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17th P.V. DANCKWERTS MEMORIAL LECTURE

TEN YEARS OF SUSTAINABILITY: WHERE DO WE GO FROM HERE?†

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Ten years ago the Rio de Janeiro environmental summit injected a new urgency into the imperative that economic development must be done in ways that can be sustained for future generations. Since that summit, the concept of 'Sustainability' has become widely accepted as a uniting and purposeful focus for the twenty-first century. In the decade since Rio science and technology has made some of its greatest ever contributions to reducing the environmental footprint of human activity, but the scorecard is still mixed. We have acknowledged some of the weaknesses of reductionist, individualist approaches that contribute to 'the tragedy of the (social and environmental) commons'. The challenge for chemical engineering is to evolve to suit this new context, so that it may continue to make a valued and knowledgeable contribution, emerging as a more sustainable profession.

It was G. K. Chesterton who remarked that the great trap for logicians was that while the world seemed reasonable it was not quite. That seems a good place to start the 2002 Danckwerts Lecture. I have noted that many distinguished preceding Danckwerts lecturers have used the opportunity to point to growing needs in the ongoing development of the chemical engineering profession. I can only assume that their words have been heeded in some measure, because the evidence in front of me is of a healthy, energetic and well trained profession.

However, to paraphrase Chesterton, while it may seem reasonable that well trained and healthy is well prepared, that may not quite be so. Perhaps one of the enduring qualities of the Danckwerts lecture is that it represents a rare opportunity to put the thinking that underlies the chemical engineering profession into the shop for a check up.

Chemical engineers working in the 'post industrial' age have been invigorated by the challenges of the 1992 Rio de Janeiro environmental summit. Our achievements since that time have been subject both to plaudits and criticisms. Nevertheless, there has been almost universal endorsement of the drive to 'sustainable development' that was called for at that summit.

Indeed, the most vocal critics would argue that 'Rio' did not go far enough, advocating a more penalizing approach for activities that are the least sustainable.

Of the many possible definitions of 'sustainability' the 'Brundtland' (The World Commission on Environment and Development, 1987) definition of the goal of sustainable development arising from the 'Rio' summit has struck a chord with governments, industry, financial institutions, environmental policy advocates and individuals as a direction against which our activities and plans should be measured.

> Sustainable Development means the advance of human prosperity in a way that does not compromise the potential prosperity and quality of life of future generations.

It is worthwhile to consider carefully the meaning of the Brundtland definition. Prosperity advancement is taken for granted. It is recognized, however, that this advancement must be managed to occur within particular constraints. If it were to be achieved in the manner of those who are already the most prosperous the overwhelming evidence is it could be very short lived.

THE CHALLENGE TO ACTION

There are as many readings onto the Brundtland definition by way of proposed directions as there are interested groups, but at least its challenge is clear, not least of all for us.

The challenge is one of balance and direction, not one of absolutes. There can be little doubt that many individual activities that we are engaged in daily are not sustainable if continued for enough generations. Some of them are already affecting the health and prosperity of future generations, but even some of these activities are paradoxically essential to the health and prosperity of future generations, because they provide a platform to that health and prosperity. 'Advancement' requires starting from where we are, with a determination to get to somewhere else.

For example, we are tempted to look at energy-intensive processes with a jaundiced eye as unsustainable, contributing to greenhouse emissions. One example is primary aluminium

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smelting. However, even with close to perfect recycling, which would eventually reduce primary aluminium needs, we may still need to build up the stock of lightweight aluminium in energy-efficient vehicles if we are to ultimately achieve energy efficiency in transportation. We cannot do that without smelting primary aluminium now. Clearly, smelting more aluminium with significantly lower greenhouse gas emissions satisfies the sustainability test.

The test of sustainability requires us to think long and hard about that type of decision. The value of the test of sustainability is not so much in what it stops us from doing, but in what it encourages us to do differently. For governments, corporations and entire industries this has become a very public test since Rio.

