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The effect of strain rate and temperature on the yielding and impact behaviour of dual-phase chromium-containing 3CR12 steel

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SYNOPSIS

Some aspects of the mechanical behaviour of chromium-containing dual-phase 3CR12 steel were investigated as a function of the temperature and strain rate. The yield stress was found to depend on both the temperature and the strain rate, with no substantial differences between the longitudinal and the transverse directions. The strain-rate sensitivity decreased with increasing temperature. The yield stress could be presented as a function of a temperature-strain-rate parameter. Impact test results showed substantial differences between the energy absorption of the transverse and longitudinal specimens above the ductile-brittle transition temperature. Changes in energy absorption with temperature were gradual for specimens in both orientations, and the transition from ductile to brittle behaviour occurred between 373 and 173 K. Strain rates ahead of the tip of notches with different geometries were calculated and measured experimentally.

SAMEVATTING

Enkele aspekte van die meganiese gedrag van tweefase-3CR12-staal wat chroom bevat is as'n funksie van die temperatuur en die vervormingstempo ondersoek. Daar is bevind dat die vloeispanning afhanklik is van beide die temperatuur en die vervormingstempo met geen wesentlike verskille tussen die langs- en dwarsrigtings nie. Die gevoeligheid van die vervormingstempo het met toenemende temperatuur afgeneem. Die vloeispanning kon as 'n funksie van 'n temperatuur-vervormingstempo-parameter uitgedruk word. Slagtoetsresultate het wesentlike verskille tussen die energie-absorpsie van die langs- en die dwarsrigtingmonsters, bó die rek-brosoorgangstemperatuur, getoon. Veranderings in energieabsorpsie met temperatuur is geleidelik vir beide monsteroriënterings en die oorgang van rek- na brosgedrag het tussen 373 en 173 K plaasgevind. Vervormingstempo voor die keepspitse met verskillende geometrieë is bereken en eksperimenteel gemeet.

Introduction

Many important practical applications require knowledge of the mechanical behaviour of materials over a wide range of strain rates and temperatures. The combined effect of strain rate and temperature has therefore been studied extensively so that a better understanding of the performance of materials under service conditions can be obtained. This behaviour is often described by appropriate constitutive equations that facilitate the use of the results for engineering purposes.

During the past two decades, intense interest has been focused on the development of steels with an attractive combination of ductility, work-hardening rate, and strength. These properties were achieved by the production of high-strength low-alloy steels characterized by a microstructure consisting of a dispersion of hard martensite particles in a soft, ductile ferrite matrix. Although the term 'dual phase' used to describe these steels refers to the presence of two major phases, small amounts of bainite, pearlite, and retained austenite may also be present[1,2].

From the results published in the literature[1,2] it can be concluded that dual-phase steels have a higher strain-rate sensitivity than conventional high-strength steels. Moreover, different martensite contents can influence the strain-rate dependence rather drastically, and the strain-rate sensitivity can vary markedly with the temperature.

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More recently, a 12 per cent chromium dual-phase steel[3,4], known under the trade name 3CR12 and produced by Middelburg Steel & Alloys (Pty) Limited, Middelburg, Transvaal, has been added to the class of dual-phase steels. The higher chromium content of this steel, which is in many ways directly comparable with other low-alloy dual-phase steels, results in significantly improved corrosion resistance, and hence leads to a greater potential range of applications. In an earlier investigation[5] it was found that this alloy showed continuous yielding and a three-stage work-hardening behaviour under tensile loading, similar to that reported for other low-alloy dual-phase steels[1,2].

The purpose of this paper is to evaluate the effect of strain rate and temperature on the yielding and impact properties of 3CR12 steel.

Material and Experimental Procedures

Specimens for all the tests were prepared, from commercial-quality plate in the as-received condition, in two orientations: parallel to and transverse to the rolling direction. The chemical composition of this batch of 3CR12 steel is given in Table I. The dependence of yielding on the strain rate, was determined by means of tensile tests carried out at low and high strain rates using a 100 kN Instron servohydraulic testing machine and a Tinius Olsen impact tester instrumented with a Dynatup system respectively. The elastic strain rates were determined from the strain history monitored by strain gauges glued to the specimens.

