# research and development in titanium

## implications for a titanium metal industry in australia

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# foreword

Australia has substantial rutile and ilmenite resources, with a world ranking of 1 and 2, respectively, and accounts for around 86 per cent of world synthetic rutile production. Australia's exports of rutile, ilmenite and synthetic rutile were valued at around $0.7 billion in 2006-07. Rutile and synthetic rutile are used in the production of titanium tetrachloride ($TiCl_4$), a key input in the titanium metal industry.

The main objective in this study is to examine the role of government in supporting the TiRO/CSIRO R&D project and the potential development of a titanium metal industry in Australia. In recent years, CSIRO has developed the TiRO process to produce titanium powder. The next stage in the TiRO/CSIRO R&D project is to invest in a pilot plant, likely to be located in Western Australia in close proximity to major resource deposits and related processing facilities.

In general, policy intervention to encourage technology research, development and demonstration can be justified on economic efficiency grounds. Should the government decide to invest in the TiRO pilot plant project, this is likely to enhance prospects for the development of a titanium metal industry in Australia.

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Phillip Glyde
*Executive Director*
March 2008

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# summary


- Australia is a leading producer of ilmenite (20 per cent of world production in 2006), rutile (44 per cent) and synthetic rutile (86 per cent). Australia's exports of these commodities were valued at $0.7 billion in 2006-07. Rutile and synthetic rutile are used to produce titanium tetrachloride ($TiCl_4$), a key input in the titanium metal industry.
- The objective in this study is to examine the role of government in supporting a titanium metal research and development (R&D)project and the potential development of a titanium metal industry in Australia. Under the 'light metals flagship', the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has developed a process, called TiRO, to produce titanium powder. The next stage in the project is a pilot plant to test and debug the TiRO process. The plant is likely to be located in Western Australia in close proximity to major resource deposits and related processing facilities.
- The approach taken in this study is to present information that will assist the Australian Government in its assessment of whether to support the TiRO/CSIRO R&D project to the pilot plant stage. An economic assessment of the pilot plant project cannot provide the Australian Government with an unambiguous policy recommendation because the final assessment of policy options relies to some extent on the subjective judgment of the government. Should the government decide to invest in the TiRO pilot plant project, this is likely to enhance prospects for the development of a titanium metal industry in Australia through the commercialisation of the TiRO process or, if this technology proves to be not viable, by importing a successful technology.

## technology and market developments

- Titanium metal production uses the Kroll process under which titanium sponge is produced as an intermediate product. Relatively high production and fabrication costs have limited the use of titanium metal to specialty applications where its physical properties, such as strength, appearance, weight and biocompatibility, justify its high cost relative to other metals. Twenty organisations, including CSIRO, are currently conducting R&D projects into continuous processes for the production of titanium metal.
- Since 2001, when the Australian Government previously examined the potential to establish an Australian titanium metal industry, there has been a significant turnaround in the world titanium market. Recent strong growth in world consumption of titanium mill products has been supplied by increased production and stock drawdown. World titanium sponge production increased at an average annual rate of 11.6 per cent between 2000 and 2006, and the industry's capacity utilisation rate has

increased from 60 per cent in 2000 to 95 per cent in 2006. Governments in both the United States and CIS countries have depleted government stockpiles of titanium sponge. Reflecting these market developments, the real US price of titanium sponge increased at an average rate of 12.5 per cent a year between 2000 and 2006.

- Major end use applications of titanium mill products include industry (49 per cent of world consumption in 2005), commercial aerospace (31 per cent), military (10 per cent, of which 7 per cent is military aerospace), consumer (8 per cent) and medical (2 per cent). The main consumers of titanium mill products are north America (30 per cent of world consumption in 2005), the European Union (24 per cent), China (15 per cent) and Japan (12 per cent).
- Six countries produce titanium sponge — Japan (30 per cent of world production in 2006), the Russian Federation (24 per cent), Kazakhstan (19 per cent), China (11 per cent), the United States (9 per cent) and the Ukraine (8 per cent).
- Over the period 2005–11, world consumption of titanium mill products is projected to increase strongly at an average annual rate of around 6.8 per cent. Significant investment in new productive capacity, required to satisfy increased titanium demand, will be based on the Kroll process. Major projected sources of growth in world titanium demand are industrial and aerospace applications. Strong growth is also projected for titanium consumption and production in China over the medium term.

## the technology innovation process

- Key stages in the technology innovation process include technology R&D, adoption and transfer. Private investors assess the profitability of potential investment projects throughout the technology innovation process taking into account the risks associated with the activity. Technical risk tends to be high at the R&D stage and diminishes as the new technology is demonstrated and commercialised. Unit production costs tend to be reduced through 'proving up' the technology, by the experience acquired in applying the technology (learning by doing benefits) and as the technology is used on a large scale (economies of scale).
- The economic rationale for consideration of government intervention in the technology innovation process is based on the presence of market failure, including positive externalities and risk. Positive externalities occur in the technology innovation process since the investment undertaken by one firm tends to provide unpriced benefits to other firms. Technology push policy options encourage R&D activity by providing greater economic incentives for private investment in R&D by reducing the costs and/or risks of the activity (including, for example, patents and tax incentives) and through direct support for public investment in R&D (including publicly funded R&D projects and public–private partnership arrangements).
- The development and deployment of technologies that reduce titanium metal production costs would enhance the cost competitiveness of

titanium in the world titanium market relative to substitutes such as steel and aluminium. Technology adoption is likely to lower industry costs, reduce the world price of titanium and increase titanium consumption in several end use applications including, most importantly, industrial, consumer and medical applications.

- In this report, three long run growth scenarios for world titanium consumption are presented to indicate the future possible impact of technology adoption. Between 2011 and 2025, world titanium consumption is projected to increase at an average annual rate of:
  - 4 per cent in the low growth scenario— no technology adoption
  - 7 per cent in the medium growth scenario — limited technology adoption
  - 10 per cent in the high growth scenario — moderate technology adoption. In this scenario, technology development and deployment has a greater impact on the long run growth path for world titanium consumption but the penetration of titanium into new end use applications is still assumed to be limited.

## tiro pilot plant project in australia

- In a recent assessment by ACIL Tasman, the pilot plant project to test and debug the TiRO process developed by CSIRO is valued at $126 million in present value terms. This valuation incorporates an 11 per cent probability that a commercial plant will be established with a profit of $1.3 billion in present value terms.
- In assessing the role of government, it is important to distinguish between the profitability assessment by a private investor and the expected net return to society. Positive externalities and risk cause a divergence between private and social net returns. The ACIL Tasman estimate indicates that the direct net economic benefits of the pilot plant project are expected to be positive. There are also likely to be significant indirect net economic benefits from the pilot plant project.
- Australia's participation in the TiRO pilot plant project increases the probability that the international research effort will be successful in discovering a major new technology that reduces production costs in the titanium metal industry. For example, an international research effort comprising twenty independent R&D projects, each with a probability of success of 10 per cent, has an overall 88 per cent probability of discovering a major new technology.
- If Australia is successful in commercialising the TiRO process, economic benefits may include: the development of a titanium metal industry in Australia, royalty payments from intellectual property rights, increased competition in the world titanium market and increased diversification in the geographic location of titanium production facilities.
- If the TiRO process is not successful at the pilot plant or demonstration plant stage, an alternative path to the development of an Australian titanium metal industry may be to import a successful technology.

# 1 introduction

Australia has substantial ilmenite and rutile resources, accounting for 21 per cent and 36 per cent, respectively, of world reserves in 2006 (USGS 2007; based on $TiO_2$ content). Ilmenite is used to produce synthetic rutile, and rutile and synthetic rutile are used to produce titanium tetrachloride ($TiCl_4$), which is a key input in the titanium metal industry. Australia is a leading producer of ilmenite (20 per cent of world production in 2006), rutile (44 per cent) and synthetic rutile (86 per cent) (TZMI 2007). In 2006-07, Australia's exports of rutile, ilmenite and synthetic rutile were valued at around $0.7 billion, representing less than 1 per cent of Australia's total mineral resources exports (ABARE 2008).

In 2001, the Australian Government examined the potential to establish an Australian titanium metal industry in a study undertaken by the Department of Industry, Science and Resources and subsequently through the Light Metals Action Agenda (DISR 2001a,b). The key finding from these assessments was that the development of a titanium metal industry in Australia based on the existing Kroll process was not a viable option. There were also concerns about limited future growth potential in the world titanium market.

Two major developments have occurred since 2001. Following the Light Metals Action Agenda process, CSIRO established the 'light metals flagship' and has since developed the TiRO process to produce titanium powder (CSIRO 2006). In addition, there has been strong growth in the world titanium market.

The objective in this study is to examine the role of government in supporting the TiRO/CSIRO R&D project and the potential development of a titanium metal industry in Australia. Investment in a pilot plant, likely to be located in Western Australia in close proximity to major resource deposits and related processing facilities, is the next stage in the further development of the TiRO/CSIRO technology.

The approach taken in this study is to present relevant background information on technology and market developments (chapters 2–4) and to undertake an economic assessment of the role of government and technological change in the titanium market (chapters 5, 6). It is beyond the scope of this study to examine the impact of any future possible greenhouse gas policy response on the world titanium market, although some brief comments on the general nature of these impacts are provided.

# 2 recent technology developments

Titanium has a range of physical properties, such as high strength to weight ratio and resistance to corrosion, that provide it with a quality advantage over substitute metals such as steel and aluminium. However, relatively high metal production and processing costs have limited its use to specialised applications such as aerospace, electricity generation and medical. The development of new technologies is likely to reduce production costs in the titanium industry and extend end use applications of titanium metal.

In this chapter, information is presented on the key stages in the titanium supply chain and current R&D projects that aim to develop lower cost production processes to enhance the cost competitiveness of titanium relative to substitute metals.

## titanium supply chain

The titanium supply chain (figure a) includes mining and basic processing, chemical processing and metal processing to obtain titanium metal products that are intermediate inputs in end use applications. More detailed information is provided in, for example, Roskill (2007).

### mineral sands mining and basic processing

Heavy mineral sands deposits are created on beaches over millions of years as waves and wind remove light quartz from the sand and leave behind the heavier minerals. A single mine site will often supply a mix of minerals such as rutile, ilmenite, leucoxene and zircon. The mining process is fairly simple — the sands are either strip mined or dredged and then transported to a mineral separation plant. The plants use physical methods, such as gravity separation spirals and magnets, to separate the different minerals.

The titanium dioxide ($TiO_2$) content of rutile and ilmenite is around 95 per cent and 60 per cent respectively (Lines 2007). Ilmenite must be upgraded to high $TiO_2$ content titanium slag or synthetic rutile before it can be chemically processed into titanium tetrachloride ($TiCl_4$), which is a key input in the titanium metal industry.

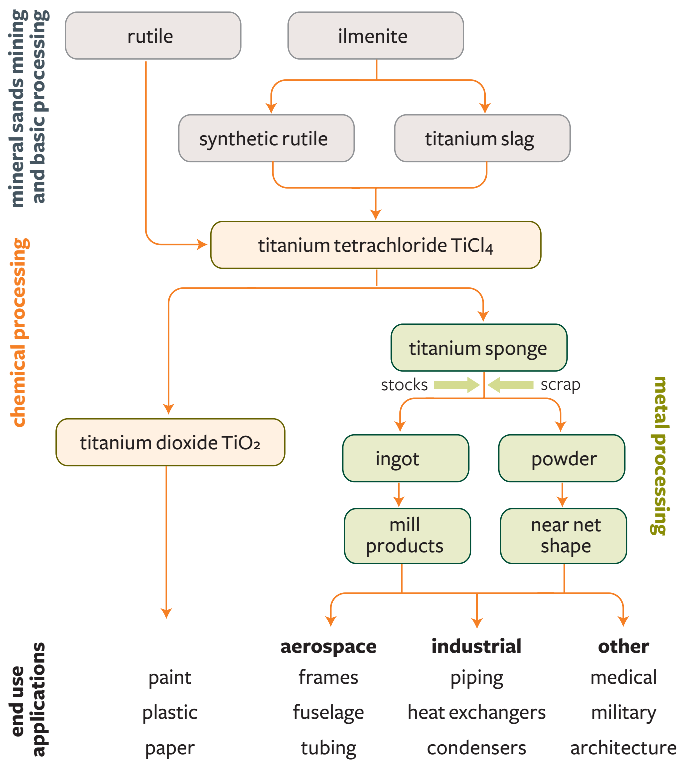
In the Russian Federation, the Ukraine and Kazakhstan, ilmenite is upgraded by transforming it into titanium slag. In all other countries, ilmenite is upgraded by transforming it into synthetic rutile. Two methods are used to produce synthetic rutile

— the Becher process and the Benilite process. The Becher process is used in Australia, while the Benilite process is used elsewhere in the world. The Becher process involves reduction, aeration and acid leaching. The Benilite process also involves reduction and acid leaching but in the presence of different chemicals. Synthetic rutile is produced in seven locations world-wide. There are three plants located in Western Australia that have a total capacity of 800 000 tonnes a year, accounting for around 86 per cent of global synthetic rutile capacity in 2006 (Roskill 2007).

## chemical processing

Rutile, synthetic rutile and titanium slag must be converted into $TiCl_4$ before it can be further processed into pure $TiO_2$ or titanium metal. In 2006, around 97 per cent of $TiCl_4$ was processed into $TiO_2$ powder with the remainder used in the titanium metal industry (TZMI 2007). To produce $TiO_2$ powder, $TiCl_4$ is superheated in the presence of oxygen. Plants that produce $TiO_2$ are often vertically integrated from the mine. This is the case for the Tiwest joint venture in Western Australia.

