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TC S361
Instrumentation and Testing Techniques
(Free Courseware)

香港公開大學
THE OPEN UNIVERSITY OF HONG KONG

Contents

Chapter 1 Concepts of Measurements

1.1 Introduction

Welcome to this free courseware module, which is part of the OUHK course *TC S361 Instrumentation and Testing Technique. TC S361* is a five-credit, higher-level course that is part of the BSc/Bsc (Hons) in Product Design, Testing and Certification programme degree programme at the OUHK.

TC S361, like most OUHK courses, is presented in the distance learning mode using print-based materials. The materials for this module have been specially adapted to make them more suitable for studying online.

Normal study units in OUHK courses contain study content, activities, self-tests, and assigned readings. This module retains most of these elements, so you can have a taste of what an OUHK course is like. In addition to this module's topics on units of measurement and principles of measurement traceability, the original unit also includes topics on calibrating instrument systems, instrumentation and measurement errors, and measurement uncertainty.

Measurement is a big part of our daily lives. You have to pay your water bill according to your monthly volume usage. If you are paid via an hourly rate, the company you work for will measure the working hours you have put in each day. When you fill your car with gasoline, it must be measured so you know how much you are expected to pay. You may want to know if the butcher stall gives you enough meat for the money you have paid.

Similar measurement-related questions appear in the testing and certification industry. For example, are toys that may carry trace amounts of toxic elements safe for children? Are electrical products safe to use? And so on.

Measurement is the activity by which we compare a physical quantity of an object with a standard. We can of course use a wide range of measuring instruments to perform such measurements, from simple rulers and balances to accelerometers and electronic microscopes.

But when we are using an instrument to take a measurement, how can we be sure that the instrument is accurate or not? This is crucial when we are doing business with foreign countries, since both parties, i.e. suppliers and customers, must know about and agree upon the same measurement units and standards. These standards are needed to ensure that such trade is fair.

This module starts with an overview of the two important standards of measurement units: British standard and SI units. Concepts related to measurement traceability are then explained in the second section.

This module should take you about six hours to complete, including the time you will need to complete the activities and self-tests.

Good luck, and enjoy your study!

1.2 Units of measurements

Before we look at units of measurement, let's watch a short online video in Activity 1 (Page 2) that discusses the need for measurement.

You learned in the module introduction that when we do business with foreign countries, both parties — the sellers and the customers — need to know and hold to the same measurement units and standards to make sure each trade is fair. Let's begin, therefore, by taking a closer look at what those units are, and how they are used.

1.2.1 Activity 1

This video clip (http://www.youtube.com/watch?v=UA9O5mmllrw) gives you the chance to take a look at a Coordination Measuring Machine (CMM), a three-dimensional device for measuring the geometrical characteristics of the parts of a product. It is a widely-used machine in metal parts manufacturing. The video lasts around eight minutes.

After watching the video, you should now have a rough idea of why measurements, standards and traceability are needed.

1.2.2 The International System of Units (SI units)

The *International System of Units* (SI units) is the most widely used unit system in science, engineering, and in our daily life. Please refer to the following online article for a brief history of SI units.

Reading

'International System of Units' (http://en.wikipedia.org/wiki/International_System_of_Units).

The SI units system has been adopted globally, except for in the United States, Liberia and Myanmar (Burma). Canada has adopted the SI units for all legal purposes, but imperial/US units (which will be discussed later in this section) are also still in use there. The United Kingdom has officially adopted SI units.

The Hong Kong official unit system is the SI unit system. You should find that the package of rice you have bought from supermarket shows the mass in kilograms. Because Hong Kong is a centre for international trade, keeping to the right standards is crucial here.

Common unit systems used in Hong Kong

The most common units systems used in Hong Kong are:

- the International System of Units (SI units);
- Imperial units; and
- ancient Chinese units.

In fact, in Hong Kong, the Weights and Measures Ordinance (http://www.legislation.gov.hk/blis_pdf.nsf/6799165D2FEE3FA94825755E0033E532/1FCB26A2D9143FF2482575EE0036D664/%24FILE/CAP_68_e_b5.pdf), Chapter 68, Laws of Hong Kong provides a legal framework to protect consumers from fraudulent or unfair trading practices in connection with quantities.