The challenge to positive action is also contained in Principle 15 (the 'precautionary' principle) of the Rio agreement of global governments (United Nations Environmental Programme, 1992). This principle states that:

> lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

'Lack of full scientific certainty' is a term that most scientists would recognize as too absolute, especially given recent revelations that even the speed of light in a vacuum may be situational (Davies *et al.*, 2002). The precautionary principle *demands* action where the consequences of inaction are uncertain. It makes no judgement about postponing *development* where there is 'lack of full scientific certainty'. As engineers we are in the business of finding preferred pathways through uncertainty. There is no action we can take, even in the interests of 'sustainable development', if we must first all have full scientific certainty.

Indeed, there are dangers in being thought of as holders of certain absolute truths. We should perhaps prefer to be thought of as sources of certain specialist knowledge (and as not too ignorant of many other sources of knowledge).

THE TRAGEDY OF THE COMMONS

A common perception leading into the Johannesburg environmental summit in 2002 was that we have achieved little since Rio. Quoting *The Economist* of July 2002:

> By nearly universal agreement, those grand aspirations have fallen flat in the decade since that summit. Little headway has been made with environmental problems such as climate change and loss of biodiversity. Such progress as has been achieved has been largely due to three factors: more decision-making at local level, technological innovation and the rise of market forces in environmental matters.

That this perception is 'out there' is not because of our lack of successes but because of rather more noticeable failures. There are perhaps two types of failure that are worthy of reflection.

The first and most obvious is a continuation of 'the tragedy of the commons'. Whatever our other successes may have been we are continuing to threaten resources that provide otherwise renewable life sustaining services. The greenhouse gas content of the atmosphere continues to increase, threatening the ability of the atmosphere to allow heat to escape from the biosphere. Land continues to be desertified as a result of tree clearing and water table elevation. Available fresh water quality is declining. Forests that protect the land and provide oxygen are being destroyed. Algal blooms threaten health and food production. The number of extinct and endangered species continues to grow.

Not everywhere in all cases, but in many cases. Perceptions of these failures are such that evidence of locally positive environmental performance does not translate into generalizations about global progress. Rather, it is believed by most that the local environment is an exception in a world that is in general decline (Lomborg, 2001).

When considering the tragedy of the commons, 'we' are the 'they' that 'they' are blaming. That is the tragedy of the commons.

As a profession it is in our best interests to become a better 'they'. We are 'guilty by association' with the industrial interests we are seen to serve. It will not be enough to point to our various successes while the tragedies of the commons continue. We must be able to explain 'to the person who sweeps the design room floor' how we are pulling our weight, and what our new approaches are, to paraphrase Rutherford. It is for us to cheer loudest when a positive contribution is made to a 'commons' issue. And, more importantly, we must be prepared to promote, design and operate projects in a manner that appeals to project owners while reducing the 'all of life' contribution of these projects to the tragedies.

This imperative was recognized by The Institution of Chemical Engineers (IChemE) with its London Communique, subscribing to the following challenge:

> To use our skills to improve the quality of life: foster employment, advance economic and social development, and protect the environment.
> This challenge encompasses the essence of sustainable development. We will work to make the world a better place for future generations.

The second type of failure is one of local impact. Even relatively rare and temporary environmental emissions that affect local communities will quickly override other 'sustainability' impacts, particularly less observable positive effects on the commons. We cannot expect to justify our failures by pointing to our successes. Fallout, noise and odour can be more damaging to perceptions than energy consumption and greenhouse emissions.

It appears to be part of the human condition that alarms are more clearly heard than 'all clears'. Certainly there seems little point explaining the global responsibility of an operation to people that are even occasionally provided with evidence of local failures.

HOW GREEN ARE OUR ARMBANDS? A 10-YEAR REVIEW

An assessment of the contributions of chemical engineers in the last 10 years or so can be nothing more than a series of snapshots, given the diversity of activities that engages our profession. Fortunately some of these contributions have been well documented (World Resources Institute, 2002).

Looking first at the efficiency of some of our major industries (Table 1) there have been some remarkable gains in energy and water effectiveness. In the core territory for chemical engineers, the inertia of starting 'from where we are' has not prevented substantial progress.

