Unclassified **ENV/JM/MONO(2002)12**

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development **28-Mar-2002**

English - Or. English

ENV/JM/MONO(2002)12
Unclassified

ENVIRONMENT DIRECTORATE
JOINT MEETING OF THE CHEMICALS COMMITTEE AND
THE WORKING PARTY ON CHEMICALS, PESTICIDES AND BIOTECHNOLOGY

OECD Environment, Health and Safety Publications
Series on Risk Management, No. 15

NEED FOR RESEARCH AND DEVELOPMENT PROGRAMMES IN SUSTAINABLE CHEMISTRY.

English - Or. English

JT00123375

OECD Environment, Health and Safety Publications

Series on Risk Management

No. 15

NEED FOR RESEARCH AND DEVELOPMENT PROGRAMMES IN SUSTAINABLE CHEMISTRY

IOMC

INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS

A cooperative agreement among

UNEP, ILO, FAO, WHO, UNIDO, UNITAR and OECD

Environment Directorate
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
Paris 2002

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The work of the OECD related to risk management is carried out by the Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology, with Secretariat support from the Environmental Health and Safety Division of the Environment Directorate. As part of its work on risk management, the OECD has issued 'status report' monographs on five substances that were, or continue to be, the subject of review: **lead**, **cadmium**, **mercury**, **selected brominated flame retardants** and **methylene chloride**. It has also published two volumes of the **proceedings of the OECD Cadmium Workshop** held in Saltsjöbaden, Sweden, in 1995 and a **survey report on methylene chloride**, supplementing the information presented in the Risk Reduction Monograph on methylene chloride (see list of publications on page 4). In 1996, OECD Environment Ministers endorsed a **Declaration on Risk Reduction for Lead** to advance national and co-operative efforts to reduce the risks from lead exposure.

OECD has also published, as part of its work on risk management, workshop reports and guidance documents concerning methodologies on non-regulatory initiatives, collection and recycling of nickel-cadmium batteries, sustainable chemistry and socio-economic analysis.

The Environment, Health and Safety Division publishes documents in several different series, including: Testing and Assessment; Good Laboratory Practice and Compliance Monitoring; Pesticides; Risk Management; Harmonization of Regulatory Oversight in Biotechnology; PRTRs (Pollutant Release and Transfer Registers); and Chemical Accidents. More information about the Environmental Health and Safety Programme and EHS publications is available on the OECD's web site (see next page).

This publication was produced within the framework of the Inter-Organization Programme for the Sound Management of Chemicals (IOMC).

This publication is available electronically, at no charge.

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The Inter-Organization Programme for the Sound Management of Chemicals (IOMC) was established in 1995 by UNEP, ILO, FAO, WHO, UNIDO, UNITAR and the OECD (the Participating Organizations), following recommendations made by the 1992 UN Conference on Environment and Development to strengthen co-operation and increase international co-ordination in the field of chemical safety. The purpose of the IOMC is to promote co-ordination of the policies and activities pursued by the Participating Organizations, jointly or separately, to achieve the sound management of chemicals in relation to human health and the environment.

TABLE OF CONTENTS

FOREWORD

In 1998, OECD Member countries initiated work on a new project aimed at facilitating the development of environmentally benign chemicals. As a first step, a workshop was held in Venice, Italy (15-17 October, 1998) [ENV/JM/MONO(99)19] to identify effective techniques and approaches in the field of sustainable chemistry and to identify activities that can further the development and use of sustainable chemistry programmes. This includes such things as recognising and rewarding sustainable chemistry accomplishments; disseminating technical information; promoting the incorporation of sustainable chemistry principles into various levels of chemical education; and promoting the research, discovery and development of innovative sustainable chemistry technologies.

A second workshop was held in Tokyo (11-12 October 2000) to develop background material for a guidance document that can assist OECD countries and others develop effective research and development programmes within the context of sustainable chemistry (e.g., an institution which is researching improvements to a specific industrial process). This guidance document is based on the discussions in Tokyo, and additional input by OECD Member countries.

GUIDANCE FOR ESTABLISHING RESEARCH AND DEVELOPMENT PROGRAMMES IN SUSTAINABLE CHEMISTRY

The purpose of this document is to provide guidance to governments which would like to develop their own programmes to promote R&D in sustainable chemistry that take account of national priorities and policies. It can be used as written to establish national programmes, or to develop more focused national guidance as an initial step for building such programmes.

What is sustainable chemistry?

Sustainable chemistry is the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. Within the broad framework of sustainable development, government, academia and industry should strive to maximise resource efficiency through activities such as energy and non-renewable resource conservation, risk minimisation, pollution prevention, minimisation of waste at all stages of a product life-cycle, and the development of products that are durable and can be re-used and recycled[1].

Appendices I and II provide a number of examples of sustainable chemistry activities.

1. Background

Our life is supported and enriched by an enormous variety of chemical products that have been invented by chemists and chemical engineers, and produced by the chemicals industry. But at the same time, we have learned from the experiences of past decades that OECD countries are faced with environmental concerns including the unsustainable use of non-renewable natural resources, the degradation of ecosystems and the disruption of the environmental systems that support human life. The general public now expects chemists and chemical engineers to work to minimise and reduce adverse effects on human health and the environment associated with the production and use of chemical products. For this reason, chemists and chemical engineers have a great influence on, and thus bear a responsibility for, protecting the global environment. To this end, a new concept of, or approach to, chemical technology is needed.

“Sustainable chemistry” is a relatively new concept and scientific area that aims to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. In doing so, it can contribute to achieving a cleaner, healthier, and sustainable environment and improving the image of chemistry as a problem solving science in society. The concept of sustainable chemistry considers the social as well as practical aspects associated with the development of chemical products using innovative technologies.

[1] Proceedings of the OECD Workshop on Sustainable Chemistry; 15-17 October, 1998 [ENV/JM/MONO(99)19]

The application of some of the approaches that we now call sustainable chemistry is not unprecedented. Examples of sustainable chemistry, although few, have been reported in the scientific literature for decades; however, these early examples were random in nature and not driven by any consistent concept or a particular focus on human health and environmental impacts of traditional chemical research and chemical activities. As a new and specific focal area of scientific research, sustainable chemistry was first articulated in the early 1990s and has gained wider currency in the last few years.

Despite these early examples of sustainable chemistry research, the concept was not adopted until recently for a number of reasons. While there has been tremendous innovation in the design of chemical products and processes since the beginning of the 20th century, the driving force was not the minimisation or reduction of environmental impacts due to the production and use of these products. These impacts were not identified until the later part of the 20th century (*e.g*. a Nobel Prize was awarded in 1948 to researchers working on DDT, a substance now banned around the globe for its fatal effects on avian species; CFCs, once widely used as a refrigerant because of their low toxicity to humans and excellent performance, are currently being phased out due to their damaging effects on the environment).