TABLE I
COMPOSITION OF THE SPECIMENS
Expressed in percentages by mass

C	S	Mn	Si	Ti	Cr	Ni	N	Fe
0,022	0,012	1,41	1,45	0,38	11,31	0,69	0,013	Balance

The tensile tests were carried out at temperatures between 77 and 273 K with the specimens immersed in a liquid coolant. The temperature of the coolant was kept constant to within ± 1 K. At higher strain rates, as obtained on the instrumented impact tester, the specimens were kept in a specially built container attached to the hammer. The container was removed from the sample immediately before the hammer was dropped. Temperature measurements on a dummy specimen showed that, over the duration of an impact experiment, the temperature change of a specimen was less than 2 K.

Impact tests were carried out on the Tinius Olsen impact tester at temperatures between 77 K and 673 K using DVM, ISO-V (Charpy), Schnadt, and pre-cracked Charpy specimens. The specimens were held submerged in a liquid coolant or were kept in a heater for twenty minutes at the test temperature prior to testing.

Results

Dependence of the Yield Stress on the Strain Rate at Different Temperatures

The dependence of the yield stress (0,2 per cent offset) on the testing temperature at three different strain rates for the longitudinal specimens is shown in Fig. 1. The yield-stress values obtained from the transverse specimens were generally about 10 per cent higher than those from the longitudinal specimens, but a similar temperature dependence was observed for both orientations. At a temperature of 77 K all the specimens, independent of the applied strain rate, fractured in a completely brittle mode, but it was assumed that the fracture at this temperature was caused by stresses close to the proof stress. The sensitivity of the yield stress to the strain rate is also temperature-dependent, being lower at higher temperatures as can be seen from Fig. 2. There is only a slight difference between the strain-rate sensitivities of the longitudinal and transverse specimens, and this can be neglected for all practical purposes.

So that the practical applications of the experimental results can be simplified for other combinations of strain rate and temperature, the yield-stress data can be represented as a function of the temperature–strain-rate parameter introduced by Bennett and Sinclair[6]. This representation was used previously to describe changes of the yield stress in other materials with complicated multiphase structures[7]. More recently, Meyer and Staskewitsch[8] studied the mechanical properties of low- and high-alloy steels at strain rates up to $5 \times 10^3\ s^{-1}$, and presented the yield stress and the ultimate tensile strength as a function of the temperature–strain-rate parameter.

Bennett and Sinclair[6] showed that the low-temperature yielding behaviour of body-centred cubic metals can be described by the following equation:

$$\dot{\epsilon} = A\dot{\epsilon}^{-H(\sigma)/RT}, \quad\quad (1)$$

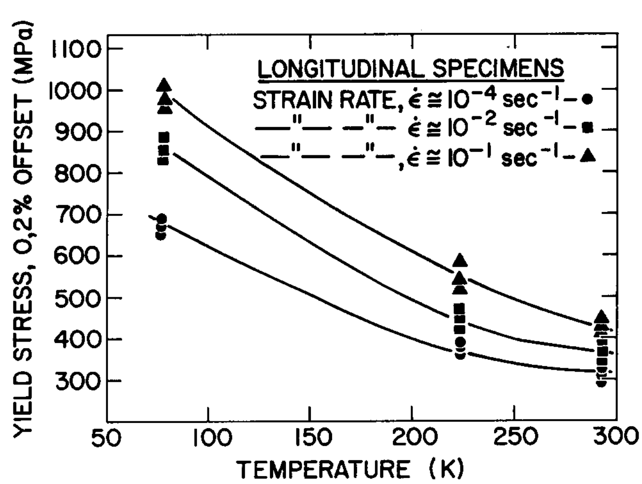

Fig. 1—Dependence of the yield stress (0,2 per cent offset) on temperature at different strain rates. Longitudinal specimens

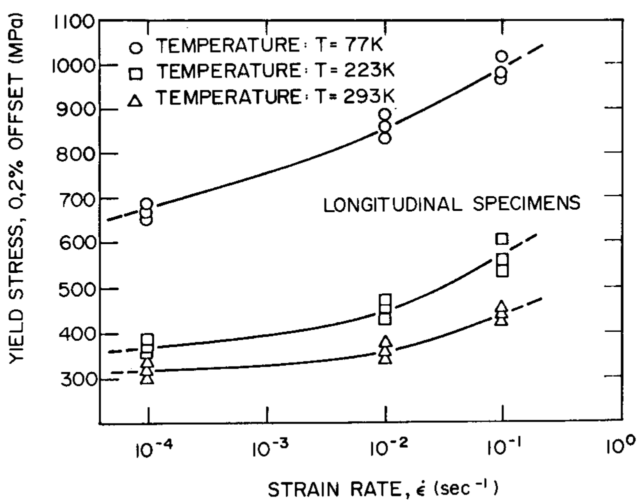

Fig. 2—Dependence of the yield stress (0,2 per cent offset) on strain rate at different testing temperatures. Longitudinal specimens

where $\dot{\epsilon}$ = strain rate,
A = frequency factor,
$H(\sigma)$ = stress-modified activation energy which can be linearly related to the yield stress[9],
R = gas constant, and
T = temperature.

