer and more plastic than NaI(Tl), it can withstand severe shocks, acceleration and vibration as well as large temperature gradients and sudden temperature changes. These properties make it suitable for space experiments. Finally, CsI(Tl) does not contain potassium. It would also appear to be very suitable for industrial applications.

CsI(Na)

The density and atomic number of CsI(Na) are about the same as those of CsI(Tl). The light conversion efficiency is about 85% of that of NaI(Tl). Its emission spectrum extends from 320 nm to 540 nm. CsI(Na) is slightly hygroscopic.

$\text{CaF}_2(\text{Eu})$

$\text{CaF}_2(\text{Eu})$ consists of low-atomic number materials and this makes it an efficient detector for beta particles and x-rays. Thus its application in density gauges is limited.

LiF(Eu)

This is an efficient thermal-neutron detector and has no application for density gauges.

8.3 THE PHOTOMULTIPLIER TUBE

8.3.1 GENERAL DESCRIPTION

The photomultiplier tube or phototube is an integral part of a scintillation counter. Without its amplification, a scintillator is useless as a radiation detector. The photomultiplier is essentially a fast amplifier, which in picoseconds amplifies an incident pulse of visible light by a factor of a million.

The photomultiplier consists of an evacuated glass tube with a photocathode at its entrance and several dynodes in the interior (Figure 21 on page 69). The photons produced in the scintillator enter the phototube and hit the photocathode, which is made of a material (Cs-Sb) that emits electrons when light strikes it. The electrons emitted by the photocathode are guided, with the help of an electric field, towards the first dynode, which is coated with a substance (Cs-Sb or Ag-Mg) that emits secondary electrons, if electrons impinge on it. This process is repeated for each successive dynode. Typical commercial phototubes may have up to 15 dynodes.

The electrons produced in the phototube are directed from one dynode to the next by an electric field established by applying a successively increasing positive voltage to each dynode. The voltage difference between two successive dynodes is of the order of 80-120 V.

A very important parameter of every photomultiplier tube is the spectral sensitivity of its photocathode, which for best results should match the scintillator spectrum. Another important parameter is the magnitude of the dark current. The dark current consists mainly of electrons emitted by the cathode after thermal energy is absorbed. This process is called thermionic emission and a 50-mm diameter photocathode may release as many as 10^5 electrons/s at room temperature. Obviously, the magnitude of the dark current is important in cases where the radiation source is very weak. Both the dark current and spectral response should be considered when a phototube is purchased. Recall that the electrons are guided from one dynode to the next by an electric field. If a magnetic field is present, it may deflect the electrons such that not all of them hit the next dynode. To reduce the magnetic effect, the phototube can be surrounded with a cylindrical sheet of μ -metal.

8.3.2 ELECTRON MULTIPLICATION IN A PHOTOMULTIPLIER

The electron multiplication (N) in a photomultiplier can be written as [Tsoufanadis, 1983]:

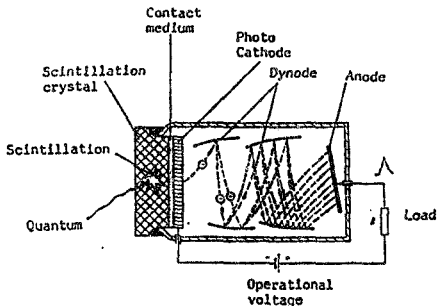


Figure 21. Schematic diagram of photomultiplier interior

$$M = (\theta_1 \epsilon_1)(\theta_2 \epsilon_2) \dots (\theta_n \epsilon_n) \quad (8.3)$$

where

n = number of dynodes

$$\epsilon_i = \frac{\text{number of electrons collected by } i\text{th dynode}}{\text{number of electrons emitted by } (i-1)\text{th dynode}}$$

$$\theta_i = \frac{\text{number of electrons emitted by } i\text{th dynode}}{\text{number of electrons impinging upon } i\text{th dynode}}$$

If θ_i and ϵ_i are constant for all dynodes, then

$$M = (\theta \epsilon)^n \quad (8.4)$$

The quantity ϵ depends on the geometry. The quantity θ depends on the voltage between successive dynodes and on the material of which the dynode is made. The dependence of θ on voltage is of the form

$$\theta = kV^a \quad (8.5)$$

where

$V = V_i - V_{i-1}$ = potential difference between any two successive dynodes.

k, a = constants (the value of a is about 0.7)

Thus the multiplication M becomes

$$M = \epsilon^n (kV^a)^n = CV^{an} \quad (8.6)$$

where $C = (\epsilon k)^n$ = constant, independent of voltage.

Eq. 8.6 indicates that the value of M increases with the voltage V and the number of stages n . The number of dynodes is limited, because as n increases, the charge density between two dynodes distorts the electric field and hinders the emission of electrons from the previous dynode with the lower voltage. If one takes $n=10$ and $U_2=4$, a typical value, M becomes equal to 10^6 .

To apply the electric field to the dynodes, a power supply provides a voltage adequate for all the dynodes. A voltage divider, usually an integral part of the preamplifier, distributes the voltage to the individual dynodes. When reference is made to the phototube voltage, one means the total voltage applied.

8.4 DEAD TIME OF SCINTILLATION COUNTERS

The dead time or resolving time, is the minimum time that can elapse after the arrival of two successive particles and still result in two separate pulses. For a scintillation counter, this time is equal to the sum of three time intervals:

1. Time it takes to produce the scintillation, essentially equal to the decay time of the scintillator.
2. Time it takes for electron multiplication in the phototube, of the order of 20-40 ns.
3. Time it takes to amplify the signal and record it by a scalar. The recovery time of commercial scalars is of the order of μ s. The time taken for amplification and discrimination is negligible.

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Thus the multiplication M becomes

$$M = \epsilon^n (kV^a)^n = CV^{an} \quad (8.6)$$

where $C = (\epsilon k)^n$ = constant, independent of voltage.

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To apply the electric field to the dynodes, a power supply provides a voltage adequate for all the dynodes. A voltage divider, usually an integral part of the preamplifier, distributes the voltage to the individual dynodes. When reference is made to the phototube voltage, one means the total voltage applied.

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By adding the three abv. components, the resulting dead time of a scintillation counter is of the order of tens to hundreds of microseconds. Thus scintillators are detectors with fast responses.

8.5 SOURCES OF BACKGROUND IN SCINTILLATION COUNTERS

The major background source is the dark current, which is the leakage current flowing in the photomultiplier when no scintillations are being produced. Other background sources are naturally occurring radioisotopes, cosmic rays and phosphorescing substances.

It is however possible to discriminate between these sources and gamma ray radiation, thus background radiation is not much of a problem for industrial density gauges using scintillation detectors.

8.6 INDUSTRIAL SCINTILLATION DETECTORS

Although the scintillation counter is the oldest method of radiation detection, it is only since the development of the photomultiplier tube that it has become accepted in industry and today it is no doubt the most important detector in use.

The primary advantage of the scintillation counter is its high efficiency (normally 35% but up to 85%) and its discrimination ability between radiation intensity and radiation energy allowing it to differentiate between clean gamma-rays and background radiation. Because of its high sensitivity the detector can be used with a low energy and collimated beam thus reducing the health hazard. The count rate of the detector is high, varying from 25 000 to 125 000 counts/sec. The output pulse which varies with the operating voltage (between 600 and a 1000 volts) is normally 1V.

The limitations of the scintillation counter is that since the output pulse voltage depends on the operating voltage a high precision voltage stabilizer must be used. Also, the surrounding temperature could influence the tube amplification. The scintillation crystal is highly hygroscopic and care must be taken, not to accidentally open the atmospheric tight enclosure.

There are still widespread rumours about the mechanical weakness of the scintillation counter and its sensitivity to vibration. It may be stated however, that scintillation counters are employed in rockets in the military and space fields, where they are subjected to extremes of vibration and acceleration.

8.7 CONCLUSION

Until now scintillation counters have not been considered reliable and stable enough for industrial applications. These problems have now been overcome and it is expected that the scintillation counter will become the predominant detector for counting applications. The main advantage of the scintillation counter is its high efficiency, between 40 and 80%, allowing a corresponding reduction in source size when compared to the ionization chamber. The higher efficiency also allows a collimated beam to be used which further reduces the health hazard. A further advantage is the much higher counting rate of the scintillation counter which allows for less deviation in the measurement mean or a faster response for the same deviation.

It should therefore be clear that given a choice between the ionization chamber and scintillation counter, the scintillation counter should be used. The smaller source size and collimated beam which result from its use minimizes the health hazard which increases the acceptability of a nuclear density gauge.

When any instrument is used there is a question of the validity and accuracy of the measurement. As radiation is a statistical phenomenon, the output of a radiation detector will have some statistical variance. Statistics and errors in nuclear measurement are discussed in the following chapter.

9.0 STATISTICS AND ERRORS IN NUCLEAR MEASUREMENTS

9.1 INTRODUCTION

In the previous chapters it was shown that nuclear disintegrations are statistical in nature. Thus, to fully understand results obtained from measurements of nuclear disintegrations, some knowledge of statistics is necessary. The chapter is not meant to be a tutorial on statistics, but rather, is meant to illustrate the effects of the statistical nature of radiation and how they can be compensated for.

9.2 THE ERRORS, ACCURACY AND PRECISION OF MEASUREMENTS

A measurement is an attempt to determine the value of a certain parameter or quantity. In attempting any measurement the following two axioms regarding the result of the measurement should be kept in mind.

Axiom 1 No measurement yields a result without an error.

Axiom 2 The result of a measurement is almost worthless unless the error associated with that result is also reported.

The term error is used to define the following concept:

$$\text{Error} = (\text{measured quantity}) - (\text{true value})$$

or Error = estimated uncertainty of the measured quantity

The result may be reported in two ways:

1. $R \pm E$; In which case E is the absolute error. (R and E have the same units).
2. $R \pm e\%$; Where $e = (E/R)100$ = relative error (dimensionless).

In most cases, the relative error rather than the absolute error is reported. The important thing to understand is that $R \pm E$ does not mean that the correct result is bracketed between $R - E$ and $R + E$. It only means that there is a probability that the correct result has a value between $R - E$ and $R + E$. The most common probability values used are the standard error and the probable error.

THE STANDARD ERROR

If the result of a measurement error is reported as $R \pm E_s$ and E_s is the standard error, then there is a 68.3% chance for the true result to have a value between $R - E_s$ and $R + E_s$.

THE PROBABLE ERROR

By definition, the probable error is equally likely to be exceeded or not. Therefore, if the result of a measurement is $R \pm E_p$ and E_p is the probable error, then there is a 50% chance for the result to be between $R - E_p$ and $R + E_p$.

Other errors used include the nine-tenths, ninety-five hundredths and ninety-nine hundredths error. The type of error used should always be quoted with the result.

Related to the error of a measurement are the terms accuracy and precision. The accuracy of an experiment is, how close the result of the measurement is to the true value of the measured quantity, and is the difference between the real value and the measured value. The precision of the measurement, is on the other hand, related to the number of significant figures representing the result.

Limitations in the accuracy and precision of measurements result from many causes. Among the most important are:

1. Incorrectly calibrated instruments.
2. Algebraic or reading errors of the observer.
3. Uncontrolled changes in environmental conditions, such as temperature, pressure and humidity.
4. Inability to construct arbitrarily small measuring meter-sticks, rods, pointers, clocks, lenses, etc.
5. A natural limit of sensitivity for any real measuring instrument detecting individual effects of atoms, electrons, molecules and protons.
6. Imperfect method of measurement in most cases.
7. Unknown exact initial state of the system. Or, even if the initial state is known, it is impossible to follow the evolution of the system.
8. Statistical nature of some processes, e.g. radioactive decay. There is a probability that a radioactive atom will decay in the next 10s and this is as much information as one can report on the matter.

Most measurements of applied nuclear science involve the counting of nuclear events. Events of this nature follow a statistical law - the Poisson statistics - which is simple and easy to apply. In many cases, the inherent statistical error, due to the fundamental fluctuations in the rate of occurrence of the events, is the principle error. It becomes important to be able to predict or calculate the error. Generally speaking, the stability of the counting apparatus is such that the fundamental statistical error will dominate if it is greater than 1%.

9.3 THE NORMAL DISTRIBUTION

Before proceeding with the discussion of Poisson statistics, first consider the normal distribution to which a large class of physical measurements conform. Most measurements of quantities which have a continuously variable magnitude appear to fit the normal distribution, which states that the probability dP that the quantity x will lie between x and $x + dx$ is [Tittle, 1965]:

$$dP = (1/s\sqrt{2\pi}) e^{-(x-m)^2/2s^2} dx \quad (9.1)$$

where m is the mean value of the distribution and s is the standard deviation, a measure of the width of the distribution factor. A plot of $y = dP/dx$ vs. x is the well known "bell-shaped curve".

Measurements give a set of values of x which are regarded as members of the population described by the distribution. The choice of distribution for the description is arbitrary. There is no assurance that a given series of measurements will actually fit a normal distribution or any other distribution. One of the most important applications of statistics to measurements is, in fact, the investigation of the question of whether a particular set of measurements fits the assumed distribution.