In addition, increased regulation throughout the latter part of the 20th century, among other things, discouraged industry from re-evaluating and replacing long-used commercial technologies (there are numerous examples of industry's dependence on 40-, 50-, and even 60-year old commercial processes). A lack of understanding of structure-activity relationships, until recent decades, prevented a thorough understanding of the consequences of these older, long-used technologies, as well as an ability to identify the source of their negative impacts**.**

The concept of sustainable development described in Agenda 21 was proposed and endorsed by UNCED in 1992. Since then, it has been recognised globally by governments, academic institutions and industry. With respect to the production and use of chemical products, chemists and chemical engineers realised that "end-of-pipe" solutions were not always an efficient or effective way of minimising or reducing the impacts of chemical products on society. More attention was focused on R&D in the development of environmentally benign chemicals during the last decade. These efforts have been limited, however, to independent activities within each segment of a given discipline or individual company.

In parallel to this work, OECD governments were examining their own policies to see whether new and innovative approaches could be established which would result in more effective techniques for managing risk from chemical products and processes. In February 1998, the OECD Joint Meeting of the Chemicals Committee and Working Party on Chemicals, Pesticides and Biotechnology, endorsed the start of work on a "sustainable chemistry" initiative. As a first step, they agreed that a workshop should be held. This workshop, which took place in Venice in October 1998, was hosted by the Inter-university Consortium, Chemistry for the Environment (Italy) and co-sponsored by the governments of Germany, Italy, Japan and the United States, in co-operation with the International Union of Pure and Applied Chemistry (IUPAC) and the Business and Industry Advisory Committee to the OECD (BIAC). The workshop focused on the policy and programmatic aspects of sustainable chemistry initiatives, with a mandate to:

- identify the types of sustainable chemistry activities already underway, supported in part by the results of a survey in OECD countries?;

- identify effective techniques and approaches in the field of sustainable chemistry (including educational approaches), considering problems and highlighting solutions; and

- identify activities that could further the development and use of sustainable chemistry.

Before the workshop, a survey was carried out to collect basic information on sustainable chemistry activities recently completed or ongoing in OECD countries. These included activities initiated by governments, academia and industry, and managed by one of these parties alone or collaboratively (*e.g.* through government/industry partnerships). The United States Environmental Protection Agency made a report summarising survey responses and identifying trends across OECD countries. (A copy of the proceedings from the workshop and the survey report is available at the following internet website: http://www.oecd.org/ehs/ehsmono/index.htm#RISK)

It was evident from the responses to the survey and the presentations and interventions made during the workshop that considerable interest and enthusiasm exist among governments, industry, NGOs and academia both for sustainable chemistry's basic concepts and for practical applications. Further, many stated that it was imperative to integrate sustainable chemistry thinking into the fields of chemistry and environmental sciences, and throughout the vast array of industrial sectors that they affect.

One of the major recommendations made at the Venice workshop, and later endorsed by the Joint Meeting, was that although OECD cannot fund or carry out actual research, it should encourage Member countries to undertake such research and facilitate the development of effective research activities in institutions and other organisations. In response, a second survey was sent to Member governments, industry and academia to collect information on current research and to identify organisations that are willing to actively engage in sustainable chemistry activities. In total, 70 responses were received from 13 countries and one international organisation. The survey indicated that a number of organisations had undertaken work (or were in the process of doing so) on R&D in sustainable chemistry and many were interested in co-operative research at the fundamental or pre-competitive level, and many saw value in the establishment of an information exchange network to promote co-operation.

The results of this survey were used as a foundation for discussion at a second workshop on sustainable chemistry, held in Tokyo (11-12 October 2000), hosted by the Japanese Ministry of International Trade and Industry and co-sponsored by the governments of Japan and the US in co-operation with the Japan Chemical Innovation Institute. One of the main objectives of the workshop was to develop guidance to assist OECD countries and others in developing effective research and development programmes. (It should be noted that some non-OECD countries have also been active in promoting and engaging in sustainable chemistry activities.) This document is based on the results of the survey, and with the support of, and input from, participants at the workshop.

2. Scope of sustainable chemistry

2.1. Benefits of sustainable chemistry

The ultimate goal of sustainable chemistry is to contribute to the realisation of a "sustainable society", with the help of chemical technology. Chemical technology development for pollution prevention is universally regarded as a high priority area of sustainable development. Innovative technology development for waste treatment, although an important and necessary activity, is a priority primarily in countries confronted with a serious problem from accumulated chemical wastes.

There can be significant human health and environmental benefits from sustainable chemistry. A minor change in product or process design can result in significantly lower hazard and associated risk by substantially reducing or completely eliminating hazardous material used in or generated from the product or process. In addition, energy consumption can be minimised and renewable resource utilisation maximised.

In addition to the benefits to human health and the environment, sustainable chemistry technologies in some cases are economically competitive for and advantageous to the companies that apply them. In the second OECD survey on sustainable chemistry, governments indicated that they support sustainable chemistry research because it is an economically efficient and non-regulatory way of improving the protection of human health and the environment. Chemical manufacturers with active sustainable chemistry research programmes listed long-term profitability that is compatible with environmental protection and the protection of the health and safety of employees and customers as an objective. The majority of industry responses did not indicate any major problems in developing, manufacturing or marketing their sustainable chemistry products or processes. Some responses indicated that the competitiveness of sustainable chemistry technologies is not always apparent and may even be viewed as a disadvantage because the costs of environmental damage recovery and waste disposal caused by traditional products are not reflected in their final price.

In addition to providing environmental, health and economic benefits, sustainable chemistry promotes the idea that chemistry can be used for beneficial purposes, such as remedying environmental problems. It can help alter the perception of some members of the public that chemistry is a field of science that harms human health and the environment in spite of the benefits it may bring. Moreover, sustainable chemistry can attract prominent young students to the field of chemistry. Also, because of the scientific innovation and rigour at the core of sustainable chemistry, academic institutions that responded to the second survey on sustainable chemistry indicated that they had gained an increased scientific understanding of the properties of chemicals and chemical processes through their work on sustainable chemistry.