**a** the titanium supply chain



## metal processing

The current method for producing titanium metal uses the Kroll process where titanium sponge is produced as an intermediate product. The Kroll process is costly because it takes a number of days to convert a batch of $TiCl_4$ into titanium sponge, which needs to be physically removed from the reaction vessel and melted to produce titanium ingot (more detailed information on the Kroll process is provided in appendix A).

The ingot is worked into mill products such as wire, bar, sheet, plate, coil and tube. This stage of production tends to produce 40 per cent scrap, on average, which is remelted into ingot (Roskill 2007). Scrap can also come from recycling end use products, especially from aerospace applications.

Titanium powder is also produced in small amounts as a byproduct of melting the ingot. Ingots can also be intentionally destroyed to produce greater quantities of titanium powder. Titanium powder can be directly melted into an end use form that avoids the need for milling. Titanium powder currently makes up around 5–7 per cent of global titanium metal consumption (CSIRO communication).

The three stages of metal production — sponge, ingot and mill — are often integrated into a single firm. However, there are currently no metal producing firms that are integrated with a mine. In 2006, there were fourteen companies involved in the production of titanium metal (table 1). The

### 1 titanium sponge producers and capacity, 2006

| company | country | operational capacity kt | share of total % |
|---|---|---|---|
| vsmpo avisma | russian federation | 32.0 | 23.9 |
| sumitomo titanium | japan | 24.0 | 18.0 |
| ust-kamenogorsk titanium & magnesium | kazakhstan | 23.0 | 17.2 |
| toho titanium | japan | 15.0 | 11.2 |
| zunyi titanium stock | china | 10.0 | 7.5 |
| titanium metals corp (timet) | united states | 8.6 | 6.4 |
| zaporozhye titanium & magnesium | ukraine | 8.5 | 6.4 |
| ati allvac (allegheny technologies) | united states | 3.4 | 2.5 |
| jiangxi jintai enterprises | china | 2.4 | 1.8 |
| fushun jinming titanium | china | 2.0 | 1.5 |
| chaoyang hundred sheng | china | 2.0 | 1.5 |
| jinzhou huashen | china | 1.5 | 1.1 |
| huludao titanium | china | 1.0 | 0.7 |
| alta group | united states | 0.3 | 0.2 |
| total | | 133.7 | 100 |

*Source*: Roskill (2007).

largest producer is located in the Russian Federation and accounted for 24 per cent of global capacity. Overall, the top four producers accounted for 70 per cent of global capacity, the next four producers accounted for 23 per cent and six companies accounted for the remaining 7 per cent.

The regional distribution of global capacity in 2006 was 47 per cent in CIS countries (the Russian Federation, Ukraine and Kazakhstan, each with one producer), 29 per cent in Japan (two producers), 14 per cent in China (six producers) and the remaining 9 per cent in the United States (three producers).

## end use applications

Around 93 per cent of $TiO_2$ is used as a white pigment in paint, plastic and paper — its high refractive index makes it ideal in this role (TZMI 2007). It is also used in sunscreens and as a photocatalyst in chemical based solar cells.

Titanium metal is used in specialty applications where its physical properties such as strength, appearance, weight and biocompatibility justify its high cost relative to other metals — information on some key quality attributes of titanium and substitute metals is given in box 1. Historically, aerospace applications have dominated titanium metal consumption — titanium's high strength to weight ratio makes it an ideal material for use in fuselages, bolts, frames and panels.

In the industrial sector, titanium is used mainly in power generation, chemical processing and marine engineering. In these industries, titanium is used to make condensers, tubing and heat exchangers — titanium's high corrosion resistance makes it well suited to these applications. Titanium is also used in a large number of other applications such as military armour, architecture, watches, eye glasses, sports equipment and medical implants.

# r&d projects on titanium production processes

The first method of producing titanium to be commercialised was the Hunter process, which involved the reduction of $TiCl_4$ in the presence of sodium rather than magnesium. The Hunter process was made redundant with the exploitation of economies of scale in the Kroll process.

Despite gradual efficiency improvements in the Kroll process, the widespread use of titanium metal is hampered by the high costs of production and the fabrication of end use products. If costs could be reduced, titanium's unique physical qualities and the abundance of its ores would likely lead to large increases in its use. The potential for widespread titanium use combined with its military applications has encouraged research into new methods of producing titanium.

## box 1 quality attributes of titanium and substitute metals

Some key quality attributes of titanium are compared with those of substitute metals including magnesium, steel, aluminium, iron and copper in the table below.

Titanium has the highest strength to weight ratio of any metal up to 500 degrees Celsius (Roskill 2007). The tensile strength of commercially pure titanium is equal to that of steel alloys and twice that of the most commonly used aluminium alloy (6061-T6). Some titanium alloys exhibit tensile strengths over three times greater than commercially pure titanium. For its strength, titanium is also light — titanium is around 45 per cent lighter than most steels and even though it is twice as strong as common aluminium alloys, it is only around 60 per cent heavier.

Titanium is also notable for its corrosion resistance. It is resistant to corrosion from dilute acids, wet chlorine gas and salt solutions. When titanium is exposed to air at high temperature, a protective oxide coating develops that aids in corrosion resistance. At room temperature, titanium resists oxidation in air.

### physical properties of titanium and substitute metals

| | density | tensile strength | strength to weight ratio | corrosion rate |
|---|---|---|---|---|
| | g/cm$^3$ | PSI | | mm a year |
| titanium (commercially pure grade 2) | 4.5 | 40 000 | 8869 | 0.0003 |
| magnesium (pure) | 1.7 | 14 000 | 8046 | 0.3 |
| steel (316 series) | 8.0 | 33 000 | 4110 | 0.03 |
| aluminium (alloy 1199) | 2.7 | 5000 | 1852 | 0.1 |
| iron (pure) | 7.9 | 7250 | 921 | 0.1 |
| copper (annealed) | 9.0 | 4830 | 539 | 0.04 |

*Source*: www.matweb.com

Titanium's physical properties do create some drawbacks in commercial use (Roskill 2007). Its affinity for air, although beneficial in end use products, causes problems at the melting and alloying stages of production. This results in most of the stages of the Kroll process being conducted in inert atmospheres or vacuum, which increases the difficulty of extraction and fabrication. Also, despite its high corrosion resistance, titanium still corrodes rapidly in phosphoric, hydrochloric and sulphuric acids, hot caustic soda, dry chlorine, ammonium chloride (above 520°C), ammonia (above 150°C) and hydrogen sulphide (above 150°C).

Twenty organisations are currently conducting research into new methods of producing titanium (table 2). Research into new production methods has focused mostly on either the electrolytic reduction of titanium, a process similar to the smelting of aluminium, or the chemical production of titanium powder. The electrolytic reduction of titanium from titanium tetrachloride or titanium dioxide precursors has, so far, not demonstrated success toward commercialisation. However, chemical processes to produce titanium powder, such as the CSIRO's TiRO process, are showing promise. The chemical process closest to commercialisation is the Armstrong process marketed by ITP, which also produces titanium powder.

## tiro/csiro process

The TiRO process has been developed recently by the CSIRO as an alternative method for producing titanium metal. It relies on the same chemistry as the Kroll process but allows $TiCl_4$ to be turned directly into commercially pure titanium powder. It differs from the Kroll process as it produces powder not sponge and does so in a continuous, not a batch, process. The TiRO process also requires less labour than the Kroll process.

In the 2001 assessment of the titanium industry, it was found that Australia did not necessarily have a competitive advantage in producing titanium

### 2 current r&d projects on titanium production processes

| process name / organisation | country | process | output |
|---|---|---|---|
| tiro/csiro | australia | chemical | powder |
| armstrong / international titanium powder (itp) | united states | chemical | powder |
| emr / mse (university of tokyo) | japan | electrolysis | powder |
| ffc cambridge | uk and united states | electrolysis | powder |
| idaho research foundation | usa | chemical | powder |
| idaho titanium technologies | usa | chemical | powder |
| mer corp | usa | electrolysis | powder |
| os (kyoto university) | japan | other | powder |
| peruke (pty) ltd | south africa | chemical | powder |
| preform reduction (university of tokyo) | japan | chemical | powder |
| sri international | usa | other | powder |
| vartech | usa | chemical | powder |
| bhp billiton polar™ titanium | australia | electrolysis | liquid titanium |
| csir | south africa | other | liquid titanium |
| gtt s.r.l. | italy | electrolysis | liquid titanium |
| qit (rio tinto) | canada | electrolysis | liquid titanium |
| tresis international | usa | chemical | liquid titanium |
| mir-chem | germany | chemical | other |
| mit two-year titanium initiative | usa | electrolysis | other |
| south african titanium (peruke) | south africa | other | other |

*Source*: Roskill (2007).

sponge (DISR 2001a). The TiRO process may be able to provide Australia with a competitive advantage in the production of titanium — this is as a result of TiRO's continuous process and low use of labour reduce costs. The output of the TiRO process, titanium powder, also means that the expensive and wasteful fabrication of titanium mill products can be avoided. Titanium powder can be formed directly into finished parts using powder metallurgy, a process known as near net shape fabrication. Alternatively, the powder can always be melted into ingots and machined as normal. More detail on the technical specifics of the TiRO process is provided in appendix A.

## other research projects

The electrolytic reduction of titanium would produce solid or liquid metal. Liquid metal production would make titanium production similar to many other metals. However, the electrolysis must take place at very high temperatures, around 1700 degrees Celsius, and the process involves a number of technical challenges. GTT s.r.l. have pursued this method since around 1980, with little success. BHP Billiton and Rio Tinto have also supported research into electrolytic reduction.

Four groups have received funding from the US Department of Defense — SRI International, MER, FFC Cambridge and ITP. Of these four, the Armstrong process, being marketed by ITP, is the closest to commercial implementation.

In 2006 ITP were producing 16 tonnes a year of commercially pure and alloyed titanium metal using the Armstrong process. The Armstrong process uses the same chemistry as the Hunter process, the reduction of $TiCl_4$ with sodium. The Armstrong process is, however, nearly continuous. There are currently plans to construct an 1800 tonne a year pilot plant to commence production in 2008. The Illinois Government is offering US$700 000 to support the project.

Importantly, ITP has produced titanium containing less that 0.05 per cent oxygen. This is low enough to have the metal classed as commercially pure grade 1. The current TiRO process operated on the laboratory scale is producing metal with an oxygen content that is above the 0.25 per cent mandated for grade 2 commercially pure titanium, the goal of the project. Promising research addressing this issue is in progress and CSIRO believes that this problem can be fixed in a larger scale pilot plant (CSIRO 2006).

Parts, including racing car brakes, have already been produced from ITP powders and the company is beginning the certification of its powder to industry standards. However, it is not clear whether the ITP process significantly reduces the cost of producing titanium. It uses sodium, a difficult material to work with, and it relies on the same feedstock, $TiCl_4$, as the Kroll process. Its main advantage is the ability to produce titanium powder, which can allow for near net shape fabrication.

# 3 recent developments in the world titanium market

There have been a number of important developments in the titanium industry since 2001 — prices have risen, government stocks have been liquidated and capacity utilisation has increased. These events have occurred as a result of strong growth in titanium demand since 2003, especially for aerospace and industrial applications. The use of titanium in industrial applications has increased sharply since 2003, reflecting China's emergence into the world market and its use of titanium in non-aerospace applications.

This chapter provides information on recent developments in titanium consumption, production, prices, stocks and the availability of raw materials used to produce titanium.

## titanium consumption

### recent developments in titanium sponge consumption, stocks and prices

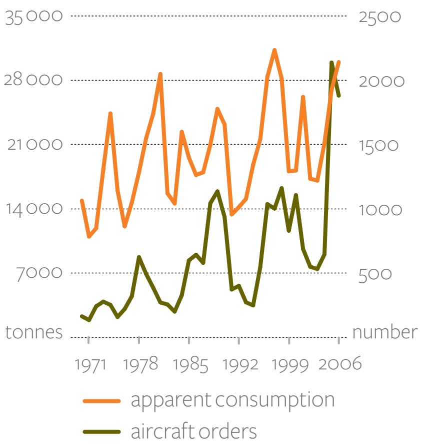
Titanium sponge is an intermediate form of titanium metal. It is the output of the Kroll process and must be purified and remelted into titanium ingot (there is further discussion of this process in appendix A). Titanium sponge is a useful stage in the supply chain for analysis as it has the most available data and, as it excludes scrap and waste, is a true indicator of production activity.

Since 2001, there have been significant developments in the global titanium sponge industry. The real price of titanium sponge in US dollars has risen by around 130 per cent between 2001 and 2006; this is comparable to the largest historical price increases. The US Government has liquidated its strategic titanium stockpile that it had been holding since the 1950s and there has been a reduction in excess production capacity.

#### *consumption*

Titanium's use in specialised applications, especially the aerospace industry, means that demand for titanium metal has been highly variable. For example, apparent consumption of titanium sponge in the United States is currently in its seventh cycle since 1970 (figure b). The last fall in US apparent consumption occurred in 2002, following the impacts of the 11 September 2001 terrorist attacks in the United States on the airline industry. Recently, apparent consumption in the United States has

b apparent consumption of titanium sponge and commercial aircraft orders in the united states



increased strongly, from 17 000 tonnes in 2003 to 30 000 tonnes in 2006, reflecting a strong recovery in aircraft orders (figure b).

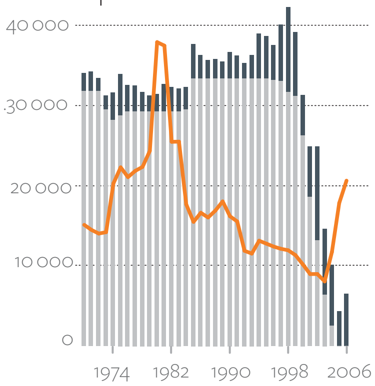
## prices

The recent rise in consumption has been accompanied by a rise in price (figure c). This is in contrast to the period 1994–2003 when, despite fluctuations in consumption, the real price of titanium fell on average by 5.5 per cent a year. This period corresponds with the sale of government stocks in the CIS and United States. The sale of stocks was able to offset fluctuations in consumption and allowed for a consistent fall in prices over the period.