Ordinarily the value of interest is the quantity m . To obtain an estimate of m , the observations, x , are averaged to obtain what is called the observed mean, x' . If there are enough measurements, an estimation of the standard deviation (s) from the set of observed values $x - x'$, can be obtained. It can then be decided whether the measurements fit the assumed distribution. In the case of the normal distribution it is generally necessary to have about 20 measurements in order to obtain reliable estimates of s and the "goodness of fit". However, it is sometimes necessary to rely on smaller sets of data.

The best estimate of s is given by [Tittle, 1965]

$$s = \frac{1}{(n-1)} \sum_{i=1}^n (x_i - x')^2 \quad (9.2)$$

where n is the number of observations. In this equation the factor $n-1$ in the denominator, rather than n , results in the use of x' instead of m

in the numerator. The true mean m is never known exactly. Consider, as an example the data in Figure 22 on page 76.

Analysis of Geiger-Mueller Counter Data.

Test	x	$x - x'$	$(x - x')^2$
1	209	-18	324
2	217	-10	100
3	248	21	441
4	235	8	64
5	224	- 3	9
6	223	- 4	16
7	233	6	36
Totals	1589	0	990

Figure 22. Example of Standard Deviation Computation

The mean for the above set of data is

$$x' = 1589/7 = 227.$$

The standard deviation for the above set of data is

$$s = \sqrt{((990)/(7-1))} = 12.8.$$

The question of interest is: How well does the observed mean represent the true mean? The standard deviation of the mean S_m , is given by the relation

$$S_m = s/\sqrt{n} \quad (9.3)$$

or $12.8/\sqrt{7} = 4.9$ in the example. The result would therefore be quoted as

$$m = 1589 \pm 4.9 \quad (9.4)$$

where the quoted error is the standard deviation or standard error.

9.4 THE POISSON DISTRIBUTION

Poisson's distribution describes most of the counting observations made in experimental and applied nuclear physics, and is given by [Tittle,1965]:

$$P_x = \frac{x^m e^{-m}}{x!} \quad (9.5)$$

where P_x is the probability of observing x events when the average for a large number of tries is m events. In this distribution, x and m are integers - one point of difference from the normal distribution, where the variable is continuous. If m is a fairly large number, say 100 or larger, the Poisson distribution is adequately approximated by a special normal distribution

$$dP \approx (1/\sqrt{2\pi m}) e^{-(x-m)^2/2m} dx \quad (9.6)$$

where by comparison with Eq. 9.1 the standard deviation is

$$s = \sqrt{m} \quad (9.7)$$

The standard deviation of a normal distribution approximating a Poisson distribution is therefore specified when m is specified. In most cases Eq. 9.6 is an adequate representation of the Poisson distribution, even if m is as low as 20. Therefore the relation between the standard deviation s and the probable error r of the normal distribution, where

$$r = 0.6745s \quad (9.8)$$

may be used.

If the data in Figure 22 on page 76 represents seven counts made in a set of uniform time intervals, the predicted Poisson standard deviation would be $m = \sqrt{(1589/7)} = 15.1$. A simple test of counting data is to compute s from the residuals and from m and see if they agree. If they disagree appreciably, this test does not tell anything about the significance of the disagreement. The chi-square test, discussed next, is recommended as a better test.

9.5 THE CHI-SQUARE TEST OF GOODNESS OF FIT

Pearson's chi-square test determines the probability P that repetition of the observations would show greater deviations from the assumed distribution than those observed in the first trial. The quantity chi-square is defined as follows:

$$\chi^2 = \frac{(\text{observed value})_i - (\text{expected value})_i}{(\text{expected value})_i}^2 \quad (9.9)$$

The data should be subdivided into at least five classifications (i), each containing at least five events. In the counting application, the expected value is the average count observed.

The number of degrees of freedom F is the number of groups of data minus the number of imposed conditions. For the Poisson distribution

$$F = n - 1 \quad (9.10)$$

where n is number of observations. The imposed condition is the specification of m . In the case of the normal distribution, an additional specification is that of s , hence $F = n - 2$.

From a knowledge of F and χ^2 , computed from the experimental data, the value of P is obtained by consulting a table, or from a graph. The ideal value of P is 0.5. A greater value indicates that the fluctuations are less than one would expect from the assumed distribution. If P lies between 0.1 and 0.9, it is generally assumed the distribution corresponds to the observed one, but if P is less than 0.02 or greater than 0.98, the assumed distribution is highly unlikely. In this event, it is advisable to repeat the observations or to examine the counting apparatus for possible malfunction.

It is just as bad to get a set of data that is "too consistent" as it is to get inconsistent data. This may indicate for example that spurious pulses of a uniform rate are mixed in with the desired pulses. Too much inconsistency (a small value of P) usually means instability of some component such as the high voltage supply. It can also simply mean an unlucky run, which should be kept in mind if the apparatus performs satisfactorily after one seeming malfunction.

In the example of Pearson's chi-square test in Figure 22 on page 76, $F=6$ and $P=0.6$, which is a little consistent but quite acceptable.

9.6 CHAUVENET'S CRITERION FOR REJECTING A READING

Occasionally a reading is obtained which, although valid in the normal sense that no malfunction occurred and the reading may well be a member of the correct population, deviates so much from the mean that it adversely affects the observed mean. The criterion established by Chauvenet states that such a reading is to be rejected if it has a deviation greater than that corresponding to the $1/2n$ probability limit (the $1 - 1/2n$ error). For example in a series of 10 readings, if $x - \bar{x}$ exceeds 1.96s (the 0.95 error), that reading should be rejected, and the mean should be recomputed with the reading omitted from consideration.

9.7 PROPAGATION OF ERRORS

When two quantities are combined by addition or subtraction, the error of the sum or difference is not the simple sum of the errors of the individual quantities, but is less than that because of the probability that the errors may partially cancel. The law of addition of independent errors is

$$s = \sqrt{(s_1^2 + s_2^2)} \quad (9.11)$$

where s is the quoted error and s_1 and s_2 are the individual errors.

When quantities are multiplied or divided, the fractional or per cent errors add quadratically. For example if 100 ± 5 is divided by 20 ± 2 the result is

$$\begin{aligned} & 5 \pm \sqrt{(5\%)^2 + 10\%} \\ & = 5 \pm 11.2\% \\ & = 5 \pm 0.56 \end{aligned}$$

9.8 DEAD TIME LOSSES

Type I Systems - Type I systems are paralyzable systems. In a paralyzable system, a photon entering the system during the dead time of the previous photon detected will retrigger the dead time. (c.f. retriggable and non-retriggable monostables.) These systems count only intervals which are longer than the dead time T . These systems are not used in industrial applications.

Type II Systems - These are nonparalyzable systems; i.e. an impulse arriving during a dead interval cannot institute another dead interval. Self-quenching GM counters as well as ionization and scintillation counters are members of this group. The true impulse rate N is given in terms of the observed rate n and the dead time T by

$$N = n / (1 - nT) \quad (9.12)$$

9.9 BACKGROUND COUNTING TIMES

If it is possible to count the background radiation, it is possible to find an optimum division of time between background and sample counting. This however does not apply to industrial applications where it is not possible to perform just background counting in an on-line instrument.

9.10 THE CASE OF THE DECAYING SOURCE

The methods described here assume the source disintegrations do not decrease appreciably during the counting period, i.e. the counting period is very much less than the half life, as is usually the case.

9.11 CONCLUSION

Statistics are an essential part of any nuclear measurement and an understanding of statistics is essential when analysing radiation measurement. It was shown that the statistical error can be minimized by obtaining as high a count as possible and by averaging the count over as large a data set as possible. The size of the count and the data set must however be weighed against the response time of the meter.

This concludes the review of the basic theory behind radiation measurement and its application to density measurement. In order to apply nuclear instruments an appreciation of the health hazards and associated legal requirements is essential. These aspects are discussed in the following chapter.

10.0 HEALTH PHYSICS AND LEGAL REGULATIONS

10.1 INTRODUCTION

Any instrument or piece of equipment can constitute a serious hazard if it is not properly utilized, and nuclear based instrumentation is no different. If the correct precautions are observed there is no reason why nuclear based instrumentation should not be as safe, or even safer than much of the equipment commonly encountered in any industrial environment. It is the potential health hazard which causes many to shy away from nuclear instruments, and it is indeed, this health hazard which leads to the use of nuclear based instruments being regulated by law.

The intention of this chapter is to outline the potential threat any nuclear source imposes, to provide advice on the protection of users of nuclear sources from ionizing radiation and to review the legal requirements which must be met when nuclear sources are used.

Much of the material is taken from a guidance produced by the Paper and Board Industry (UK) Advisory Committee (IAC) to assist British mills in meeting their legal obligations and to avoid health risks. This material is not legally binding but is highly recommended [PBI,1983]. For further information, Tsoulfanidis[1983] gives a thorough discussion on the calculation of dose rates.

10.2 HEALTH PHYSICS

Health Physics is the discipline that consists of all the activities related to the protection of individuals and the general public from potentially harmful effects of ionizing radiation. Ionizing radiation comes from two sources:

1. Natural or background radiation that is emitted by radioisotopes which exist on or inside the earth, as well as radiation incident upon the earth from outer space. Humans have been exposed to this natural radiation as long as they have lived on planet.
2. Human-made radiation which is emitted by all the radioisotopes that have been produced through nuclear reactions (mainly fission), as well as radiation produced by machines used in medical installations (e.g. X-ray machines) or in scientific laboratories (e.g. accelerators).

Health physics is concerned with the protection of people from radiation. Since the background radiation has always been on our planet at about the same level everywhere, there is not much a health physicist can do to protect individuals or populations from background radiation. Hence, health physics is, essentially, concerned with human-made radiation.

10.3 EFFECT OF EXPOSURE

Exposure to ionizing radiation can result in interference with the structure of atoms because of ionization. The extent of this depends on the dose received, the type of radiation and the energy of radiation. In the case of humans, such exposure may result in some atoms of the matter contained within human cells behaving in an abnormal manner. This can result in complete destruction of these cells or interference with their normal method of reproduction. These effects are termed somatic. When large numbers of cells are destroyed the effect can usually be seen; where there is interference with normal cell reproduction, the effect is normally long term and can result in the development of cancers.

When exposure to radiation results in cells not reproducing themselves in an identical form, because the genetic material is altered, the damage can result in the development of hereditary defects in subsequent generations. This is termed the genetic effect. The somatic effect therefore concerns individuals, whereas the genetic effect is of concern to society as a whole.

Gamma and X-ray radiation of sufficient energy can penetrate and pass through the body when it is exposed to such radiation sources. The hazard is thus both external and internal and can be somatic, and if the reproductive organs are involved a genetic risk.

Beta radiation has relatively little penetrating power and the hazard from such radiation external to the body is only to the surface area and is a somatic risk only. Ingestion, inhalation or absorption of the beta-emitting substance itself into the body becomes an internal exposure hazard and can be a somatic and, in some cases a genetic risk.

Most alpha radiation is stopped completely by the skin and therefore presents little or no external radiation hazard and no external somatic risk. As for beta-emitting particles, ingestion, inhalation or absorption of the alpha-emitting substance has both a somatic and genetic risk.

It is prudent to assume that there is some risk from any dose of radiation above the zero level and that risks to health vary with the dose of radiation received. It is recognised that exposure continuously at the rate of 50 millisievert per year (Sievert (Sv) is a measure which quantifies the equivalent absorbed dose.) throughout the whole of a person's working life would lead to an increased probability of the development of cancers.

Legislation in Great Britain has followed the recommendation of the International Commission on Radiological Protection. Persons liable to receive more than 15 millisieverts per year from their work exposure need to be designated as classified workers and are then subject to medical supervision and dose monitoring throughout their working life in such employment.

10.4 PRINCIPLES OF PROTECTION

10.4.1 BASIC CONCEPTS

The basic concept of radiological protection, and hence the regulatory control, is to keep the radiation dose as low as reasonably practicable. Methods of achieving this protection include minimum sources, collimation, maximum working distance from source and appropriate shielding.

The radiation source should be of the lowest activity and energy necessary for the intended purpose taking into account the performance required and the need to avoid replacing sources too often. The latter can result in unnecessary frequent exposure.

A radiation source emits radiation in all directions and so the source holder should be designed to ensure that radiation is shielded off except in the direction of the "window". This radiation should be adequately collimated, to ensure that it is directed perpendicular to the window as a useful beam and aligned so that it does not spread appreciably. Note that when ionization chambers are used as detectors, it is normal to have several degrees divergence in the beam.

The radiation source should be mounted as far away as reasonably practicable from any normal working area, and wherever possible the beam directed away from that area. The radiation dose (Tsoulfanidis[1983]) varies with the distance from the source according to the inverse square law. Thus, if the distance is doubled, the dose rate is reduced by a factor of four.