The frequency factor A, which has a value of about $10^8\ s^{-1}$, was found to be independent of the stress. Bennett and Sinclair[6] showed that changes in the yield stress can be usefully presented as a function of the so-called 'temperature–strain-rate parameter', $RT\ln(A/\dot{\epsilon})$, which is a representation of the apparent activation energy of yielding. In their experiments, strain rates were changed over five orders of magnitude while the temperature range was between 100 and 500 K.

Equation (1) can be rearranged as follows:

$$\sigma_y = QRT_o\left(\frac{T}{T_o}\ln\frac{A}{\dot{\epsilon}}\right)^{-m}, \quad\quad (2)$$

where $(T/T_o)\ln(A/\dot{\epsilon})$ is a dimensionless temperature–

strain-rate parameter, T_0 is a constant temperature (assumed to be 1800 K, which is approximately the liquidus temperature), and Q and m are constants. A least-squares fit of the experimental results was used to determine the numerical values of the constants Q and m, which were found to be as follows:

$$Q = 0{,}952\,\text{MPa mol J}^{-1}$$
$$m = 0{,}619.$$

Consequently, the constitutive equation becomes

$$\sigma_y = 780\left(\frac{T}{1800}\ln\frac{10^8}{\dot{\epsilon}}\right)^{-0{,}619}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

Fig. 3 presents the experimental data in terms of this function. A small scatter can be observed from the plot, but it is clear that this functional correlation can be used to establish values of the yield stress for different combinations of temperature between 77 and 500 K and strain rate between 10^{-4} and $10^2\,s^{-1}$. The relationship in equation (3) is valid for 3CR12 steel in the as-received condition. For material in other heat-treated conditions, a similar correlation function will probably be found, but with different values of the constants Q and m.

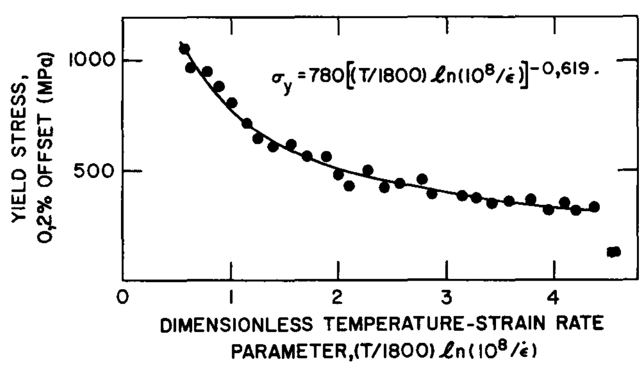

Fig. 3—Yield stress (0,2 per cent offset) versus the dimensionless temperature–strain-rate parameter

Evaluation of the Conventional Impact Properties

Impact tests are generally used to obtain the relationship between absorbed fracture energy and temperature. These curves for many steels show a relatively sharp transition between ductile and brittle behaviour.

The information supplied by these tests is useful for design purposes—albeit only on a qualitative basis—since measured values of absorbed impact energy cannot be related to any of the design parameters, with the exception of some empirical relationships for specific materials. However, it must be realized that there are a number of difficulties inherent in the impact test procedure, some of which are associated with the dimensions of the test pieces. The standard impact specimen has limited thickness, and hence does not fully represent material used in a structure with a substantially greater thickness. The standard specimens will always be subjected to less constraint than a large structure built of the same material.

Another factor that influences the results of an impact test is the geometry of the notch in the specimen. This is a rather complicated relationship because it combines the constraint problem with the strain rate at the tip of the crack. The sharper the notch, the higher the strain rate that can be expected at the tip of the notch. When a material is strain-rate sensitive, the combined effects of thickness and strain rate can drastically influence the shape of the curve of energy absorption versus temperature.