In the late 1970s an increase in aircraft orders resulted in price growth averaging 5 per cent a year from 1977 to 1979. In 1980, however, prices increased by 56 per cent to US$37 900 a tonne (in 2006 dollars). This price spike can be attributed largely to an increase in orders for aircraft. Airlines sought to add new fuel-efficient aircraft to their fleet — a response to the oil price rises of the late 1970s. This increase in orders encouraged the hedge buying of titanium sponge and mill products by aircraft manufacturers (Panel on Assessment of Titanium Availability 1983). Capacity expansions in Japan and the United States combined with recession in 1982-83 brought prices back down to around US$16 000 a tonne by 1987.

The end of the cold war, which reduced titanium demand for military applications, and a further recession in the early 1990s initiated a downward trend in real prices that continued until 2003. In 2004 and 2005 prices rose by an average of almost 50 per cent a year. In 2006, prices rose by 16 per cent to reach over US$20 600 a tonne, an increase comparable in scale to that of the late 1970s although from a lower base.

**c** titanium sponge stocks and prices in the united states




## stocks

The US Government began accumulating a titanium sponge stockpile in the early 1950s. In 1995, when the stockpile was at its largest, it contained 33 400 tonnes of titanium sponge. The primary purpose of the stockpile was to have titanium sponge available for use in a national emergency. A secondary purpose was to encourage expansion of titanium sponge manufacturing capacity through purchases (Panel on Assessment of Titanium Availability 1983). Between 1997 and 2005 the US Defense Logistics Agency sold the entire stockpile.

A similar accumulation occurred in the Soviet Union. From the mid-1990s, countries in the CIS sold off this stockpile. The depletion of government stockpiles means that new production must replace stockpile sales and also be able to satisfy increases in demand.

## titanium consumption, by end use application and region

Titanium mill products, such as wire, bar, sheet, plate, coil and tube, are a result of the working of ingot. Mill products are the most common form in which titanium is sold to manufacturers to produce final products for consumption. The consumption of mill products is a good indicator of final titanium consumption.

In 2005, the industrial applications sector consumed the most titanium mill products (table 3). It had also shown the strongest rate of growth since 2003 and was the only sector to increase its share of total consumption between 2003 and 2005. The overall growth rate of titanium mill products, 24 per cent, is heavily reliant on the strong growth of the industrial applications sector as no other sector grew by more than 10 per cent and consumption in three of the smaller sectors actually decreased.

In 2005, countries in the OECD — including the European Union, the United States and Japan — accounted for around two-thirds of titanium mill product consumption (table 4). North America was the largest consumer, followed by the European Union. These two accounted for over half of total world consumption. China accounted for a greater percentage of consumption than Japan and actually consumed more titanium than north America and the European Union when aerospace is excluded.

### 3 world consumption of titanium mill products, by major end use application, 2003 - 2005

| | 2003 | | 2005 | | |
|---|---|---|---|---|---|
| | level | share of total | level | share of total | growth rate a |
| | kt | % | kt | % | % |
| **aerospace** | | | | | |
| commercial aerospace | 23.0 | 35.4 | 25.5 | 30.6 | 5.3 |
| military aerospace | 7.0 | 10.8 | 6.0 | 7.2 | –7.4 |
| total | 30.0 | 46.2 | 31.5 | 37.9 | 2.5 |
| **industrial applications** | 24.0 | 36.9 | 41.1 | 49.4 | 30.9 |
| **consumer and other applications** | | | | | |
| consumer | 7.0 | 10.8 | 6.4 | 7.7 | –4.4 |
| medical | 1.5 | 2.3 | 1.7 | 2.0 | 6.5 |
| other military | 1.9 | 2.9 | 2.3 | 2.8 | 10.0 |
| other | 0.6 | 0.9 | 0.2 | 0.2 | –42.3 |
| total | 11.0 | 16.9 | 10.6 | 12.7 | –1.8 |
| **total** | 65.0 | 100 | 83.2 | 100 | 24.0 |

**a** average annual growth rate from 2003 to 2005.
*Source*: Roskill (2007).

Patterns of consumption of titanium mill products vary significantly from country to country. As Boeing is located in America and Airbus in the European Union, consumption in the aerospace sector is relatively high in these two regions. Consumption in the industrial sector is fairly evenly spread throughout the globe. However, as a percentage of domestic consumption, industrial uses are particularly strong in Asia. In China, 50 per cent of total titanium consumption is in the industrial sector. This proportion rises to 70 per cent in Japan, Chinese Taipei and the Republic of Korea.

## titanium production

This section focuses on production of titanium sponge, an intermediate form of titanium metal. As was previously mentioned, titanium sponge is a useful stage in the supply chain to analyse as it has the most available data and, as it excludes scrap and waste, is a true indicator of production activity.

Recently, both production and capacity have been increasing. Production has, however, been increasing faster than capacity. This has led to an increase in utilisation rates. China has had the strongest production growth but still makes up a small percentage of global production.

### titanium sponge production

In recent years the production of titanium sponge has increased (figure d). Since 1993 production has been cyclical, but with an upward trend. This has resulted in an average annual growth rate of 5.2 per cent over the period. This compares with other base metals such as aluminium (average 4.2 per cent over the period) and copper (3.4 per cent).

**4 consumption of titanium mill products, by end use application and region, 2005**

| | aerospace | | industrial | | consumer and other | | total | |
|---|---|---|---|---|---|---|---|---|
| | level | share of total | level | share of total | level | share of total | level | share of total |
| | kt | % | kt | % | kt | % | kt | % |
| north america | 16.4 | 52.1 | 7.5 | 18.2 | 1.4 | 13.2 | 25.3 | 30.4 |
| european union | 9.8 | 31.1 | 8.4 | 20.4 | 1.8 | 17.0 | 20.0 | 24.0 |
| china | 1.2 | 3.8 | 7.6 | 18.5 | 3.4 | 32.1 | 12.2 | 14.7 |
| japan | 0.6 | 1.9 | 7.4 | 18.0 | 2.1 | 19.8 | 10.1 | 12.1 |
| russian federation | 3.0 | 9.5 | 1.8 | 4.4 | 0.2 | 1.9 | 5.0 | 6.0 |
| chinese taipei and south korea | 0.3 | 1.0 | 6.4 | 15.6 | 1.5 | 14.2 | 8.2 | 9.9 |
| other | 0.2 | 0.6 | 2.0 | 4.9 | 0.2 | 1.9 | 2.4 | 2.9 |
| total | 31.5 | 100 | 41.1 | 100 | 10.6 | 100 | 83.2 | 100 |

*Source*: Roskill (2007).

Production was at its lowest in 1994 when 43 300 tonnes of titanium sponge were produced worldwide. Only a third of sponge capacity was being used at this time. This low in production corresponds with a period of low consumption owing to weak aircraft orders. In 1998, 22 000 tonnes of capacity was decommissioned — 8200 tonnes in the United States, 5000 tonnes in the Russian Federation and 9000 tonnes in Kazakhstan. In 1999 a further 4000 tonnes was decommissioned in both the Russian Federation and Kazakhstan.

Between 2003 and 2006, production increased from 74 000 tonnes to 124 000 tonnes, at an average rate of 19 per cent a year. Recent production increases have occurred in response to the exhaustion of the US and CIS stockpiles and higher titanium sponge prices.

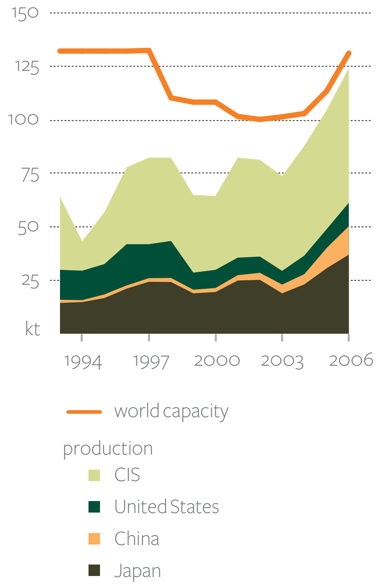
These production increases have been accompanied by increases in productive capacity. In 2003, productive capacity was 102 000 tonnes; by 2006 it had increased to 131 000 tonnes, an average annual growth rate of 9 per cent. The slower growth of capacity relative to production resulted in an increase in capacity utilisation. In 2004, the last year of shipments from the US government stockpile, capacity utilisation rates increased for the first time since 2001. This increase continued and by 2006 utilisation rates were around 95 per cent. This compares with aluminium, another light metal, where utilisation rates in 2006 were 90 per cent.

Since 1993 production of titanium sponge has increased in all countries except for the United States. It is important to note that discussion of average annual growth rates is not truly representative of production activity in the titanium sponge industry. This is because of the cyclical nature of production (figure d). Production of titanium sponge has been strongly influenced by orders for commercial aircraft, which fluctuate depending on investment cycles, macroeconomic conditions and geopolitical events. Average annual growth rates do, however, give an indicator of general trends and there has been a general trend toward increasing production in most countries.

The largest increase in production has been in China, where production increased on average by 18.3 per cent a year between 1993 and 2006, although this was from an extremely small base of only 1500 tonnes, representing 2.3 per cent of total world production. By 2006, Chinese production was 13 000 tonnes, 11 per cent of total world production (table 5).

In Japan, production growth has been particularly strong since 2000. Between 1993 and 1999, production increased at an annual average rate of 4.6 per cent, from 14 000 tonnes to 19 000 tonnes. From 2000 to 2006, production grew at an annual average of 11 per cent, reaching 37 000 tonnes. Over the full period, the average annual growth rate in Japan was 7.5 per cent.

**d** titanium sponge production, by region, and world productive capacity



Strong production growth from countries in the CIS can be mostly attributed to a recovery of production in the Ukraine. No titanium sponge was produced in the Ukraine between 1994 and 1997. In 2006, 10 000 tonnes of titanium sponge was produced in the Ukraine. In Kazakhstan, despite a fall in capacity, production increased on average by 8.2 per cent a year between 1993 and 2006. In 2006, Kazakhstan produced 23 000 tonnes of titanium sponge, implying that they were operating at full capacity (table 5). In the Russian Federation, production grew on average by 2.1 per cent a year between 1993 and 2006. This is, however, more indicative of Russia's high level of production in 1993, around 36 per cent of world production.

In the United States, production fell from 14 000 tonnes in 1993 to 11 000 tonnes in 2006 — an average rate of decline of 1.8 per cent a year. This can be attributed to the closure of almost 21 000 tonnes (71 per cent) of US production capacity during the period. In 2006, 3400 tonnes of new capacity was brought on line in the United States, resulting in production increasing from 8800 to 11 000 tonnes.

The titanium sponge capacity data in table 5 differs from that in table 1 because of the different data sources being used. Table 1 contains data from Roskill (2007), while table 5 contains data from the US Geological Survey.

## 5 titanium sponge production and capacity, by country

| | 2001 | | 2006 | | |
|---|---|---|---|---|---|
| | level | share of total | level | share of total | growth rate a |
| | kt | % | kt | % | % |
| **production** | | | | | |
| japan | 24.9 | 30.2 | 37.0 | 29.8 | 8.2 |
| russian federation | 26.1 | 31.7 | 30.0 | 24.1 | 2.8 |
| kazakhstan | 14.4 | 17.5 | 23.0 | 18.5 | 9.8 |
| united states | 8.2 | 10.0 | 11.0 | 8.8 | 6.1 |
| china | 2.5 | 3.0 | 13.3 | 10.7 | 39.7 |
| ukraine | 6.3 | 7.6 | 10.0 | 8.0 | 9.7 |
| total | 82.4 | 100 | 124.3 | 100 | 8.6 |
| **capacity** | | | | | |
| japan | 26.0 | 25.6 | 39.0 | 29.7 | 8.4 |
| russian federation | 26.0 | 25.6 | 32.0 | 24.4 | 4.2 |
| kazakhstan | 22.0 | 21.6 | 23.0 | 17.5 | 0.9 |
| united states | 14.8 | 14.6 | 12.3 | 9.4 | –3.6 |
| china | 6.9 | 6.8 | 15.0 | 11.4 | 16.8 |
| ukraine | 6.0 | 5.9 | 10.0 | 7.6 | 10.8 |
| total | 101.7 | 100 | 131.3 | 100 | 5.2 |

**a** average annual growth rate between 2001 and 2006.
*Source*: Roskill (2007), USGS.

The major difference between the two sources is China's sponge capacity. Roskill (2007) estimates China's titanium sponge production capacity in 2006 as 18 000 tonnes, while the US Geological Survey estimates China's capacity to be 15 000 tonnes.

## titanium powder production

There are no reliable data available on the production of titanium powder. Global powder production is estimated to be no more than 10 000 tonnes a year and is probably more likely to be around 8400 tonnes a year. Most powder production takes place in the Russian Federation, the Ukraine and Japan. Russia and the Ukraine each have production capacity of around 2000 tonnes a year. Exports of titanium powder from Japan average around 3000 tonnes a year, which gives an indication of the volume of production. China also has a titanium powder plant with a capacity of around 1000 tonnes a year. Production in the United States and European Union probably amounts to a few hundred tonnes a year (Roskill 2007).

# mineral sands mining

## ilmenite and rutile resources

In 2006, world reserves of ilmenite and rutile were an estimated 606 million tonnes and 52 million tonnes of titanium dioxide content respectively (table 6). China has the world's largest reserves of ilmenite, around a third of global reserves; China has no recorded rutile reserves. The quality and accessibility of Chinese reserves is unknown. Australia has the world's second largest reserves of ilmenite and the largest reserves of rutile — the location of mineral sands deposits in Australia is indicated in map 1 (based on Geoscience Australia information). India has the world's third largest reserves of ilmenite and rutile.