Medical supervision is required in circumstances where the foregoing methods of protection cannot continue to be provided during maintenance, repair or replacement of the radiation source equipment. Persons who might as a result be exposed during that work to a radiation dose of more than 7.5 microsievert per hour need to be made classified workers.

Classification requires the person to undergo specific medical examinations and to wear some form of personal dose meter. A health register and dose record have to be maintained for each classified person and be available for inspection by that person. The classified person may be subject to an annual medical examination dependant upon the radiation dose being received. No classified person should receive more than 50 milliSievert in a year and working methods and procedures need to be examined and reappraised whenever a classified person reaches a 15 milliSievert total dose.

10.4.2 WHAT AN EMPLOYER SHOULD DO

The Paper and Board Industry (UK) Advisory Committee (IAC) recommends that the employer should ensure that:

1. A suitable person is appointed and is readily available to advise on radiological protection and relevant legal requirements.
2. The most suitable source of ionizing radiations for the purpose required is used and that the minimum activity commensurate with satisfactory economic performance is employed.
3. The source of ionizing radiation is sited at a suitable position so as to restrict the potential of exposure to as few persons as it is reasonable to achieve.
4. Any source of ionizing radiation is installed with adequate shielding so that during normal use no persons are exposed to radiation.
5. The equipment is provided with suitable warning signals and notices, interlocked barriers and shielding as appropriate and that these are all regularly maintained in an efficient state.
6. Those persons who might be exposed to ionizing radiations during maintenance work are classified and have been subject to medical examination, provided with suitable dosimeters and that records of medical examinations and any radiation doses received are maintained.
7. Persons conducting such work are provided with such shielding as is reasonably practicable for their protection during that work. They should also have been informed of any risk involved, the precautions to be observed and the methods by which the work should best be carried out.
8. All persons operating any machine or equipment in which a source of ionizing radiation is installed have been informed of the precautions taken and instructed not to misuse or interfere with the equipment.
9. Suitable monitoring equipment is provided or is readily available.
10. The location of each source of ionizing radiation, the type of radiation, and its activity is always known by keeping an appropriate up to date record and the operation of a check procedure.

11. The use and misuse of ionizing radiations is notified to the enforcing authority and any loss, leakage or damage of a source and any incident where a person may have been unnecessarily exposed is notified to the authority and properly investigated.
12. Contingency plans have been made and are familiar to all persons who need to know, to cater for accident situations such as fire, explosion or impact that may have interfered with the integrity of the source and any safety equipment.
13. Persons other than his employees are not put to any risk to their health and safety as a result of his use of ionizing radiations.

10.4.3 WHAT AN EMPLOYEE SHOULD DO

The Paper and Board Industry (UK) Advisory Committee (IAC) recommends that the employee should:

1. Not interfere or misuse any safety devices provided for his protection against exposure to ionizing radiations.
2. Report immediately to his employer any failure of an interlock or warning signal, or damage to any shield or barrier.
3. Wear and use where necessary any safety equipment provided for his protection.
4. Operate and use the equipment only as instructed.

10.4.4 WHAT AN SUPPLIER SHOULD DO

The Paper and Board Industry (UK) Advisory Committee (IAC) recommends that the supplier, agent or installer should:

1. Determine the use for which the equipment is intended and the position at which it is intended to be used.
2. Provide the most suitable source of ionizing radiations for the required purpose.
3. Provide and/or install the equipment with appropriate shielding, barriers, interlocking arrangements, warning signals and notices.
4. Ascertain where necessary that the equipment has been properly installed.
5. Provide information and instructions so that the equipment may be properly used without risk to ionizing radiations.

11. The use and disuse of ionizing radiations is notified to the enforcing authority and any loss, leakage or damage of a source and any incident where a person may have been unnecessarily exposed is notified to the authority and properly investigated.
12. Contingency plans have been made and are familiar to all persons who need to know, to cater for accident situations such as fire, explosion or impact that may have interfered with the integrity of the source and any safety equipment.
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4. Ascertain where necessary that the equipment has been properly installed.
5. Provide information and instructions so that the equipment may be properly used without risk to ionizing radiations.

10.5 LEGAL REQUIREMENTS

Conditions for the acquisition, possession, disposal, importation, export, use and conveyance of radioactive nuclides in South Africa are governed at present by the Atomic Energy Act, 1967 (Act 90 of 1967).

The latest conditions governed by the act are contained in the Government Gazette, No. 3105, of 28 November 1980. It should be noted that the Act is subject to change and as such it is the onus of the user of radioactive nuclides to be familiar with the latest regulations.

The major points of note are:

(Note that these are only major points, and it advisable to consult the latest regulations before purchasing or using radioactive material.)

1. A permit must be obtained to store or use radioactive materials.
2. Suitable (as determined by the act) storage must be arranged.
3. A responsible person and alternatively, with duties laid down in the act, must be appointed. This person shall if required by the Board, submit himself for an examination or test by the Board.
4. The concentrations of radioactivity in air and water to which persons are exposed, shall not exceed the values determined from time to time by the board.
5. Applications for authority to use radioactive material (sealed sources) for industrial radiography must be submitted to the Board on the designated form.
6. The holder of the authority shall ensure that permanently built-in sealed sources in apparatus such as eliminators of static electricity, level gauges, density meters and thickness gauges are tested for leaks at intervals not exceeding twenty-four months and all other sealed sources tested at intervals not exceeding six months. Particulars of such tests shall be entered in the source register.

10.6 EMERGENCY PROCEDURES

The employer should make such plans as are necessary, and ensure that the appropriate staff are made aware of them, and also have any equipment necessary to cater for a fire, explosion or impact accident involving a source of ionizing radiation. These plans should be in the form of written procedures, regularly updated.

The following matters need to be considered in such plans:

1. Exclusion from the area concerned of all persons except classified workers and persons otherwise authorised.
2. Notification to the person appointed to advise on radinological protection or any other organization retained to advise.
3. Monitoring to determine the extent of the radiation or contaminated area.
4. Provision of emergency shielding in the form of sand bags, lead sheet or bags of lead shot.
5. Identification of persons who might have been exposed to radiation or who might have ingested, inhaled or otherwise absorbed radioactive material.
6. Medical examination of and the provision of biological samples from those concerned if necessary.
7. Notification of the incident to the enforcing authority.

10.7 CONCLUSION

An appreciation of the health hazards and legal requirements relating to the use of nuclear density gauges is essential to anybody considering the application of these instruments. Nuclear based instrumentation is subject to legal regulation in South Africa and the necessary procedures must be followed before using such instruments. The two facts of most concern to the prospective user is that a permit must be obtained to possess a nuclear source and that a responsible person and alternate must be appointed to oversee their use.

The fact that these instruments are regulated by law, may seem to imply that these instruments are more dangerous than other equipment commonly found in an industrial environment. This is in fact not the case, and the regulations are primarily aimed at monitoring the locations of nuclear sources in the country and ensuring their safe disposal. The regulations and safety procedures are no more onerous than those applying to many other dangerous chemicals.

Chapter's Five to Nine have discussed the theory of nuclear radiation applicable to density measurement in a general sense. The following chapter discusses the application of this theory in commercial instruments.

11.0 GAMMA RAY INSTRUMENTS IN AN INDUSTRIAL ENVIRONMENT

11.1 INTRODUCTION

In this chapter gamma ray instruments in an industrial environment are discussed. The intention is to relate the material in the earlier chapters, i.e. the survey and selection of instruments for the slurry monitoring system, to the theoretical material given in the latter chapters together.

When an instrumentation engineer purchases a density or level gauge, he typically obtains a complete unit. It is now common for manufacturers to include the high voltage supply and preamplifier for the detector into the detector housing. The supplier will supply a radiation source of a given type and strength based on the buyers data. Thus it is difficult to know the tradeoffs made in the selection of the instrument components and the suitability of the instrument to different process conditions, e.g. a change in process material.

To enable the user of nuclear gauges to gain a better understanding of the above, this chapter discusses applications of nuclear gauges and gives some insight into the tradeoffs made by the supplier when specifying an instrument to suit a customers application.

11.2 INDUSTRIAL INSTRUMENTS

Industrial instrumentation based on gamma radiation is becoming widely accepted in several industries such as mining, petroleum and the chemical industry. Their primary advantages are that they are

1. Non-contacting.
2. Maintenance free.
3. Reliable.
4. Accurate.
5. Simple to calibrate.
6. Clamp-on in many cases.

Despite their disadvantages (mainly concerning the health hazard if improperly used, and the associated legal regulations), they will continue to be widely used and will come to dominate their sphere of application.

All nuclear instruments are based on the attenuation of the gamma-ray photons as they pass through the material. The attenuation is governed by the equation

$$I = I_0 \exp(-U \cdot L) \quad (11.1)$$

where I_0 is the number of gamma photons emitted by the source and I the number of gamma photons reaching the detector. L is the pathlength of the gamma rays in the material. U is the linear attenuation coefficient and is the product of material density and the mass absorption coefficient. U is also the probability of a gamma photon passing through the material. Thus for any number of gamma photons (I_0) emitted by the source, there is always some probability U , governed by the type of material, that I gamma photons will pass through the material. (See Chapter 6.) Thus any change in the material or its density or the pathlength can be detected. Therefore the following measurements (amongst others) are possible:

1. The density of the material if the pathlength is fixed.
2. The thickness of the material if the density is fixed.
3. The solids content of a slurry, as density varies with concentration.

11.3 FACTORS INFLUENCING DENSITY MEASUREMENT

Although only the factors influencing density measurement will be discussed, the principles apply to all the industrial applications. When a user buys a nuclear density gauge, the supplier will request certain information and will supply an instrument to meet the specified requirements. In most cases all the user then has to do is install the meter and calibrate it. The intention of this section is to indicate the tradeoffs made in specifying an instrument. This will provide a means of judging the difference between two meters specified by different suppliers, or to judge the difference in two products from the same manufacturer.

In a nuclear density gauge the following factors affect the performance of the meter:

1. The type of source which affects the penetration capability and the life of the source (half-life).
2. The type of detector which influences the source strength.
3. The health hazard which limits the source strength.
4. The secondary electronics which influences the performance of the meter.

Density measurement in slurry pipelines is based on Eq. 11.1 with L being fixed and U varying with the density. In order to determine the density the following must be known:

1. The value of I_0 .

2. The attenuation (i.e. I/I_0) as a function of density.

First consider the detected gamma photons I , i.e. the photons passing through the material. The value of I has a statistical variation owing to the statistical nature of the emitted photons I_0 . In order to obtain an accurate and repeatable measurement it is necessary to minimize the relative error of I .

In the chapter on statistics (chapter 9), it was shown that the standard deviation for a Poisson distribution, (which governs radioactive decay) is

$$s = \sqrt{m} \quad (11.2)$$

where m is the mean. It was also shown for a set of measurements, the standard deviation of the observed mean S_m , is given by the relation

$$S_m = s/\sqrt{n} \quad (11.3)$$

where s is the standard deviation of the set and n is the number of measurements in the set. Therefore the relative error e is:

$$e = S/I_{av} \quad (11.4)$$

$$\text{where } S = s/\sqrt{n} \quad (11.3)$$

$$\text{but } s = I_{av} \quad (11.2)$$

therefore

$$e\% = (1/\sqrt{(I_{av} \cdot n)})100 \quad (11.5)$$

Eq. 11.5 shows that the relative error can be reduced in two ways;

1. By increasing the average count (I_{av}).
2. By increasing the size of the data set (n).

The average count depends on the count rate and the period of counting. It has an upper limit determined by the overflow value of the counter. The count rate is limited by the maximum count rate of the detector, which is determined by the detector dead time, and the source size which has an upper limit determined by the health hazard, i.e. larger sources require thicker shielding. The count period and the data set size is limited by the response time of the meter, i.e. the longer the count period or the greater the data set the longer the response time of the meter.

The mean count value is also influenced by the range of measurement required. To increase the sensitivity of the meter the difference between the maximum and minimum count values over the given density range must be as large as possible.

The source size which determines I_0 is influenced by four main factors and is given by the relation

$$I_0 = I / (A \cdot n \cdot SA \cdot HL)$$

(11.6)

where

- A is the absorption factor. For a required detected count value, the detected count value must be increased by the absorption factor to obtain the source count.
- n is the efficiency of the detector. For any number of photons striking the detector only a certain fraction will be detected. To compensate for this the source must be increased proportionally. This effect can be reduced by using a detector with the highest possible efficiency.
- SA is the solid angle factor. Since, the source emits radiation in all directions, the source is shielded in all directions except the direction of the detector in order to prevent stray radiation and minimize the health hazard. For high efficiency detectors such as scintillation counters the emitted radiation is collimated into a single beam. For low efficiency detectors such as ionization chambers the beam is allowed to diverge slightly to increase the number of detected photons.
- HL is the half life factor. Because the number of disintegrations emitted by the source halves over the half-life period, the size of the source must be increased initially to maintain the desired count rate at the end of its useful life. For example, assume the life of the meter is five years. For a Cobalt-60 source which has five year half-life the size of the source would have to be doubled to ensure the required count after five years. For Caesium-137 which has a 30 year half-life the size would only have to be increased by a factor of 1.12.