If you would like to find out more about this legal framework, you can explore this article on 'Weights and measures (http://www.customs.gov.hk/en/consumer_protection/weights_measures/index.html)' from Hong Kong's Customs and Excise Department (http://www.customs.gov.hk/).

1.2.2.1 Base units

The SI unit system distinguishes physical units into two classes:

- base units; and
- derived units.

These two categories cover all the units that affect our daily lives (e.g. length, mass, pressure, temperature, flow rate, etc.).

In the following reading, the National Institute of Standards and Technology (NIST) in the USA provides a good introduction to the SI units.

Reading

National Institute of Standards and Technology, US, 'SI units (http://physics.nist.gov/cuu/Units/)'.
Follow the links under the heading 'Essentials of the SI'.

If you would like to read more, you have the option of going to the website for the international standards organization called the Bureau International des Poids et Mesures (BIPM) (http://www.bipm.org/en/home/) for its information on the SI units (http://www.bipm.org/en/si/).

Each measurement unit has a base quantity that has been adopted by convention. In each coherent system of units, there is only one base unit for each base quantity. Each of these base units can be further decomposed. There are seven base units, each representing, by convention, different kinds of physical quantities. Learn more about these base units in Table 1.1.

Measurement	Units	Explanation
Unit of length	Metre	The metre is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.
Unit of mass	Kilogram	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
Unit of time	Second	The second is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.
Unit of electric current	Ampere	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2 × 10−7 newton per metre of length.

Table 1.1: Definitions of the SI base units

Measurement	Units	Explanation
Unit of thermodynamic temperature	Kelvin	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Unit of amount of substance	Mole	1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is 'mol.' 2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
Unit of luminous intensity	Candela	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Table 1.1: Definitions of the SI base units

Source: http://physics.nist.gov/cuu/Units/current.html

To maintain constant standards for some base units, prototypes are held for comparison. Figure 1.1 shows you a prototype for the kilogram.

Fig. 1.1: The standard for mass

Source: http://www.itc.gov.hk/ch/quality/scl/mm/mm2.htm

The Society of Construction Law (HK) (http://www.scl.hk/) keeps this primary mass standard in its laboratories located in Wan Chai. SCL uses this working mass as the basis for comparisons with samples submitted for calibration.

1.2.2.2 Derived units

A derived unit is a measurement unit for a derived quantity. Derived units combine different base units, examples of which you can see in Table 1.2. These derived units are obtained by the mathematical signs for multiplication.

Measurement	SI derived units
Velocity	Metre per second
Angular velocity	Radian per second
Mass Flow rate	Kilogram per second
Flow rate	Litre per second

Table 1.2: Example of SI derived units

1.2.2.3 Activity 2

Visit the HKSAR Water Supplies Department webpage (http://www.wsd.gov.hk/en/customer_services_and_water_bills/water_and_sewage_tariff/water_and_sewage_tariff/index.html) and find out what unit the department used to calculate your water bill. Is it a base unit or derived unit?

1.2.2.4 Prefixes

When we measure some kinds of units, we face a problem: the long string of digits needed to write out the measured data. For example, let's say a private car travels over 100,000,000 metres. It is difficult for car users to understand how far the car really has gone. Scientists have found ways to reduce the number of digits in measurement units by adding prefixes before base units.

100,000,000 metres = 100,000 kilometres

A prefix can be added to a unit to produce a multiple of the original unit. All multiples are integer powers of ten. Figure 1.2 sets out the standard prefixes for the SI units.