2.2. Methods for assessing sustainable chemistry products and processes

It is often necessary for government, industry and others to judge whether a product or process falls within the definition of sustainable chemistry, or to prioritise products or processes amongst several options. Therefore, it is important for them to develop criteria (or metrics) and methods for assessing sustainable chemistry products or processes. Although ideally these criteria should be practical and similar across countries, it is actually very difficult, and may not be practical, to develop common rigorous criteria because benefits and disadvantages of a sustainable chemistry product or technology sometimes depend on cultural, economic and other factors which vary across countries. Therefore, simple and clear criteria that contain only essential factors will be most useful and most likely to be accepted universally. Such fundamental criteria should include the following factors:

1. determination of the impact on human health and the environment;

2. determination of the safety of workers or users throughout the production processes or life cycle of products;

3. a comprehensive evaluation of energy consumption and resource use; and

4. an evaluation of each of the above factors (1-3) conducted at the local, country/regional or global levels.

Based on these fundamental criteria, each country or organisation needs to establish its own specific criteria that reflect its particular situation. Based on the specific situation and knowledge levels of users, the most appropriate methods can be selected. In the case of research and development, the methods should be optimised for evaluating and selecting technological options that fit the research targets of research managers, researchers and engineers to the maximum extent possible. In the case of funding, nonspecialists such as politicians, industry leaders and others will use the methods, and therefore only simple and general methods are suitable.

Ideally, the development of these methods should contain a comprehensive evaluation of the inter-relationships among products and processes throughout the entire life cycle of the products, from the use of raw materials to production, and end use to recycling and disposal. This should also include an assessment of the potential risks posed by new or modified products and processes being considered. Life Cycle Assessment (LCA) has been used (and may be the most promising tool) to evaluate the environmental load caused by a product. However, significant time and resources - both financial and human - are needed to conduct such assessments because a considerable amount of data must be collected and examined for all stages of the life cycle of the product. Someone conducting an LCA needs to balance the added value of more detail and precision in the LCA, with the cost of conducting such an LCA. Furthermore, the conclusions of such assessments may be fairly subjective in nature. Thus, it is not an easy task for a country or organisation to develop independently an assessment method on sustainable chemistry without any supporting guidelines.

In this respect, OECD can provide general and fundamental criteria (and methods) which can help countries and regions develop their own more specific assessment criteria. One practical approach for developing general criteria is to extract essential indices by categorising the factors that are raised by experts. For instance, these criteria or factors can be collected from countries that have sustainable chemistry award programmes and use such criteria to identify candidates and select winners. The criteria and assessment methods should be sufficiently flexible so that countries and organisations can modify the methods when they gain experience.

3. Areas of sustainable chemistry R&D

3.1 Categories of sustainable chemistry R&D

Sustainable chemistry products or processes fall within three broad categories:

i) Use of renewable or recycled feedstocks;
ii) Increased energy efficiency, or using less energy for the same or greater output; and
iii) Avoidance of substances that are persistent, bioaccumulative and toxic.

3.2 General areas of sustainable chemistry R&D

Areas of sustainable chemistry R&D generally include:

- Pursuing product and process designs that take into consideration the impacts on human health and the environment by reducing the use and generation of hazardous materials.
- Developing processes that contribute to the minimisation of the releases of pollutants and the formation of by-products, residues, and wastes.
- Pursuing process designs that are practical and widely applicable in a variety of manufacturing processes.
- Developing technological or operational systems that reduce energy and resource consumption and promote the cyclic utilisation of materials and chemicals.
- Developing innovative technologies that reduce the dependency on non-renewable feedstocks by promoting the utilisation of renewable feedstocks.

- Developing innovative products that enable materials to be recycled into chemical resources, thus preserving environmental resources.
- Developing concepts and procedures for anticipating the consequences of chemical products and processes on human health and the environment.

Some parts of these areas have been implemented by enterprises as a part of the chemical industry's Responsible Care®[2] programme.

3.3 Examples of sustainable chemistry R&D

The technical areas related to sustainable chemistry can be classified into technology for chemical processes and technology for products.

3.3.1. Examples of chemical <u>process</u> technology development include:

- Using alternative feedstocks that are more innocuous and renewable.
- Developing alternative synthetic pathways, such as the use of catalysis and biocatalysis, photochemistry, and biomimetic synthesis.
- Designing simpler reaction processes that reduce energy consumption and minimise the use and release of hazardous chemicals.
- Developing alternative reaction conditions for increased selectivity and waste reduction.

3.3.2. Examples of chemical <u>product</u> technology development include:

- Designing chemical products to minimise impacts on human health and the environment.
- Designing chemical products that have inherently less hazardous properties.
- Designing chemical products that have reduced toxicity, flammability, and explosion potential.

4. Collaboration and role of sectors for developing R&D on sustainable chemistry

4.1 Collaboration

Practically all the chemical manufacturers, research organisations, and academic institutions responding to the second survey on sustainable chemistry said that they were actively involved in sustainable chemistry research. Some government departments and industrial or professional societies are also involved in related research. There was widespread support for an international information exchange mechanism on sustainable chemistry research. Chemical companies indicated that they would, in general, be prepared to exchange the results of pre-competitive research, but information about new products under development and improved processes is often confidential. Overall there was considerable support for further co-operative research in specific areas of sustainable chemistry.

2 . Responsible Care® is the chemistry industry's initiative to communicate with neighbors, and protect the environment, employees and communities

The promotion and implementation of sustainable chemistry relies on a number of key actors: government, academia, industry, professional societies and NGOs. Each can play an important role either independently or working in collaboration with other actors. For academia and industry, sustainable chemistry is a voluntary way to move toward a sustainable environment and society. For government, sustainable chemistry is a non-regulatory way of making regulations work more effectively. Collaboration of the key actors is essential to make sustainable chemistry activities like R&D, education and information exchange as effective as possible. Collaboration across different regions and disciplines will further promote and enhance sustainable chemistry globally. The following sections describe approaches that the various actors can consider in order to promote the application of sustainable chemistry. Although these approaches can be considered in typical situations common to many countries, it is important to understand that they may not always be applicable to every situation in every country.

4.2 Role of government

Governments can promote sustainable chemistry R&D using basically two different approaches. The policy they select will depend on the situation of the country. Under one approach, governments can establish and fund programmes on sustainable chemistry R&D. According to the second OECD survey on sustainable chemistry, national research agencies, governments or multi-national programmes generally fund academic programmes. In addition, parts of industrial programmes are often supported by government funds. Governments, in general, can provide funds for basic and pre-competitive research. However, financial support for sustainable chemistry R&D that aims to improve practical manufacturing processes such as scale-up of lab-scale processes, develop new infrastructures, or modify existing infrastructures, should be considered only when the benefits are expected to accrue to a large segment of the public. Practically, governments can orient sustainable chemistry R&D programmes by adjusting the distribution of funds for fundamental and applied research or by commanding competitive and targeted funds depending on policies.