The attenuation as a function of density is given by Eq. 11.1. To calculate the density directly from this equation would require a knowledge of U and the absolute value of I_0 . Because these quantities are never known explicitly, they are "calculated" by calibrating the meter against one or several known reference values. In some cases the calibration curve is computer generated by the manufacturer according to the clients specifications. The source decay must also be compensated for. This either done automatically or by periodic recalibration.

11.4 SPECIFYING A NUCLEAR DENSITY GAUGE

A nuclear density gauge comprises of a source, a detector, a mounting bracket and associated electronics. A particular gauge will use a predetermined detector, mounting bracket and electronics, thus the specification of the gauge boils down to the selection of type and size of source.

The majority of manufacturers provide mounting brackets of various sizes allowing the user to clamp the density gauge on to correspondingly sized

pipes. One manufacturer, namely Krohne, mounts the density gauge onto a section of pipe which must then be inserted into the system.

11.4.1 THE NUCLEAR SOURCE

The specifications of the source size must be done by the supplier based on the client's data. The primary objective is to minimize the source size and thereby the health hazard. The source size is a tradeoff between the health hazard and the accuracy, rangeability and life-time of the meter. The source size and hence the health hazard, can be reduced by using scintillation counters rather than ionization chambers as detectors. In order to increase the accuracy as high a mean count as possible as possible must be obtained, but the variation in the count must be large enough to ensure sufficient sensitivity over the measuring range. To increase the lifetime of the meter the half-life of the source must be as long as possible. A longer half-life also results in a smaller initial source size as the size is chosen to give a sufficient count rate at the end of the meter life.

The type of source used is dependant on its penetration ability, and its half-life. Three sources are commonly used. Americium-241 which has a low penetration capability (0.060 MeV radiation), but a long half-life (433 years). Caesium-137 which has a moderate penetrating capability (0.662 MeV radiation) and half-life (30 years) and Cobalt-60 which has a high penetration capability (1.17 - 1.33 MeV radiation) but short half-life (5 years). Americium-241 is seldom used as it does not have sufficient penetration for most applications. Cobalt-60 is not usually used in density gauges because of its short half-life, but is most commonly used in level gauge applications which have long measuring paths and where the short half-life is not a limiting factor. It may be used in density gauge applications for high SG materials and long measuring paths at the expense of frequent calibration. Caesium-137 is the most common in density gauge applications, but may be used in level measurement for low density materials and short measuring paths. The half-life of Caesium-137 (30 years) results in a 3% error after one year if the decay is not compensated for.

To calculate the source size from the clients data, manufacturers use empirical formulae based on the above aspects, the characteristics of their own hardware and the clients specifications. The formulae used differ from manufacturer to manufacturer and basically just consists of an equation that works and results in a suitable specification. It is thus not possible to give an equation which can be used to check the source size against any application. The formulae used by a specific manufacturer are usually given in the manual accompanying the density gauge. If it is desired to change the application, these formulae can be used to check the suitability of the source to the new application.

11.4.2 THE DETECTOR

As was previously discussed (See Chapter 7 and Chapter 8) three types of detectors are used.

1. The Geiger-Mueller counter.

The GM counter has a long dead time and is thus inappropriate in accurate counting applications. GM counters are applied to situations such as level measurement, where it is only necessary to detect the absence or presence of radiation.

2. The Ionization Chamber.

The ionization chambers main advantages are its simplicity and reliability. However because it has a low efficiency, typically 1%, it is gradually being superseded by the scintillation counter.

3. The Scintillation Counter.

The scintillation counter is becoming the predominant detector for counting applications largely due to its higher efficiency (typically between 40% and 80%).

11.4.3 ANALOGUE OR DIGITAL SIGNAL CONDITIONING

The associated signal conditioning electronics can be either analogue or digital. As opposed to previous analogue based systems, recently released density gauges are now all microprocessor based. The differences are best discussed by considering the application of each type in commercially available meters.

11.4.3.1 Analogue Signal Conditioning

In analogue signal conditioning the output is 'calculated' by means of analogue signal processing.

As an example of analogue signal conditioning, consider the signal converter used in the Krohne Density Gauge [Krohne, 1984]. Figure 23 on page 94 shows the block wiring diagram for the Krohne DH80 Radiometric Density meter.

Block diagram

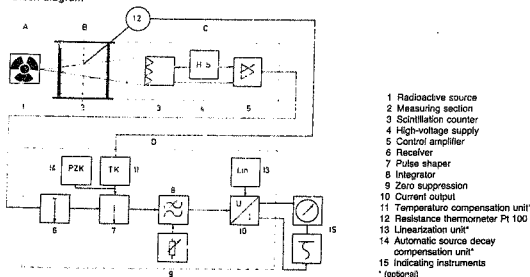


Figure 23. Krohne DH80 Block Wiring Diagram

The measuring head (C) contains the precision high-tension generator (4) for the supply of the photomultiplier (3) and signal amplifier (5), which compensates for temperature and ageing effects upon the counter tube. In addition, the multiplier pulses are normalized in the control amplifier and conducted at low impedance to the subsequent signal converter.

In the signal converter a Schmitt-Trigger (6) regenerates the incoming pulses. The resulting fast rising edges trigger a monostable multivibrator (7) whose pulse width can be adjusted to compensate for the isotope decay or temperature effects (11). The integrator (8) connected to the monostable output converts the voltage-time-area of the pulses into a direct voltage, where any chosen measuring range can be set by the zero-suppression circuit potentiometer. The density proportional output voltage of the integrator is converted in the output stage (10) into a direct current of 0..20 mA or 4..20 mA.

The non-linearity of the pulse rate change with density, which becomes predominant when the product of the density change times measuring length becomes very large, is solved by the plug-in linearisation (13) circuit. This circuit simulates the error function and, by means of compensation, reduces the measuring error to a value within the measuring tolerance.

Important disadvantages of analogue electronics include the following

1. A major limitation is that the signal converter requires frequent calibration as a result of component drift with time.
2. Calibration is also required to change the engineering units of the output.
3. All limits, calibration values and time decay, linearization and temperature compensation values are set by potentiometers. This method is susceptible to calibration errors and component drift.

11.4.3.2 Digital Signal Conditioning

Unlike analogue systems, microprocessor based systems mathematically calculate the specific gravity using the theoretical equation. As the system is microprocessor based, it allows for greater flexibility and the incorporation of extra features.

As an example of digital signal conditioning consider the signal converter used in the MCI Digital Density Gauge[MCI, 1984]. The MCI signal converter consists of two modules.

The Detector Microprocessor Module comprises of a scintillation detector to convert gamma rays into electrical pulses, and a microprocessor with input circuits to receive the electrical pulses, calculate SG or percent solids and provide the required outputs to an isolated 4-20 mA current loop (and other outputs). The operating program is stored in ROM and operating constants are stored in non-volatile RAM.

A communications module comprising of a keyboard and display to allow the operator to communicate with the microprocessor is provided. All communications with the processor are in key-coded instructions, entered through the keyboard. This module is normally located inside the detector/microprocessor module, but it may be remote in a separate enclosure.

The MCI density gauge has the following inputs and outputs :

1. A LCD display which can be set to display count rate, SG or percent solids, or mass flowrate.
2. A fully isolated 4-20 mA output selectable between SG and percent solids.
3. A fully isolated 4-20 mA output for solids mass flowrate.

4. A serial current loop to drive an external device. This output is selectable between SG/percent solids and mass flowrate.
5. A 4-20 mA input from an external flowmeter.

The following calculations are performed during operation of the density gauge.

Calculation of Specific Gravity

The basic gamma ray absorption equation is -

$$I = I_0 \exp(-U \cdot SG \cdot L) \quad (11.7)$$

where

I = strength of radiation beam emerging from the fluid.

I_0 = strength of radiation beam entering fluid.

U = Mass attenuation coefficient for fluid.

SG = SG of the fluid.

L = path length of gamma rays in the fluid.

The MCI gauge does not measure the number of pulses entering the detector over a fixed time period, but rather measures the rate at which pulses are detected. Thus, I_0 is the count rate with no fluid present and I the count rate with the fluid present. To measure the count rate, the user enters the desired count (100 000 is recommended) to ensure an acceptable statistical deviation. The gauge then measures the time taken to reach the specified value and calculates the count rate which is then used in subsequent calculations. The problem with this technique is that the period between measurements is not fixed. As the fluid density increases fewer gamma rays will reach the detector and a longer time period will be required to accumulate the desired count. The MCI gauge also implements a moving average over the last four measurements. This further reduces the standard deviation and also serves to smooth out random fluctuations in the slurry density.

It was shown in section 3 of this chapter that to calculate the specific gravity directly from the gamma ray absorption equation requires a knowledge of I_0 . In the MCI gauge, I_0 is not measured directly, but inferred from another measurement. It is known that the SG of water is 1. Therefore, to calculate I_0 the pipe is filled with water and the count rate is measured. Therefore for water, using eqn. 11.7 we have

$$C_w = C_s \exp(-U \cdot L) \quad (11.8)$$

where

C_w = count rate for pipe filled with water

Cs = Count rate for empty pipe

Rearranging eqn. 11.8 we have -

$$Cs = Cw \cdot \exp(U \cdot L) \quad (11.9)$$

Using eqn. 11.7 the SG for a slurry is -

$$Cs1 = Cs \cdot \exp(-U \cdot SG \cdot L) \quad (11.10)$$

where

Cs1 = count rate for pipe filled with slurry

Substituting for Cs using Eqn. 11.9 we get -

$$Cs1 = Cw \cdot \exp(U \cdot L) \cdot \exp(-U \cdot SG \cdot L) \quad (11.11)$$

Rearranging eqn. 11.11 and solving for SG we get -

$$SG = 1 + (\ln Cw - \ln Cs1) / UL \quad (11.12)$$

where

Cw = count rate with pipe filled with water.

Cs1 = count rate with pipe filled with slurry.

U = Mass absorption coefficient for the slurry.

SG = SG of the slurry.

L = path length of gamma rays in the slurry.

Eqn. 11.12 is the equation implemented in the MCI density gauge.

In order to calculate the SG, the gauge must be standardised on a pipe filled with water. The count rate for this measurement is then taken to be a constant. The count rate can however change as a result of the source decay, dirt buildup on the walls (decreases L) or wearing of the walls (increases L). Therefore the gauge must be regularly re-standardised.

So that it is always possible to re-standardise the gauge without having to re-fill the pipe with water, the concept of standardising with the pipe empty has been introduced. An absorber is inserted into the beam in the source holder when the lever is in the STANDARDISE position, and the count rate for the empty pipe is measured. This is the AIR-STANDARD count rate. The microprocessor then implements the equation -

$$Cw = S1 \cdot S3 / S2 \quad (11.13)$$

where

Cw = corrected water count rate.

S1 = initial measurement of water count rate.

S2 = initial measurement of air standard.

S3 = latest measurement of air standard.

In effect the water count rate is scaled according to the change in the air count rate. The initial air count rate and the initial water count rate are taken during installation.

The automatic source decay also operates on the S3 value. This value is decreased by a small amount every three days. Whenever a new S3 value is externally entered the source decay factor is restored to one and the correction process starts anew.

Calculation of Percent Solids

The microprocessor is programmed to output percent solids on request.

$$PS = 100.SS.(SG - 1)/(SG.(SS - 1)) \quad (11.14)$$

where

PS = percent solids by weight.

SS = specific gravity of dry solids.

SG = slurry specific gravity.

Calculation of Solids Mass Flow.

The microprocessor is programmed to calculate solid mass flow by accepting an analogue 4-20 mA input from an external flow meter.

$$SF = F.(SG - 1).SS/(SS - 1) \quad (11.15)$$

where

SF = solids mass flow in tonnes/hr

SG = specific gravity of slurry.

SS = specific gravity of dry solids.

F = volume flow of slurry in cu.m/hr. (from external flowmeter.)

Microprocessor based signal conditioning has several advantages including the following.

1. Being digital the meter is free from drift associated with analogue components.
2. The theoretically exact density equation is implemented with no requirements for extras such as linearisers to provide for precise output. The constants in the formula are easily altered to allow for different settings. This would not require recalibration as would be the case in an analogue system.
3. It is simple to calibrate. In many cases the calibration can be predicted exactly in advance of installation as the value of the mass attenuation coefficient can be calculated from a knowledge of the process material and all other constants can be obtained from the customers requirements.
4. Additional features are easily included. It is common for manufactures to include a digital display and mass flow computation capability into the meter. The data convertor can accept an analogue input signal from a flow meter, multiply the flow by SG, and output solids mass flow on a separate 4-20 mA isolated current loop.
5. All ranging, calibration, display and automatic source decay compensation can be done in software, thereby eliminating complex and frequent calibration.
6. All constants, standards and control parameters can be set independently and changed at will, using simple keystrokes on the module keypad. Outputs of all variables can be automatically ranged over preset HI-LO values. For example, assume the SG ranges between 1.0 and 1.5. To scale the output so that 4 mA corresponds to a SG of 1.0 and 20 mA to a SG of 1.5 the user enters the constants into the microprocessor RAM by means of the keypad. If the process is changed such that the upper SG limit is now 2.0, to rescale the output the user only has to re-enter the upper constant. This is a major advantage over an analogue instrument which would typically require costly and time consuming recalibration.
7. The pulse counting period is easily altered. This allows counting statistics can be controlled by requiring a preset number of counts to be accumulated before each calculation of SG.
8. Previous counts can be stored and thus a data set developed. This allows random short term changes in the slurry density to be smoothed out, by outputting a moving average over the data set and thereby increasing the accuracy of the meter.
9. The dynamic range of the detector is extended by using the microprocessor to correct for the dead time.
10. The gauge can be operated as a digital ratemeter. To do this the gauge is put into the ratemeter mode and a count limit entered. The time to reach the count limit is measured and the count rate is calculated and displayed.
11. A test signal can be generated internally for use in checking operations.