Multiples	**Name**		**deca-**	**hecto-**	**kilo-**	**mega-**	**giga-**	**tera-**	**peta-**	**exa-**	**zetta-**	**yotta-**
	Symbol		da	h	k	M	G	T	P	E	Z	Y
	Factor	10^0	10^1	10^2	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}	10^{21}	10^{24}
Fractions	**Name**		**deci-**	**centi-**	**milli-**	**micro-**	**nano-**	**pico-**	**femto-**	**atto-**	**zepto-**	**yocto-**
	Symbol		d	c	m	µ	n	p	f	a	z	y
	Factor	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}	10^{-21}	10^{-24}

Fig. 1.2: Standard prefixes for the SI units of measure

We use length and mass as examples:

1 metre (1 m) = 10 dm = 100 cm = 1000 mm
1 kilogram (1 kg) = 1000 grams (g) = 100000 mg

1.2.3 Imperial units

The Imperial unit system also includes the United States' customary units, and is still commonly used in the USA and to some degree in Canada. When you read a Federal law or a safety standard (e.g. ASTM F963) in the USA, it still shows Imperial units. For example, you can access the USA Federal Law (http://www.gpo.gov/fdsys/pkg/

CFR-2011-title16-vol1/content-detail.html) to see how Imperial units are still used in the standards provided there.

The Imperial unit system was first defined in the British Weights and Measures Act of 1824. The system then came into official use across the UK.

If you are interested in the history of the Imperial unit system, you can refer to this article (http://physics.info/system-english/).

1.2.3.1 Differences between the US and British customary systems

The United States uses US customary units, although most of them are identical to Imperial units. For some measurements, such as for liquid volume, both the USA and the UK use the fluid ounces as their units.

There are numerous examples of such discrepancies.

Discrepancies between US and British customary units

There are notable differences between US and British customary units in, for example, measures of volume. The US customary bushel and the US gallon, and their subdivisions differ from the corresponding British Imperial units as follows:

- US fluid ounce = 1.041 British fluid ounces
- British fluid ounce = 0.961 US fluid ounce
- US gallon = 0.833 British Imperial gallon
- British Imperial gallon = 1.201 US gallons.

1.2.3.2 Converting Imperial units to SI units

Because the metric system is already widely used globally, the United Kingdom and United States published guidelines to the public for converting Imperial units to SI units respectively:

- *United Kingdom*: British Standard: BS350
- *United States*: The International System of Units (SI) — Conversion Factors for General Use by NIST.

Read the following document for a further introduction to Imperial units, and to see how they are converted to SI units.

Reading

Butler, K, Crown, L and Gentry, E (eds) (2006) *The International System of Units (SI): Conversion Factors for General Use* (http://www.nist.gov/pml/wmd/metric/upload/SP1038.pdf), NIST Special Publication 1038.

You should now be aware of the relevant conversion factors (For example, when we convert 1 kg to Imperial units (pounds) we need to multiply the measurement in kilograms by a factor of 2.20462.) to convert SI units to Imperial units.

When a product is to be shipped to a country where Imperial units are used, but which was weighed and labelled with SI units in its country of origin, conversion of units is necessary. In such cases, you will find this online calculator (http://hurri.kean.edu/~yoh/calculations/units/home.html) helpful; you can use it for conversion of units without memorizing all the conversion factors:

This article also answers some frequently asked questions about SI units.

Download (http://www.opentextbooks.org.hk/system/files/resource/10/10385/10397/media/SI_FAQs_EN.pdf)

In this section we have discussed the metric and Imperial unit systems. When we conduct a test or measurement with reference to a country's requirements/standards, we need to know what unit system must be followed. Some electronic instruments can display results in different unit systems. In this case, we need to know what conversion factor has been used. Otherwise, this conversion can be an error source and cause measurement uncertainty.

In the next section we will discuss measurement (i.e. metrological) traceability.

1.2.3.3 Self-test 1

More and more enterprises do business with enterprises in mainland China, so they need to know mainland China's official unit system. Do some online research to identify the official units system in mainland China, and which regulations state the requirements.

1.2.3.3.1 Self-test 1 feedback

The China Metrology Law (中華人民共和國計量法) Article 3 states that China has adopted the SI units as its official units system. You can find this law here:

- English version (http://www.cqc.com.cn/english/ProductCertification/CCC/PolicyInformation/webinfo/2006/12/1260497022789344.htm)
- Chinese version (http://www.cnca.gov.cn/rjwzcfl/flfg/fl/579.shtml).

