Green and Sustainable Chemistry at the SRC-GC in Australia: Current Status and Opportunities for the Future.

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Green and Sustainable Chemistry (GCS) forms an integral part of the research landscape within Australia. Although not yet attracting the levels of attention from the various Australian State and Federal Governments or industry that are warranted on scientific, let alone economic, grounds, the concepts and outcomes of green and sustainable chemistry in their broadest context are increasingly providing the necessary drivers for change. Representative of this paradigm shift and a leader in this field within Australia is the Centre for Green Chemistry at Monash University. The research effort of the Centre addresses several key green chemistry challenges with elegance of the design approach, sustainability of the process and risk reduction as the goals. In this presentation, some recent developments will be described within the context of the GSC initiatives within this Centre and more broadly within Australia.

The Centre for Green Chemistry at Monash University which is a Special Research Centre funded by the Australian Government through the Australian Research Council (ARC). Within the research-funding framework supported by the Federal and State Governments, the research of the Centre is closely aligned with the National Research Priorities of Australia, viz.

- An Environmentally Sustainable Australia
- Promotion and Maintenance of Good Health
- Frontier Technologies for Building and Transforming Australian Industries
- Safeguarding Australia

The Centre for Green Chemistry is accommodated in custom-built laboratories and offices within Building 75 (the Science Technology Research & Innovation Precinct) and the adjacent Building 23 at the Clayton Campus of Monash University (Figure 1, below). The Centre was established in January 2000. As a centre of research excellence, the Centre for Green Chemistry offers an exciting, challenging and productive environment for talented and committed young scientists to gain training and research experience from the level of postgraduate studies through to postdoctoral career development. The Centre's achievements are annually measured against its key performance indicators of success and through alignment of its research program with its strategic plan for future development. Evidence of successful development of the core and applied research activities of the Centre, such as those highlighted in its recent Annual Reports, represents a key determinant of the Centre's performance profile.

Figure 1: The Centre for Green Chemistry's research activities and administration are undertaken from suites of dedicated offices and laboratories within Building 75 [left] and the adjacent special facility within Building 23 [right] at Monash University, Clayton.

The core research activities of the Centre have historically been focused around two interlocking areas of capability - Cleaner Synthesis Technology and Green Biotechnology. These capabilities have recently been strengthened through inclusion of advanced aspects of Electrochemistry and Photochemistry as part of the Centre's strategic developments. In pursuing its short- and long-term goals, the Centre aims to address through innovation:

- major issues facing the chemical and allied manufacturing industries,
- the training of a critical mass of experienced graduate researchers and experts,
- the development of multidisciplinary depth and level of achievements expected for a Special Research Centre of Australian Research Council.

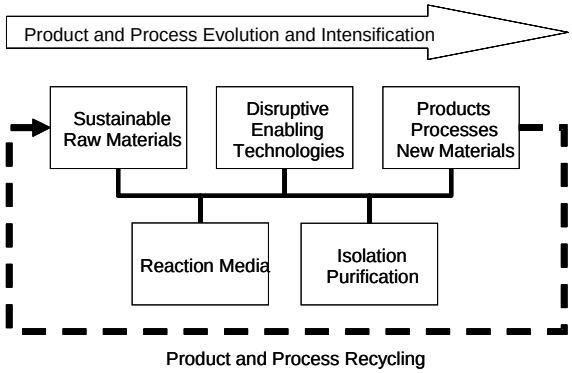

Figure 2: The Centre's research activities draw upon the consideration of whole-of-cycle, natural manufacturing supply chains coupled with process intensification.

The goal of the Monash Centre for Green Chemistry is thus to develop from a base of fundamental science elegant solutions to challenges associated with molecular science discoveries and their translation into a commercial setting with avoidance of current unsatisfactory industrial and environmental outcomes. The reduction of risk associated with the development of new chemical/ biological processes – in terms of their toxicological, environmental or financial impact --- represents a central tenet behind the Centre's research strategy. To this end, the Centre's research program focuses on technologies that have at their core hazard-free, waste-free, energy-efficient synthesis and application of non-toxic products without sacrificing efficacy of function. This goal is being achieved through creative design and skilful implementation of procedures and technologies, incorporating *inter alia* the principles of product and process evolution and intensification that generate at source less waste as by-products and which result in chemical and biological products that can be incorporated into a whole-of-cycle, natural manufacturing supply chain. The conceptual flow of the Centre's research program can be summarised as shown in Figure 2, with the outcomes new products, processes and materials and new monitoring technologies.