Under the other approach, governments can facilitate the consideration and application of sustainable chemistry R&D by supporting efforts which aim at educating and informing industry and the general public of the importance and benefits of sustainable chemistry. One possible role for government would be to identify incentives and disincentives for the promotion of sustainable chemistry and to use this information to modify or develop their policies accordingly. When appropriate, the use of incentives, such as a reduction in taxes or the use of subsidies, can be an effective way of supporting R&D by academia and industry in the field of sustainable chemistry.

4.3 Role of academia

In many countries, a primary role of academia is to meet the requirements of society and industry, and to define cutting edge research by continuously challenging innovative chemical technologies while steering efforts towards sustainability. It is also the responsibility of academia to expand the technical options available to industry. Many members of society are concerned about the potential adverse effects of chemicals on human health and the environment, but at the same time they are strongly dependent on the availability and benefits of the innovative chemical products that are introduced to the market. As such, it is important that academic research be cutting edge, practically applicable to industrial processes and products, and considerate of the impacts to human health and the environment. Education and training of the public and workers about the importance of sustainable chemistry R&D is another essential role of academia. Such educational activities should not be limited to students but should also cover engineers, managing directors and other workers in the chemicals industry. Academia also can enhance the credibility and accountability of chemistry within society by educating and enlightening the public about safer products and process designs. Another important role of academia is to verify whether new technologies developed by industry are in accordance with the concept of sustainable chemistry and to systematise post-competitive research to expand the possibilities of chemistry for the next generations.

4.4 Role of industry

Industry should be aware of potential adverse effects of their products and processes on human health and the environment. Sustainable chemistry can be a voluntary and effective way for industry to prevent these adverse effects. The primary role of industry is to design and manufacture products in line with the concept of sustainable chemistry. Industry considers that society and the market successfully accept a new product only when the product meets societal needs or demands. The response of society to a given product often depends on the cost to be borne by individuals or the public. In addition, public perception of the environmental impacts of a product can affect its market value. Industry is, therefore, encouraged to continue improvement, incremental or revolutionary, of its manufacturing processes and products according to the environmental, social and economic principles of sustainable chemistry. Small and medium-sized chemical enterprises engaged in R&D may have the potential to promote challenging technological innovation in sustainable chemistry as they may be less bound by existing technologies. It is a fundamental responsibility of industry to provide society with product data that have been identified as important through risk assessments. The collection of toxicological and environmental safety data on major chemical products (*e.g*. the OECD High Production Volume Programme) and the development of databases with information on chemical products, physical and toxicological hazards are also important. Such overall activities will enhance the reputation of the chemicals industry and will also strengthen the competitiveness of products in the market along with improving the performance and reducing the costs associated with such products, especially in the long term. Responsible Care® is another important voluntary activity of the chemicals industry with a complementary aim to support the development of sustainable chemistry. Although several codes of Responsible Care® are in line with the approach of sustainable chemistry, it places more emphasis on safe management throughout the entire life cycle of products within an enterprise. Sustainable chemistry, by its very nature, puts more emphasis on the development of new and innovative technologies and it needs to be promoted throughout the chemicals industry. A synergetic effect would be expected through effective co-ordination or collaboration between both of these initiatives.

4.5 Role of professional societies and NGOs

The role of professional societies and NGOs is to help activate and develop discussion on sustainable chemistry research and results, and on how those results meet societal objectives. Specifically, professional societies provide journals and symposia, which encourage peer review to maintain scientific quality. Professional societies can also provide professional accreditation and career planning, which promote life-long service in the fields of interest to sustainable chemistry. Moreover, professional societies can facilitate establishing assessment criteria and international standards regarding sustainable chemistry R&D. In some cases, NGOs may be engaged in the verification and evaluation of new sustainable chemistry technologies in collaboration with academia. Both professional societies and NGOs provide publicity, information dissemination, and an interface between the scientific community and interested members of the public. Another important role of NGOs is to provide feedback to improve sustainable chemistry programmes so that they meet societal needs. Proposals based on such feedback can have a significant impact on the decision-making processes for R&D programmes.

4.6 Gaps or critical needs

According to the second OECD survey, there were no major problems associated with the development and adoption of sustainable chemistry technologies. However, gaps and critical needs remain which may pose obstacles to the wide acceptance of sustainable chemistry activities. One such gap or critical need arises from an evaluation of the benefits and costs of sustainable chemistry processes and products. It is essential that any sustainable chemistry technology or product be competitive in the marketplace, at least in the long term. However, some of those technologies, even if they are beneficial in the long term, will not be able to survive economically without incentives. Economic incentives, such as subsidies or tax reductions, could be effective in these cases. For such important decision-making, appropriate criteria to assess the long-term benefits of sustainable chemistry technologies need to be established.

As described in the Background section of this report, a considerable number of commercial processes, which were developed when environmental regulations were less strict than today, have been in existence for a long time and are still being used now. Industry opposition to the replacement of these processes with newer, safer and cleaner ones discourages innovative R&D for sustainable chemistry processes. Regulatory relief by governments - with the aim of promoting sustainable chemistry - may be effective in such cases, though the justification for the original regulation should still be considered and the problems carefully examined. It is also important to note that regulatory relief does not remove industry's compliance responsibilities. Furthermore, it is taken for granted that intellectual property rights associated with sustainable chemistry R&D should be respected and protected. It should be emphasised, however, that good sustainable chemistry technologies prove their merits only when they are widely accepted and utilised by industry. Thus, consideration should be given to ways that can balance the protection of intellectual property rights with the wide diffusion of sustainable chemistry technologies.

Academia and the public generally regard sustainable chemistry as an activity for the benefit of man and the environment, that should thus be pursued from a global perspective. Industry tends to consider that the importance of sustainable chemistry has long been well recognised, and sustainable chemistry approaches have been incorporated, where possible, into company Responsible Care® programmes. But, so far, for many companies meeting the challenges posed by the innovative technologies of sustainable chemistry is not generally regarded as a high priority area in Responsible Care®. In order for sustainable chemistry to gain greater acceptance and more financial support within Responsible Care® programmes, it is critical to provide industry leaders with a clear and persuasive explanation of why R&D in sustainable chemistry is important for industry.

APPENDIX I

Examples of Programmes to Promote Sustainable Chemistry R&D

1. United States

In the area of sustainable chemistry, much experience has been gained in the United States. The Presidential Green Chemistry Challenge, launched in March 1995, provides the best example of sustainable chemistry activity there. The programme provides recognition for accomplishments in sustainable chemistry by academia, industry, and government. The green chemistry technologies that are recognised clearly demonstrate the benefits of sustainable chemistry research. The programme has catalysed further research, development, and implementation of competitive sustainable chemistry technologies in industry, which has resulted in considerable reduction of hazards to human health and the environment.