1.3 Principles of measurement traceability

In the last section we discussed both imperial and SI unit systems. By understanding the principles of measurement traceability or metrological traceability, we can know how a measuring instrument is traceable to SI units, and if it complies with ISO/IEC17025.

When you are using a ruler to measure length, do you ever think about whether the ruler is accurate or not? And is the equipment resolution high enough for your purposes? If we do not know how accurate an instrument is, we cannot be sure its measured values are true.

Instruments must therefore be calibrated regularly to make sure that they are accurate. In the product testing industry, most standards will specify the accuracy and resolution requirements for the instruments we use. For example: BS EN71-1: 2011, Clause 8.25.1.1, states that the apparatus shall be capable of measuring thickness to an accuracy of 1 μm according to ISO4593. See how this requirement is set out:

8.25 Plastic sheeting

8.25.1 Thickness (see 4.3, 5.3 and Clause 6)

8.25.1.1 Apparatus

Measuring device, capable of measuring thickness to an accuracy of 1 μm according to ISO 4593.

Fig. 1.3: An example of measurement accuracy and resolution requirementson

Even if you have considered these factors, you must also consider the other instrument that has been used to compare with the ruler, i.e. in this activity called 'calibration'. In other words, a chain of reliable measurement (i.e. metrological traceability) must be established to ensure the measurements we make are accurate. This is why we require calibration and consider metrological traceability in product testing.

The Joint Committee for Guides in Metrology (JCGM) (http://www.bipm.org/en/committees/jc/jcgm/) defines metrological traceability (also called measurement traceability) as the 'property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty' (JCGM 2008 (Joint Committee for Guides in Metrology (JCGM) (2008) JCGM 200: 2008 International Vocabulary of Metrology: Basic and General Concepts and Associated Terms, http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2008.pdf.), 29).

In the ISO/IEC17025: 2005 edition (http://www.iso.org/iso/catalogue_detail.htm?csnumber=39883), **Clause 5.6 Measurement Traceability** (Figure 1.4) requires that all equipment used for tests and/or calibration shall be calibrated before being put into service. You will learn more about metrological traceability and the metrological traceability chain in the following sections.

5.6 Measurement traceability

5.6.1 General

All equipment used for tests and/or calibrations, including equipment for subsidiary measurements (e.g. for environmental conditions) having a significant effect on the accuracy or validity of the result of the test, calibration or sampling shall be calibrated before being put into service. The laboratory shall have an established programme and procedure for the calibration of its equipment.

NOTE Such a programme should include a system for selecting, using, calibrating, checking, controlling and maintaining measurement standards, reference materials used as measurement standards, and measuring and test equipment used to perform tests and calibrations.

Fig. 1.4: The ISO/IEC17025 requirement for measurement traceability

Now complete the following reading.

Reading

Please read pages 4–5 from the American Association for Laboratory Accreditation (A2LA) (2011) *P102: A2LA Policy on Measurement Traceability* (http://www.a2la.org/policies/A2LA_p102.pdf).

You should also have a look at the measurement traceability services provided by the Hong Kong SAR Government in the next reading.

Reading

Standard and Calibration Laboratory of the Innovation and Technology Commission (http://www.itc.gov.hk/en/quality/scl/trace.htm), Hong Kong SAR Government.

You should now have a better idea of the requirements and definition of measurement traceability.

1.3.1 Metrological professional bodies

As measurement traceability is very important in pure science and engineering, every country faces the same problem of maintaining it, and needing to standardize practices and promote the concept of metrological traceability. The International Committee of Weights and Measures (CIPM) (http://www.bipm.org/en/committees/cipm/), formed by the International Bureau of Weights and Measures (BIPM) (http://www.bipm.org/en/home/), the International Federation for Clinical Chemistry (IFCC) (http://www.ifcc.org/) and the International Laboratory Accreditation Cooperation (ILAC) (http://www.ilac.org) therefore agreed to establish the Joint Committee for Traceability in Laboratory Medicine (JCTLM) (http://www.bipm.org/en/committees/jc/jctlm/) with the main objectives of providing leadership in identifying reference materials and reference methods appropriate to meeting 'higher order' requirements.