Table 1 demonstrates the effectiveness of competitive forces in bringing about improvements. No competitor can afford to be using 40% more energy than the best in the industry. That would not be 'sustainable', even taking the narrow, individualist view.

The success of our industry in replacing chlorofluorocarbons with effective products that do not harm the ozone layer (Figure 1) is to our great credit, and has shown leadership and alliance that we should now attempt to replicate in other 'tragedies of the commons'. The advantage in this case was the limited number of suppliers of these chemicals and existing knowledge of the near-equivalent effectiveness and ease of synthesis of alternatives. There is, however, a disturbing trend to greater use in the more quickly developing economies in Asia, reflecting the validity of concerns for sustainability in the context of economic development leading into Rio.

These trends are reproduced by 'smokestack' pollutants. Figure 2 demonstrates that in developed 'post industrial' economies we have very effectively reduced sulphur dioxide emissions to the atmosphere by fuel replacement and sequestration. However, the trends in developing economies are far less encouraging.

Looking, however, at atmospherically long-lived emissions, notably carbon dioxide, the industrialized world continues to grow at rates that at least match the developing world. Since 1996 China's economic growth has been at least 25% and carbon dioxide emissions are agreed to have remained largely flat across this time (if not having fallen as sometimes unreliable official statistics indicate, Figure 3). However, this trend is soon expected to be reversed when

Table 1. Core chemical engineering efficiencies are improving.

Industry	Years	Efficiency Gain Per Unit Output
EU chemical industry	1985–1996	34% less energy
US chemical industry	1974–1998	43% less energy
European paper industry	1975–1997	50–80% less water
European and Canadian paper industry	1990–1998	10.5% less energy
Steel industry in 10 OECD countries	1971–1991	20% less energy

Source: OECD, 2001.

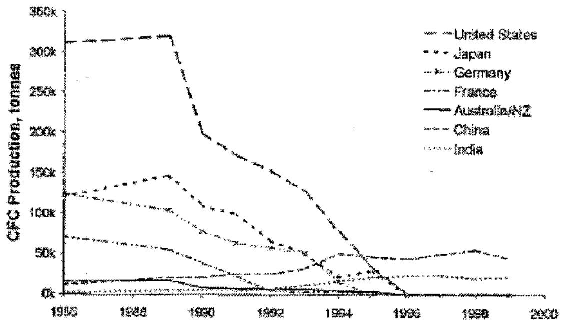

Figure 1. Chloroflurocarbons demonstrate success. Source: UNEP 2000.

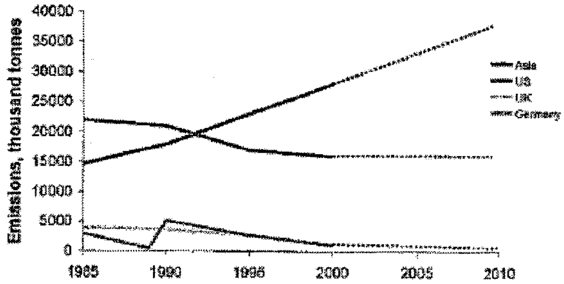

Figure 2. SO_x demonstrates Rio concerns. Source: WRI.

closures of inefficient state-owned enterprises cease to make a large contribution (US Embassy Communication, 2001).

Failure to stem the increase in atmospheric carbon dioxide levels (Figure 4) is an excellent example of the complex dynamics that are at work. Where competitive advantage cannot easily be attached to local solutions to tragedies of the commons, there must be mechanisms that drive 'me too' since traditional market forces will not as easily drive 'me first'.

The lesson from other pollutants, such as sulphur dioxide, is that success in these areas can be driven by co-development of sequestration technology and regulation (or at least the expectation of regulation) in the equivalent of an 'arms race'.