## ilmenite and rutile mining

The most commonly recovered mineral from heavy mineral sands deposits is ilmenite. In 2006, world production of ilmenite concentrate was around 11.7 million tonnes (table 7). Production from Canada, South Africa and Australia, the top three producers, accounted for around 65 per cent of global production. China and India are also significant producers of ilmenite, producing 1.0 million tonnes and 0.7 million tonnes respectively in 2006.

In 2006, seven countries produced a total of 522 000 tonnes of rutile concentrate. Australia, the world's largest producer of rutile, accounted for 44 per cent of global production. Western Australia accounts for around half of Australia's rutile production.

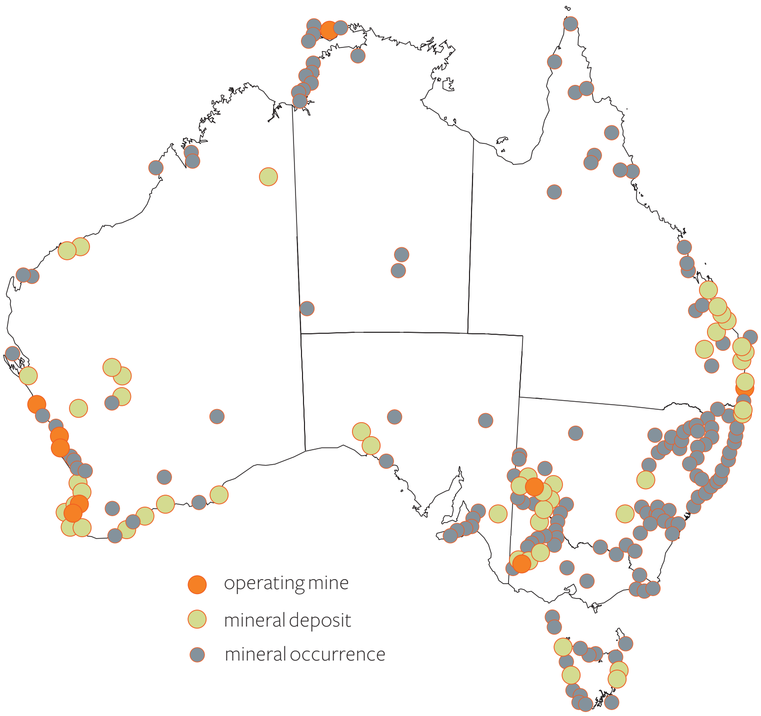
As the vast majority of titanium is not used to produce metal, global production of synthetic rutile was 818 000 tonnes in 2006 (only 7 per cent of ilmenite production). Australia was the world's largest producer of synthetic rutile in 2006, producing around 86 per cent of the world total. Australia has been the world's largest producer of synthetic rutile for at least the past fifteen years. All of Australia's synthetic rutile is currently produced in Western Australia. However, Austpac Resources has entered into an agreement with BHP Billiton to construct a synthetic rutile pilot plant in New South Wales (3000 tonnes a year) with production to commence in the second half of 2008. A feasibility study for a plant capable of producing 60 000 tonnes of synthetic rutile a year would commence at some stage thereafter. This means that synthetic rutile may be produced outside Western Australia from the second half of 2008.

## 6 reserves of ilmenite and rutile, by country, 2006

| | rank | | reserves | | share | |
|---|---|---|---|---|---|---|
| | ilmenite | rutile | ilmenite a | rutile a | ilmenite | rutile |
| | no. | no. | mt | mt | % | % |
| china | 1 | – | 200 | 0 | 33 | 0 |
| australia b | 2 | 1 | 130 | 19 | 21 | 36 |
| india | 3 | 3 | 85 | 7.4 | 14 | 14 |
| south africa | 4 | 2 | 63 | 8.3 | 10 | 16 |
| norway | 5 | – | 37 | 0 | 6.1 | 0 |
| canada | 6 | – | 31 | 0 | 5.1 | 0 |
| mozambique | 7 | 7 | 16 | 0.5 | 2.6 | 0.9 |
| brazil | 8 | 4 | 12 | 3.5 | 2.0 | 6.7 |
| united states | 9 | 8 | 6.0 | 0.4 | 1.0 | 0.8 |
| cis/ukraine | 10 | 5 | 5.9 | 2.5 | 1.0 | 4.8 |
| vietnam | 11 | – | 5.2 | 0 | 0.9 | 0 |
| malaysia | – | – | 0 | 0 | 0 | 0 |
| thailand | – | – | 0 | 0 | 0 | 0 |
| sierra leone | – | 5 | 0 | 2.5 | 0 | 4.8 |
| other | – | – | 15 | 8.1 | 2.5 | 16 |
| total | – | – | 606 | 52 | 100 | 100 |

**a** $TiO_2$ content. **b** Geoscience Australia compiles Australia's ilmenite and rutile reserves.
*Source*: USGS (2007).

## 1 location of mineral sands deposits, mines and occurrences in australia




## 7 production of ilmenite, rutile and synthetic rutile, by country, in 2006

| | rank | | | production | | | share | | |
|---|---|---|---|---|---|---|---|---|---|
| | ilmenite | rutile | synthetic rutile | ilmenite | rutile | synthetic rutile | ilmenite | rutile | synthetic rutile |
| | no. | no. | no. | kt | kt | kt | % | % | % |
| china | 4 | – | – | 1030 | 0 | 0 | 8.8 | 0 | 0 |
| australia | 3 | 1 | 1 | 2378 | 232 | 703 | 20 | 44 | 86 |
| india | 6 | 5 | 2 | 685 | 18 | 85 | 5.9 | 3.4 | 10 |
| south africa | 2 | 2 | – | 2384 | 122 | 0 | 20 | 23 | 0 |
| norway | 5 | – | – | 850 | 0 | 0 | 7.3 | 0 | 0 |
| canada | 1 | – | – | 2787 | 0 | 0 | 24 | 0 | 0 |
| mozambique | – | – | – | 0 | 0 | 0 | 0 | 0 | 0 |
| brazil | 11 | 7 | – | 121 | 2 | 0 | 1.0 | 0.4 | 0 |
| united states | 8 | 6 | – | 461 | 11 | 0 | 3.9 | 2.1 | 0 |
| cis/ukraine | 7 | 4 | – | 470 | 63 | 0 | 4.0 | 12 | 0 |
| vietnam | 9 | – | – | 350 | 0 | 0 | 3.0 | 0 | 0 |
| malaysia | 10 | – | 3 | 165 | 0 | 30 | 1.4 | 0 | 3.7 |
| thailand | 13 | – | – | 5 | 0 | 0 | 0 | 0 | 0 |
| sierra leone | 12 | 3 | – | 14 | 74 | 0 | 0.1 | 14 | 0 |
| other | – | – | – | 0 | 0 | 0 | 0 | 0 | 0 |
| total | – | – | – | 11 700 | 522 | 818 | 100 | 100 | 100 |

*Source*: TZMI (2007), ABARE.

# 4 medium term outlook for the world titanium market

Overall, strong growth in consumption of titanium metal is expected over the next five years, with significant investment in new productive capacity based on the Kroll process. Only relatively small quantities of titanium powder are expected to be produced. The large projected increase in production, particularly in China, is expected to drive titanium prices back to levels nearer their long term historical average.

## titanium consumption

The price of titanium sponge is projected to decline over the medium term. Prices are expected to fall in real terms (2006 dollars) to around US$10 000 a tonne by 2009 and then to rise again in 2011 to around US$15 000 a tonne. The fall over the short term reflects an increase in global production, particularly in China. The rise toward the end of the outlook period reflects increased capacity utilisation at the melting and milling stages of production, which will flow on to strong demand for titanium sponge and an increase in prices.

Titanium consumption is projected to grow strongly over the medium term (table 8), driven by a five year backlog of aircraft orders and continued high levels of economic growth in the emerging economies of China and India.

Industrial applications are expected to continue to have the highest rate of growth over the outlook period — accounting for around 60 per cent of overall growth in consumption of titanium mill products. Use of titanium mill products in industrial applications is expected to increase strongly in China and India. This is attributed to expansions in power generation and chemical processing that are expected to occur as these two countries continue to experience high rates of economic growth.

Strong growth is also expected in aerospace applications as Boeing and Airbus attempt to clear a five year backlog of orders. Increased use of titanium in new aircraft designs adds further potential for growth above the expected high construction rates. Wide body and double aisled aircraft are expected to consume proportionately more titanium than narrow bodied and single aisled aircraft. An industry trend toward larger aircraft, particularly in the airfreight sector, is expected to further increase the use of titanium in aerospace applications.

### 8 world consumption of titanium mill products, by major end use application, 2005-2011 a

| | 2011 consumption | 2011 share of total | growth rate, 2005-2011 b |
|---|---|---|---|
| | kt | % | % |
| aerospace | 45 | 36 | 6.2 |
| industrial | 65 | 53 | 8.0 |
| consumer and other | 13 | 11 | 3.8 |
| total | 124 | 100 | 6.8 |

a data for 2005 are provided in table 3. b average annual growth rate.
*Source*: Roskill (2007).

On a regional basis, the strongest growth in consumption of titanium mill products is expected to occur in China (table 9), where consumption is projected to more than double from 12 000 tonnes in 2005 to 25 000 tonnes in 2011 — an average annual growth rate of 12 per cent. By 2011, China is expected to have increased its share of global titanium mill product consumption from 15 per cent to 20 per cent (figure e). Chinese Taipei, the republic of Korea and other countries, dominated by India, are also expected to increase their shares of mill product consumption, while the consumption shares of north America, the European Union, Japan and the Russian Federation are all expected to decrease.

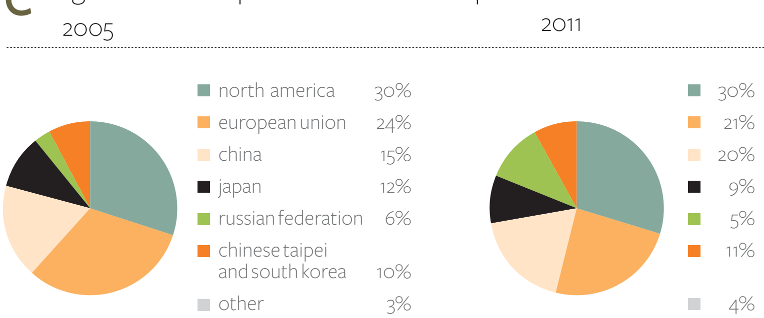
## titanium production

The most significant development in production over the medium term is the projected increase in China's titanium sponge production from 13 000 tonnes in 2006 to 61 000 tonnes in 2011 — an average annual growth rate of 35 per cent. By 2011, China is expected to have increased its share of global titanium sponge production from 11 per cent to 27 per cent (figure f). However, it should be noted that some of the planned expansions in China may be delayed because of environmental concerns. Of the current producers, only Ust Kamenogorsk in Kazakhstan, Zaporozhye in the Ukraine and specialty producer Alta Group in the United States have not announced plans to expand their productive capacities by 2011.

US production of titanium sponge is expected to grow on average by around 18 per cent a year from 11 000 tonnes in 2006 to 25 000 tonnes in 2011. This is a result of around 15 000 tonnes of new capacity being brought on line in the next three years. Strong growth in production is also expected in China (averaging around 35 per cent a year) as production increases from 13 300 tonnes in 2006 to 61 000 tonnes in 2011 (table 10).

Toward the end of the outlook period, capacity utilisation at the melting and milling production stages is projected to increase as consumption is

**e** regional consumption of titanium mill products




### 9 world consumption of titanium mill products, by region, in 2011 a

| | 2011 consumption | 2011 share of total | growth rate, 2005-2011 b |
|---|---|---|---|
| | kt | % | |
| north america | 37.4 | 30.3 | 6.7 |
| european union | 25.4 | 20.5 | 4.1 |
| china | 24.5 | 19.8 | 12.3 |
| japan | 11.5 | 9.3 | 2.2 |
| russian federation | 6.0 | 4.9 | 3.2 |
| chinese taipei and south korea | 13.7 | 11.1 | 8.9 |
| other | 5.1 | 4.1 | 13.3 |
| total | 123.6 | 100 | 6.8 |

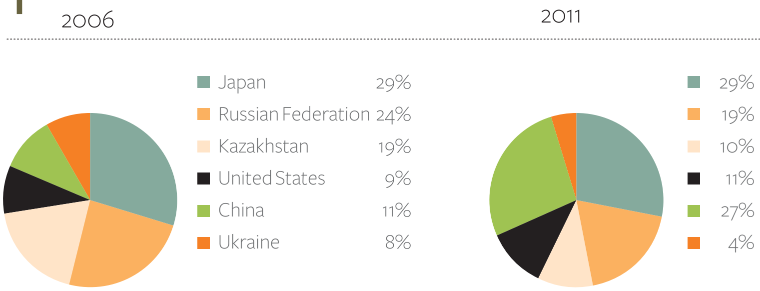
a Data for 2005 are provided in table 4. b average annual growth rate.
*Source*: Roskill (2007)

### 10 forecasts of titanium sponge production, by country, 2006-2011 a

| | 2011 consumption | 2011 share of total | growth rate, 2005-2011 b |
|---|---|---|---|
| | kt | % | % |
| japan | 63 | 28.2 | 11.2 |
| russian federation | 42 | 18.8 | 7.0 |
| kazakhstan | 23 | 10.3 | 0.0 |
| united states | 25 | 11.1 | 17.6 |
| china | 61 | 27.1 | 35.4 |
| ukraine | 10 | 4.5 | 0.0 |
| total | 223 | 100.0 | 12.4 |

a data for 2006 are available in table 5.
b average annual growth rate.
*Sources*: Roskill (2007), TZMI (2007), ABARE projections.

f production of titanium sponge, by country




projected to increase faster than known capacity expansions (Buch 2006). However, it is expected that there will be enough available capacity to satisfy demand.