Figs. 4 and 5 show the experimental results for longitudinal and transverse specimens of 3CR12 steel in three conventional impact tests, namely DVM, ISO-V (Charpy), and Schnadt, as well as the results obtained with pre-cracked Charpy specimens. The introduction of fatigue pre-cracked specimens was judged to be necessary because all the abovementioned conventional methods use specimens with relatively blunt notches. These conventional methods, therefore, do not give a definite view of the brittle fracture behaviour to be expected in a material containing a sharp flaw.

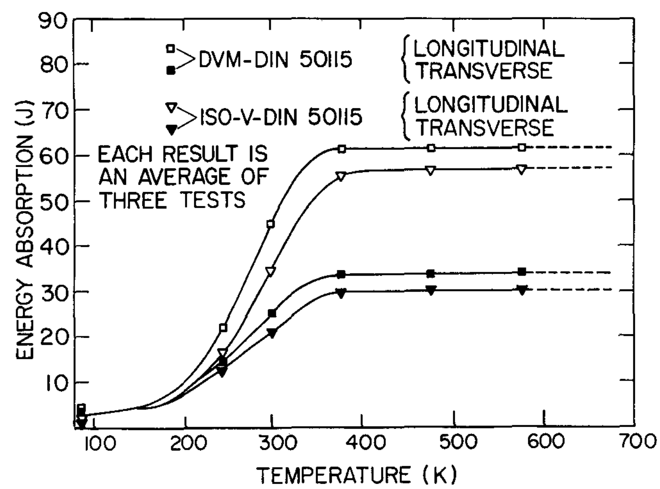

Fig. 4—Absorbed energy versus temperature for DVM and ISO-V specimens tested in the longitudinal and transverse directions

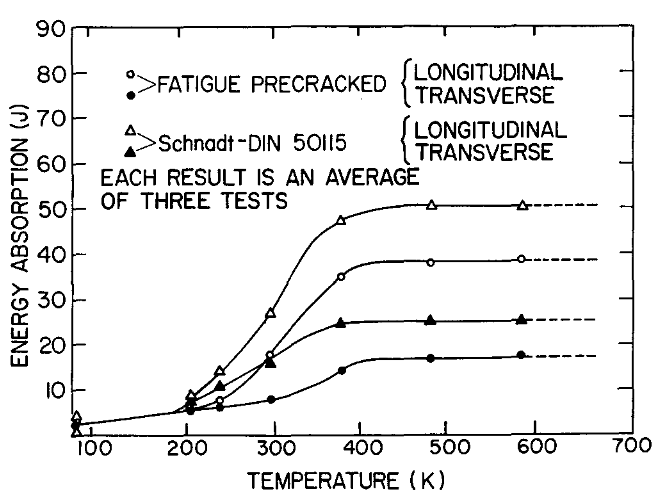

Fig. 5—Absorbed energy versus temperature for Schnadt and fatigue pre-cracked Charpy specimens tested in the longitudinal and transverse directions

Strain Rates at the Tip of Different Notch Geometries

When a notched bar is bent by a dynamically applied load, the material is deformed at the tip of the notch at

TABLE II

EFFECT OF THE NOTCH GEOMETRY ON THE ELASTIC STRAIN RATE DURING IMPACT TESTING

Temperature K	Strain rate, s^{-1}						
	Calculated value			Experimental value*			
	Irwin[10]	Shoemaker and Rolfe[11]	Rosenfield and Hahn[12]	DVM	ISO-V	Schnadt	Pre-cracked Charpy
	$\dot{\epsilon} = \frac{2\sigma_y}{EK}\dot{K}$	$\dot{\epsilon} = \frac{2\sigma_y}{Et}$	$\dot{\epsilon} = \frac{10\sigma_y}{EK}\dot{K}$				
213	$0{,}45 \times 10^2$	$0{,}80 \times 10^2$	$2{,}3 \times 10^2$				
300	$0{,}34 \times 10^2$	$0{,}65 \times 10^2$	$1{,}8 \times 10^2$	$0{,}93 \times 10^2$	$1{,}13 \times 10^2$	$1{,}3 \times 10^2$	$2{,}9 \times 10^2$
373	$0{,}27 \times 10^2$	$0{,}45 \times 10^2$	$1{,}5 \times 10^2$				

* Average of three measurements

strain rates that depend on the geometry of the notch. There is no analytical method for the calculation of these strain rates, even if purely elastic behaviour is assumed. The problem is still more complicated when a plastic zone develops ahead of the tip of the notch. Some approximate solutions are given by Irwin[10], Shoemaker and Rolfe[11], Rosenfield and Hahn[12] (Table II), as well as by Eftis and Krafft[13]. All of these solutions are similar, and are basically functions of the stress-intensity factor, K, the stress-rate intensity factor, $\dot{K}$, Young's modulus, E, and the yield stress, σ_y.