12. The printed circuit boards can be designed for fault finding using signature analysis techniques.
13. It is possible to incorporate PID control with the parameters being set by a supervisory computer.

11.5 CONSIDERATIONS IN DENSITY GAUGE APPLICATIONS

The following guidelines must be borne in mind when using density gauges. [Williams, 1979]

1. Air in line.

Air bubbles are a nuclear gauge's worst enemy as air represents an uncontrolled second variable with drastically different gravity (0.001 SGU when related to water). Extreme care must be taken to eliminate air. This is important when using centrifugal pumps which often suck in air through the seals. This problem can often be eliminated by directing a continuous stream of water onto the pump shaft seal.

2. Full pipe flow.

The pipe must be full of process material. Therefore a desirable location is under a positive head or where flow is upward.

3. Stratification.

If settling of the slurry may occur best results are obtained by directing the radiation beam vertically instead of across the pipe, or installing at a pump discharge.

4. Sampling means.

Since sampling is often required for calibration, intelligent installation of sampling valve(s) is necessary in the vicinity of the gauge. If stratification can occur, multiple taps are desirable.

5. Bypass valving for agglomerating streams.

If the slurry has sticky properties permitting build-up, a bypass must be installed to allow periodic cleaning as build-up on the pipe will cause gauge calibration changes and drift.

6. Vibration

When the gauge is located very close to a heavily vibrating pump or compressor, manufacturers may recommend neoprene jacketing or the like to reduce hammering. However vibration must be severe to require this.

7. Corrosion in pipe.

Changes in pipe wall will cause gauge drift, since the density of metal is great with respect to the liquid. Periodic recalibration will remove this effect as a source of error.

8. Temperature compensation.

Temperature compensation can be provided, by means of an external temperature sensor, if the density varies greatly with temperature.

9. Sampling techniques.

If calibration by sampling is necessary it must be ensured that the sampling cup is properly cleaned, the operator does not just tick the valve thereby not getting the thicker particles, or overflow the cup. Typically 5 to 10 samples per point must be taken to ensure a representative measurement.

10. Effect of solid's specific gravity on change

If the gauge is calibrated in %solids the assumption is made that the specific gravity of the solids is reasonably constant.

If the SG varies from 3.5 to 4.2 SGU the percent solids indication will rise 4% of full scale when the gauge is calibrated 40% solids as zero, and 70% solids as full scale. If the gauge is to be used for mass flow this effect can be ignored.

11. Mass flow calibrations.

The span of the density gauge is usually calibrated to be 1.00 for 0% gauge output so the mass flow multiplier will be 0 for 0 solids. Linearity correction is also usually required as there is often a wide span and therefore non-linearity.

11.6 CONCLUSION

This chapter discussed the application of nuclear physics and radiation in commercial nuclear density gauges.

Three sources are available for use, with Caesium-137 being most commonly used as it provides the best balance between half-life and penetration

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11.6 CONCLUSION

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capability. The source size is subject to several factors and is usually calculated on manufacturers proprietary empirical formulae. Two detectors are commonly used, the ionization chamber and the scintillation counter which is gradually superseding the former. The prime advantage of the scintillation counter is that it allows a much smaller source size and a collimated beam to be used compared to instruments using ionization chambers.

The most striking difference in commercial instruments is in the signal conditioning electronics. Most commercial instruments are still based on analogue electronics, but microprocessor based systems are being introduced. The advantage of the latter is that all computations are performed mathematically which allows for much greater flexibility and versatility. *The use of a microprocessor also allows for a better man machine interface with recalibration being performed via a keypad rather than by means of potentiometers.* As microprocessor based systems become more common, self-calibrating and self-diagnostic instruments will become the norm.

This concludes the review of the principles behind the instruments capable of meeting the project requirements. The following chapter discusses the evaluation of a mass flow system based on a magnetic flowmeter and a nuclear density gauge.

12.0 EVALUATION OF KROHNE MASS FLOW SYSTEM

12.1 INTRODUCTION

In order to explore a commercially available nuclear-based mass flow system, this chapter discusses the Krohne Mass Flow System which was made available for evaluation. A brief description is given of the system, and this is followed by a detailed description of the test rig and methodology employed in evaluating the system. Finally the test results are analysed in detail.

12.2 OPERATING PRINCIPLES

The Krohne Mass Flow system used in this project consists of an AC magnetic flowmeter and a nuclear density gauge. The source and the detector of the nuclear density gauge are mounted onto a section of pipe which has the same internal diameter as the magnetic flowmeter. The pipe section and the magnetic flowmeter are bolted together.

The signal conditioning for both the magnetic flowmeter and the nuclear density gauge are performed in separate field housings. The primary and field housing of the magnetic flowmeter are connected via shielded cable as is the detector and field housing of the density gauge.

The system was supplied in the following configuration:

1. A Nuclear Density Gauge comprising of
 - a. A rubber lined measuring section of diameter 150mm. The nuclear source and detector are mounted onto the measuring section, thus ensuring accurate alignment of the radiation beam.
 - b. A 10 milliCurie Caesium-137 source contained in a shuttered housing. The shutter may be locked in either the open or closed position. In the open position the source is exposed and a collimated beam passes through the material in the pipe and onto the detector.
 - c. A Scintillation Counter detector, which allows for the very small source size. The photomultiplier tube and associated high voltage supply is built into the detector housing.
 - d. A data converter mounted in a field housing. The data converter supplies a regulated +15 Volt supply to the detector and receives the output pulses from the detector. These pulses are then converted into a scaled 4 - 20mA current output. The system was calibrated such that 4mA corresponds to an SG of 1.5 and 20mA to

an SG of 2.0. (See Chapter 11 for a description of the signal conditioning electronics.) An ammeter with a LCD display is mounted on the field housing. The ammeter displays the loop current as a percentage of full scale where 20mA corresponds to 100% fullscale.

- e. A galvanic isolator to isolate the current loop from the receiving instruments. This is used primarily to increase the compliance of the current loop. The current loop on the converter can drive a maximum load of 1000 ohms.
2. A Magnetic Flowmeter comprising of -
- a. A X2000 fused aluminium oxide measuring head employing AC excitation and a pipe diameter of 150mm. The fused aluminium oxide lining is a recent Krohne development and is extremely abrasion and temperature (up to 180 degree Celsius) resistant. The X2000 head has a separate mains connection for the AC excitation voltage. The measuring head used in the evaluation system had a 16 bar maximum pressure rating, as this is the highest pressure rating of stock items.
 - b. A field housing type TIV 50/F_1 containing the data converter electronics. The data converter is connected to the measuring section by a shielded cable. The data converter receives the induced signal voltage from the electrodes, as well as an in-phase reference voltage obtained from the excitation voltage via a small transformer. The signal voltage is then scaled to a 4 - 20mA output where 4mA corresponds to a flow of 0m/s and 20mA to a flow of 1 m/s. The converter has a range potentiometer which allows the maximum flowrate scale to be changed. Changing the maximum flowrate e.g. to 3m/s does not require recalibration of the meter. An analogue ammeter is mounted on the converter which measures and displays the loop current as a percentage of full scale where 20mA corresponds to 100% (full scale), and 4mA corresponds to 20%. Two jacks are provided to insert an external ammeter into the current loop to allow for zero setting. The meter provided with the converter is not suitable for the setting of the live zero (4mA).
3. An Analogue Mass Flow Multiplier.

This receives a 4 - 20mA current from both the flowmeter and the density gauge and outputs their product as a scaled 4 - 20mA signal corresponding to the dry solids mass flowrate.

$$\text{i.e. } I_{mf} = K \cdot I_d \cdot I_f$$

where

I_{mf} = Output current corresponding to Dry solids mass flowrate

I_d = Current input from density gauge (Percent solids)

I_f = Current input from flowmeter (Volumetric flowrate)

$K = \text{constant equal to SG dry solids } K_1$

$K_1 = \text{Output current scale factor}$

The complete system block diagram is shown in Figure 24.

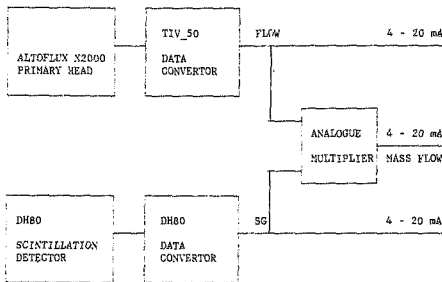


Figure 24. Mass Flow System Block Diagram

12.3 THE TEST RIG

The test rig is shown in Figure 25 on page 106.

The system piping is connected in a loop configuration. A double acting piston pump with a pump capacity of 45 m³/hr and maximum head of 75 bar is fed from a local storage tank. The material is pumped through the pipe (approximate length of 200 meters), up a vertical section of pipe and into a hopper mounted on loadcells. The hopper is mounted directly above and feeds into the local storage tank of the pump. The mass flow system is mounted onto the vertical section of pipe. The flowmeter zero is set by stopping the pumps as no cutoff valve was installed into the pipe.

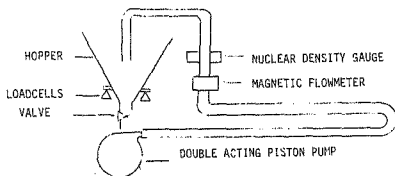


Figure 25. Schematic of Test Rig

A pressure transducer was installed to monitor the pressure fluctuations. As the flowmeter has a lower pressure rating (16 bar) than the pump head, it is necessary to install the flowmeter at the end of the pipe section. In an actual installation, the flowmeter must be sufficiently rated to be installed immediately after the pump to prevent time delays in the control system.

The outputs from the pressure transducer, loadcells, magnetic flowmeter and density gauge are connected to chart recorders for data acquisition purposes.

The density gauge and flowmeter outputs were also connected to a single chip BASIC microcomputer (the INTEL 8052AH). Interfacing was by means of an 8 bit analogue to digital converter. The system was used to scale the current outputs of the density gauge and flowmeter, thus resulting in a considerable time saving. The data logging program also performed a moving average over the last one hundred flowmeter readings, thus allowing the average flowrate to be determined.

12.4 TEST METHODOLOGY

The emphasis in the tests was on proving the principles of the instrumentation. Therefore, the primary consideration was the correlation between the measured values and the expected values. A good indication of the correlation is given by the linearity of the curve. Of secondary importance was the accuracy of the Krohne instrumentation itself. In order to correctly assess the accuracy of the instrumentation, the measured values must be compared to a traceable standard. It is also necessary that the accuracy of the data logging equipment exceeds that of the measured value. In the test rig, this was not the case as the Krohne flowmeter was specified to 0.5% accuracy, (traceable to Dutch Standards), whereas the resistors used in the test rig to convert the 4 - 20 mA current to a voltage were only of 1% accuracy. Thus, the accuracy of the instrumentation could only be determined to limits in the accuracy of the data logging equipment.

Load cells were used to determine the slurry mass flowrate. The hopper was emptied into the local storage tank and then allowed to fill up. After a measured time period of the mass of the material is measured and the hopper was again emptied into the local storage tank and the cycle repeated. Therefore

$$\text{Flowrate (m}^3\text{/hr)} = \frac{\Delta V(\text{m}^3) \times \text{Cal}(\text{kg/m}^3) \times 3600(\text{sec/hr})}{\Delta T(\text{sec}) \times \text{SG} \times 1000(\text{kg/m}^3)}$$

Where the calibration factor for the loadcells was 1.606 kg/mV. Note, to assess the flowmeter, an accurate value for the SG must be obtained.

The specific gravity of the material is determined by taking samples of the material at regular intervals, after which the wet samples were weighed. The samples were then dried and reweighed. The SG is then given by the following formula:

$$\text{SG}_{\text{slurry}} = 1/(1 - C_w + C_w/\text{SG}_{\text{dry solids}})$$

Where

$$\text{SG}_{\text{slurry}} = \text{Slurry SG}$$

$$\text{SG}_{\text{dry solids}} = \text{Dry solids SG}$$

$$C_w = \text{Concentration by weight}$$

$$= (\text{sample dry mass})/(\text{sample wet mass})$$

The above measurements were then compared to the corresponding measurements taken from the magnetic flowmeter and nuclear density gauge.