Through the programme, research in sustainable chemistry at US universities has also increased, leading to the use of new technologies and products. Furthermore, the programme has significantly contributed to a better image of chemistry. (To provide examples of sustainable chemistry technologies and indicate some of the benefits that they provide, a brief summary of the award winning technologies of the Presidential Green Chemistry Challenge programme is given in Appendix II. It should be noted that the programme receives on average 100 nominations per year, of which five are selected as award winners.)

2. Japan

The Ministry of International Trade and Industry (MITI) has been supporting R&D in chemical technologies for the realisation of a sustainable society. An important research programme initiated by MITI, the New Sunshine Project, has been in place since 1992. The programme aims at developing innovative technology for achieving sustainable growth while solving energy and environmental issues. It covers the following areas: renewable energy, advanced utilisation of fossil fuels, energy transportation and storage, systematisation technology, environmental technology, *etc*.

On the initiative of MITI and with government financial support, several national projects related to sustainable chemistry are being promoted under the New Sunshine Project by research consortiums composed of chemical companies, national research institutes and universities. The Simple Chemistry Program, which started in 1995, is a research programme on green production processes. It aims to minimise energy and resource consumption by simplifying production processes, using, for example, novel catalytic reactions, *etc*. The Supercritical Fluids Program, which started in 2000, aims to develop advanced chemical processes using supercritical fluids, which are benign to the environment.

Under the initiative of industry and academia, the Green & Sustainable Chemistry Network (GSCN) was founded by chemistry-related societies and associations on March 2000. The main mission of the GSCN is to promote R&D on GSC through activities such as encouraging collaboration (both nationally and internationally), information exchange, communication and education, and making proposals to funding agencies.

3. Germany

In 1997 the federal government adopted the programme “Research for the Environment”. It focuses on integrated environmental protection, with consideration given to the model of sustainable development. The objective of the programme is the promotion of measures to ease the burden on the environment, reduce the costs of environmental protection and improve the competitiveness of industry. These measures will concentrate on bringing about environmental innovations, including technical, institutional and social innovations. The chemicals industry is one sector covered by this programme. Promotional projects are underway in the areas of environmentally compatible structuring of production processes (clean production) and product-related environmental protection. In addition, BMBF[3] has supported studies regarding the influence of environmental policy on the innovative behaviour of companies as well as research on environmental education and consumers habits.

Within the framework of the chemistry dialogue of the BMBF, a formalised dialogue concerning sustainable chemistry was conducted from 1998 to 1999. Organisations dealing with research and development (*e.g*. DECHEMA[4], VCI[5], BAuA[6], BgVV[7]), education and training (*e.g*. GDCh, IG BCE) and the chemicals industry participated in the discussions. As a result a two-day status seminar was organised in April 1999, which took place with about 100 participants. The aim of the status seminar was to reach a consensus on recommendations to the federal government for further activities and measures in the area of sustainable chemistry. The three working groups “Education and Training”, “Research and Development” and “Market and Economy” held discussions and compiled catalogues of necessary research tasks. These catalogues have been summarised in a document that serves as the basis for further discussions on research programmes in the area of sustainable chemistry. As a follow-up, three different working parties "Renewable Resources", "Optimisation of Processes" and "Sustainable Design of Products" have been established. These working parties will give advice to the BMBF on funding further programmes in the area of sustainable development in chemistry. Furthermore, a DECHEMA working party on "Metrics for Sustainable Chemistry" has been established.

4. Spain

In Spain, a Conference on Green Sustainable Chemistry was established in 1999 by the Institut Universitari de Ciencia i Tecnologia (IUCT) with the support of the Ministry of the Environment of the Autonomous Government of Catalonia. The aim of the Conference, which is held annually, is to promote R&D initiatives in industry and academia and to provide a framework for the dissemination of current R&D initiatives. The Spanish Ministry of Science and Technology, under the new National Plan for R&D (2000-2004), provides several programmes offering funding for innovation in the field of industrial sustainable technologies and pollution prevention.

In 1998, the Spanish Association of Fine Chemical Manufacturers (AFAQUIM) signed an agreement with IUCT to promote and develop sustainable green chemistry research projects which might be of general interest to the fine chemicals sector.

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[3] BABF: Federal Ministry of Research and Education

[4] DECHEMA: Society for Chemical and Biological Technology

[5] VCI: German Chemical Industry Association

[6] BAuA: Federal Institute for Occupational Safety and Health

[7] BgVV: Federal Institute for Consumer Health Protection and Veterinary Medicine

5. UK

The government-funded Engineering and Physical Sciences Research Council (EPSRC) initiated a five-year funding programme on clean technology in the early 1990s, which kick-started much research into green chemistry. Further to this, EPSRC and the Royal Academy of Engineering funded 10 Clean Technology Fellowships for recognised senior university researchers. These Fellowships were used to relieve the academics of their teaching duties, allowing them time to concentrate on research and 'public understanding' issues.

Over recent years there have been other initiative connected to sustainability, including funding of waste minimisation projects. There is now a gradual switch away from 'end of pipe' initiatives to prevention. The result of this is that in 2000 the government established the Sustainable Technology Initiative that provides funding for research projects (preferably multi-partner) connected with the broad issue of sustainability.

The year 2000 also saw the launch of the government-sponsored UK Green Chemistry Awards. The ideas behind these awards are to 1) encourage more, particularly young academics, to carry our research on green chemistry, and 2) to publicise and provide case studies from green chemistry products and processes developed by industry.

6. Australia

The development of green chemistry research in Australia has been supported by the federal government through the Australian Research Council (ARC) Special Research Centre grant scheme. A Special Research Centre - the Centre for Green Chemistry - was established at Monash University in 2000 to 'enable special concentrations of staff and resources for research and research training of a longer term nature' in the field of green or sustainable chemistry. The primary goal of the SRC scheme is to 'support excellent basic research and research training which has strong international links'. This is to be achieved by developing links with universities and research organisations both nationally and internationally. Direct interaction with CSIRO (Commonwealth Scientific and Industrial Research Organisation) and developing interactions with key industries are seen as being vital to the effectiveness of the Research Centre in acting as a catalyst for the development of green chemistry research in Australia.