As the Kyoto process has shown, progress based on targets without pathways can be very slow. Renewable energy sources (excluding hydropower), including wind

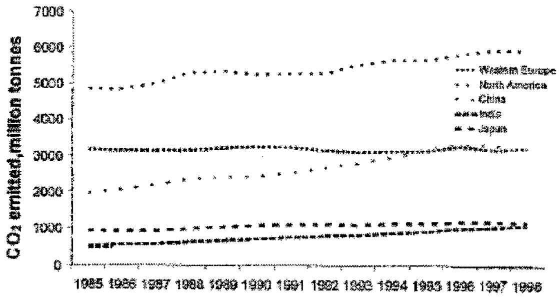

Figure 3. Apart from short-term improvements carbon dioxide emissions trends have continued. Source: UNEP.

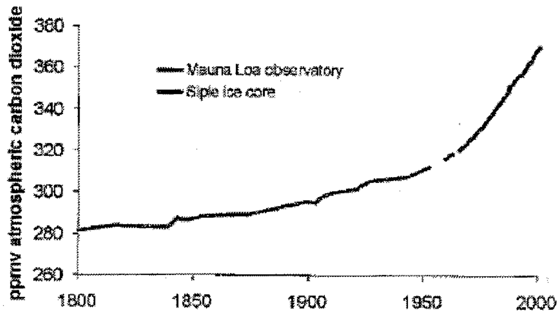

Figure 4. A potential tragedy of the commons. Source: CDIAC.

energy, biomass, solar heating and photovoltaics continue to make a relatively insignificant contribution to global energy supply (Figure 5). However, growth rates in photovoltaics and wind turbine energy from a very low base have been impressive since Rio (Figure 6), reflecting advances in technology that have greatly reduced the cost and increased the capture effectiveness of these energy sources (Figure 7; Ruby and Dee, 2001).

The combination of market forces and technology developments suggests that renewable energy sources may not be the only path to emission reduction in the near term.

Clean coal energy based on coal and petroleum coke gasification has increased by about 50% since the Rio summit to now approach 1% of all coal consumed (Figure 8; Simbeck, 2001). Its growth is expected to escalate as its costs begin to compete with direct coal combustion as a source of power. Gasification is the most developed pathway to decarbonized distributed energy from coal via hydrogen, and ultimately to geological or biological carbon dioxide sequestration.

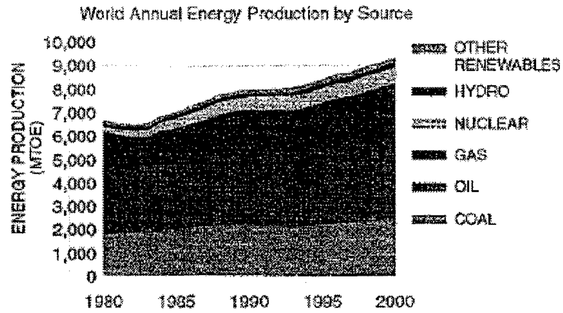

Figure 5. Renewables still insignificant, small net growth. Source: WRI, Reference IEA.

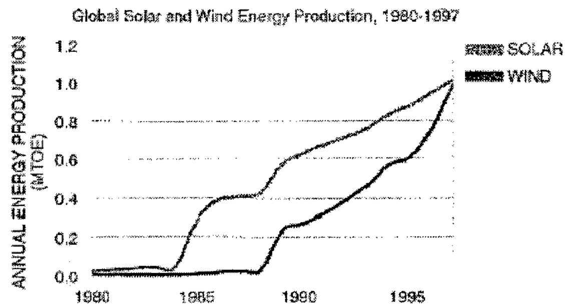

Figure 6. Co-development of targets and technology. Source: WRI, Reference IEA.

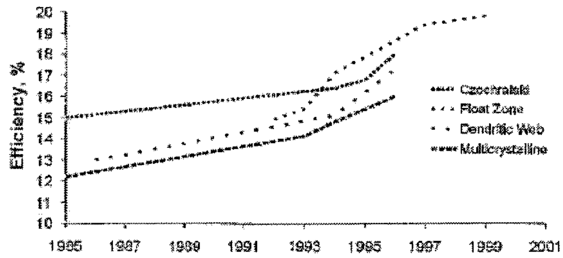

Figure 7. Remarkable advances in rapid thermal processed silicon photovoltaics. Source: Sandia.