Within the Australasian region, the Centre for Green Chemistry at Monash University represents a unique demonstration site, with the capability to provide significant outcomes across a broad spectrum of the chemical, biological and biomedical fields. To this end, the Centre strives to provide leadership in a number of key areas associated with process and product development that are based on enabling technologies, pioneered or advanced by the Centre. The Centre acts as an intellectual hub that attracts talented staff based elsewhere within Australia and who collaboratively interact with the Centre's staff applying these strategic principles.

Thus, the Centre has a range of collaborations with staff based within various departments (notably Chemistry, Pharmacy, Materials and Chemical Engineering) at Monash University; with staff at other Australian Universities (notably the University of Melbourne, University of Newcastle, University of Queensland, Swinburne University of Technology, University of West Australia and University of Tasmania) and various universities in the USA, China, Japan, Germany, Italy, South Africa, Taiwan, India, Denmark and Sweden. Similarly, the Centre has close collaborations with staff based at several CSIRO Divisions (Molecular and Health Technologies, Minerals, Manufacturing and Infrastructure Technology, Forestry and Forest Products), several of which have major laboratory facilities at their Clayton site adjacent to Monash University and with staff based within State and Federal Government research laboratories, and devoted to sustainable developments in the primary,

secondary and manufacturing industries. Moreover, the Centre has close connections to research based in laboratories working in related fields of sustainability and sponsored by the Australian Government Cooperative Research Centre program. Over the past several years, a network of industrial partnerships has also been established with Australian and multi-national companies prominent in the chemical, pharmaceutical and biotechnology fields, reflecting the focus of the core research activities and capabilities of the Centre.

In order to improve traditional, inefficient processes or to replace them by superior alternatives, fresh thinking is required about the nexus between chemical- and biocatalyst-mediated synthetic methods, the selection of starting materials and reactants and the use of renewable resources. These considerations directly impact on how waste can be avoided, hazard and risk reduced, product life cycles improved and sustainability achieved. The Centre has positioned itself to offer enabling technologies, which addresses these problems with the (current) emphasis on the development of high-value, low-volume chemicals for target markets. Illustrative of such applications has been the development by my Centre colleagues (Rosamilia, Scott, Strauss, Org. Letts (2005) 7 1525-1528) of a ‘green’ technology for the synthesis of 2- and 4-arylmethyl N-substituted and N,N-disubstituted anilines using the distillable ionic liquid, DIMCARB as part of a multi-component reaction. In our work, attention has, in particular, been placed on the choice of media conditions involving environmentally benign solvents and ionic liquids, with reaction conditions selected for improvement in the levels of atom economy. Various solvent-free processes have been documented. The products so derived are based on cleaner routes for their synthesis as well as new or improved processes for their isolation and purification.

Within the chemical, pharmaceutical and biotechnology industries the application of natural manufacturing approaches, and Green Biotechnology in particular, has gain considerable momentum over the past decade. Product portfolios frequently generate at the point of sale multipliers of more than 10-50 fold over cost of goods. To support these opportunities, several important Green Biotechnology strategies are employed within the Centre, based on the application of more benign synthesis/production approaches coupled with sophisticated methods of analysis. In this area of research capability, new chemistries are being developed for the modification of natural and synthetic polymer surfaces and other types of support materials to allow the selective capture and release of target molecules in functional state. Technologies within this capability field also permit 'molecular engineering' of new types of chemical and biochemical substances and systems with enhanced functionality or improved modes of molecular recognition. Where feasible, improved methods for on-line monitoring are also employed to predict and analyse performance of these new systems.

