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| **Institution:** University of Cambridge | | |
| **Unit of Assessment:** UoA12 | | |
| **Title of case study:** Recycling inert gases in manufacturing processes | | |
| **Period when the underpinning research was undertaken:** 2006-2012 | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** | **Role(s) (e.g. job title):** | **Period(s) employed by submitting HEI:** |
| Professor J.S Dennis | Head of School of Technology Professor of Chemical Reaction Engineering | 1999 to present |
| Dr Stuart Scott | Reader in Energy and Thermodynamics | 2004 to present |
| **Period when the claimed impact occurred:** 1.8.2013 to date | | |
| **Is this case study continued from a case study submitted in 2014?** No | | |

## 1. Summary of the impact (indicative maximum 100 words)

Fundamental research into solid-state oxygen carriers at the University of Cambridge has been used to develop a device – the ArgonØ™ – which cleans and recycles inert gases that are used particularly in the manufacture of silicon wafers for solar PV panels and microelectronic devices.

These noble gases are needed to provide an inert atmosphere during the manufacturing process. Manufacturers typically discard the contaminated gases after use but ArgonØ™ gives them a cost-effective means of cleaning and recycling them.

Gas Recovery and Recycle Ltd (GR2L) has to date exported more than 70 of its ArgonØ™ gas recycling units to six countries, generating GBP6,200,000 in revenues since 2017, making an estimated total saving for its customers in this period of USD37,000,000 and creating five to 10 jobs across the supply chain.

## 2. Underpinning research (indicative maximum 500 words)

The main research was undertaken at the University of Cambridge between 2006 and 2010 led by Professor John Dennis and Dr Stuart Scott. In conventional chemical looping combustion (CLC) a solid-state oxygen carrier is used to provide the oxygen that will combust the fuel. The oxygen carriers are used in a fuel reactor to oxidise a fuel to carbon dioxide and water and are then looped back into a second air reactor to be re-oxidised. The net effect is that the $CO_2$ is not contaminated with nitrogen from the air and, once the water is condensed and removed, can be sequestered in the earth or used as a process stream. This process has shown significant promise as a technique for carbon capture.

The research was concerned primarily with the performance of copper-based oxygen carriers at high temperatures, but in order to understand the underlying kinetic mechanisms the team also explored their behaviour at low temperatures. Initial experiments with pure copper oxide indicated that the oxygen-carrier needed to be supported. Alumina was trialled as a support using three different methods: mechanical-mixing, wet-impregnation and co-precipitation. The co-precipitated particles performed the best and it was discovered that they were surprisingly reactive with carbon monoxide and hydrogen even at temperatures as low as 250°C. [R1, R2, R3]

Between 2010 and 2013, Scott evaluated the reduction and oxidation of the co-precipitated material over many hundreds of cycles of reduction and oxidation in a packed bed reactor. [R4] describes how various packed beds of copper-based oxygen carriers were investigated over 100 cycles of low temperature (673 K) CLC with hydrogen as the fuel gas. The oxygen carriers were uniformly mixed with alumina in order to investigate the level of separation necessary to prevent agglomeration. It was found that a mass ratio of 1:6 oxygen carrier to alumina gave the best performance in terms of stable, repeatable hydrogen breakthrough curves over the 100 cycles. In order to quantify the average separation achieved in the mixed packed beds, two sphere-packing models were developed. Both models predicted that average 'nearest neighbour' particle separation drops to near zero for oxygen carrier mass fractions less than 0.25.

Scott’s work showed that copper oxide supported on alumina could be made into a stable and effective oxygen carrier which would be durable over many cycles of reduction and oxidation. [R4] It was this stability and durability, combined with its ability to reduce many fuel gases at temperatures as low as 250$^{o}$ C [R3] that led Dr Rob Grant, founder of GR2L, to identify a new commercial application for the research findings: decontaminating noble gases, such as argon. High purity argon (greater than 99.999%) is used as a shield gas to create an inert environment for the production of silicon ingots, which are then made into wafers for solar cells and microelectronic devices.

## 3. References to the research (indicative maximum of six references)


[R1] Chuang, S.Y., Dennis, J.S., Hayhurst, A.N. & Scott, S.A. (2008). Development and performance of Cu-based oxygen carriers for chemical-looping combustion. *Combustion and Flame*, **154**, 109-121. doi: 10.1016/j.combustflame.2007.10.005

[R2] Chuang, S.Y., Dennis, J.S., Hayhurst, A.N. & Scott, S.A. (2009). Kinetics of the chemical looping oxidation of CO by a co-precipitated mixture of CuO and $Al_2O_3$. *Proceedings of the Combustion Institute*, **32**, 2633-2640. doi: 10.1016/j.proci.2008.06.112

[R3] Chuang, S.Y., Dennis, J.S., Hayhurst, A.N. & Scott, S.A. (2010). Kinetics of the oxidation of a co-precipitated mixture of Cu and $Al_2O_3$ by $O_2$ for chemical looping combustion. *Energy & Fuels*, **24**, 3917-3927. doi:10.1021/ef1002167

[R4] Harper, Ryan N.; Boyce, Christopher M.; Scott, Stuart A. (2013). Oxygen carrier dispersion in inert packed beds to improve performance in chemical looping combustion. *Chemical Engineering Journal*, **234**, 464-474. doi:10.1016/j.cej.2013.08.090



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Outputs published in peer-reviewed journals.