The evaluation of the mass flow system was performed using a goldslime slurry, with a solids concentration between 50% and 80%, which corresponds to a SG range of 1.5 to 2.0. However, at the lower SG range, the slurry becomes a dilute slurry and is no longer in a paste form.

12.5 TEST RESULTS

The major results are the comparison of the measured flowrate to the actual flowrate (as determined by the load cells) and the measured SG to the actual SG as determined by weighing. The results of the tests are shown in the following graphs.

Figure 26 on page 110 shows the measured flowrate versus actual flowrate for several different slurry specific gravities. Irrespective of the solids concentration there is a strong correlation between the measured and actual values. The flowmeter is accurate (as determined by the loadcells and SG) to within 5% of the expected value, thus satisfying the project requirements. The meter does however consistently give a slightly lower reading than the expected value. This is possibly due to the zero being lower than expected. However when the meter was tested with water, an accurate reading was obtained, thus possibly indicating that the flowmeter was only reading lower than expected during the gold-line tests. Tests over a longer time period will show up any consistent inaccuracy.

Figure 27 on page 111 shows the measured specific gravity versus actual specific gravity for several different flowrates. Again, there is a strong correlation between the measured and actual values. The measurement of the SG is also independent of the flowrate (See Appendix C) at the higher SG ranges. At the lower SG ranges, the density rises with increasing flowrate. The reason for this is that the slurry is no longer a paste, but is now a dilute slurry and settling of the solids occurs at the lower flowrates. As the flowrate is increased, more solids are carried in suspension and the density gauge correctly reads the corresponding rise in SG.

As it was necessary to calibrate the density gauge, the gauge accuracy is determined by the calibration values. As the same method was used to calibrate and evaluate the density gauge, a quantitative assessment of the accuracy cannot be given.

As seen in Figure 26 on page 110 and Figure 27 on page 111 the mass flow system meets the project requirements in terms of the accuracy of the measured values. However, there are two other factors which influence its suitability to the project.

1. Figure 28 on page 112 shows a chart recording of the pressure fluctuations in the pipe. It can clearly be seen that the pressure is highly impulsive and the mass flow system must be capable of withstanding the impulsive pressures produced. The mass flow system must also be capable of withstanding the severe vibration resulting from the pressure impulses.
2. Figure 29 on page 113 shows the chart recordings of the flowmeter output at several different pump stroke rates. When the pump is operating at its lowest capacity the stroke rate is 5 strokes/min. At the maximum pump capacity, the stroke rate is 17 strokes/min. When pumping high concentration slurries, the slurry momentarily stops

flowing during the piston changeover period. This can clearly be seen on the chart recorder. (Note, the chart recorder reading does not fall to zero as the flowmeter has a 10 sec. time constant.) For the flowmeter to output the average reading the time constant must be increased. The time constant must be at least twice the duration of the pump stroke intervals at the slowest pump speed.

12.6 MASS FLOW SYSTEM EVALUATION

The mass flow system is clearly capable of providing a measurement of the slurry mass flow and solids concentration. There is a strong correlation between the measured and expected values, clearly indicating the validity of the measurement technique. The only adjustments to the flowmeter was the setting of the magnetic flowmeter zero. This is however a periodic requirement and a characteristic of all present AC excited magnetic flowmeters.

During the evaluation of the flowmeter, the zero drifted noticeably between tests. During operation with the coal and flyash slurries, the zero, once set remained relatively stable. However, during the actual evaluation of the flowmeter using a goldslime slurry, the zero drifted with a change in concentration of the slurry. The drift was more pronounced when the slurry was in a dilute phase. The drift would lead to errors in the measurement of the flowrate if a wide variation in the concentration is required. However, further tests would be necessary to determine if this is a characteristic of all AC excited magnetic flowmeters, or only a characteristic of the test model.

Although the system was supposed to be precalibrated, on taking delivery it was found that the density gauge was out of calibration. Calibration of the gauge on site is possible and was undertaken. However, the calibration process is extremely time consuming and error prone. This is particularly true at the higher SG range (a solids content in the region of 80%), where the slurry assumes a paste form, as it becomes difficult to mix in dry material and to obtain a representative sample. The difficulty in calibrating an analogue density gauge clearly outlines the advantages to be gained from a microprocessor based system.

Calibration is further complicated in high concentration slurry systems, as it is not possible to provide a bypass for the instrumentation, since solidification of the slurry in the dead leg can occur.

In order to employ the system in a working installation, the time constant of the flowmeter must be increased to at least twice the period of the lowest stroke rate. This is a consequence of the use of double acting piston pumps and the high viscosities of the high concentration slurry. Failure to include a sufficiently long time constant can result in fluctuating readings.

Meas. vs. Exp. Flowrate

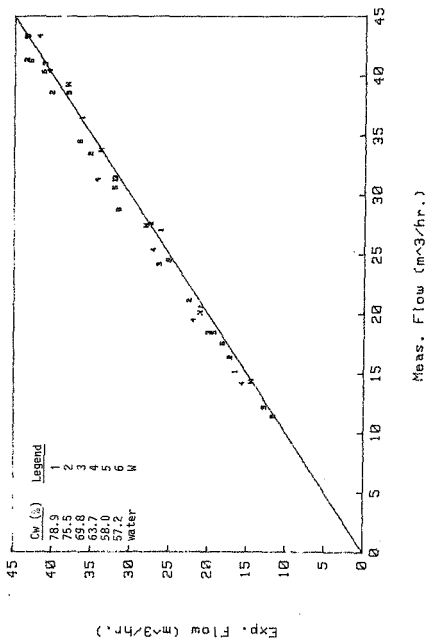


Figure 26. Measured vs. Actual Flowrate

Meas. vs. Exp. SG

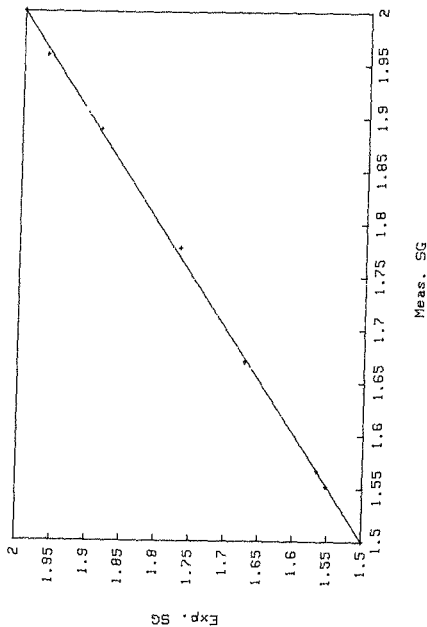


Figure 27. Measured vs. Actual Specific Gravity

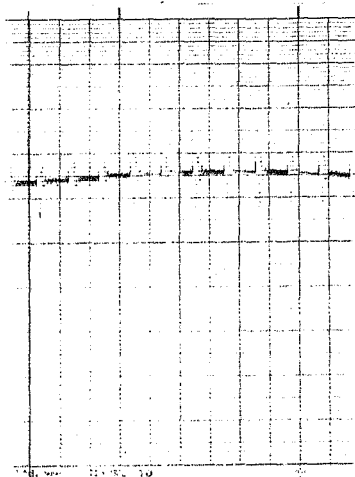


Figure 28. Slurry Pressure Recordings

tuations in the control system. (Note: This is only true if positive displacement pumps are used. Centrifugal pumps will give a fairly uniform flowrate.)

A more important reservation in the use of the system is the capability of the mass flow system to withstand the high pressures and vibration in the slurry pump system. During the test period of approximately 2 months duration the system showed no susceptibility to vibration, but the long term effect has not been determined. A more critical consideration is the pressure rating of the mass flow system. The system must be capable of withstanding the high average pressures (up to 100 bar) and the periodic peak impulsive pressures. The system offered for evaluation was a low

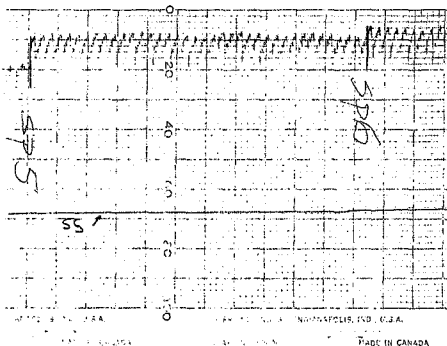


Figure 29. Slurry Velocity Profile

pressure system and it is still necessary to determine the capability of a rated meter to withstand the pressure impulses.

It can be noted that during the course of the system evaluation, the system was used on coal, flyash and goldslime slurries. The SG of the slurries varied widely (up to 1.3 for coal, 1.5 to 1.7 for flyash, and 1.5 to 2.0 for goldslime), however the solids content always ranged between 50% and 85%. In all cases the flowmeter showed no deviation in its capability to accurately measure the flowrate. The density gauge, once correctly calibrated, correctly measured the SG in the range 1.5 to 2.0.

The mass flow multiplier was not used and therefore not tested. This however has no bearing on the tests as the multiplier is an external device to the Krohne instrument, and does not affect the measurement of the volumetric flowrate or SG, i.e. the operation of the either magnetic flowmeter or the density gauge.

12.7 CONCLUSION

The Krohne mass flow system offered for evaluation met all the measurement accuracy requirements of the project. The system offered for evaluation incorporates a nuclear density gauge based on an analogue signal converter and thus does not offer the flexibility of the newer microprocessor based systems.

Before the system can be installed in a working installation the following must be performed:

1. The time constant on the magnetic flowmeter must be increased to compensate for the periodic fluctuations in the system resulting from the double acting piston pump. The time constant must be at least twice the period of the slowest stroke rate, or preferably field adjustable.
2. The mass flow system must be capable of withstanding the severe vibration encountered in the pipe line.
3. The mass flow system must be capable of withstanding the high average pressure the pump is capable of producing (up to 100 bar), as well as the periodic impulsive pressures in the slurry system.

The above considerations are all applicable to the manufacture of the mass flow system and not to the principle or operation of the system. The tests have shown that AC excited magnetic flowmeters and a nuclear density gauge are suitable for the measurement of the mass flowrate and concentration of paste slurries and can be used if the above mentioned criteria are satisfied.

13.0 CONCLUSION

This report discussed the choice of instrumentation suitable for measuring the concentration and mass flowrate of high density 'paste' slurries. The slurry system itself is unique and still in the development stage. The uniqueness of the system results from the high density of the slurry and the use of pneumatically conveyed powder, in this case cement. Like many new techniques, the requirements and characteristics of the system fall outside the general limits of commercial hardware. The system pumping pressure is much higher than most flowmeters can normally tolerate, and this results in the meter having to be specially made up which in turn results in high prices and long delivery times and limits the availability of off-the-shelf replacements.

The most important point arising out of the project, is that an instrument is only as good as the principles on which it is based! Many principles are used in the design of related instrumentation, e.g. flowmeters, and thus the choice of instrument initially requires a choice of measuring principle most suited to the application. Once a suitable principle has been chosen, a specific instrument embodying that principle can then be selected or designed. A major section of this project concerned the survey into different measuring principles suitable to the project. The survey resulted in the specification of a magnetic flowmeter and a nuclear density gauge. The principles, characteristics and application of these instruments were then considered in detail.

Magnetic flowmeters were specifically designed for measuring the flowrate of slurries and no degradation in performance was found in high density slurry applications. In the project only an AC excited flowmeter was evaluated. Although DC meters have many advantages, they suffer in performance when used in slurry applications, due to noise being induced when the slurry particles collide with the electrodes. However, high concentration slurries assume a homogeneous form and are usually pumped at low velocities. These factors may make it possible to use DC excited flowmeters for high concentration slurries, and this probability should be investigated to allow for the advantages, (most important of which is the auto zero characteristic) stemming from the use of DC excited magnetic flowmeters. A magnetic flowmeter, namely the Kent Veriflux [Kent, 1985], has recently been developed which combines both AC and DC operation. It is claimed that this meter has the advantages of both types of excitation, i.e. autozero and operation in slurry applications.

Nuclear instruments are capable of a variety of measurements and can be extensively used in the process control industry. There is however a lack of knowledge relating to the principles, use and applications of nuclear instruments. To rectify this problem an in depth study into the theory behind nuclear instruments was undertaken. The latter chapters of this project report serve as a guide to the use and application of these instruments.

Nuclear instruments are now entering a second phase, and in line with other instrumentation are becoming more intelligent and easier to use. The use of advanced detectors are minimizing the source size and the health hazard, thereby increasing their acceptability. The use of microprocessor based electronics has resulted in an integrated meter. This makes it possible to satisfy all the project requirements with a flowmeter and an intelligent density gauge. The newer density meters are not yet freely available in South Africa and so it is advised that they be evaluated in the mean time to allow for their rapid introduction when their availability increases.

