The opportunity to establish a titanium metal industry in South Africa is elucidated through South Africa’s position as major raw material producer and by illustration of the multitude of applications of titanium arising from its unique physical and chemical properties. Key challenges to realise the opportunity of a local titanium metal industry are explained and a high level analyses of South Africa’s competitive position in this field is presented. Technological imperatives that have to be satisfied are identified and explained.

The challenge to realize the opportunity is not trivial. However the government through the Department of Science and Technology has accepted the challenge. Ultimately, government together with the business community will have to collaborate to turn the opportunity into a practical reality.
Titanium applications and markets

Comprehensive overviews of the titanium market are available\textsuperscript{7,10,11} and annually good updates are given at the conference of the International Titanium Association\textsuperscript{12}. It is not the intention of this paper to summarize all these market studies, but rather to show how the various properties and combinations of properties of titanium are leading to ever increasing new applications for the metal.

Aerospace applications

The main driver for the use of titanium in the aerospace industry is the ever increasing demand for higher fuel efficiency. In order to achieve higher fuel efficiencies, lighter and stronger materials are required for reducing the weight of aircraft. The high strength-to-weight ratio of titanium renders it suitable for many structural applications.

In aircraft engines, the high-temperature strength of titanium is an additional property that makes it the preferred material for many turbine components.

Another property of titanium that is important is its compatibility with carbon fibre-reinforced composites. Composites are being used increasingly because of their high strength-to-weight ratio and it has been found that aluminium is not sufficiently resistant to the corrosion caused by the electrochemical potential difference between carbon and aluminium, whereas titanium is.

As a result of these factors the percentage of titanium relative to the total mass of materials used in aircraft is steadily increasing in new models. It is therefore both the increase in demand for new aircraft, as well as the increasing use of titanium in new aircraft that are causing a large increase in the demand by the aerospace industry for titanium.

Armour industry

The demands in the armour industry that create applications for titanium are manoeuvrability, bullet-proofing and the high-temperature strength of gun barrels.

Decreasing the weight of armoured vehicles and canons significantly increases their manoeuvrability and hence the survival of such weapons. In spite of its high cost, titanium is therefore being used in a number of new weapons, both for armour-plating and for gun barrels.

Table I
Titanium reserves, production and value

<table>
<thead>
<tr>
<th></th>
<th>South Africa</th>
<th>World</th>
<th>Approximate value*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>South Africa</td>
</tr>
<tr>
<td>Reserve base</td>
<td>244 Mt TiO(_2)</td>
<td>(\text{\textsuperscript{6}}\ \text{1} 500) Mt TiO(_2)</td>
<td></td>
</tr>
<tr>
<td>Annual production (2008^*)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sponge</td>
<td>0</td>
<td>180 kt Ti</td>
<td>M$ 480 p.a.</td>
</tr>
<tr>
<td>Ingot</td>
<td>0</td>
<td>7 179 kt Ti</td>
<td>M$ 4 500 p.a.</td>
</tr>
<tr>
<td>Mill products</td>
<td></td>
<td>7 113 kt Ti</td>
<td>M$ 7 000 p.a.</td>
</tr>
</tbody>
</table>