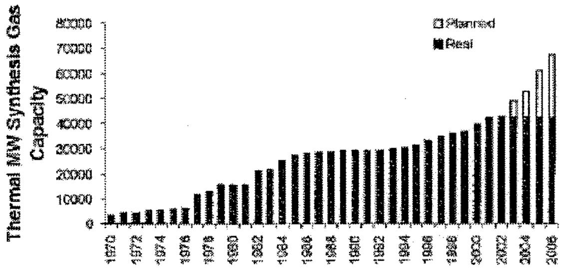

Figure 8. Clean coal, a sustainable step on the path to renewable energy. Source: SFA Pacific.

Despite promising developments, it seems unlikely that the world will obtain a significant proportion of its energy from non-fossil fuel sources within the next two decades. No matter which fossil fuel source is used it will contribute to elevation of atmospheric carbon dioxide unless carbon dioxide is sequestered in an environmentally benign form, away from existing biosystems. That is, fossil fuel consumption, with fuel distributed in decarbonized form (electricity or hydrogen) is a necessary platform to a more sustainable world. Co-development of targets and pathways for carbon dioxide sequestration is required if there is to be a practical resolution to increasing atmospheric carbon dioxide. In future, our measures may well focus more on emission reduction than on the use of renewables.

Our 10-year review for chemical engineering should cover more than the process industries given the wide ranging employment and influence of chemical engineers. Better water distribution for irrigation, and better and more targeted fertilizer application has allowed continued advances in crop yields in the 'green' revolution, with the tragic exception of Africa (Figure 9). As a result of these advances that have continued over the last decade we have never been better positioned to feed the world (but we still have not developed politico-economic distribution systems that ensure that all receive basic nourishment).

Advances in food supply have not been limited to the land. Aquaculture, itself an 'engineering process', now supplies one-third of all fish consumed globally, providing an important supplement to the ability of natural fisheries to support human needs (Figure 10).

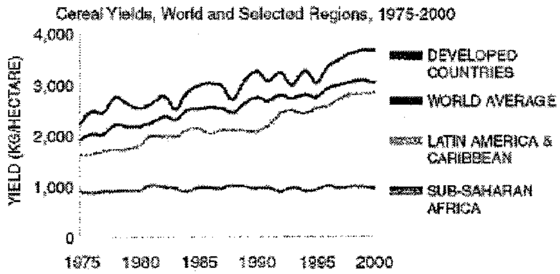

Figure 9. The green revolution. Source: WRI, referencing FAOSTAT.

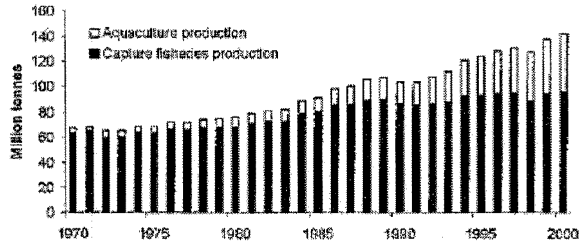

Figure 10. Thirty percent of fish produce is farmed. Source: WRI, referencing FISHSTAT.

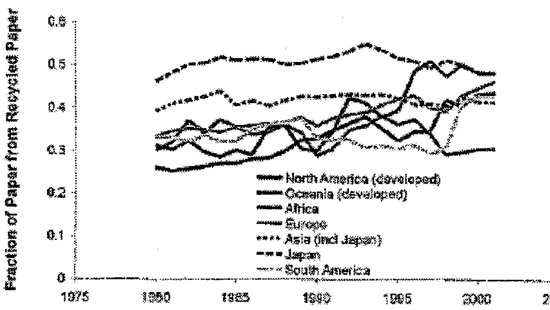

Figure 12. Paper recycling hits limits. Source: FAOSTAT, after WRI.