There are no reliable data available on the production of titanium powder. However, production is estimated to be no more than 10 000 tonnes and is probably more likely to be around 8400 tonnes (Roskill 2007). Given current production techniques, it is not expected that production of titanium powder will increase significantly. This is because of the high cost of producing commercially pure titanium powder and the powder's current limited use. It should be noted that current commercially available powders are produced by secondary processing of titanium derived from the Kroll process, with associated additional costs — for example, using a hydride–dehydride process or by melting the metal and fragmenting the liquid into fine droplets and quenching.

New productive capacity to be brought on line between 2006 and 2011 is expected to use the Kroll process to produce titanium sponge. The longer term outlook for titanium will be influenced by the extent to which new production technologies are adopted and by how much they can reduce production costs. A reduction in production costs would place downward pressure on the price of titanium mill products and increase demand for titanium. Part of this increased demand may come from entirely new applications. Three long term growth scenarios for the world titanium market are briefly considered in the next chapter.

# 5 some economic aspects of the technology innovation process

The extent to which new titanium technologies are developed and deployed will have major implications for the world titanium market, demand for Australia's rutile and ilmenite resources and the potential development of an Australian titanium industry. A domestic titanium industry, if developed, is most likely to be located at least initially in Western Australia in the proximity of major mineral sands deposits and related processing facilities. Private investment in a domestic titanium plant is also most likely to occur as a result of the further development and commercialisation of the TiRO/CSIRO process for producing titanium powder, although this is not the only option for the development of a domestic titanium industry.

In this chapter, the economic rationale for considering government intervention in technology R&D, adoption and transfer is discussed and some economic aspects of the technology innovation process in the world titanium market over the longer term are examined. The implications of this analysis for the TiRO/CSIRO R&D project and the potential development of an Australian titanium industry are discussed in the next chapter.

## role of government in encouraging technology r&d, adoption and transfer

It is useful to examine the role of government in encouraging technology R&D, adoption and transfer before considering issues specific to the titanium market. There are three main parts to the discussion in this section:

- key stages in the technology innovation process
- economic incentives for private investment in the development and deployment of new and enhanced technologies
- the role of government in addressing market failures and implementing policy options to encourage technology R&D, adoption and transfer.

Each of these aspects is discussed in turn.

### technology innovation process

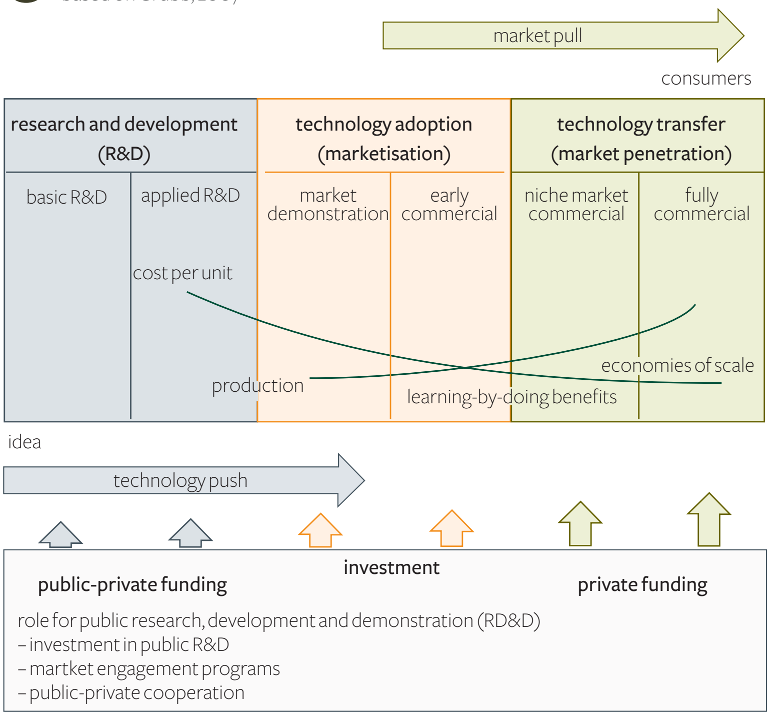
A major focus in this study is to examine the potential for the further development and commercialisation of the TiRO process developed to date in an R&D project at CSIRO. A brief overview of the technology innovation process is presented in figure g to highlight some key linkages between R&D projects and subsequent stages in the technology innovation process.

The process of technological change is often categorised into three broad stages —R&D, technology adoption and technology transfer. These stages may be subdivided to clarify aspects in the demonstration and commercialisation of new and enhanced technologies. The following definitions draw on ABS (2002) and Grubb (2007).

- research and development — research into, and the development of, new and enhanced technologies. R&D activity extends to modifications to existing products/processes and ceases when work is no longer experimental:
  - *basic research* — original work undertaken primarily to acquire new knowledge without a specific practical application
  - *applied research* — original work undertaken to acquire new knowledge with a specific application, including to determine possible uses for the findings of basic research or to determine new methods or ways of achieving some specific and predetermined objectives

- technology adoption — the initial commercialisation of new and enhanced technologies (technology leaders):
  - *market demonstration* — test and demonstrate the performance, viability and potential market of the technology

**g** key stages in the technology innovation process
based on Grubb, 2007



- *early commercial* — adoption of the technology by established firms or the establishment of firms based around the technology

- technology transfer — the more widespread commercialisation of new and enhanced technologies (technology followers):
  - *niche market commercial* — market accumulation process in which the use of the technology expands in scale, often in niche markets
  - *fully commercial* — diffusion of the technology on a large scale.

## private investment in the technology innovation process

Private firms identify and assess the economic viability of investment projects at each stage in the technology innovation process. A useful framework for considering the profitability assessments of investment projects is outlined in box 2 — this framework has been used in a range of policy assessments (see, for example, Hogan 2003, 2007).

Notably, for risk averse private investors, the profitability assessment of a risky project is assumed to be based on the project's certainty equivalent value (CEV). A risky project is assessed to be profitable if the certainty equivalent value is zero (a marginal project) or positive (an economic project). The certainty equivalent value is equal to the expected net present value (ENPV) less a risk premium (RP) — the expected net present value is the probability weighted sum of the net present value of each possible outcome and the risk premium is the amount that compensates the investor for the risks associated with the project. The higher the risks, the lower the assessed profitability or economic viability of the project (all else assumed to be constant).

The risk profile of potential investment projects changes throughout the technology innovation process (figure g). Technical risk tends to be high at the R&D stage and diminishes as the new technology is demonstrated and commercialised. Investors become relatively more concerned about policy and economic risks during the commercialisation phases.

Unit production costs tend to be reduced in three ways through the technology innovation process:

- 'proving up' the technology — costs are reduced as the technology is 'proved up' through testing, debugging and demonstrating its market viability
- learning by doing benefits — firms tend to reduce unit production costs further by improving on products and/or processes based on actual experience acquired in applying the new technology
- economies of scale — unit production costs tend to be reduced as the technology is used on a large scale.

## box 2 an economic framework for decision making under risk – certainty equivalent approach

In this box, an economic framework is presented for assessing the profitability of investment projects. The decision criteria to assess project profitability vary according to the riskiness of the project and the attitude of investors to incurring risk. The decision criteria are summarised in the table. Further information is provided in, for example, Hogan (2007).

### decision criteria for profitability assessments of investment projects

| risk/attitude toward risk | profitability measure | profitability assessment | | |
|---|---|---|---|---|
| | | uneconomic | marginal | economic |
| risk free project | net present value (NPV) | < 0 | = 0 | > 0 |
| risky project | | | | |
| - risk neutral investor | expected net present value (ENPV) | < 0 | = 0 | > 0 |
| - risk averse investor | certainty equivalent value (CEV) | < 0 | = 0 | > 0 |

*risk free projects — net present value*

Consider first a risk free investment. In the absence of risk, investors are assumed to summarise the profitability of a potential resource project by calculating the net present value. The net present value of a risk free project is the sum of the annual net cash flow over the duration of the project discounted at the risk free interest rate (assumed to be the long term government bond rate or LTBR). The net present value, NPV, in year 0 prices may be presented simply in algebraic terms as:

1 $$NPV = \sum_s V_s/(1+i_{rf})^s$$

where $V_s$ is the net cash flow of the project in year s, $i_{rf}$ is the risk free interest rate and $\sum_s$ is the summation sign over all years in the project (with $s = 0,1,2, ... T$, where $T$ is the final year in the project life). Projects may be ranked according to net present value since it is a measure of the return to the investment. A project with a net present value that is greater or equal to zero is assessed to be profitable since it indicates that the investment will achieve a return that is greater or equal to the risk free interest rate.

*risky projects with risk neutral investors — expected net present value*

In the presence of risk, risk neutral investors are assumed to summarise the profitability of a potential investment project by calculating the expected net present value. A risk neutral investor is indifferent to the risk that an outcome may be either worse or better than expected. In this case, the investor is assumed to be able to identify a range of possible outcomes that reflect the significant sources of risk and assign (objective or subjective) probabilities to each of these outcomes. For example, price is usually considered to be a major source of risk and hence project profitability may be assessed under a range of possible price outcomes. The expected net present value is the probability weighted sum of the net present value of each possible outcome.

continued...

Reductions in both technical risk and unit production costs are important given the increased investment expenditure associated with the commercialisation phases of the technology innovation process.

Overall, some key aspects of the profitability assessment of projects in the technology innovation process include the following:

- R&D projects — profitability assessments are based on the likelihood of discovering new or enhanced technologies that result in a future profit stream sufficiently large to compensate for the risks associated with the activity. Private investors tend to focus mainly on applied research and experimental development work where the commercial applications are

## box 2 an economic framework for decision making under risk – certainty equivalent approach *continued*

The expected net present value, *ENPV*, in year 0 prices may be presented simply in algebraic terms as:

2 $$ENPV = \sum_k Pr_k NPV_k$$

where $Pr_k$ is the probability that a possible outcome k may occur (noting that each probability has a value in the range from 0 to 1, and probabilities must sum to 1 — that is, $0 < Pr_k < 1$ and $\sum_k Pr_k = 1$), $NPV_k$ is the net present value of the project in possible outcome $k$ and $\sum_k$ is the summation sign over possible outcomes (with $k = 0,1,2, \ldots K$ where $K$ is the total number of possible outcomes).

For risk neutral investors, projects may be ranked according to the expected net present value since it is now the relevant measure of the expected return to the investment. A project with an expected net present value greater or equal to zero is assessed to be profitable since it indicates that the investment is expected to achieve a return that is greater or equal to the risk free interest rate.

*risky projects with risk averse investors — certainty equivalent value*

In the presence of risk, risk averse investors are assumed to summarise the profitability of a potential investment project by calculating the certainty equivalent value. A risk averse investor is relatively more concerned about the risk of unexpected losses than the risk of unexpected gains. The certainty equivalent value of a project is the amount where the investor would be indifferent to investing in the risky project or accepting a risk free investment with a certain return. For risk averse investors, the certainty equivalent value is the expected net present value less a risk premium that provides adequate compensation for the risks associated with the project.

In simple algebraic terms, the certainty equivalent value, *CEV*, of a project for a risk averse investor may be expressed as:

3 $$CEV = ENPV - RP$$

where *ENPV* is the expected net present value, as defined previously, and *RP* is the risk premium.

more apparent — that is, in areas that are substantially less risky in terms of capturing the benefits from the R&D project (see, for example, Hogan 2004).

- technology adoption — technology leaders are involved in the market demonstration and early adoption of new and enhanced technologies and, as a consequence, tend to incur additional costs and risks than would otherwise be the case. The profitability assessments of these investments take into account the possibility that, if the technology is successful, there is the potential to earn supernormal profits in the short to medium term before other firms adopt the successful technology. Project costs and risks may be lowered through learning by doing effects.
- technology transfer — technology followers adopt a wait and see approach to the success of new and enhanced technologies and, as a consequence, tend to benefit through lower costs and risks in the investment project. Project costs and risks may be lowered through learning by doing benefits as well as by achieving economies of scale.

The rate of adoption and diffusion of new and enhanced technologies is influenced by a range of factors. As outlined in Heaney et al. (2005), factors driving the level of capital investment in an industry include the expected demand growth and the need for increased productive capacity, the size and age structure of the existing capital stock and the need to replace or refurbish existing capacity, the policy setting and impediments to investment more generally. Thus, for example, the speed of adoption in an industry that is characterised by large scale investment that is often long lived and irreversible tends to be slower than in an industry characterised by small scale investment.

## policy options to encourage the technology innovation process

### *economic rationale for government intervention*

Failure of private markets to produce an optimal level of goods or services provides the economic rationale for consideration of government intervention. Two important sources of market failure to consider when assessing the role of government in encouraging technology R&D, adoption and transfer are the presence of positive externalities (spillover or third party effects) and risk.

In general, externalities occur as a byproduct or side effect of an economic activity. For example, a positive externality occurs when the actions of a firm have a positive impact on others (third parties) where these impacts are not fully reflected in the price of the good or service. Investment in knowledge or information by a firm is likely to result in positive externalities through the public good characteristics of information. A public good is nonrivalrous and nonexcludable. Information is nonrivalrous because consumption by one firm does not affect consumption of the information by another firm. Information is nonexcludable if it is not possible to allocate property rights or enforce these property rights at reasonable cost.

Two sources of positive externalities in the technology innovation process are:

- positive externalities in R&D activity — at the R&D stage, as noted earlier, a private firm is likely to invest in acquiring information provided the benefits of the information to the firm over time are assessed to exceed the costs and risks of the investment. The profitability assessment does not take into account any benefits that cannot be captured by the firm.
- positive externalities through learning by doing — in subsequent stages of the technology innovation process, particularly for technology followers, positive externalities arise as the costs and risks of technology adoption tend to be reduced somewhat through learning by doing effects. The flow-on benefits from learning by doing require the information to be passed on to others.