An important point arising out of the project is the signal conditioning electronics used in instrumentation. Many advantages are to be gained by making the electronics microprocessor based. The most important being the flexibility, ease of use and better man-machine interface. As microprocessor systems become more common, more advanced features such as auto-calibration, self-diagnosis and advanced signal processing can be incorporated. These features will improve the instruments employing them, with a corresponding increase in performance of the associated control system.

This project concentrated on the instrumentation for the slurry. Before the backfill system can be implemented, instrumentation must be found to measure the mass flowrate of pneumatically conveyed powders. A possible solution is to use a nuclear density gauge to determine the effective cross-sectional area of the powder, and a doppler or a vortex shedding flowmeter to determine the average velocity of the powder particles.

APPENDIX A. GLOSSARY OF NUCLEAR TERMS

Alpha Particle	Nuclear particle of mass 4 units carrying 2 units of positive charge. Will not penetrate skin, and ranges only a centimetre or so in air. Emitted by radioisotopes such as uranium 238, thorium 225, plutonium 210, etc.
Beta Particle	Nuclear particle of mass $1/1860$ units carrying 1 unit of negative charge. Will penetrate skin and has a range of up to 6m in air. Emitted by many radioisotopes.
Becquerel (Bq)	The measure of quantity of radioactivity. A substance has an activity of 1 Bq if 1 atom of it disintegrates every second. This is the new SI unit gradually replacing the curie. $1 \text{ Bq} = 2.7 \times 10^{-11}$ curies.
Bremsstrahlung	Radiation produced by the rapid deceleration of a beta particle, such as when it is caused to bombard a heavy material. The radiation is identical to X-radiation. Bremsstrahlung is therefore an additional hazard which may arise when handling beta-emitting radioisotopes.
Contamination	Radioactive materials released from their normal containment into the working environment. It may be present on working surfaces or airborne.
Curie	A measure of quantity of radioactivity. 1 curie of radioactivity is such that 3.7×10^{10} atoms of it are disintegrating every second. This unit is gradually being replaced by the becquerel.
eV	Electron volts. A measure of energy of a particle or radiation. 1 eV is the energy attained by an electron when accelerated between electrodes which have an electrical voltage of 1 volt between them.
Element	A substance which cannot be chemically decomposed into simpler substances.
Electron	Atomic particle of mass $1/1860$ units carrying one unit of negative charge. Differs only from the beta particle in its origin, which is from outside the nucleus of the atom.

Gamma	Nuclear radiation. Will penetrate considerable thicknesses of lead or concrete and has a very long range in air. Emitted by many radioisotopes in association with either an alpha or a beta particle. Gamma radiation is electromagnetic radiation with energy of the order of MeV.
Half-life	The time in which half the amount of atoms present in a given amount of radioactive material disintegrate. The value of the half-life is characteristic of a particular radioisotope and varies from millionths of a second to millions of years.
Ionization	The process by which an electron is stripped from its parent atom. When radiation strikes an electron it loses energy in ionizing that electron.
Neutron	Nuclear particle of mass 1 unit carrying no charge.
Proton	Nuclear particle of mass 1 unit carrying 1 unit of positive charge.
Rad	The abbreviation for "radiation absorbed dose". A measure of energy deposited in a medium.
Rem	The abbreviation for "rad equivalent man". A measure of the damage caused by exposure to radiation, and is gradually being replaced by the sievert (1 rem = 0.01 Sv).
Sievert (Sv)	This is the new SI unit replacing the rem. It quantifies the equivalent absorbed dose.
X-radiation	Radiation produced when materials are bombarded with electrons. X-radiation is electromagnetic radiation with energy of the order of eV.

APPENDIX B. MASS ATTENUATION COEFFICIENTS

The following table of mass attenuation coefficients, in cm^2/g , for gamma rays were interpolated from values given in Hubbell[1969]. The coefficients are given for a gamma energy of 0,662 MeV, which is the energy of gamma radiation for Caesium-137.

^1H	0.153	^{56}Fe	0.0732
^{12}C	0.0777	^{63}Cu	0.0722
^{14}N	0.0775	^{208}Pb	0.1093
^{16}O	0.0776	^{232}U	0.0759
^{23}Na	0.0743	Air	0.0774
^{27}Al	0.0744	Water	0.0861
^{28}Si	0.0774	Concrete	0.0777
NaI	0.0759	Pyrex Glass	0.0772

The total mass attenuation coefficient for a compound or a mixture is:

$$\mu_c (\text{m}^2/\text{kg}) = \sum W_i \mu_i (\text{m}^2/\text{kg})$$

where

μ_c = total mass attenuation coefficient for a compound or mixture

W_i = weight fraction of i th element in compound

μ_i = total mass attenuation coefficient for i th element.

APPENDIX C. MASS FLOW EVALUATION TEST RESULTS.

C.1 COMPUTED RESULTS.

The following values are the calculated averages for each test.

Flowmeter setting = 1.768

DH80 settings: Zero = 7.279 ; Range = 2.581 ; Isotope = 0

TEST 1

SG(meas) = 1.959 ; SG(exp) = 1.966 ; Cw = 78.9 %

FLOW(meas)	FLOW(exp)
15.03	16.21
20.18	20.62
26.90	25.89
31.10	31.75
36.35	36.07

TEST 2

SG(meas) = 1.889 ; SG(exp) = 1.886 ; Cw = 75.5 %

FLOW(meas)	FLOW(exp)
16.23	16.95
21.03	22.22
27.49	27.17
33.35	34.88
38.50	39.88
41.24	43.15

TEST 3

SG(meas) = 1.777 ; SG(exp) = 1.768 ; Cw = 69.8 %

FLOW(meas)	FLOW(exp)
12.03	12.47
18.34	19.74
24.06	26.05
31.38	31.77
40.90	40.79

TEST 4

SG(meas) = 1.670 ; SG(exp) = 1.6735 ; Cw = 63.7 %

FLOW(meas)	FLOW(exp)
14.06	15.38
19.36	21.65
25.27	26.77
31.16	34.00
40.31	40.21
43.20	41.52

TEST 5

SG(meas) = 1.567 ; SG(exp) = 1.567 ; Cw = 58.0 %

FLOW(meas)	FLOW(exp)
11.30	11.32
18.33	19.00
30.50	31.73
38.45	37.70
43.15	43.10
43.20	43.05

TEST 6

SG(meas) = 1.552 ; SG(exp) = 1.553 ; Cw = 57.2 %

FLOW(meas)	FLOW(exp)
17.40	17.86
24.40	24.83
28.66	31.26
34.40	36.29
40.21	40.96
41.14	42.60

WATER TEST

FLOW(meas)	FLOW(exp)
14.19	14.18
19.96	20.72
27.31	27.72
33.61	33.53
39.13	37.86

C.2 READINGS FOR EVALUATION OF MAGNETIC FLOWMETER.

Loadcell calibration factor = 1.606 kg/mV - 385 kg.

Flowmeter setting = 1.768 ;

$$\text{Flowrate(m}^3\text{/hr)} = \frac{\Delta V(\text{mV}) \times \text{Cal}(\text{kg/mV}) \times 3600(\text{sec/hr})}{\Delta T(\text{sec}) \times \text{SG} \times 1000(\text{kg/m}^3)}$$

TEST 1

Speed 1

SG(meas) = 1.958

LC emp(mV)	308.9	354.9	377.9	380.7	---
LC full(mv)	398.0	443.8	463.7	468.6	---
Time (sec)	17	15	15	17	---
Flw(exp).SG	30.302	34.266	33.071	29.894	---
Flow(exp)	15.41	17.42	16.82	15.20	---
Flow(meas)	15.1	14.8	15.2	15.03	---

Speed 2

SG(meas) = 1.9558

LC emp(mV)	250.9	371.4	377.3	---	---
LC full(mv)	393.5	457.0	468.5	---	---
Time (sec)	21	12	13	---	---
Flw(exp).SG	39.26	41.24	40.56	---	---
Flow(exp)	20.07	21.08	20.07	---	---
Flow(meas)	20.0	21.0	21.1	19.8	---

Speed 3

SG(meas) = 1.959

LC emp(mV)	243.9	226.4	229.5	---	---
LC full(mv)	401.2	409.4	407.0	---	---
Time (sec)	18	21	20	---	---
Flw(exp).SG	50.52	50.38	51.31	---	---
Flow(exp)	25.78	25.71	26.19	---	---
Flow(meas)	27.0	26.7	27.0	---	---

Speed 4

SG(meas) = 1.955

LC emp(mV)	284.6	265.4	253.5	—	—
LC full(mv)	428.9	420.2	404.6	—	—
Time (sec)	13	15	14	—	—
Flw(exp).SG	64.18	59.67	62.40	—	—
Flow(exp)	32.82	30.52	31.91	—	—
Flow(meas)	32.2	30.1	31.1	—	—

Speed 5

SG(meas) = 1.9485 slight air in pipe

LC emp(mV)	291.5	281.6	318.4	—	—
LC full(mv)	414.4	407.8	407.4	—	—
Time (sec)	10	11	7	—	—
Flw(exp).SG	71.06	66.33	73.51	76.83	—
Flow(exp)	36.46	34.04	37.72	—	—
Flow(meas)	36.3	36.1	36.4	—	—

Speed 6

SG(meas) = —

LC emp(mV)	—	—	—	—	—
LC full(mv)	—	—	—	—	—
Time (sec)	—	—	—	—	—
Flw(exp).SG	—	—	—	—	—
Flow(exp)	—	—	—	—	—
Flow(meas)	—	—	—	—	—

TEST 2

Speed 1

SG(meas) = 1.8921

LC amp(mV)	230.1	142.3	244.3	244.0	—'—
LC full(mv)	325.7	331.3	340.4	342.9	—'—
Time (sec)	18	16	17	18	—
Flw(exp).SG	30.71	32.16	32.68	32.77	—'—
Flow(exp)	16.23	16.99	17.27	17.31	—'—
Flow(meas)	16.2	16.3	16.1	16.3	—'—

Speed 2

SG(meas) = 1.8921

LC amp(mV)	242.9	245.1	263.9	—'—	—'—
LC full(mv)	352.7	344.9	367.2	—'—	—'—
Time (sec)	15	14	14	—	—
Flw(exp).SG	42.32	41.21	42.66	—'—	—'—
Flow(exp)	22.36	21.78	22.54	—'—	—'—
Flow(meas)	21.0	21.0	21.1	—'—	—'—

Speed 3

SG(meas) = 1.8897

LC amp(mV)	241.8	240.7	239.0	245.2	—'—
LC full(mv)	341.7	345.8	394.7	375.3	—'—
Time (sec)	12	12	17	14	—
Flw(exp).SG	48.13	50.64	52.95	53.73	—'—
Flow(exp)	25.46	26.79	28.02	28.43	—'—
Flow(meas)	27.4	27.5	27.65	27.5	—'—

Speed 4

SG(meas) = 1.8897

LC emp(mV)	246.1	273.4	247.9	257.8	---
LC full(mV)	383.2	398.1	384.6	383.8	---
Time (sec)	12	11	12	11	---
Flw(exp).SG	66.05	65.54	65.86	66.23	---
Flow(exp)	34.95	34.68	34.85	33.04	---
Flow(meas)	33.2	33.5	33.4	33.3	---

Speed 5

SG(meas) = 1.8848

LC emp(mV)	238.5	254.0	247.9	245.9	---
LC full(mV)	418.0	426.7	433.8	422.7	---
Time (sec)	14	13	14	14	---
Flw(exp).SG	74.13	76.81	76.77	73.01	---
Flow(exp)	39.33	40.75	40.73	38.73	---
Flow(meas)	38.4	38.6	38.7	36.3	---

Speed 6

SG(meas) = 1.8848

LC emp(mV)	244.2	249.6	246.0	258.5	---
LC full(mV)	429.7	421.1	423.4	455.5	---
Time (sec)	13	12	13	14	---
Flw(exp).SG	82.5	82.63	78.9	81.36	---
Flow(exp)	43.77	43.84	41.86	43.16	---
Flow(meas)	41.1	41.3	41.35	41.2	---

TEST 3

Speed 1

SG(meas) = 1.7990

LC amp(mV)	217.2	222.6	219.9	—'—	—'—
LC full(mv)	298.8	296.5	300.8	—'—	—'—
Time (sec)	22	19	21	—'—	—'—
Flw(exp).SG	21.44	22.49	22.27	—'—	—'—
Flow(exp)	12.12	12.72	12.59	—'—	—'—
Flow(meas)	12.1	12.0	12.0	12.0	—'—

Speed 2

SG(meas) = 1.8014

LC amp(mV)	223.2	223.4	226.3	224.9	—'—
LC full(mv)	350.3	340.5	339.4	341.5	—'—
Time (sec)	21	19	19	19	—'—
Flw(exp).SG	34.99	35.63	34.42	35.48	—'—
Flow(exp)	19.66	20.02	19.34	19.94	—'—
Flow(meas)	18.36	18.33	18.33	—'—	—'—