However, the development of the ability to produce food has come at a number of costs to sustainability. It is widely considered that land is being desertified by salinity and clearing at such a rate that if continued it will ultimately threaten the ability of future generations to meet their food needs, and will threaten biodiversity through loss of habitat.

Inland waterways are becoming polluted through the effects of rising water tables and eutrophication via dissolved nutrients derived from fertilizers. These effects also flow on to coastal waters. Increases in algal blooms, with sometimes toxic impact have in part been attributed to the nutrients (Figure 11; Anderson, 1995).

Recently evidence has emerged that nutrient levels in coastal waters can have an impact on the global spread of cholera via blooming of phytoplankton that are grazed by zooplankton that in turn can carry the cholera bacterium (Colwell, 1996). Satellite images are now being used to predict possible cholera outbreaks and vaccinate accordingly. It seems that there will continue to be no shortage of cases where 'lack of full scientific knowledge' produces unexpected effects in the environment. In particular, eutrophication looks like a 'precautionary principle' issue, demanding action. Like greenhouse, it is a tremendous challenge.

Per capita consumption of paper products has increased (driven rather than mitigated by the availability of electronic data), but, importantly for us, the proportion delivered as recycled paper has stalled in industrialized economies (Figure 12; World Resources Institute Earth Trends, 2001). Given the short cycle time of paper this cannot be sheeted home to any disjoint between discard rates of recyclable material and demand. Paper recycling still represents a substantial challenge.

Metals on the other hand have longer cycle times in most applications, so supply of potentially recyclable material is a smaller fraction of growing consumption. Given this context it is encouraging to see the increasing extent to which metals like aluminium are produced from recycled material (Figure 13; European Aluminium Association, 2002). Recycling of aluminium from automotive applications now exceeds 95%. Dismantling and scrap sorting processes have made major contributions to this impressive record. Indeed, in giving waste a value, a key step is to design the initial product so that during recycling, sorting into separate and hence more valuable components, is simplified and cheap.

Renewable sources of chemicals have also started to become available via the impact of biotechnology. It is estimated (Bachmann *et al.*, 2000) that 2% of the total chemical market is now produced via biotechnology acting on plant-derived matter in fermentation, bio-catalysis and plant-based production, focused on the higher value fine chemicals. Projections have production of commodity polymers becoming commercial by 2010.

Advances in other areas, such as the green revolution, have reversed a focus from technology for food production from hydrocarbons in the 1980s to technology for 'petrochemicals' production from carbohydrates in the twenty-first century. Perhaps this change in focus is a good example of finding

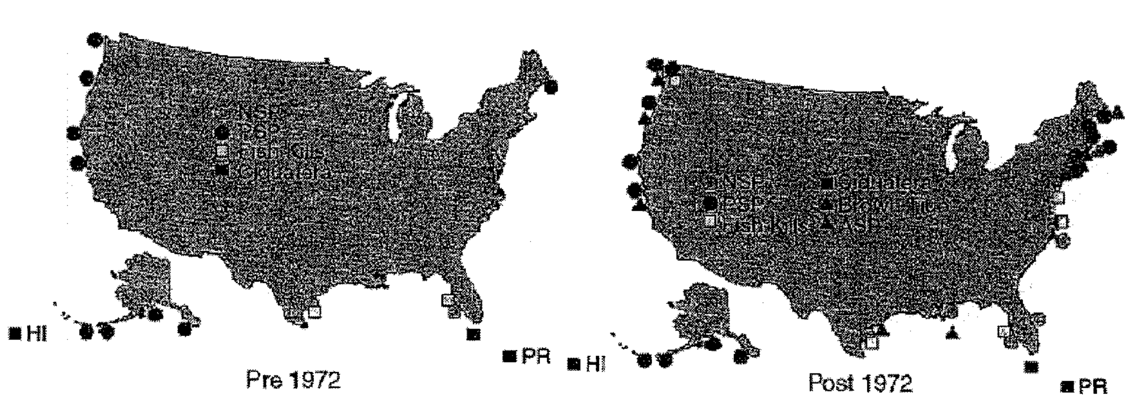

Figure 11. Harmful algal blooms are increasing.