Compared with the optimal outcome, there is likely to be a shortfall in private investment in technology R&D, adoption and transfer owing to the presence of these positive externalities. Profit incentives to invest in the technology innovation process are further reduced by the presence of risk. The combination of positive externalities and relatively high risks is likely to be most significant for the shortfall in private investment in R&D projects.

### *policy options*

Ideally, to provide an economic assessment of the role of government, policy options that address significant sources of market failure need to be identified and ranked, where feasible, according to the expected net economic benefits, including implementation costs. Only policy options that are expected to result in positive net economic benefits should be considered for implementation. From an economic perspective, the policy option that is expected to achieve the highest net economic benefits is the preferred policy option.

In practice, a range of policy options may be implemented to address an identified market failure. It is often useful to distinguish between policy options that encourage R&D in new and enhanced technologies and policy options that encourage technology adoption and transfer (see, for example, Hogan et al. 2007). These policies may also be referred to as technology push policies and market pull policies, respectively, in the technology innovation process and a mix of these policy approaches may be adopted in practice (figure g; Grubb 2007). It should be noted that policies that encourage investment in R&D tend to result in higher rates of technology adoption and transfer and, conversely, policies that encourage technology adoption and transfer provide economic incentives that tend to result in increased investment in R&D:

- encouraging R&D (technology push policies or supply side policies) — there are several policy options that encourage R&D activity by providing greater economic incentives for industry investment in R&D (by reducing the costs and/or risks of the activity) and through direct support for public investment in R&D (including publicly funded R&D projects and public–private partnership arrangements). Policy options to encourage investment in R&D include: intellectual property rights (for example, patents, trademarks and copyright); government support for R&D through grants, subsidies and tax incentives; and joint ventures between private companies and/or public research organisations (for example, a joint venture partnership is an important mechanism to share the costs and risks of an economic activity between different partners as well as providing private partners with direct learning by doing benefits).
- encouraging technology adoption and transfer (market pull policies or demand side policies) — there are several policy options that encourage technology adoption and transfer by providing greater economic incentives for industry investment in new and enhanced technologies. Examples of policy options to encourage investment in technology adoption and transfer include: setting government technology and performance standards (including energy efficiency standards); government support for technology adoption through grants, subsidies and tax incentives; and joint ventures.

Grubb (2007) discussed the role of publicly funded RD&D (research, development and demonstration) projects and the transition to privately financed operations. In the current study, the market engagement programs identified by Grubb (2007) are most relevant. Market engagement programs aim to move a trial technology from public R&D funding to engagement with the private sector and include:

- technology incubators — these are government funded organisations that specialise in developing private firms out of public based research.
- acceleration programs — these programs field test technologies to debug the technologies and reduce the costs and risks to private investors.

Some key economic aspects of the technology innovation process in the world titanium market are discussed in the remainder of this chapter.

# technology innovation process in the world titanium market

Information on the titanium supply chain and current R&D projects on titanium production processes was provided in chapter 2. A broader focus on the technology innovation process in the world titanium market is presented in this section, including some discussion of the economic incentives on the supply side and demand side of the market.

## key directions in technology development and deployment

The technology innovation process in the world titanium market has focused on three main areas:

- quality characteristics of titanium metal
- production costs
- fabrication costs.

Titanium metal is used both in its commercially pure (CP) form and in several titanium based alloys that have been developed to meet the quality requirements for specific end use applications (DISR 2001b). CP titanium is composed of a minimum of 99.2 per cent titanium plus elements such as oxygen, nitrogen, carbon and iron, and titanium based alloys contain 2–20 per cent or more of aluminium, vanadium, tin, chromium and/or zirconium (DISR 2001b). CP titanium, which generally has lower tensile and yield strengths than the titanium based alloys, accounts for around 30 per cent of titanium mill products — CP titanium is used extensively in industrial applications where corrosion resistance is a major quality requirement (Norgate and Wellwood 2006; also see box 1).

As indicated in chapter 2, two production technologies have been commercialised in the world titanium industry — the Kroll process and the Hunter process. The Kroll process is used to produce titanium sponge that generally has a titanium content of between 99.2 per cent and 99.8 per cent (Roskill 2006). The Hunter process was developed to produce higher quality sponge for aerospace applications. Over time, however, with improvements to the Kroll process and better melting techniques, the quality of titanium sponge has become less critical and all the major producers now use the Kroll process (Roskill 2007). Technological change in the industry has been mainly characterised by incremental improvements in the production process, with production costs also reduced through economies of scale and learning by doing effects (DISR 2001a; Roskill 2007).

The major focus of current R&D efforts in the world titanium metal industry is to achieve significant cost reductions in the production and fabrication of titanium metal rather than to develop titanium based alloys with enhanced properties (Froes et al. 2007). The importance of the production and fabrication stages in the industry's cost structure is indicated in table 11. The development and deployment of technologies that reduce titanium production and processing costs would enhance the cost competitiveness of titanium relative to substitutes such as steel and aluminium (see also box 1).

Both the Kroll and Hunter production technologies are relatively high cost batch processes and subsequent fabrication of parts involve an average wastage of 40 per cent (Roskill 2007). An important objective in current R&D activity is to develop a continuous production process for titanium metal to substantially reduce production costs (see chapter 2). In several of these R&D projects, including the TiRO/CSIRO project, titanium metal is produced in powder form (table 2). Powder metallurgy (PM) techniques in which items are directly fabricated from titanium powder may be utilised to reduce fabrication costs (Norgate and Wellwood 2006). Examples of near net shape applications using castings and PM techniques that have the potential to reduce fabrication costs are provided in Froes et al. (2007).

## implications of technology development and deployment for end use applications of titanium metal

The development and deployment of a new titanium production process is likely to lower industry costs, reduce the world price of titanium and increase titanium consumption in end use applications. The responsiveness of demand to a price fall is likely to vary between different current and potential end use applications. The long term adjustment of the world titanium market to technological change is illustrated in box 3 using a simplified graphical approach.

There are four different end use applications in the world titanium market:

- established end use application with no demand response
- established end use application with a demand response
- developing end use application
- new end use application.

### 11 recent comparison of the cost of titanium and selected substitute metals contract prices, year not specified

| | titanium a | steel | aluminum |
|---|---|---|---|
| | US$/lb | US$/lb | US$/lb |
| ore | 0.22 | 0.02 | 0.10 |
| metal | 5.44 | 0.10 | 1.10 |
| ingot | 9.07 | 0.15 | 1.15 |
| sheet | 15.00-50.00 | 0.30-0.60 | 1.00-5.00 |

a The ore price is for rutile and the metal price is for titanium sponge. The corresponding price of $TiCl_4$ is US$1.00/lb.
*Source*: Froes et al (2007).

## box 3 illustrative impact of technological change in the world titanium market

In this box, a simplified graphical analysis is used to illustrate some key aspects of the long term adjustment in the world titanium market to technological change.

*world titanium market*

The long run adjustment in the world titanium market to technology development and deployment is illustrated in figure i. The development and deployment of a significant production technology in the world titanium metal industry reduces the long run marginal cost of production — the industry's supply curve — from $S_1$ to $S_2$.

The world titanium demand curve represents the marginal benefit of titanium in all end use applications and is given by *D* — the industry's demand curve. This is derived by summing horizontally the individual demand curves for different end use applications (the implied scale on the horizontal axis in the figure differs from the scale in other figures in this box).

Prior to the adoption of the new technology, the world titanium market is in equilibrium at the titanium price, $P_1$, where the supply curve intersects the demand curve — at this point, world titanium production, which is assumed to be equal to world titanium consumption, is given by $Q_1$. Following the adoption of the new technology, the world titanium price falls to $P_2$ and world titanium production and consumption increases to $Q_2$. Overall, the world titanium metal price is reduced and titanium is more competitive with substitute metals in end use applications — that is, there is a fall in the price premium of titanium over substitute commodities and an increase in world titanium consumption. The net economic benefits of the technological change are indicated by the shaded area in the figure (this is equal to the net increase in the consumer surplus and producer surplus where the producer surplus may be interpreted as incorporating the return to the mineral resource).

*impact of a world titanium price fall on demand in different end use applications*

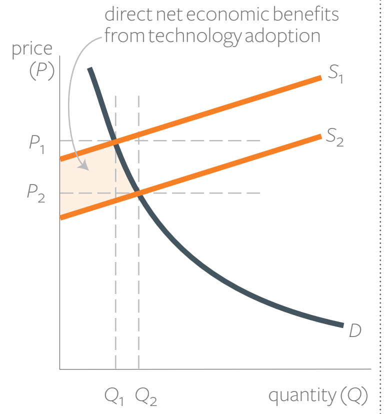
The price responsiveness of titanium demand — that is, the extent to which titanium consumption increases as a result of the price fall — varies between different end use applications. The impact of technological change on four established and potential end use markets, referred to as applications A to D inclusively, is illustrated below.

*1. established end use application A, no demand response*

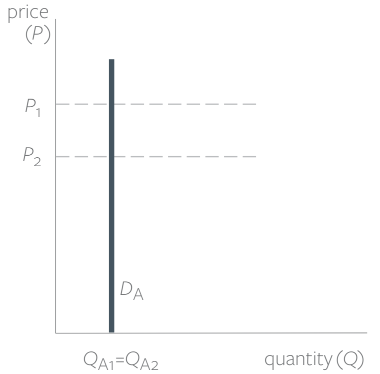
End use application A is assumed to be an established titanium market segment where there is no demand response following a titanium price fall — that is, titanium use is unaffected by price in this market segment. In figure ii, demand in end use application A is given by the vertical curve $D_A$ — the demand curve represents the marginal benefit of titanium in the end use application. Prior to the adoption of the new technology, this market segment demands titanium up to the point where the titanium price, $P_1$, intersects the demand curve — that is, titanium consumption is given by

*continued...*

i world titanium market

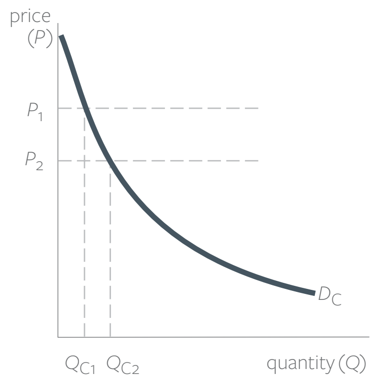



ii established end use application A, no demand response



iii established end use application B, with demand response


iv developing end use application C




v new end use application D


## box 3 illustrative impact of technological change in the world titanium market *continued*

$Q_{A1}$ in end use application A. Following the adoption of the new technology, the world titanium price falls to $P_2$ but titanium consumption is unchanged — that is, $Q_{A1} = Q_{A2}$ in end use application A.

This case may be broadly indicative of aerospace applications where titanium is a relatively small cost component in the construction of commercial and military aircraft. One factor that will influence the outcome in practice is the extent to which new technologies reduce the price of the very high quality titanium metal required in aerospace applications. The main focus of R&D projects is to reduce the cost of producing titanium for non-aerospace applications (Roskill 2007).

*2. established end use application B, with demand response*

End use application B is assumed to be an established titanium market segment where titanium consumption increases following a titanium price fall. In figure iii, demand in end use application B is given by the curve $D_B$. Titanium consumption in this end use application increases from $Q_{B1}$ to $Q_{B2}$ when the titanium price falls from $P_1$ to $P_2$ following the adoption of the new technology.

This case may be illustrative of industrial applications, such as tubing, where the benefits associated with the higher quality characteristics of titanium in the end use application is assessed against its price premium. The outcome for medical applications may fall between those illustrated for end use applications A and B, although this market segment is relatively small.

*3. developing end use application C*

End use application C is assumed to be a developing titanium market segment where titanium consumption is still relatively small but has the potential to increase significantly following a titanium price fall. In figure iv, demand in end use application C is given by the curve $D_C$. Titanium consumption in this end use application increases from $Q_{C1}$ to $Q_{C2}$ when the titanium price falls from $P_1$ to $P_2$ following the adoption of the new technology.

This case may be indicative of cookware applications if the titanium price falls sufficiently for titanium cookware to be cost competitive in the high quality end of the consumer market. Similarly, the use of titanium in architecture, building and construction has the potential to expand considerably depending on the extent of the price fall.

*4. new end use application D*

End use application D is assumed to be a new titanium market segment where titanium is not currently used but has the potential to be cost competitive following a titanium price fall. In figure v, demand in end use application D is given by the curve $D_D$. Titanium consumption in this end use application increases from zero to $Q_{C2}$ when the titanium price falls from $P_1$ to $P_2$ following the adoption of the new technology (that is, $Q_{C1} = 0$).

This case may be indicative of automotive applications, such as automotive exhaust systems, if the titanium price falls sufficiently for titanium to be cost competitive with stainless steel systems.

For example, aerospace is an important established end use application, accounting for 38 per cent of world consumption of titanium mill products in 2005 (table 3). Detailed long term projections for the world commercial aerospace industry by Boeing and Airbus indicate passenger traffic growth rates may increase at an average annual rate of around 5 per cent in the twenty years to 2025 (Airbus 2006; Boeing 2006; Roskill 2007). Demand for titanium will increase with the projected growth in the world aircraft fleet, although a significant fall in the price of titanium may not significantly alter this growth path. In addition, there is some uncertainty about the extent to which technological change will result in lower prices for the very high quality titanium metal required in aerospace applications — the main focus in R&D projects is to achieve significant cost reductions in producing titanium for non-aerospace applications (Roskill 2007).

By contrast, industrial applications are an important established end use market for titanium mill products that are likely to be more price responsive than aerospace applications (Roskill 2007). Industrial applications of titanium include a wide range of uses in the chemical/petrochemical, power, oil and gas, water supply, automotive, marine and construction industries. In 2005, industrial applications accounted for 49 per cent of world consumption of titanium mill products in 2005 (table 3).