1.3.2 Metrological traceability chain

The users of measuring instruments must understand the instruments' working principles before use. This is because we must know an instrument's limitations, sources of errors, and so on, so that we can get precise measured data. Here we will discuss the general principle of the 'metrological traceability chain'.

The metrological traceability chain (also called a measurement chain) is the linkage of the elements that make up measuring equipment or a measuring system, which channels the transfer of a measurement signal from the input of the measurand (the particular quantity being measured, e.g. temperature of liquid, or width of a table also called a measurement chain) to the output of the measured value.

The VIM defines it as sequence of measurement standards and calibrations that is used to relate a measurement result to a reference.

Click this link to watch the video: http://www.opentextbooks.org.hk/system/files/resource/10/10385/10402/media/A%20measurement%20process_0.mp4

In a typical measurement process, a person uses an instrument to measure the mass of a substance. The substance is placed on an electronic balance. The sensor, for example a load cell, will be activated, and the measured signal is converted and processed through the signal conditioner and signal processor. The mass value will be shown on the display panel of the electronic balance.

1.3.2.1 Activity 3

Visit the SHIMADZU Corporation website — Learning about electronic balances and read 'How electronic balances work (http://www.shimadzu.com/an/hplc/support/lib/lctalk/66/66lab.html)'.

After you read this document, you should have a better idea of how a metrological traceability chain is associated with equipment working principles.

1.3.3 Traceability infrastructure

You have now learned about *metrological traceability* and the *metrological traceability chain*. You may then ask who is responsible for handling instrument accuracy checking (also called calibration). The purpose of checking is to make sure that an instrument has the same or similar accuracy as other similar instruments. In this section, we will introduce the calibration hierarchy (the sequence of calibrations from a reference to the final measuring system, through which the outcome of each calibration depends on the outcome of the previous calibration).

ISO/IEC 17025 requires testing organizations/laboratories to calibrate their instruments before putting them into service. Every country has a national metrology institute (NMI) to maintain measuring standards. All measurement standards trace back to SI units. An NMI will use the measuring standard to calibrate equipment from its country's other laboratories.

For example: all reference laboratories send their instruments to an NMI for calibration before they provide the calibration service to the other testing laboratories. In this section we discuss this infrastructure and how it works.

The National Centre for Biotechnology Information at the US National Library of Medicine defines traceability as being realized by the establishment of a measurement infrastructure that consists of three levels. Figure 1.5 illustrates this hierarchy.