Table II
Typical properties of metal alloys

<table>
<thead>
<tr>
<th></th>
<th>Titanium and/or alloys</th>
<th>Aluminium and/or alloys</th>
<th>Iron and/or alloys</th>
<th>Nickel and/or alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>600–1300</td>
<td>200–500</td>
<td>500–1300</td>
<td>600–1 400</td>
</tr>
<tr>
<td>25°C</td>
<td>300–750</td>
<td>n.a.</td>
<td>300–600</td>
<td>250–1 000</td>
</tr>
<tr>
<td>600°C</td>
<td>4 420–4 860</td>
<td>2 650–2 800</td>
<td>7 400–8 200</td>
<td>7 900–9 800</td>
</tr>
<tr>
<td>Density (kg/m(^3))</td>
<td>1</td>
<td>0.85</td>
<td>0.65</td>
<td>0.6</td>
</tr>
<tr>
<td>Normalized strength-to-weight ratio</td>
<td>115</td>
<td>72</td>
<td>215</td>
<td>200</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>1 668</td>
<td>660</td>
<td>1 538</td>
<td>1 455</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>6.7–9.8</td>
<td>18–24</td>
<td>10–14.7</td>
<td>7.6–14.4</td>
</tr>
<tr>
<td>Relative corrosion resistance</td>
<td>Excellent; fosters oseointegration</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>C-fibre compatibility</td>
<td>Good</td>
<td>Galvanic corrosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-compatibility</td>
<td>Excellent; fosters oseointegration</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Thermal expansion coefficient (10(^{-6})/K)</td>
<td>4.8–9.0</td>
<td>30–50</td>
<td>9.1–75</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>Stable and variable by anodizing</td>
<td>Stable and variable by anodizing</td>
<td>Stable and variable by anodizing</td>
<td>Stable and variable by anodizing</td>
</tr>
</tbody>
</table>
Naval applications
Titanium’s corrosion resistance to seawater, and the advantage of a lowering of the centre of gravity as a result of the metal’s low density, are leading to applications for titanium in bridge structures and heat-exchange equipment. Again, high-temperature strength is important for gun barrel applications.

Off-shore oil industry
In the off-shore oil industry, corrosion resistance to seawater is of primary importance. The cost of an oil spillage and the cost of underwater repairs in deep oceans could far exceed the cost of using titanium and hence titanium is a natural choice.

Furthermore, the cost of laying underwater oil pipelines is strongly affected by the weight of the material that has to be shipped and handled. The high strength-to-weight ratio of titanium results in less material being required and this is an additional cost factor that strengthens the economic argument for choosing titanium.

In the drilling operation itself, the mass of the drill shafts that have to be handled is also a critical factor that makes titanium a preferred choice of material.

It is expected that as cheap land-based oilfields become depleted, offshore oil-recovery operations will increase and these will move into increasingly more difficult conditions, such as deeper seabeds and increasing remoteness, which will lead to a steady and increasing demand for titanium-based components and structures.

Water desalination and the chemical industry
Seawater desalination is a steadily growing market to satisfy the fresh water needs of the increasing populations of arid countries along various coastlines. The excellent corrosion resistance of titanium and its good heat-transfer properties makes it the preferred material of construction for desalination plants.

In the chemical industry corrosion is one of the largest causes of premature equipment failure and contributors to maintenance cost. It is primarily the corrosion resistance of titanium that makes it a preferred material of construction in many applications, e.g., in the chlor-alkali industry. Its good heat-transfer properties and high strength are secondary benefits.

Power-generation industry
Energy efficiency and environmental concerns are key driving forces in the electric power-generation industry. Titanium’s excellent resistance to acid corrosion makes it a suitable material for heat recovery below the acid dew-point of flue gas from coal- and oil-fired burners, which in turn leads to an increase in efficiency and hence also lower carbon emissions; all of these factors favour the selection of titanium for heat exchangers in this application.

Automotive industry
The key factors that drive the selection of materials in the automotive industry are cost and fuel efficiency. In spite of its high cost, titanium’s particular combination of favourable properties is creating applications in this industry.

In particular, its high strength-to-weight ratio and its elasticity make it particularly suitable for coiled springs; its corrosion resistance against salt water makes it a strong contender for exhaust systems in colder climates where salt is sprayed on roads at times in winter to lower the freezing point of water on the roads; and its high strength-to-weight ratio and high-temperature strength make it suitable for engine components such as engine valves and conrods.

Architecture
In the building industry it is specifically the aesthetic appeal of titanium and its corrosion resistance that make it a fashionable material for cladding, and for visible structures and support frames.

Sport and leisure
Both performance and fashion are factors that affect consumer preferences in this market. In this regard titanium’s high strength-to-weight ratio and its elasticity improves the performance of sports equipment, whereas its aesthetic appeal and its corrosion resistance make it a fashionable and practical choice.