Several end use applications for commercially pure (CP) titanium that have the potential to expand significantly, particularly with a lower world titanium price, are discussed in Norgate and Wellwood (2006):

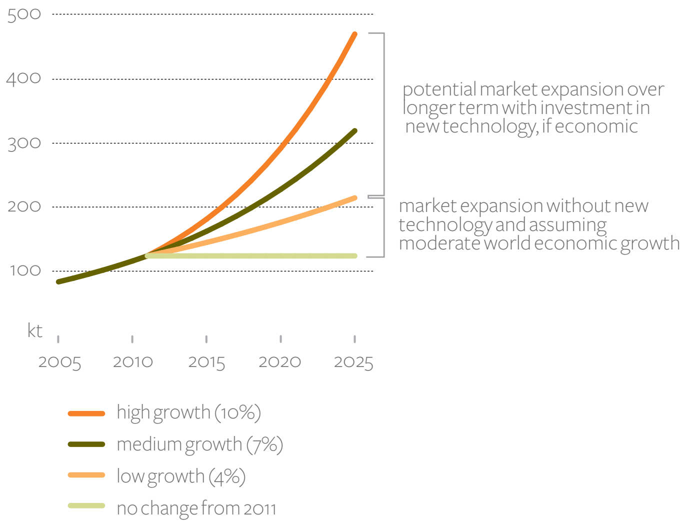
- tubing — CP titanium is currently widely used in tubing applications in, for example, power plants and heat exchangers. The quality advantages of titanium in these applications include corrosion resistance and long life. Demand for titanium in these applications has the potential to increase significantly with a lower titanium price.
- medical implants — medical implants currently represent a small end use market for titanium. Despite its relatively high price, titanium is used in surgical components because it has proved to be completely inert and is more compatible with body fluids and tissues than other metals (Roskill 2007). Demand for CP titanium in medical implants is likely to increase strongly over time, particularly with aging populations in industrialised economies, and a fall in the price of titanium may result in a slightly stronger growth path. The discovery of a CP titanium with a higher strength would expand the potential uses of titanium in medical implants.
- architecture, building and construction — titanium is currently used in relatively small quantities in architecture, building and construction applications reflecting its low density and weight, attractive appearance, good corrosion resistance and minimal maintenance needs. For example, in Japan, titanium has been used in hundreds of buildings, mainly near the sea, because of the corrosive environment. Demand for titanium in these applications has the potential to increase significantly with a lower titanium price.

- cookware — cookware is currently a small end use market for titanium. Titanium has the potential to compete with stainless steel in the high quality end of the market. Demand for CP titanium in cookware has the potential to increase significantly with a lower titanium price.
- automotive exhaust systems — there is potential for CP titanium to fully replace stainless steel in this application. Two quality characteristics of titanium are important in this application — corrosion resistance increases the lifetime of exhaust systems, reducing or avoiding the replacement costs associated with other systems, and a titanium exhaust system would be up to 50 per cent lighter than the alternative, increasing the fuel efficiency of the motor vehicle. Titanium will be cost competitive with the substitute metal in this application if the price premium for titanium does not exceed the benefits associated with the higher quality titanium exhaust systems.

It is apparent from the above discussion that there are major uncertainties in the long run outlook for the world titanium market. On the supply side, major uncertainties include the timing and extent of the development and deployment of any new production and fabrication technologies, and the impact of these technologies on industry costs. On the demand side, there are major uncertainties about the extent to which demand in various end use applications will increase in response to a lower world titanium price.

Three long run growth scenarios for world titanium consumption in end use applications are presented in figure h (this outlook assessment draws on information provided in Roskill 2007 and Holz 2006). Over the medium

**h** long term growth scenarios for world titanium consumption in end use applications



term, between 2005 and 2011, world consumption of titanium mill products is forecast to continue to increase strongly at an average annual rate of 6.8 per cent (see table 8 in chapter 4). Over the longer term, between 2011 and 2025, world titanium consumption is projected to increase at an average annual rate of 4 per cent in the low growth scenario, 7 per cent in the medium growth scenario and 10 per cent in the high growth scenario.

The growth scenarios presented in figure h represent a relatively conservative set of possible long run growth paths for world titanium consumption. The low growth scenario represents a relatively pessimistic outlook that is achievable without the deployment of new technologies and assuming moderate world economic growth over the longer term. The medium and high growth scenarios represent long term growth paths that allow for the deployment of new technologies assuming these are found to be economic. The high growth scenario allows for technology development and deployment to have a greater impact on the long run growth path for world titanium consumption although the penetration of titanium into new markets or end use applications is still assumed to be limited in this outlook scenario.

The final outcome for the future expansion of the world titanium market will be influenced by the extent to which international titanium R&D efforts result in new technologies that reduce titanium production and fabrication costs and, if economic, the timing of the uptake of these technologies.

The introduction of policies to limit greenhouse gas emissions is also likely to have a significant impact on the long run outlook for the world titanium market, although only some general comments are noted here. A significant new titanium production technology, if adopted, is likely to result in lower energy costs than would otherwise be the case (with or without a greenhouse gas policy response). The energy efficiency of established titanium plants varies widely — in particular, Japan has relatively energy efficient plants compared with those in China (Roskill 2007). The introduction of greenhouse gas policies is likely to increase the cost competitiveness of any new titanium production technology compared with the established technology, but the critical cost comparison should be with Japan's established plants.

The production processes for titanium and its key substitutes tend to be relatively energy intensive. As a consequence, the introduction of greenhouse gas policies would place upward pressure on the prices of these products. Historically, the use of titanium in aerospace applications has been cost effective since its high strength to weight ratio resulted in lower fuel costs. Under greenhouse gas policies, to the extent that energy prices are higher than would otherwise be the case, there may be further switching toward titanium in end use applications that value these quality attributes. A detailed assessment of the net impact of these supply side and demand side influences on the world titanium market is beyond the scope of this study.

# 6 implications for the tiro pilot plant project and an australian titanium metal industry

The role of government in encouraging the further development and possible commercialisation of the TiRO process and the potential development of an Australian titanium metal industry is examined in this chapter. An initial assessment of the TiRO/CSIRO R&D project that was undertaken by ACIL Tasman in 2006 is presented first. Several further issues are then discussed, with a focus on the potential role of the Australian Government in facilitating the technology innovation process in the titanium market and in enhancing prospects for the development of an Australian titanium metal industry.

## acil tasman estimates of the value of the tiro/csiro r&d project

In October 2006, ACIL Tasman released an initial assessment of CSIRO's 'light metals flagship' (LMF) research program (ACIL Tasman 2006). The five themes in the LMF program are alumina, aluminium, magnesium, aluminium and magnesium manufacturing, and titanium.

As given in ACIL Tasman (2006, pp. 37–8), the 'main goal of the titanium theme is to establish a 20 000 tonne per annum titanium metal industry in Australia by 2012. The theme is split into three streams. These are:

- to optimise Australia's resource base
- to develop continuous scaleable metal production technologies and
- to establish new markets through low cost fabrication technologies.'

The focus in this section is on ACIL Tasman's assessment framework and estimates of the value of TiRO, the CSIRO patented technology for producing commercially pure titanium. ACIL Tasman notes that the assessment framework used in the report aims to provide conservative estimates of the value of an R&D program from the bottom up. The assessment framework for the TiRO/CSIRO R&D project, based on ACIL Tasman (2006), is presented in table 12.

# 12 simplified sequence of possible outcomes from the tiro/csiro r&d project

| variable a | unit | 1 | 2 | 3 | 4 | 5 | 6 | total b |
|---|---|---|---|---|---|---|---|---|
| **simplified decision tree** | | | | | | | | |
| | | tiro/csiro r&d project | | | | | | |
| ENPV | | $107.17m | | | | | | |
| Pr | | 0.15 | 0.85 | | | | | |
| | | abandon | invest in pilot plant | | | | | |
| K, T | | | $10m, 2 years | | | | | |
| ENPV | | | $126.08m | | | | | |
| Pr | | | 0.4 | 0.6 | | | | |
| | | | abandon | invest in demonstration plant | | | | |
| K, T | | | | $32.4m, 2 years | | | | |
| ENPV | | | | $215.64m | | | | |
| Pr | | | | 0.3 | 0.7 | | | |
| | | | | not viable abandon | viable technology | | | |
| ENPV | | | | | $314.47m | | | |
| Pr | | | | | 0.5 | 0.5 | | |
| | | | | | not cost competitive with overseas technology abandon | no better overseas technology (or no overseas technology) | | |
| ENPV | | | | | | $643.89m | | |
| Pr | | | | | | 0.5 | 0.5 | |
| | | | | | | abandon | invest in commercial plant | |
| K, T | | | | | | | $146.9m, 2 years | |
| ENPV | | | | | | | $1 302.74m | |
| **ENPV calculations for the r&d and pilot plant projects** | | | | | | | | |
| **tiro/csiro r&d project** | | | | | | | | |
| Pr | no. | 0.15 | 0.34 | 0.15 | 0.18 | 0.09 | 0.09 | 1.00 |
| NPV | $m | 0.00 | –8.26 | –14.96 | –14.96 | –14.96 | 1302.74 | – |
| Pr*NPV | $m | 0.00 | –2.81 | –2.29 | –2.67 | –1.34 | 116.27 | – |
| ENPV | $m | – | – | – | – | – | – | 107.17 |
| **pilot plant based on the tiro process** | | | | | | | | |
| Pr | no. | – | 0.40 | 0.18 | 0.21 | 0.11 | 0.11 | 1.00 |
| NPV | $m | – | –8.26 | –14.96 | –14.96 | –14.96 | 1302.74 | – |
| Pr*NPV | $m | – | –3.30 | –2.69 | –3.14 | –1.57 | 136.79 | – |
| ENPV | $m | – | – | – | – | – | – | 126.08 |

a Pr=probability, K=capital cost, T=no. years to complete investment phase, NPV=net present value, ENPV=expected net present value. See ACIL Tasman (2006) for further information. b Probabilities of possible outcomes sum to 1.00. ENPV is the probability weighted sum of the net present values of possible outcomes.
Source: Based on ACIL Tasman (2006).

## tiro/csiro r&d project

ACIL Tasman (2006) assessed the value the TiRO/CSIRO R&D project where a successful outcome is investment in a commercial plant in Australia. ACIL Tasman (2006) identified three key investment stages in the successful progress of the TiRO/CSIRO R&D project to the development of an Australian titanium metal industry:

- pilot plant — the aim is to test the technology in a pilot plant over a two year period at an assumed cost of $10 million
- demonstration plant — the aim is to confirm the scalability of the technology in a demonstration plant with an annual production capacity of 1500 tonnes; this phase is assumed to take two years to complete and cost around $32 million
- commercial plant — the aim is to construct a commercial plant with an annual production capacity of 20000 tonnes; the construction phase is assumed to take two years to complete and cost around $147 million.

Six possible outcomes from the TiRO project are considered in the simplified decision tree presented in the first part of table 12:

- possible outcome 1 — the TiRO project is abandoned (15 per cent probability of this outcome occurring)
- possible outcome 2 — the TiRO project proceeds to the pilot plant stage to test the technology but is then abandoned (34 per cent probability)
- possible outcome 3 — the TiRO project proceeds to the demonstration plant stage to confirm the scalability of the technology but is then abandoned (15 per cent probability)
- possible outcome 4 — the demonstration plant indicates that the TiRO process is viable but is abandoned as it is not cost competitive with an overseas technology (18 per cent probability)
- possible outcome 5 — the demonstration plant indicates that the TiRO process is viable and there is no overseas technology but is abandoned (9 per cent probability)
- possible outcome 6 — the TiRO project proceeds to the commercial plant stage (9 per cent probability of success).

The variables listed in the first column of table 12 are defined in the footnote and are consistent with those used in the economic framework for investment decisions presented in box 2. It should be noted that ACIL Tasman (2006) uses slightly different terminology — net present value (NPV) is referred to by ACIL Tasman as the net return in NPV terms and the expected net present value (ENPV) is referred to as the weighted average value in NPV terms. The two approaches are identical if the discount rate used by ACIL Tasman is assumed to be the risk free interest rate — in this case, the

ENPV is the appropriate profitability measure for a risk neutral investor. If the discount rate incorporates a risk premium, however, the weighted average value in NPV terms is an approximation of the certainty equivalent value (CEV) of the project (that is, a risk adjusted valuation) — the CEV is an appropriate profitability measure for a risk averse investor. In table 12, the discount rate is assumed to be the risk free interest rate and the weighted average value in NPV terms is assumed to be equal to the ENPV.

The net present value of each possible outcome and calculations for the expected net present value is provided in the second part of table 12 for the TiRO/CSIRO R&D project. As indicated above, there is a 9 per cent probability of success in establishing a commercial plant in Australia based on the TiRO process — the net present value of this outcome is $1303 million. The expected net present value of the TiRO/CSIRO R&D project is $107 million.

## tiro pilot plant project

The ACIL Tasman estimates have been used to derive the expected net present value of the pilot plant project. It is assumed that the decision is whether to proceed with the investment in the pilot plant to test and debug the TiRO technology or not. In this case, there are five possible outcomes with an 11 per cent probability of success in establishing a commercial plant in Australia. The expected net present value of the pilot plant project is estimated to be $126 million.

A risk averse investor in the pilot plant would need to assess the risk profile of the possible outcomes including:

- a 40 per cent probability that the pilot plant will be abandoned, with a loss of $8 million in NPV terms
- a 49 per cent probability that the project will subsequently be abandoned before the commercialisation stage, with a loss of $15 million in NPV terms
- an 11 per cent probability that a commercial plant will be established, with a profit of $1.3 billion in NPV terms.