The strain rates at the tip of the pre-cracked Charpy specimens were evaluated by means of the solution given by Irwin[10], which can be written as follows:

$$\dot{\epsilon} = \frac{2\sigma_y}{Et} = \frac{2\dot{K}}{EK}\sigma_y. \quad (4)$$

Substitution of equation (4) into equation (2), which shows the dependence of the yield stress σ_y on strain rate $\dot{\epsilon}$ and temperature T, yields

$$\dot{\epsilon} = B(\ln A/\dot{\epsilon})^{-m}, \quad (5)$$

where $B = (2Q\,RT_o\,\dot{K}/EK)\,(T/T_o)^{-m}$.

From equation (4) it can be seen that, at constant temperature, the strain rate $\dot{\epsilon}$ depends either on the time t, or on $\dot{K}/K$. The interchangeable relationship between t and $\dot{K}/K$ is true on the assumption that the time of load application at the crack tip is the same as that of load application to the specimen. For a given strain-rate-sensitive material, it can be expected that changes in the notch geometry will lead to differences in the load application time, t, at the elasto-plastic boundary near the crack tip. However, it is reasonable to assume that, for small changes in notch geometries, the differences in load-application time will be rather insignificant. The value of the stress-rate-intensity factor, $\dot{K}$, was taken from the literature[14] as being approximately 3×10^5 MPa $\sqrt{m}\,s^{-1}$ for a striking velocity of about 5 m s^{-1}. The critical stress-intensity factors were taken from unpublished experimental results.

For the experimental determination of strain rates at the crack tip, impact specimens with different notch geometries (DVM, ISO-V, Schnadt, and fatigue pre-cracked Charpy specimens) were instrumented with strain gauges, and then tested on the instrumented impact tester. The strain rates were then derived from the traces of strain versus time recorded on a storage oscilloscope.

It must be pointed out that the measurements of the strain rates were made on the surfaces of the specimens, and therefore they are only partly representative of the internal strain rates, because of the different states of stress and strain. On the surface the prevailing conditions can be assumed to be plane stress, while inside the specimen plane strain conditions are likely to predominate.

Table II shows calculated strain rates at the elasto-plastic boundary after Irwin[10], Shoemaker and Rolfe[11], and Rosenfield and Hahn[12]. The results of the room-temperature tests in the present investigation are also included in this table.

Table II shows that the highest strain rates were obtained in the pre-cracked Charpy specimens, and the lowest in the DVM specimens. However, the difference between the strain rates in the DVM, ISO-V, and Schnadt specimens was fairly small. It can also be seen from Table II that the results predicted by Rosenfield and Hahn[12] were found to be closest to the results of the present investigation.

Discussion

The mechanical behaviour of the as-received 3CR12 steel is similar in many respects to the behaviour of high-strength steels in the dual-phase condition.

The yield stress shows a definite dependence on temperature and strain rate, and no substantial difference was found between the behaviour of the longitudinal and the transverse specimens. The sensitivity of the yield stress to the strain rate is temperature-dependent, being lower at higher temperatures. It was shown that the yield stress can be presented as a function of the temperature–strain-rate parameter. The scatter of the experimental results owing to the calculation function was found to be minimal.

The results of impact tests show substantial differences in the energy absorption by the transverse and longitudinal specimens above the ductile–brittle transition temperature. The impact strength of longitudinal specimens is approximately 40 per cent higher than that of transverse specimens. There is a marked change in energy absorption with temperature. The transition in the energy absorption is gradual for both types of specimens (longitudinal and transverse), and occurs in the same range of temperatures (173 to 337 K). The degree of energy decrease was found to be different for both types of specimens, and could not be fully related to the changes in the mechanism of fracture as revealed by fractographic studies.