Speed 3

SG(meas) = 1.8014

LC amp(mV)	229.6	229.9	232.2	236.7	—'—
LC full(mv)	341.8	356.1	355.5	350.2	—'—
Time (sec)	14	16	15	15	—'—
Flw(exp).SG	46.34	45.60	47.52	46.06	—'—
Flow(exp)	26.04	26.63	26.71	25.89	—'—
Flow(meas)	24.1	24.1	24.0	24.05	—'—

Speed 4

SG(meas) = 1.7990

LC emp(mV)	238.6	234.8	237.5	234.2	_____
LC full(mv)	401.9	406.9	408.0	415.8	_____
Time (sec)	16	18	17	19	_____
Flw(exp).SG	59.01	55.28	57.99	55.26	_____
Flow(exp)	32.96	30.88	32.39	30.87	_____
Flow(meas)	30.50	30.60	30.70	30.70	_____

Speed 5

SG(meas) = 1.7965

LC emp(mV)	249.2	246.1	248.6	_____	_____
LC full(mv)	433.5	433.9	431.7	_____	_____
Time (sec)	15	15	14	_____	_____
Flw(exp).SG	71.04	72.39	75.62	_____	_____
Flow(exp)	39.69	40.44	42.24	_____	_____
Flow(meas)	39.5	41.7	41.46	41.6	41.0

TEST 4

Speed 1

SG(meas) = 1.6617

LC amp(mV)	221.2	223.3	220.7	236.8	—	—
LC full(mv)	307.5	308.5	308.3	309.0	—	—
Time (sec)	20	19	20	16	—	—
Flw(exp).SG	24.95	25.93	25.32	26.09	—	—
Flow(exp)	15.01	15.60	15.23	15.7	—	—
Flow(meas)	14.13	14.03	14.13	—	—	—

Speed 2

SG(meas) = 1.6666

LC amp(mV)	230.7	236.4	230.5	228.7	—	—
LC full(mv)	313.3	316.0	312.2	311.8	—	—
Time (sec)	13	14	13	14	—	—
Flw(exp).SG	36.74	37.00	36.34	34.32	—	—
Flow(exp)	22.04	22.20	21.80	20.59	—	—
Flow(meas)	19.33	19.23	19.33	19.33	—	—

Speed 3

SG(meas) = 1.6670

LC amp(mV)	232.0	232.4	235.8	—	—
LC full(mv)	327.6	327.7	330.2	—	—
Time (sec)	13	12	12	—	—
Flw(exp).SG	42.52	45.92	45.48	—	—
Flow(exp)	25.50	27.54	27.28	—	—
Flow(meas)	25.03	25.13	25.43	—	—

Speed 4

SG(meas) = 1.6715

LC amp(mV)	239.1	234.2	241.6	—	—
LC full(mV)	346.6	381.6	409.8	—	—
Time (sec)	11	15	17	—	—
Flw(exp).SG	56.50	56.81	57.20	—	—
Flow(exp)	33.80	33.98	34.22	—	—
Flow(meas)	30.83	31.03	31.33	31.53	—

Speed 5

SG(meas) = 1.674

LC amp(mV)	244.4	247.0	251.1	239.8	—
LC full(mV)	422.8	429.1	418.6	421.9	—
Time (sec)	16	15	14	16	—
Flw(exp).SG	64.18	70.19	69.17	65.80	—
Flow(exp)	38.33	41.92	41.32	39.30	—
Flow(meas)	40.0	40.6	40.1	40.5	—

Speed 6

SG(meas) = 1.6789

LC amp(mV)	247.4	240.4	241.9	—	—
LC full(mV)	428.5	413.7	429.5	—	—
Time (sec)	15	14	16	—	—
Flw(exp).SG	69.8	71.57	67.79	—	—
Flow(exp)	41.57	42.62	40.37	—	—
Flow(meas)	43.1	43.3	43.2	—	—

TEST 5

Speed 1

SG(meas) = 1.5686

LC amp(mV)	210.4	213.5	222.5	—	—
LC full(mv)	272.0	268.6	277.9	—	—
Time (sec)	20	18	18	—	—
Flow(exp).SG	17.81	17.70	17.79	—	—
Flow(exp)	11.35	11.28	11.34	—	—
Flow(meas)	11.2	11.3	11.4	—	—

Speed 2

SC(meas) = 1.5784

LC amp(mV)	221.0	224.3	218.3	—	—
LC full(mv)	308.1	317.5	319.5	—	—
Time (sec)	17	18	19	—	—
Flow(exp).SG	29.62	29.94	30.79	—	—
Flow(exp)	18.76	18.76	19.5	—	—
Flow(meas)	18.4	18.3	18.3	—	—

Speed 3

SG(meas) = 1.5906

LC amp(mV)	229.4	229.4	231.2	231.9	—
LC full(mv)	351.3	358.7	353.3	356.7	—
Time (sec)	14	15	14	14	—
Flow(exp).SG	50.13	49.84	50.42	51.54	—
Flow(exp)	31.51	31.33	31.69	32.40	—
Flow(meas)	30.5	30.5	30.5	30.5	—

Speed 4

SG(meas) = 1.5955

LC emp(mV)	236.3	236.4	233.0	---	---
LC full(mv)	380.0	392.7	370.0	---	---
Time (sec)	14	15	13	---	---
Flw(exp).SG	59.34	60.24	60.93	---	---
Flow(exp)	37.19	37.75	38.18	---	---
Flow(meas)	38.5	38.4	38.47	---	---

Speed 5

SG(meas) = 1.605

LC emp(mV)	244.8	242.0	243.4	---	---
LC full(mv)	475.4	411.9	429.5	---	---
Time (sec)	19	14	16	---	---
Flw(exp).SG	70.17	70.16	67.25	---	---
Flow(exp)	43.71	43.71	41.90	---	---
Flow(meas)	43.0	43.2	43.2	---	---

Speed 6

SG(meas) = 1.6028

LC emp(mV)	243.5	241.8	241.5	---	---
LC full(mv)	414.6	414.7	447.4	---	---
Time (sec)	14	15	17	---	---
Flw(exp).SG	70.66	66.64	70.03	---	---
Flow(exp)	44.02	41.52	43.63	---	---
Flow(meas)	43.3	43.3	43.1	43.1	---

TEST 6

Speed 1

SG(meas) = 1.5245

LC emp(mV)	219.1	222.4	302.2	228.3	---
LC full(mv)	304.4	313.0	376.8	327.1	---
Time (sec)	18	19	16	22	---
Flow(exp).SG	27.40	27.57	26.96	27.02	---
Flow(exp)	17.97	18.08	17.68	17.72	---
Flow(meas)	17.4	17.4	17.4	---	---

Speed 2

SG(meas) = 1.5343

LC emp(mV)	225.7	233.8	227.3	238.3	---
LC full(mv)	364.5	359.2	357.5	377.8	---
Time (sec)	21	19	20	21	---
Flow(exp).SG	38.21	38.16	37.64	38.42	---
Flow(exp)	24.90	24.87	24.53	25.03	---
Flow(meas)	24.4	24.4	24.4	24.4	---

Speed 3

SG(meas) = 1.539

LC emp(mV)	234.9	228.9	230.2	232.7	---
LC full(mv)	415.1	427.2	412.6	420.1	---
Time (sec)	21	24	23	22	---
Flow(exp).SG	49.61	47.77	45.85	49.25	---
Flow(exp)	32.23	31.03	29.79	32.00	---
Flow(meas)	28.5	28.6	28.6	28.8	---

Speed 4

SG(meas) = 1.5612

LC emp(mV)	233.6	234.1	233.8	_____	_____
LC full(mV)	428.8	422.6	437.9	_____	_____
Time (sec)	20	19	21	_____	_____
Flw(exp).SG	56.43	57.36	56.19	_____	_____
Flow(exp)	36.14	36.74	35.99	_____	_____
Flow(meas)	34.5	34.6	34.4	34.1	_____

Speed 5

SG(meas) = 1.5686

LC emp(mV)	238.4	239.8	242.1	_____	_____
LC full(mV)	412.8	431.2	432.4	_____	_____
Time (sec)	16	17	17	_____	_____
Flw(exp).SG	63.0	65.09	64.72	_____	_____
Flow(exp)	40.16	41.49	41.25	_____	_____
Flow(meas)	40.2	40.2	40.24	_____	_____

Speed 6

SG(meas) = 1.5759

LC emp(mV)	236.2	242.0	237.9	_____	_____
LC full(mV)	422.4	441.3	421.6	_____	_____
Time (sec)	16	17	16	_____	_____
Flw(exp).SG	67.28	67.78	66.38	_____	_____
Flow(exp)	42.69	43.01	42.12	_____	_____
Flow(meas)	41.2	41.18	41.28	40.9	_____

WATER TEST

Speed 1

LC emp(mV)	199.4	200.4	192.9	—'—	—'—
LC full(mv)	272.0	284.2	290.3	—'—	—'—
Time (sec)	30	32	42	—	—
Flow(exp)	13.99	15.14	13.4	—'—	—'—
Flow(meas)	14.19	—'—	—'—	—'—	—'—

Speed 2

LC emp(mV)	187.0	218.1	193.2	—'—	—'—
LC full(mv)	295.9	316.9	315.4	—'—	—'—
Time (sec)	30	28	34	—	—
Flow(exp)	20.98	20.4	20.77	—'—	—'—
Flow(meas)	19.96	—'—	—'—	—'—	—'—

Speed 3

LC emp(mV)	193.0	195.3	—'—	—'—	—'—
LC full(mv)	347.3	347.9	—'—	—'—	—'—
Time (sec)	32	32	—	—	—
Flow(exp)	27.87	27.57	—'—	—'—	—'—
Flow(meas)	21.25	—'—	—'—	—'—	—'—

Speed 4

LC emp(mV)	198.5	195.1	___	___	___
LC full(mv)	374.1	379.0	___	___	___
Time (sec)	30	32	___	___	___
Flow(exp)	33.84	33.22	___	___	___
Flow(meas)	33.61	___	___	___	___

Speed 5

LC emp(mV)	205.3	197.9	___	___	___
LC full(mv)	401.4	315.7	___	___	___
Time (sec)	30	18	___	___	___
Flow(exp)	37.79	37.83	___	___	___
Flow(meas)	37.86	___	___	___	___

C.3 READINGS FOR EVALUATION OF NUCLEAR DENSITY GAUGE.

Dry Solids SG $\approx$ 2.65

DH80 settings: Zero = 2.279; Range = 2.581; Isotope = 0

$$SG_{\text{slurry}} = 1 / (1 - C_W + C_W / SG_{\text{dry solids}})$$

Where

$SG_{\text{slurry}} \approx$ Slurry SG

$SG_{\text{dry solids}}$ = Dry solids SG

C_W = Concentration by weight

= (sample dry mass)/(sample wet mass)

TEST 1

Pan Mass(g)	3.3	3.2	3.3	165.3	167.9
SAM wet (g)	130.9	124.7	160.1	1360.9	1225.6
SAM dry (g)	103.3	99.3	127.1	1111.1	1004.6
Cw (%)	78.4	79.1	78.95	79.1	79.1
SG (exp)	1.953	1.97	1.9669	1.97	1.97
SG (meas)	1.958	1.957	1.962	1.958	1.962

TEST 2

Pan Mass(g)	3.2	4	3.2	—	—
SAM wet (g)	127.1	183.8	127.1	—	—
SAM dry (g)	96.7	139.5	96.7	—	—
Cw (%)	75.5	75.4	75.5	—	—
SG (exp)	1.8863	1.8858	1.8863	—	—
SG (meas)	1.8897	1.8872	1.8897	—	—

TEST 3

Pan Mass(g)	3.4	3.5	3.3	3.3	3.4
SAM wet (g)	85.2	111.4	105.4	122.1	106.9
SAM dry (g)	60.1	79.1	74.1	86.7	75.7
Cw (%)	69.3	70.1	69.34	70.2	69.85
SG (exp)	1.7592	1.774	1.7598	1.7765	1.7697
SG (meas)	1.775	1.775	1.779	1.779	1.7794

TEST 4

Pan Mass(g)	3.2	3.2	—	—	—
SAM wet (g)	79.7	72.3	—	—	—
SAM dry (g)	51.4	47.8	—	—	—
Cw (%)	63.0	64.64	—	—	—
SG (exp)	1.6455	1.6735	—	—	—
SG (meas)	1.6642	1.6764	—	—	—

TEST 5

Pan Mass(g)	3.3	171.4	3.2	—	—
SAM wet (g)	53.4	1007.0	46.5	—	—
SAM dry (g)	32.4	657.3	28.3	—	—
Cw (%)	58.08	58.13	57.97	—	—
SG (exp)	1.5665	1.567	1.565	—	1.57
SG (meas)	1.5686	1.5661	1.5686	—	1.5661

TEST 6

Pan Mass(g)	3.3	172.0	169.9	166.4	—
SAM wet (g)	44.5	242.7	966.8	1087.0	—
SAM dry (g)	26.4	211.4	604.5	713.5	—
Cw (%)	56.07	55.73	54.54	59.43	—
SG (exp)	1.5363	1.5311	1.5142	1.5874	—
SG (meas)	1.5245	1.539	1.5245	1.5784	—

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