The Royal Australian Chemical Institute Inc. (RACI) has recognised the importance of green chemistry by implementing the Green Chemistry Challenge Awards. These are open to all individuals, groups and organisations (both non-profit and for profit), including academia, government, and industry. The nominated green chemistry technology must have reached a significant milestone within the past 5 years in Australia (*e.g*. been researched, demonstrated, implemented, applied, patented, *etc*.).

APPENDIX II

Examples of Successful R&D on Sustainable Chemistry Activities

1. United States: Presidential Green Chemistry Challenge Grantees and Award Recipients

Academic Grantee. Professor Terrence Collins, Carnegie Mellon University, was selected for his development of a series of iron-based peroxide activators with applications in the pulp and paper industry, water disinfection, and the laundry field. These TAML^{TM} (tetraamido-macrocyclic ligand activators) catalysts are environmentally friendly and contain no toxic functional groups. A key use of these activators is in the pulp and paper industry, which is moving toward totally chlorine free processes to eliminate the formation of hazardous chlorinated pollutants, such as dioxin. TAML^{TM} activators enhance the oxidizing capability of hydrogen peroxide in wood pulp delignification, thereby eliminating the use of chlorine in bleaching procedures. This new technique offers potential energy savings as the first low-temperature hydrogen peroxide delignification process. TAML^{TM} activators also have applications in the laundry field, as most household bleaches are peroxide-based. The catalysts inhibit dye transfer among articles of clothing, paving the way for washing machines that use less water. Research is continuing into the water purification potential of TAML^{TM} activators, an application with global applications.

Academic Award Recipient. Professor Barry Trost was selected for the development of the concept of atom economy. The general area of chemical synthesis covers virtually all segments of the chemicals industry— oil refining, bulk or commodity chemicals, fine chemicals including agrochemicals, flavours, fragrances, *etc*., and pharmaceuticals. Economics generally dictates the feasibility of processes that are ‘practical’. A criterion that traditionally has not been explicitly recognised relates to the total quantity of raw materials required for the process compared to the quantity of product produced or, simply put, “how much of what you put into your pot ends up in your product.” In considering the question of what constitutes synthetic efficiency, Professor Barry Trost has explicitly enunciated a new set of criteria by which chemical processes should be evaluated. They fall under two categories— selectivity and atom economy. Selectivity and atom economy evolve from two basic considerations. First, the vast majority of the synthetic organic chemicals in production derive from non-renewable resources. It is self-evident that such resources should be used as sparingly as possible. Second, all waste streams should be minimised. This requires using reactions that produce minimal by-products, either through the intrinsic stoichiometry of a reaction or as a result of minimising competing undesirable reactions, *i.e.,* making reactions more selective. Achieving the objectives of selectivity and atom economy encompasses the entire spectrum of chemical activities— from basic research to commercial processes. In enunciating these principles, Professor Trost has set a challenge for those involved in basic research to create new chemical processes that meet the objectives. Professor Trost’s efforts to meet this challenge involve the rational invention of new chemical reactions that are either simple additions or, at most, produce low molecular weight innocuous by-products.

Small Business Award Recipient. Donlar Corporation was selected for its development of thermal polyaspartates (TPA), a new class of less toxic, biodegradable polymers. Donlar has also invented two highly efficient processes to manufacture TPA that are essentially waste free. The first process involves a dry and solid polymerisation step converting aspartic acid to polysuccinimide, followed by a base hydrolysis step converting polysuccinimide to polyaspartate. The second process involves the use of a catalyst during the polymerisation, which allows a lower heating temperature to be used and results in a product with improved performance characteristics, lower colour, and biodegradability. Independent toxicity studies indicate that TPA is non-toxic and environmentally safe. Many end uses of TPA have been discovered. TPA is an ideal candidate for use in water treatment as a mineral scale inhibitor, in the detergent industry as an anti-redeposition agent, in the oil and gas production industry as a scale and corrosion inhibitor, and in agriculture to improve fertilizer or nutrient management by effecting more efficient uptake of nutrients by crops.

Industrial Award Recipient in the Alternative Synthetic Pathways Category. Roche Colorado Corporation was selected for developing a new and efficient synthesis of the potent antiviral agent ganciclovir (Cytovene®). In the early 1990s, Roche Colorado Corporation developed the first commercially viable process for the production of Cytovene®. By 1993, chemists at RCC's Boulder Technology Center designed a second Guanine Triester (GTE) process for the production of Cytovene®, which, at the time, had an estimated commercial demand of approximately 50 metric tonnes per year. Compared to the first generation commercial manufacturing process, the GTE process reduced the number of chemical reagents and intermediates from 22 to 11, increased the product yield by more than 25%, eliminated the (only) two hazardous solid waste streams, eliminated 11 different chemicals from the hazardous liquid waste streams, and, of the 5 ingredients not incorporated into the final product, 4 were efficiently recycled and reused. In summary, the new GTE process clearly demonstrates the successful implementation of the general principles of green chemistry: the development of environmentally friendly syntheses, including the development of alternative syntheses utilising non hazardous and non-toxic feedstocks, reagents, and solvents; elimination of waste at the source (1.12 million kg/year liquid waste and 25,300 kg/year solid waste); and elimination of the production of toxic wastes and by-products. Roche Colorado's Guanine TriEster Process (GTE) is registered with the FDA as the current manufacturing process for the world's supply of Cytovene® and is generally applicable to the synthesis of other antiviral agents, such as acyclovir (Zorivax®).

Industrial Award Recipient in the Alternative Reaction Conditions Category. Bayer Corporation was selected for devising two-component (2K) polyurethane coatings that use water as the carrier, replacing solvents that contain volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) found in conventional 2K solventborne polyurethane coatings. In order to bring 2K waterborne polyurethane coatings to the US market, new waterborne and water reducible resins had to be developed. To overcome some application difficulties, new mixing/spray equipment was also developed. For the technology to be commercially viable, an undesired reaction of a polyisocyanate crosslinker with water had to be addressed, as well as problems with the chemical and film appearance resulting from this side reaction. The work done on the 2K waterborne polyurethanes over the past several years has resulted in a technology that provides several health and environmental benefits. VOCs will be reduced by 50-90% and HAPs by 50-99%. The amount of chemical by-products released from films in interior applications will also be reduced, and rugged interior coatings with no solvent smell will now be available. Today, 2K waterborne polyurethane is being applied on industrial lines where good properties and fast cure rates are required, for such varied products as metal containers and shelving, sporting equipment, metal and fiberglass reinforced utility poles, agricultural equipment, and paper products. Floor coatings, wood, automotive, and military applications will also benefit from the 2K waterborne polyurethane technology.