## 4. Details of the impact (indicative maximum 750 words)


ArgonØ™ has been introduced to the silicon wafer industry, with applications in solar PV panels and microelectronic devices. The product demonstrates strong economic impact, evidenced through sales revenues of GBP6,200,000 and creation of five to 10 jobs across the supply chain in the REF period. The product has been exported to eight countries. In addition, it has resulted in efficiencies and savings to customers to the tune of an estimated USD37,000,000 since 2018 [E1,E2].

The ArgonØ™ was developed by Dr Rob Grant, previously Head of Technology for BOC Edwards, based on research carried out at the University of Cambridge by Dennis and Scott into solid-state oxygen carriers. Acquiring the IP via Cambridge Enterprise, Grant set up a new company, Gas Recovery and Recycle Ltd (GR2L) in 2008, and, continuing to work with Scott, set about developing the ArgonØ™ which was brought to the market with its first sale in 2012 [E2].

Silicon wafers are key components of solar panels and microelectronic devices. The ArgonØ™ purifies the inert shield gases used in the manufacture of silicon wafers. In response to rising costs, the trend in the solar industry has been to reduce the argon purge flows to a minimum, however, this cost reduction comes at the expense of wafer purity which can result in lower performance solar cells [E3]. Previously, manufacturers typically discarded the contaminated gases after use but ArgonØ™ gives them a cost-effective means of cleaning and recycling them.

**Economic impact**

GR2L has exported more than 70 of its ArgonØ™ gas recycling unit systems to customers in eight countries: China, Malaysia, Norway, Singapore, South Korea, Taiwan, Thailand and Vietnam [E2].

The Gigastore Corporation in Taiwan was the first company to install the ArgonØ™ in 2015 [E4]. In 2018, 55 units were sold to LONGi Green Energy Technology in China, the world's largest manufacturer of photovoltaics and monocrystalline silicon wafers. Each unit was sold to LONGi at a cost of USD109,000 per unit, a cumulative cost of USD5,995,000 [E5].

Since 2017, GR2L's sales have increased significantly from a turnover of GBP400,000 in 2017/18 to more than GBP4,000,000 in 2018/19 achieving a cumulative total of GBP6,200,000 in the REF period [E1].

GR2L employs 1 FTE in the UK and has created jobs for a further five to 10 people in its UK supply chain. Its principal subcontractor is UK-based systems installation contractor, MicroGas with two more UK subcontractors supplying individual components: HPC the compressors and Time 24 Limited the control module [E2].

**Savings to customers**

In addition to the economic impact outlined above, the use of ArgonØ™ generates efficiencies and savings for companies. By purifying the inert shield gases used in the manufacture of silicon wafers, the ArgonØ™ enables manufacturers to recycle gases that would otherwise be discarded and reduce their argon consumption by more than 95%. With more than 70 systems currently in use this equates to a total saving of around USD37,000,000 across the REF period [E1].

The saving a company is able to make depends on the price of argon, which varies over time and in different markets. Much of the argon used by wafer manufacturers is produced as a by-product of steel making, which means that when steel outputs are falling, the cost of argon rises. In recent years, some countries have seen the prices of high purity argon increase by as much as 400% [E3]. Depending on the local bulk argon gas price and how effectively the manufacturer operates the system, each unit delivers savings of between USD120,000 and USD160,000 per year [E2].

Some manufacturers have responded to the increasing cost of argon by using less of it, but this approach can affect the wafer purity and hence the performance of solar cells. The issue is even more acute in the microelectronics market. These devices need ultra-high purity wafers which typically use two to three times as much argon to manufacture as those destined for solar cells [E3]. The ArgonØ™ enables manufacturers to recycle more than 95% of their argon (and other noble gases such as helium and xenon) at purity levels that exceed the Semi PV6-1110 requirements, removing 1,000s of ppm of contamination in the process [E3].

At LONGi's facility in Malaysia, 15 ArgonØ™ systems are connected to 60 CZ silicon ingot pullers, saving LONGi approximately USD5,000 per day, or just over USD1,800,000 per year. At another LONGi facility in China, an installation of 40 ArgonØ™ systems is saving the customer just under USD5,000,000 per annum [E2].

**5. Sources to corroborate the impact** (indicative maximum of 10 references)

[E1] Updated statement from CEO, Gas Recycle and Recovery Ltd
[E2] Statement from CEO, Gas Recycle and Recovery Ltd
[E3] Feature in *PES Solar* magazine, September 2018
[E4] Press release announcing installation of first ArgonØ™ system in Taiwan
[E5] Contract between GR2L and LONGi