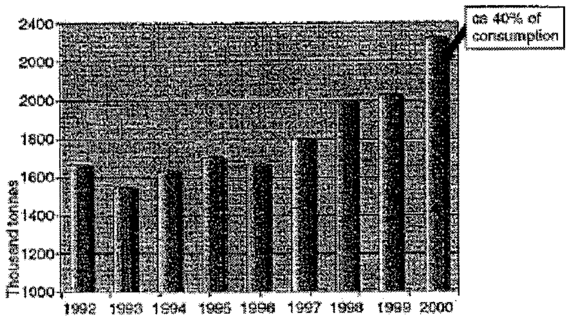

Figure 13. European recycled aluminium. Source: EAA.

pathways in the face of uncertainty. Not all pathways will survive, but we will need a host of options from which to select.

So, we have a mixed scorecard for activity since Rio. There have been many advances, driven in part by market forces and in part by co-development of regulatory targets and pathways. However, we have made less progress where these forces have not been at work, most noticeably in 'tragedies of the commons', which frustratingly seem to have been exacerbated by some of our best efforts in other areas.

THE NEW MARKET FORCES

Leading into and following the Rio summit there is a new form of influence on corporations that recognizes their increasingly transnational activities. The global nature of industrial effort comes with problems for regulation at the national level, and with opportunities for coordinating action that extends beyond national boundaries. The great success of the corporate form of resource allocation has meant that the largest corporations now have access to resources that exceed those of many national governments. The harnessing of this power to the drive for sustainability has become a recognized imperative. The corporate sector can be mobilized such that both companies and society can benefit.

There are many opinions as to the effectiveness of this strategy, but it appears to be at least widely supported. We should expect to continue to see it supported for as long as it shows the potential to deliver. Critics suggest that corporations will naturally engage in 'greenwash' rather than constructive activities, and that corporations cannot be trusted to honestly work in any direction other than immediate self interest. They point to the failures of Rio.

Supporters believe that there are new mechanisms at work that will galvanize corporations into aligning self interest with longer term global interests.

Global environmental organizations that have large influences on governments have arisen, providing information, analysis and recommendations. These organizations also help to drive public perceptions of the extent to which action is needed, and therefore have political and shareholder influence.

The level of concern emanating from Rio for the sustainability of development activities has had the following impacts (UKSIF Archive, 1992):

- growth of 'social' funds that selectively invest in successful corporations based on social and environmental criteria;
- expectations of some shareholders that corporations and funds managers will work to ensure improved environmental performance;
- expectations of some voters that governments will meet commitments made to sustainable development, and properly control the activities of corporations;
- government support for corporate activities that depends on binding commitments to certain programmes;
- alliances between business groups, global interest organizations and governments that meet the needs of all parties.

These important developments recognize that uncoordinated national regulation is a cumbersome and often inefficient process for controlling diverse activities, and can also have the effect of directing development into the least sustainable locations. The power of globally effective cooperative mechanisms is that none of the important contributors to positive outcomes is marginalized. Co-development of regulation and technology can be achieved within a global framework that affects local action.

In essence, regulation has been recognized as a last rather than first resort, and it is being supplemented by other mechanisms that make use of market and political forces. Given the adaptability of chemical engineers, we should welcome these changes.

THE 'POST INDUSTRIAL' CONTEXT

The 'wealthiest' (highest GDP per capita), 'industrialized' countries have the highest proportions (70%) of the workforce working in services industries, while the 'poorest' countries have similar proportions of the workforce working in agriculture. The wealth-generating capability of a country is enhanced by industrial activity employing up to 30% of the workforce, but not beyond this level (Figure 14; World Resources Institute, 2002).

Consequently, agrarian economies will 'industrialize' in pursuit of the advancement of prosperity, while industrial economies will move to a greater orientation on services. Where industrialization has reached saturation as a source of employment the economy is referred to as 'post industrial'. In Western Europe and North America this transition occurred in the 1980s.