In practice, a private investor would undertake a more detailed risk assessment of the profitability of the commercial plant, particularly given the market risks associated with the project. The risk adjusted value of the pilot plant, or the certainty equivalent value (CEV), would be lower than the ENPV by the risk premium that is required to compensate the private investor for the risks associated with the project.

# further issues in the economic assessment of the tiro pilot plant project

It is important to distinguish between the assessed private net economic benefits of an investment project (risk adjusted profitability or certainty equivalent value, CEV) and the expected social net economic benefits (expected social net present value, $ENPV_S$), the key criterion used to evaluate public investment options. The presence of positive externalities and risk results in a divergence between private and social net returns. Government involvement in the pilot plant based on the TiRO process would be justified if:

- private investors, taking into account potential risks, assess the project to be unprofitable (that is, CEV < 0) and
- the government assesses the expected social net economic benefits of the project to be non-negative (positive or zero) — that is, the private risk premium and/or positive externalities are expected to be sufficiently large to provide a social net return on the public investment (that is, $ENPV_S > 0$) and
- the government ranks the project against alternative public investment options and assesses there would be merit in proceeding with the project.

The CSIRO project on the TiRO process represents a significant public investment in R&D on a new production technology in the titanium metal industry. The key issue for the Australian Government at this stage is whether it has a role in supporting the R&D project to the pilot plant stage. An economic assessment of this investment decision cannot provide the Australian Government with an unambiguous policy recommendation because the final assessment of the policy options relies to some extent on the subjective judgment of the government. Instead, the approach taken in this report is to analyse relevant issues in an economic framework that will assist the Australian Government in formulating its policy response.

Some key implications from the economic analysis in chapter 5 of this report include the following:

- **investment in the pilot plant represents an extension of the R&D project that involves testing and debugging the TiRO process** — this is part of the technology RD&D (research, development and demonstration) phase.
- **consideration of policy intervention to support technology RD&D is justified on economic efficiency grounds** — this phase in the technology innovation process is a relatively high risk activity that provides flow on benefits to others. The presence of market failures, including positive externalities and risk, is the main economic justification for consideration of government support for technology development and deployment.

- the technology push policy approach emphasises R&D led innovation — R&D activity is encouraged by providing greater economic incentives for industry investment in R&D by reducing the costs and/or risks of the activity and through direct support for public investment in R&D. In this approach, policy options such as publicly funded R&D projects, public 'proof of concept' demonstration projects and associated public–private partnerships aim to address market failures.

ACIL Tasman (2006) provided a useful assessment of the TiRO project based on a simplified decision tree. This analysis indicates the direct net economic benefits of the pilot plant project are expected to be positive (details of the underlying assumptions are not available and, hence, the estimates should possibly be interpreted with some caution). There are several further issues that merit consideration by the Australian Government since these influence the assessment of any positive externalities associated with the project.

**Australia's participation in the TiRO project increases the probability that the international research effort will be successful in discovering a major new technology that reduces production costs in the titanium metal industry.** Australia's role in this research is based on its relatively abundant ilmenite and rutile resources that, in processed form, are essential inputs to the production of titanium metal. Given the quality characteristics of titanium metal, there is also significant scope for future growth in world titanium consumption in both established and new end use applications (see chapter 5).

Australia's ongoing commitment to the TiRO project would further contribute to the international research effort that currently comprises twenty R&D projects, four of which are supported by the US Government. The impact that multiple independent R&D projects may have on the probability of success in discovering a new economic technology is indicated in table 13. The probability of success for an international R&D effort is provided under the simplifying assumption that the probability of success for each individual R&D project is 1 per cent, 5 per cent or 10 per cent. International R&D activity is assumed to comprise between one and twenty individual projects.

Multiple independent R&D projects can have an important impact on the probability of success in discovering a new economic technology. For example, if the probability of success for each R&D project is 5 per cent, the probability of discovering a new economic technology increases from 5 per cent for one project to 23 per cent for five projects and 64 per cent for twenty projects. If the probability of success for each individual project is 10 per cent, which is close to ACIL Tasman's (2006) assessment for the TiRO project, an international effort comprising twenty independent projects has an 88 per cent probability of discovering a new economic technology.

If Australia is successful in commercialising the TiRO process, economic benefits may include:

- the development of a titanium metal industry in Australia — this would represent an investment in a value adding economic activity, with economywide impacts such as an increase in the value of Australia's exports.
- royalty payments from intellectual property rights — TiRO is a CSIRO patented technology that would result in royalty payments if it is used in commercial operations in Australia and/or overseas.
- increased competition in the world titanium market — in 2006, titanium sponge was produced in six countries by a total of fourteen companies (see table 1). There have been concerns in the past about the extent to which established companies may have used excess capacity as a barrier to entry to new firms, although the empirical evidence is mixed (see, for example, Koscianski and Mathis 1996). With excess capacity, firms can increase production in the short term to reduce prices and make it unprofitable for new firms to enter the industry, a practice that is referred to as predatory pricing. As a result of strong growth in demand in recent years, world capacity utilisation has increased from 60 per cent in 2000 to 95 per cent in 2006 (see chapter 3 for further information).
- increased diversification in the geographic location of titanium production facilities — the development of an Australian titanium metal industry would reduce supply risks in the world titanium market

## 13 indicative probability outcomes for an international research effort comprising one or more independent r&d projects [a]

| | probability of success for each individual r&d project | | | | | |
|---|---|---|---|---|---|---|
| | 0.01 | | 0.05 | | 0.10 | |
| no. of independent r&d projects | success | failure | success | failure | success | failure |
| | no. | no. | no. | no. | no. | no. |
| 1 | 0.01 | 0.99 | 0.05 | 0.95 | 0.10 | 0.90 |
| 2 | 0.02 | 0.98 | 0.10 | 0.90 | 0.19 | 0.81 |
| 3 | 0.03 | 0.97 | 0.14 | 0.86 | 0.27 | 0.73 |
| 4 | 0.04 | 0.96 | 0.19 | 0.81 | 0.34 | 0.66 |
| 5 | 0.05 | 0.95 | 0.23 | 0.77 | 0.41 | 0.59 |
| 10 | 0.10 | 0.90 | 0.40 | 0.60 | 0.65 | 0.35 |
| 15 | 0.14 | 0.86 | 0.54 | 0.46 | 0.79 | 0.21 |
| 20 | 0.18 | 0.82 | 0.64 | 0.36 | 0.88 | 0.12 |

**a** Each probability, Pr, is presented as a number between 0 and 1, but is referred to in percentage terms in the text — for example, 0.01 is equal to a probability of 1 per cent. **Success** is the probability that at least one R&D project in the international research effort will discover a new economic technology and **failure** is the probability that no R&D project will discover a new economic technology where success+ failure=1.00.

by extending the range of geographic locations involved in titanium production.

If the TiRO process is not successful at the pilot plant or demonstration plant stages, an alternative path to the development of an Australian titanium metal industry may be to import a successful technology. The likelihood that Australia would have a competitive advantage in titanium metal production under a new technology is likely to be enhanced since private partners in the TiRO technology innovation process would benefit through learning by doing effects. This experience would also allow private investors to undertake a more accurate assessment of the profitability of alternative titanium investment options than would otherwise be the case.

In summary, information has been presented in this report to assist the Australian Government in its assessment of whether to support the TiRO/CSIRO R&D project to the pilot plant stage. It is beyond the scope of this study to provide the Australian Government with an unambiguous policy recommendation because the final assessment of the investment decision relies to some extent on the subjective judgment of the government. Should the government decide to invest in the TiRO pilot plant project, this is likely to enhance prospects for the development of a titanium metal industry in Australia. A domestic industry may be established through the commercialisation of the TiRO process or, if this technology proves to be not viable, by importing a successful technology.

appendix

# A kroll and tiro production processes

Industrial production of titanium started in the early 1950s. Only two titanium production processes have been commercialised — the Hunter process and the Kroll process. The Alta Group's 500 tonne a year plant in the United States is the only facility that still uses the Hunter process.

## the kroll process

The Kroll process is a batch process that was developed in 1940 and involves a number of steps, some of which are labour intensive and all of which are discrete (figure i). A batch of approximately 10 tonnes takes around two weeks to complete. The process is also energy intensive owing to the high temperatures required in some of the steps.

The initial feedstock for the Kroll process is titanium dioxide ($TiO_2$) of at least 85 per cent purity — this is most commonly synthetic rutile. Once the titanium dioxide has been purified, it is combined with chlorine gas and high purity coke at 1000°C. This reaction produces titanium tetrachloride ($TiCl_4$), which must then be distilled.

The purified $TiCl_4$ is added to a steel reactor that contains magnesium and has been sealed, evacuated and filled with inert argon gas. The introduction of the $TiCl_4$ is a gradual process in order to maintain a temperature in the reactor of 850–950°C. If the temperature falls below 712°C the magnesium chloride solidifies, while if the temperature rises above 1025°C the titanium will begin to react with the iron present in the reactor itself.

Over a number of days, liquid magnesium forms and floats over a layer of magnesium chloride while a spongy mass of titanium accumulates on the floor of the reactor. The reaction consumes the magnesium and produces magnesium chloride, which is periodically removed and reprocessed into pure magnesium and chlorine.

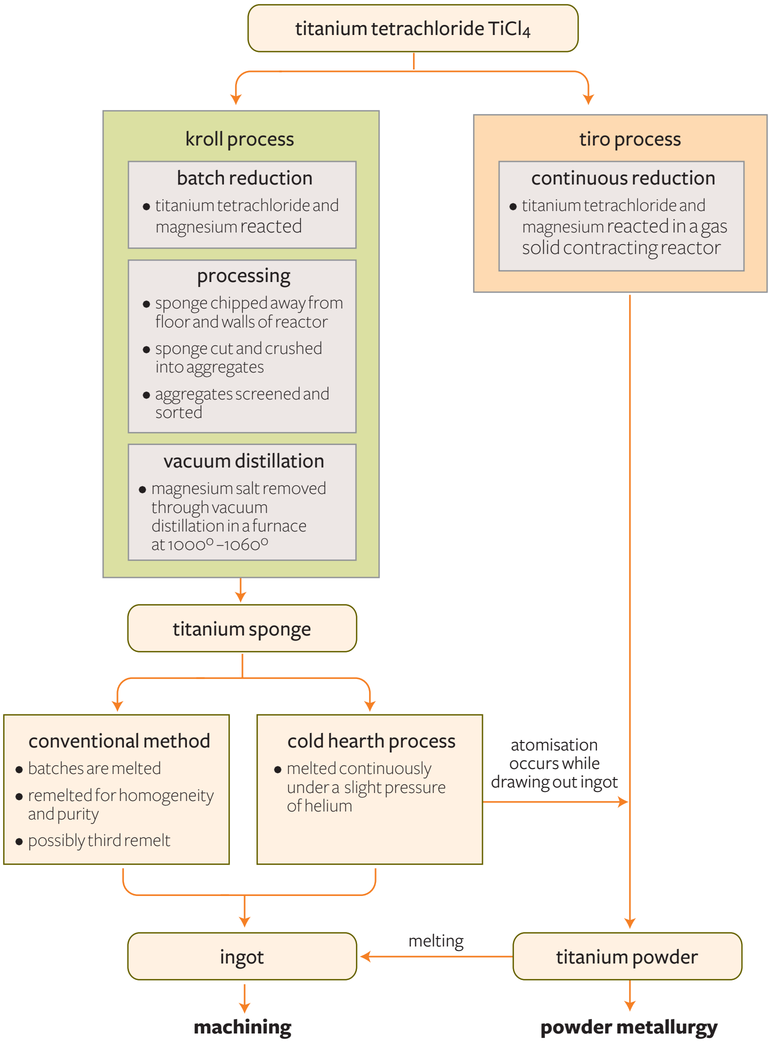
After the mixture is cooled, the sponge is jack hammered from the floor and walls of the reactor. It is then put through a process where it is first cut with a guillotine, then a shearing machine and then crushed with a jaw crusher.

Finally, the processed sponge must be purified to remove any remaining magnesium salts. This is commonly done using vacuum distillation. Vacuum distillation takes place over 85 hours at temperatures between 1000 and 1060°C.

From this point the sponge must be melted to produce ingot. Scrap and waste products are also added to the melt at this stage and make up a significant proportion of inputs.

In the traditional approach the sponge is melted up to three times, depending on the desired level of purity, to produce ingot. A newer approach, the cold hearth process, melts sponge under pressure from helium. The cold hearth process produces some titanium powder as a byproduct of drawing out the ingot. This titanium powder can be remelted into ingot or processed into finished products using powder metallurgy.

## i the kroll and tiro processes



## the tiro process

CSIRO has recently developed the TiRO process as an alternative method for producing titanium. It relies on the same chemistry as the Kroll process but allows $TiCl_4$ to be turned directly into titanium powder.

In the TiRO process, $TiCl_4$ is reacted with magnesium in a gas–solid contacting reactor. The reaction is slow at the start but as liquid magnesium chloride begins to form it is able to host the reaction and increase the reaction speed. TiRO uses a narrow operating temperature window of 62°C to allow the process to take place in a fluid bed reactor. In fluidised bed reduction solid particles are suspended in gas and behave like a fluid. This technique allows for the production of titanium powder in a continuous not a batch manner.

As titanium powder, and not titanium sponge, is produced, many of the interim steps from the Kroll process are avoided. These include the labour intensive removal of sponge from the reactor and the cutting, crushing and vacuum distillation of the sponge.

The TiRO process also permits flexibility in the shape and size of the particles it produces. This allows the packing density, surface area and roughness of particles to be altered to suit different needs.

The current TiRO process operated on the laboratory scale is producing metal with an oxygen content that is above the 0.25 per cent mandated for grade 2 commercially pure titanium, the goal of the project. Promising research addressing this issue is in progress and the CSIRO believes that this problem can be fixed in a larger scale pilot plant (CSIRO 2006).

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