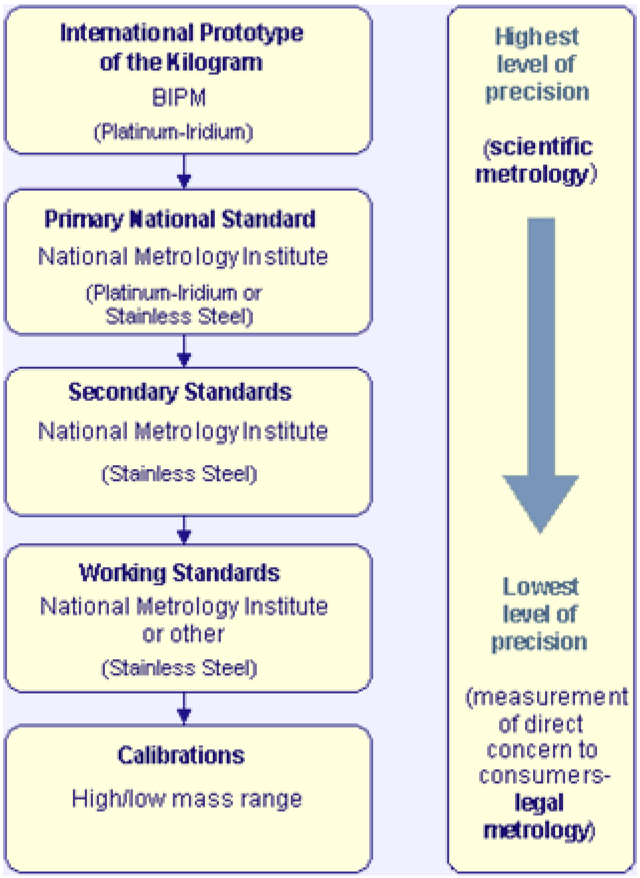

Fig. 1.5: Types of standards that exist in a particular area of metrology

Source: http://www.bipm.org/en/convention/wmd/2004/figure.html

You should note how the level of precision decreases along the chain of responsibility.

We'll now take a closer look at each level as follows:

- Level One: National Metrology Institutes (NMI);
- Level Two: Reference (Calibration) Laboratories; and
- Level Three: Testing Laboratories.

Level 1: National Metrology Institute (NMIs)

Every NMI will conduct inter-laboratory correlation and make sure that its own primary standards are consistent when compared with other NMIs. In simple terms, this means that the NMI can offer its calibration and measurement capabilities (CMC) for certifying specific reference materials. The competent NMI will be listed in the BIPM. See Table 1.3 for examples of NMIs in some different countries.

Country/ District	Example of NMI
China	National Institute of Metrology P.R.China
United Kingdom	National Physical Laboratory
United States	National Institute of Standards and Technology
Australia	National Measurement Institute

Table 1.3: Examples of NMIs in different countries

You can search for the NMIs of different countries through the BIPM website (http://www.bipm.org/en/practical_info/useful_links/nmi.html).

Level 2: Reference (Calibration) Laboratories

Reference laboratories operate at a higher metrological level than routine laboratories. The level of the results from Reference Laboratories should be appropriate for medical requirements. These laboratories are also known as expert institutions because they perform measurements with the greatest competence. A laboratory will qualify as a Reference Laboratory if it satisfies all the following requirements:

- accreditation as a calibration laboratory according to ISO 17025 and 15195
- use of a reference method that has been approved and listed by JCTLM WG2
- participation in reference laboratory ring trials.

Laboratories that satisfy these conditions will be listed in the JCTLM list of Reference Laboratories. The laboratories that fall into this category offer their calibration and measurement capabilities to Diagnostic Kit Manufacturers, Regulatory Organizations and External Quality Assessment (EQA) Organizations. NMI and Calibration Laboratories listed in JCTLM provide the required link between routine laboratories and the reference materials and measurement procedures of a higher metrological order.

Level 3: Routine (Testing) Laboratories

These laboratories provide the routine measurement services to the community and are accredited by the Hong Kong Accreditation Service (HKAS) in Hong Kong. Because the HKAS has a mutual recognition agreement with other accreditation bodies, its certificates are recognized worldwide.

1.3.3.1 Activity 4

1. Visit this website (http://www.itc.gov.hk/en/quality/scl/services.htm) to see what calibration services can be provided in Hong Kong.
2. If you have a sound level meter, visit the HKAS website (http://www.itc.gov.hk/en/quality/hkas/hoklas/about.htm) to check which laboratories are capable of doing the calibration.

1.3.3.2 Self-test 2

Let's say you have an analytical balance you need to calibrate using standard masses. Which of the following types of calibration can laboratory staff in Hong Kong conduct?

i. Using a standard mass calibrated by an accredited calibration laboratory.
ii. Using a standard mass calibrated by a standard mass manufacturer which can be traced back to the international standard.
iii. Using a standard mass calibrated by a standard mass manufacturer which cannot be traced back to an international standard.

a. i, ii
b. i
c. ii, iii
d. i, iii

1.3.3.2.1 Self-test 2 feedback

Since the standard mass being calibrated can be traced back to international standards, it can be used for the calibration of instruments.

1.4 Reference

Joint Committee for Guides in Metrology (JCGM) (2008) *JCGM 200: 2008 International Vocabulary of Metrology: Basic and General Concepts and Associated Terms*, http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2008.pdf