The Centre's core competencies include state-of-the-art combinatorial chemistry, organic and organometallic compound synthesis, catalysis, microwave chemistry, the use of novel reaction media, polymer chemistry, including the preparation of benign synthetic materials with novel functionalities that can act as catalysts/ biocatalysts; fermentation technologies and cell culture, separation technology and new methodologies for the isolation and nano-scale analysis of chemical and biological molecules and their derived mimics; and applications of novel solid phase (chemo- or bio-) reaction systems based on monolithic or molecularly imprinted functional polymers. A major activity currently being pursued is the extension of our ‘green tag’ technology (Hearn, Mooney, Spiccia, Jiang, Graham, Christensen, US and PCT Patent application WO2003042249), which is based on the use of novel molecular tag systems and association molecular recognition cassettes for the purification or specific orientation-dependent immobilisation of recombinant proteins for use in therapeutic, diagnostic or bio-catalytic purposes. To this end, the research activities of the Centre encompass a multi-disciplinary base of interlinked expertise as shown in Figure 3 (below), taking advantage of synthesis under benign conditions, including microwave-mediated meth-

ods, the favourable attributes of ionic liquids as suitable media for complex chemical reactions; new host-guest strategies for molecular recognition; catalysis and biocatalysis; solid and solution phase synthesis of novel organic and organometallic compounds; advanced separation techniques and innovative modes of product recovery; and non-invasive methods for the detection of specific substances in complex feed-

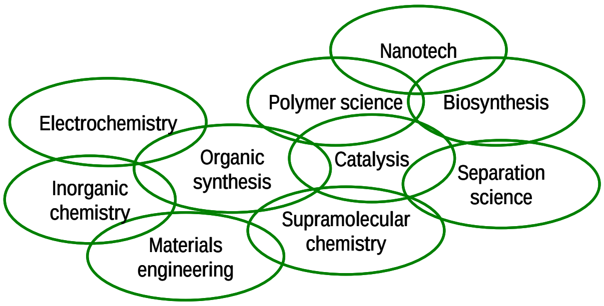

Figure 3: The Centre's core capabilities encompass a multidisciplinary base of interlinked expertise.

stocks and matrices. The outcomes of this research effort are increasingly finding industrial application, as evident from the growth in our interactions with industrial partners. Products arising from these research activities have also included:

- novel surface modified and molecularly imprinted polymeric materials for use in the manufacture of biochemical and synthetic chemical substances;
- new classes of dendritic polymers;
- new analytical methods based *inter alia* on non-invasive detection systems as part of real-time process control evaluation with biological and chemical feedstocks.

In pursuing its Mission, the Centre for Green Chemistry aims to provide both fundamental and enabling scientific outcomes through research excellence. These outcomes are intended to strategically underpin significant developments within the chemical and molecular life science fields of relevance to the industrial sector both within Australia as well as internationally. In this context, the work of the Centre enhances and parallels the commitments of other research providers within Australia, including the CSIRO (in such fields as enzymatic bioremediation, crop biofactories, water based hydrocarbon-free green drilling "muds", energy-efficient biological rubbers or green electrochemistry) or at other Australian Universities (for example in such fields as chemoenzymatic synthesis of biologically active natural products (ANU, Banwell) or one-pot synthesis of terpyridines (UWA, Raston)). The Centre is thus participating in a significant manner to the fundamental realignment that is occurring in both the advanced manufacturing industries and commerce as a consequence of the need to achieve sustainability across a broad cross-section of commercial development. As such the Centre for Green Chemistry at Monash University, as the premier national initiative in Green and Sustainable Chemistry within Australia, is committed to facilitate through research excellence and innovation the paradigm shift in socially responsible, best-practice manufacturing that is becoming the dominant economic driver for the development of the chemical, pharmaceutical and biotechnology industries.

In this presentation, recent research achievements of this Centre will be summarised and examples of the capabilities in the field of green and sustainable chemistry available elsewhere in Australia presented. Moreover, some emerging collaborative opportunities will be described and how these are being pursued by the Centre to permit increased engagements with additional national and international research partners, as well as to allow the mid- to longer-term plans for the development green and sustainable chemistry within Australia to be better charted and road mapped, concordant with Government policy directions, industry needs and public intent. For copies of our Annual Reports and further information on specific areas of core and applied research undertaken within this Centre can be obtained by contacting the Director, ARC Special Research Centre for Green Chemistry, Monash University, Box 75, Victoria, Australia 3800, by phone (Int+61-3-9905-4547), fax (Int+61-3-9905-8501) or alternatively by email (milton.hearn@sci.monash.edu.au) or by visiting our website (www.chem.monash.edu.au.greenchem).

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