Industrial Award Recipient in the Designing Safer Chemicals Category. Dow AgroSciences LLC was selected for the development of Spinosad, a selective, low-risk insecticide (registered by EPA as a reduced risk pesticide). Spinosad is produced by fermentation of a naturally occurring microorganism, Saccaropolyspora spinosa, isolated from a Caribbean soil sample. The active components, spinosyn A and spinosyn D, are macrocyclic lactones that feature two sugars attached to a tetracyclic core. This new insecticide has been effective in controlling chewing pests in cotton, trees, fruits, vegetables, turf, and ornamentals, and has demonstrated remarkable selectivity in targeting these pests without harming 70-90% of beneficial insects and predatory wasps. In addition, Spinosad exhibits low mammalian and avian toxicity, and although it is moderately toxic to fish, it is less so than many synthetic insecticides. Spinosad presents little risk to the environment, as it does not leach, bioaccumulate, volatilise, or persist in the environment (photochemical breakdown is the major degradation route). Selectivity and low toxicity recommend Spinosad as a valuable tool for pest management.

2. Japan: Examples from Japanese Industry

Sustainable chemistry-related R&D is considered to have begun in the early 1980s, although that terminology was not used then. Since then, chemical companies have been actively and widely promoting the development and industrialisation of environmentally benign chemical products and processes. Following are examples of successful technologies or products related to sustainable chemistry, which were awarded by Japan's academic societies or industrial associations.

Novel processes based on new catalysts resulting in a] reduction of energy and resource consumption:

1. γ-Butyrolactone production technology
   A novel process consisting of two-stage hydrogenation of maleic anhydride using a newly developed homogeneous catalyst of ruthenium complex. This process reduces by-products, and accomplishes product purity of more than 99.99%, while also achieving a remarkable cost reduction.

2. Continuous process for manufacturing resorcinol *via* dihydroperoxide
   Resorcinol is continuously prepared through the oxidation of m-diisopropylbenzene selectively synthesised from benzene and propene, followed by degradation of dihydroperoxide. This novel process is easier to operate and has fewer by-products compared to the conventional method by sulphonation of benzene, followed by alkaline fusion which produces much sodium sulphite as by-product.

3. Chlorine recovery process from hydrogen chloride
   This process is a novel recovery method of chlorine by gas phase oxidation of hydrogen chloride with chromium oxide-silica as catalyst. The catalyst is so active, allowing the reaction to take place at a lower temperature compared with the conventional cuprous chloride catalyst, and consequently makes a fluidised bed process possible.

4. Cyclohexanol production process *via* cyclohexene from benzene
   Cyclohexanol is produced by partial hydrogenation of benzene to cyclohexene, followed by the selective extraction of cyclohexene from the reaction mixture with dimethylacetamide and by hydration. To effectively obtain cyclohexene, a novel reduction catalyst, composed of ruthenium metal, zinc compound as promoter and silica as dispersant, is used, and a novel solid acid catalyst is applied for hydration.

5. Catalysts for α-olefin production
   α-Olefin is produced from ethylene in high yield by oligomerisation with a novel three-component catalyst composed of zirconium tetrachloride, ethylaluminium sesquichloride and triethylaluminium.

Environmentally benign and safer products

1. Copper-acrylic polymer anti-fouling ship bottom paints
   TBT (Tri-butyl tin) paints were effective and widely used, but were found to be highly toxic. Alternative paints, using copper-acrylic polymers that are less toxic, were developed to replace TBT paints.

2. Novel acaricide *Tebufenpyrad*
A novel acaricide derived from pirazole, N-(4-tert-butylbenzyl)-4-chloro-3-ethyl-1-methyl-pyrazole-5 carbox amide, was developed and industrialised. This acaricide is more environmentally benign than the conventional acaricide, and is much more effective.

3. Realisation of IPM through pheromone mating disruption
Synthetic methods for the industrial production of insect pheromones are being investigated, and the application of pheromones as agricultural chemicals is under consideration.

Pollution prevention technologies and biotechnologies

1. Ion-exchange membrane electrolysis process for caustic soda
This process was developed to avoid the latent threat posed by the mercury process, and by 1986 all production facilities were using this new process.

2. Recycling process of chemical waste using supercritical water technology
With the process that produces tolylene diisocyanate from tolylenediamine, there is much residue waste as by-product. By using supercritical water technology, the residue can be continuously converted to TDA.

3. NO_x storage reduction catalyst
The novel catalyst $Pt/Ba/Rh/ZrO_2/Al_2O_3$ was developed as a more durable and active storage reduction catalyst of NO_x for gasoline engines. This catalyst is active at a wide range of temperature, and has made the automotive direct-injection gasoline engine possible.

4. Cleaning system for substituting CFC
A new cleaning system, using the non-ionic surfactant composed of C_6-alkyl group, instead of CFC, has been developed. Through the application of a process that briefly separates oil and water by heating, this new cleaning system makes it possible to both uses less water and recycle it.

5. Ultra-low pressure reverse osmosis membranes
The composite reverse osmosis membrane is generally composed of skin layer and supporting layer. By adjusting the surface roughness of the skin membrane, it was found that much water is filterable without decreasing the stopping power of salt permeability at low pressure. This has enabled the production of high quality water and the concentration of useful materials under ultra-low pressure.

6. Hollow-fibre type asymmetric membrane manufactured by melt spinning method
This is an environmentally benign production process consisting of melt spinning, stretching and heat-setting of poly-(4-methyl-1-pentene). New membrane uses, such as the removal of dissolved oxygen from water and artificial lungs, have been developed and industrialised.

7. Enzymatic synthesis of acrylamide using immobilised micro-organism method
This process accomplishes almost 100% conversion by one step at normal temperature and pressure. Thus the process is quite advantageous with regard to energy saving, purity, cost saving, *etc*. compared to conventional chemical processes, and it is expected to become the preferred method worldwide.

8. Industrial production of high molecular weight poly-L-lactate from renewable resources
This is a novel production process of biodegradable poly-L-lactate *via* the fermentation of renewable resources such as sugar, followed by a separation and purification process of pre-polymer LL-lactide

and by ring-opening polymerisation. By using this process, the production of poly-L-lactate could be realised on a commercial scale.

3. UK: Examples from the 2000 UK Green Chemistry Award Winners

Novel Recyclable Catalysts for Atom Economic Aromatic Nitration

Dr D C Braddock (Imperial Collage): Winner of the Jerwood Salters' Environment Award.