Medical applications
The key requirements for any material used for implants are bio-compatibility, strength and corrosion resistance. Titanium’s outstanding properties in this regard make it the ideal choice for many types of implants used in orthopaedic and dental applications.

A new South African industry
Figure 1 gives a simplified structure of the titanium metal industry. Some large integrated companies cover several segments of the industry, but there are many companies that provide specialized services in only one niche in a particular segment. By establishing a local titanium industry, enterprise development across all the segments of the industry is expected with time.

The national benefits that would arise from a world-scale (20 000 tpa), low-cost (about US$20/kg milled products at 50 per cent of the current price) titanium metal plant are plentiful, with the most important being:

• Revenue of about US$400 million per annum from the milled product plant alone can be expected. Revenue could increase to almost US$1000 million per annum once a downstream industry for the production of semi-finished products has been fully developed.

• Establishing an industry will lead to many downstream manufacturing enterprises that would not be possible without such a local industry.

• There is potential for the creation of about 1 500 permanent jobs once the downstream industry has been developed to a point where semi-finished products are produced. This number could increase with more final products.

• These industries would potentially create opportunities for the establishment of small and medium enterprises and complement Black Economic Empowerment.

• Support industries could be developed.

• A large part of South Africa’s annual importation of about 800 tons of titanium in various forms (sponge, scrap, ferrotitanium, etc.) can be replaced, saving about US$5 million per annum of foreign exchange.
result of its high price (long-term average of about US$ 10/kg for sponge and US$ 20/kg for ingot). The high price of titanium metal is not a result of its scarcity, but is direct consequence of the antiquated technology used to extract the metal from its raw materials.

Therefore, to unlock the market for titanium metal it is necessary to develop new technology that will drastically reduce the production cost of the metal. In this regard it has been estimated^4 that the price–demand relationship for titanium follows a ‘1-10-100 rule’, which indicates that a US$1/pound reduction in sponge cost, combined with a 10 per cent reduction in mill production cost (value added in melting and primary fabrication) should lead to a 100 per cent increase in the demand for titanium in non-aerospace applications.

The basic raw material for the metal industry is titanium dioxide (TiO₂), which is supplied as rutile, synthetic rutile, or high-grade titanium slag. Because the titanium metal industry takes only about 5 per cent of world production of TiO₂ feedstock (the rest is used in the TiO₂ pigment industry), the current metal industry is of little consequence to the raw material producers. The cost of feedstock (mineral concentrate) is also only a small fraction of the costs of titanium at various stages of beneficiation, i.e., about US$1.2/kg of Ti vs. titanium sponge at about US$10/kg, ingot at US$20/kg and titanium mill product at about US$40/kg. Although the feedstock for titanium production is essential, the titanium metal industry has virtually no impact on the feedstock producers and the feedstock producers also have very little influence on the titanium metal industry.

The next step in the value chain is the production of titanium tetrachloride, which is metallothermically reduced to titanium sponge with either magnesium or sodium. Conceptually, the production of titanium sponge would be synergistic with a pigment plant producing TiO₂ pigment via TiCl₄, or a plant producing magnesium metal as the primary product. However, it seems that such synergy is not realized by most of the existing sponge producers and that virtually all of them produce TiCl₄ and magnesium exclusively to manufacture titanium sponge.

In South Africa it would at present also be impossible to realize any such synergy because there are no TiCl₄ or magnesium production plants in this country. If the dti’s envisaged pigment venture is implemented, synergy with pigment production could later be possible in South Africa, however.