The strain rates at the notch tips calculated by the application of approximate solutions taken from the literature were compared with the experimental results obtained at room temperature on impact specimens having four different notch geometries. The highest strain rates at the initial stage of the fracture process were found in the fatigue pre-cracked specimens, and these were closest to the semi-analytical solution given by Rosenfield and Hahn[12]. It must be pointed out that the measurements of strain rates were made on the surface of the specimen, and they may therefore only partly represent the strain rates inside the specimen owing to the different states of stress and strain. On the surface the prevailing conditions can be assumed to be those of plane stress, while inside the specimen plane strain conditions are likely to predominate.

Acknowledgement

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Health and safety

An international conference on health and safety in the minerals industry will be held in Perth, Western Australia, from 10th to 14th September, 1990. The theme is 'Future Perspectives in the Minerals Industry'.

The Conference is being organized by The Chamber of Mines and Energy of Western Australia Inc. and is co-sponsored by The Australian Mining Industry Council, The National Occupational Health and Safety Commission, and the Department of Mines of Western Australia. The American Conference of Governmental Industrial Hygienists (Inc.) is providing supporting sponsorship in North America.

The Conference programme will address major health and safety concerns of the minerals industry with technical sessions focussing on the following key issues:

- Atmospheric Contaminants
- Low-level Radiation
- Management of Hazardous Chemicals
- Fires and Explosions
- Safety management in the Minerals Industry
- International Standard Setting.

The Organizing Committee have invited keynote speakers of both national and international standing to address the Conference with a view to clarifying issues of major concern, and to provide direction for future health and safety initiatives in the mining environment.

Further information is available from the
Conference Secretary
Minesafe International 1990
The Chamber of Mines of Western Australia Inc.
7th Floor
12 St George's Terrace
Perth 6000
Western Australia.
Tel: (09) 325 2955. Fax: (09) 325 4562.
Telex: AA92792.

Symposium: Uranium Institute

The Uranium Institute's Fifteenth Annual Symposium will be held in London from 5th to 7th September, 1990.

Today's energy scene is characterized by contradictory signals, in part because of widely divergent assessments of some key variables. The first session will focus on future electricity demand, the likely impact of energy-efficiency measures and—the most important of all future influences—electricity demand can supply in developing countries.

Against this background, the Symposium will then look at nuclear programmes. Operating nuclear capacity continues to expand but, while some countries discuss new plants, others are still cutting back on earlier plans. What is the outlook for nuclear capacity? This question will be examined both in relation to national nuclear programmes and generic influences such as reactor lifetime.

Uranium appears to be abundant—a benefit in terms of potential energy supply—but the immediate reality in the market is oversupply. This is reflected in prices and exploration activity at historically low levels. What are the trends and uncertainties? One supply question will be a session subject in its own right—the recycling of nuclear fuel.

Nuclear-electricity costs have been much debated in recent years. A session will be devoted to this important topic, looking at national case studies and, more specifically, at the influence of environmental protection costs on both nuclear and non-nuclear electricity.

Nuclear environmental costs include satisfactory waste management. The nuclear industry must not only have the technical solutions, but must also ensure the political will to implement them. Progress in waste-management programmes will be reviewed, as will the cost implications.

The energy future is increasingly dominated by our understanding of its environmental implications. Central to this debate is the possibility of global warming and the institutional arrangements which may be put in place to deal with it. The session will examine developments and their likely implications.

For nuclear energy, public confidence remains the key to its future. The final session will review trends in public opinion and the main influences forming it in different countries.

The following preliminary programme has been drawn up:

The energy background
- energy versus electricity demand
- electricity demand and supply in the developing countries
- conservation and energy efficiency

Nuclear electricity programmes
- the outlook for national nuclear electricity programmes
- reactor life extension and its cost implications

Uranium supply
- supply poential from the established supplier countries
- new entrants to the market
- uranium exploration activity
- the role of inventories
- the possibility of civil fuel from military material

Recycling nuclear fuel
- practical and economic aspects of using recovered uranium
- the use of plutonium in thermal reactors
- reprocessing, enrichment and fabrication capacity for recycling

Nuclear electricity costs
- national case studies
- the environmental protection component of nuclear costs
- establishing cost comparability with other electricity sources

Radioactive waste management
- national waste-management programmes
- decomissioning experience and planning
- costs of waste management and decommissioning

The environmental imperative for energy supply
- the challenge of assessing global warming
- emerging international institutional arrangements
- the potential for reducing greenhouse gas emissions
- nuclear energy and the environment

Public attitudes to nuclear energy
- opinion research and trends
- the main influences on public opinion
- public attitudes to different energy options.

Further details are available from

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