Conventional aromatic nitration processes use nitric acid together with stoichiometric amounts of sulphuric acid which is 'wasted' at the end of the reaction. Industrial (APCI[8]) required an alternative to mixed acid systems for aromatic nitration. Ideally, the new system should require only a single equivalent of 69% nitric acid, be completely free from sulphuric acid and the catalyst employed should be recyclable. In this 'dream' system, the only side-product would be water and since the catalyst is recyclable, it represents an atom economic system. The environmental advantages of this type of nitration system are enormous since there is no excess sulphuric acid - also containing nitric acid - (the so-called 'spent acid') to dispose of. The new system should also be able to nitrate electron deficient systems such as the commercially important conversion of *o*-nitrotoluene to dinitrotoluenes. The resulting research programme has achieved all these goals, and a not inconsiderable amount of mechanistic and structural information of high academic import has been garnered about the system.

Super-Efficient Dyes for the Coloration of Cotton; the Procion XL+ Range

Dystar UK Ltd.: Winner of the Industrial Category

The new Procion XL+ range of reactive dyes for cotton has set a new benchmark in cotton dyeing efficiency. The overall R&D process leading to the dyes' invention satisfies all the Selection Criteria laid down for the UK Green Chemistry Awards, as follows.

By attacking the total cost and time of production, these dyes deliver enormous economic benefit to the dyer and the consumers of the textiles produced from the cotton. Consumers can expect high quality products at lower prices.

Critically, the economic improvements are associated with substantial environmental benefits, which have the potential to create a major impact on the dyeing industry worldwide. However, the environmental benefits do not cost the dyer a premium: they are extra advantages of products that will reduce the dyer's total production costs.

The environmental benefits may be summarised as:

- reduction in raw material usage *i.e.* dyestuff, water, salt, auxiliaries;
- reduction in the use of energy, land, manpower; and
- reduction in effluent content: colour, salt, sequestrants, heavy metals and toxic dye intermediates.

Original research carried out in the Cheadle UK labs of Dystar UK Ltd. led to the new and original science, which underpins the new products, all of which are covered by current patents.

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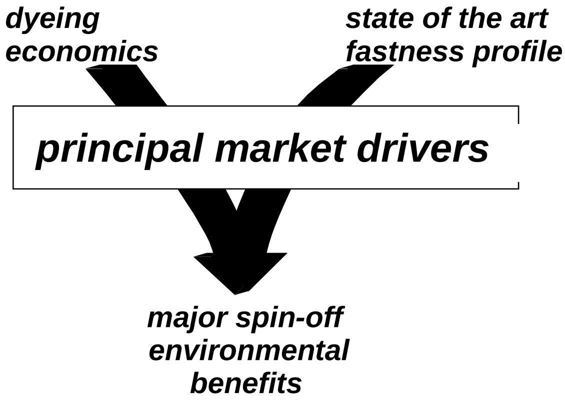
[8] APCI: Air Products & Chemicals Incorporated



Within 5 years of the start of the research phase of the project, Procion XL+ dyes are already making major inroads into the cotton dyeing market and have enormous potential to reduce the visible and invisible environmental impact of one of the most basic and fundamental industrial processes used worldwide.

Oxazolidine Diluents : Reacting for the Environment

Industrial Copolymers Limited: winner of the SME category

Over the last decade, there has been a considerable transformation in the solvent-borne industrial coatings market. Major developments have taken place in water-based coatings technology, which has now expanded from the consumer housepaint market into industrial sectors. Increasingly stringent VOC regulations have led to the development of a more viable water-based alternative to solvent borne technology. However, some limitations still exist, particularly with the key characteristics of chemical and abrasion resistance in coating performance.

Alongside the advances in water-based technology has been the development of high solids coatings. These are usually formulated with lower molecular weight components to achieve the lowest possible viscosity with the minimum use of solvent. However, there is a limit to molecular weight reduction, as this can lead to problems associated with loss of coating performance.

An example of a market that has seen the trends as described above is 2-pack polyurethane OEM coatings. Typically, these systems are comprised of an acrylic (or acrylic and polyester) polyol and an HDI-based polyisocyanate (usually biuret or trimer). These form polyurethanes possessing unique performance properties, including excellent chemical resistance and weather exposure as well as good abrasion resistance.

One possible solution to maintaining the coating benefits of solvented systems, whilst reducing the VOC, is to incorporate a reactive diluent. Incozol LV[1], a low viscosity bisoxazolidine reactive diluent, has been specifically designed to achieve high performance coatings compliant with even the strictest environmental legislation.

Incozol LV is a low viscosity bisoxazolidine reactive diluent that is activated by moisture contamination present in both the polyurethane coating components (polyol and solvent) and in the atmosphere during application. The moisture triggered ring opening allows Incozol LV, *via* chemical reaction with polyisocyanate, to be successfully incorporated into the polyurethane coating.

Incozol LV offers the benefit of reducing the VOC of polyurethane coatings beyond the present legislative demands without adversely altering cure and coating properties.

4. Germany: Examples in the BMBF[9] programme

The BMBF programme “Chemical Technology” covers research being done on how key chemical and physical technologies are contributing to sustainable chemistry. Examples of research areas financially supported by BMBF are "Catalysis", "Combinatorial Catalysis and Materials Research", "Nanotechnology", "Innovative Reactions" and "Non-linear Dynamics". Altogether 18 R&D projects have been supported over the last few years, with grants totalling 29.1 million DM.

Contributions to sustainable chemistry have been achieved by:

- increased selectivity and yield by optimised catalysis;
- reduction of by-products;
- fast and resource-saving synthesis and characterisation of new products and materials (increased efficiency);
- savings in energy and raw materials consumption by using composite membranes;
- use of dendrimers for diagnostic purposes to reduce strain on the human body;
- substitution of heavy metals in luminophors by novel zeolites;
- increase in efficiency by process intensification;
- use of alternative solvents (*i.e.* ionic liquids) or solvent-free reactions;
- increase in the space-time yield of chemical processes by non-linear optimisation algorithms;
- minimisation of energy consumption by optimised regulation algorithms (*i.e.* pressure swing adsorption for O_2/N_2 production); and
- early detection of critical process states and development of control mechanisms to avoid accidents at chemical plants (*i.e.* by neural nets or fuzzy logic)

The use of biotechnology tools (*i.e.* in production) is another way of contributing to sustainable chemistry. From 1991 to 1999, the federal government (through BMBF) has provided financial support for research projects that focus on saving energy and resources, avoiding waste and toxic by-products, and reducing pollutant emissions to air, soil and water and the release of toxic substances.. A total sum of 149 million DM was spent, of which 45 million DM were dedicated to the area of catalysis and renewal of resources. Recently, the new programme "Sustainable Bio-Production" started which supports R&D for industrial biotechnological processes and products related to sustainability.

[9] BMBF: Federal Ministry of Research and Education