**The titanium race**

The economic potential and strategic value of titanium are widely recognized. Numerous projects have therefore been undertaken at various times over the last 60 odd years to develop new processes to lower the cost of producing titanium. During the last five years several renewed attempts have been launched^3. The object of this paper is not to review the approaches, but rather to give the reader a quick reference to the current attempts that, in the author’s opinion, are the most serious or important. These are:

- **Japan**
  - Ono-Suzuki processes
  - The JTS process
- **UK**
  - The FFC process
- **USA**
  - The Armstrong process
  - The ADMA process
- **Australia**
  - The TiRO process
- **South Africa**
  - The Peruke process
  - CSIR process

**Ono-Suzuki processes**

Suzuki and Ono^15 have developed a number of new concepts to produce titanium powder from TiO₂ via electrolysis or calciothermic-assisted electrowinning. The work undertaken by them provides a sound basis for understanding the thermodynamic fundamentals underlying the recovery of titanium from titanium dioxide.

From the recent literature it is not clear whether their process concepts are being scaled up.
The JTS process
A consortium of titanium companies\textsuperscript{16} is developing the JTS process through the Japanese Titanium Society. The process entails the reduction of TiCl\textsubscript{4} with calcium, which is dissolved in molten CaCl\textsubscript{2} and is subsequently regenerated electrochemically. The CaCl\textsubscript{2} is separated from the titanium in a transport-type reactor coupled to a plasma-melting furnace to produce molten titanium on which CaCl\textsubscript{2} floats and from which it is thus separated.

This project is of industrial interest because of the participation of the major Japanese titanium companies.

The FFC process
The Fray, Farthing and Chen process\textsuperscript{17} was invented in 1996 at the University of Cambridge, UK. It entails the electrolytic deoxidation of cathodes made of titanium dioxide, in a bath of molten CaCl\textsubscript{2}. The process produces titanium in the form of loosely sintered powder.

The process is currently being developed further by the Metalysis company, which has also acquired rights to the Polar process from BHP Billiton. (The Polar process is related to the FFC process.)

The Armstrong process
International Titanium Powder (ITP) is developing the Armstrong process\textsuperscript{18}, which entails the reduction of TiCl\textsubscript{4} with sodium in a stream of excess molten sodium. The titanium product is in the form of a fine powder.

Of all the attempts to lower the cost of titanium by producing titanium powder in a continuous manner, the scaling up and development of this process is probably the most advanced.

Crystal Corporation recently purchased Millennium Chemicals, which has a major share in ITP.

The ADMA process
The ADMA Corporation\textsuperscript{19,20}, together with Boeing and the U.S. Army, recently presented very interesting results on the downstream processing of titanium hydride powder produced by their process. Their process is a modification of the Kroll process, allowing the hydriding of titanium sponge prior to removing it from a standard Kroll reactor.

The ADMA Corporation seems to be the furthest advanced in proving the acceptability of their product in downstream powder metallurgy processing.

The TiRO process
The TiRO process of the CSIRO of Australia entails continuous reduction of TiCl\textsubscript{4} with magnesium in a fluidized bed to produce titanium powder\textsuperscript{21}. The process has been demonstrated on a small pilot-plant scale.

It is believed that an industrial partner has taken an interest in the project.

The Peruke process
Anglo American Corporation is developing the Peruke process\textsuperscript{22}. The process entails the production of a fluotitanate salt and the subsequent reduction of the salt with aluminium to produce titanium powder. The process is currently being studied on a small pilot-plant scale to determine the relevant data for further scaling up of the process.

The CSIR process
The CSIR, sponsored by the Department of Science and Technology (DST), has been investigating various options for producing titanium. It has been concluded that the most promising route is continuous metallothermic reduction of TiCl\textsubscript{4} in a molten salt medium to produce titanium powder. Continuous operation of the key process steps is currently being demonstrated on a small scale.

South Africa’s competitive/comparative position

Strengths
- Consistent low-cost energy supply to energy-intensive users—even though South Africa’s electricity prices are expected to increase at rates higher than the inflation rate as new capacity is installed, it is expected that the electricity cost will remain lower than elsewhere
- Potential technologies to reduce metal production cost significantly—in this regard the technology that is being developed by Peruke (Anglo American) and the concepts developed by the CSIR might provide competitive advantages
- Extensive proven raw titanium resources
- World-class research centres (CSIR, Mintek and NECSA in particular) to collaborate in further research and development
- Political and economic stability with low sovereign risk
- A highly educated and skilled workforce—although the pool of expertise in South Africa is small, South African scientists and engineers are as good as, if not better than, anywhere else in the world
- South Africa has a track record in aerospace manufacturing, which provides a basis for producing and selling components or articles made from titanium

Weaknesses
A number of factors are preventing South Africa from realizing the potential of a titanium metal industry:
- An upfront industry to make high-purity Ti precursor feedstock is required but, apart from Huntsman Tioxide, which produces TiO\textsubscript{2} pigment via the sulphate route, no TiCl\textsubscript{4} production capacity exists in South Africa.
- There is no magnesium production plant in South Africa, making the establishment of a large Kroll plant that uses magnesium as a reductant dubious
- No primary titanium production capacity exists in South Africa, which makes the establishment of an export-orientated downstream fabrication industry uneconomical
• There are only a very small number of local people with some experience in titanium production and in downstream fabrication technologies and markets
• Most of the large titanium-consuming companies, e.g. in the aerospace industry, have long-term supply contracts with primary metal producers. South Africa has no such market or client relationships in the field of titanium metal
• For chloride-based routes, the cost of chlorine in South Africa is internationally non-competitive due to market and geographical reasons
• Distance to markets and scrap for the recycling industry may be a factor
• There is virtually no local downstream Ti industry and market (about 800 tpa), with the result that any large local titanium producer would have to export the bulk of its product from the beginning of commercial production
• Management and labour costs are significantly higher than in China and India in particular.

Technological imperatives for a creating a local industry
• Cost reductions along the whole titanium value chain
  – Competitve primary metal technology: it is unlikely that South Africa would be able to break into the titanium market without a new competitive primary metal technology.
  – Powder metallurgy: the production of final titanium components using titanium powder seems the most promising way to reduce downstream manufacturing costs.
• Titanium industry mass balance and distance from markets
  – Near net shape fabrication technologies—South Africa’s geographic position makes it uneconomical to transport metal to South Africa for fabrication and then to export manufactured products and a large volume of scrap. Local fabrication would have to produce minimal amounts of scrap.
• Reducing agent
  – High recovery efficiency, especially if magnesium is used as reducing agent
• Chlor-alkali industry balance
  – If TiCl₄ is used as precursor to produce titanium, the net chlorine consumption must be minimal in order not to upset the local balance in the chlor-alkali industry.
• Environmental
  – Minimal chemical waste—most of the waste generated in the production of titanium is in the form of metal chloride salts. Disposal or containment of these salts is expensive and hence the waste must be minimized.
  – Global warming concerns—carbon footprint and energy efficiency. All the routes to produce titanium are energy intensive and hence result in relatively large emissions of carbon dioxide. With the growing concerns about global warming, significant attention would have to be given to minimising the energy consumption.

Conclusions
Establishing a titanium industry in South Africa is a real opportunity with many potential benefits, especially wealth and job creation. However, the technical and commercial challenges to do so are not trivial.

Government has taken active steps towards realising this opportunity and it is now up to the science and engineering community to make the necessary technological breakthroughs. Ultimately, government together with the business community will have to collaborate to turn the opportunity into a practical reality.

References
7. TZ MINERALS INTERNATIONAL and EHK TECHNOLOGIES. Ti-metal: The global titanium metal industry. 2007.
D.S. van Vuuren  
Research Group Leader, CSIR

Thirty years experience in process development and design in a variety of fields and technologies including: titanium mineral beneficiation, titanium metal extraction, pre-reduction of minerals, fluidized bed combustion, roasting and/or calcination of minerals, chlorination of titanium bearing minerals, phosphoric acid purification, acid leaching of minerals, effluent treatment, solvent extraction, Fischer-Tropsch synthesis and related petrochemical technology, briquetting technology, electrolytic processes and hydrogen storage.