A 'post industrial' economy has a 'post industrial' culture that reflects the lower value that is placed on industrial activity as a source of human advancement. In these cultures, when it is said that 'you can't stop progress' it is no longer industrial progress that is the immediate focus. However, the health of industry remains important in the economy, just as does the health of agriculture.

One implication for chemical engineering is that the dominant proportion of the growth in industrial activity is in Asia and South America, where industrialization is occurring most rapidly, and is highly valued as a source of economic advancement. Chemical engineering as a profession has been a child of the industrial age. Its dominating institutions and corporate centres have evolved in industrialized societies, but now exist in a 'post industrial' context. It is important for us to understand this context, as it affects both the direction of our efforts and the nature of the best pathways.

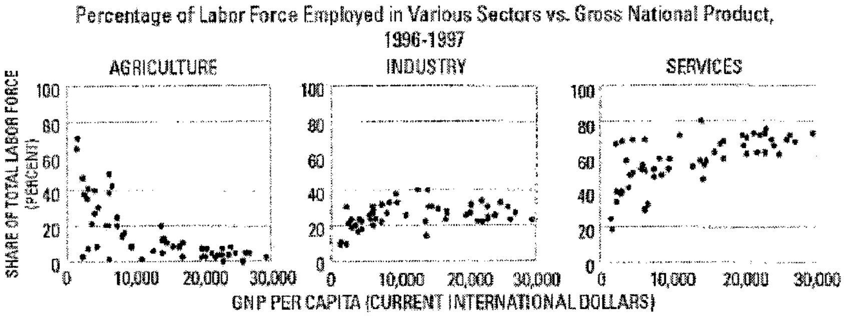

Figure 14. Activity in services is driven by wealth. Source: WRI, referencing World Bank.

Indeed 'sustainability' is a post-industrial construct, originally developed and highly valued by post-industrial societies. Global environmental organizations are products of the post-industrial age. Capital resides mainly in the hands of members of post-industrial societies. The new market forces reflect the voices of the people in these societies.

With the move both to industrialization and to services the benefits of shared infrastructure drive urbanization, and higher population densities in major cities (Figure 15; World Resources Institute, 2002). As this process continues there will be greater pressures on local air and watersheds that will affect human health, if not managed (Figure 16). This will be one of the major challenges facing the engineering professions in the early twenty-first century.

Perhaps the other great change in the context of the rise of services economies is the contribution of advanced communication systems to distributing knowledge, opinion and expertise. The 'information age' is upon us (Figure 17; World Resources Institute, 2002). Information technology is providing the infrastructure for achieving 'emergent' solutions that satisfy the common interest of sustainability. The exponential rise in the use of this technology in middle- to low-income economies is a heartening development.

In the 2000 Danckwerts Memorial Lecture (Prausnitz, 2001), Professor Prausnitz drew attention to the alienation of society from science and technology in the post-industrial age that led to the rise of 'post-Modernist' thought. Sustainability as a global objective has the potential to overwrite that trend, since it calls for a contribution from us all, and for a respect for the opinions and 'constructions' of others.

I have taken the liberty of reproducing some of the descriptive terms from Professor Prausnitz's lecture, and

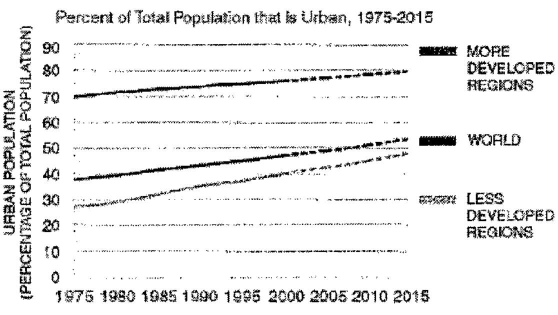

Figure 15. Infrastructure and opportunity drive urbanisation. Source: WRI, referencing UN.

superimposing directions that are emerging in the march to sustainability (Table 2). If there is to be a sustainable 'post-industrial' age I submit that it must have these qualities about it.

The shared beliefs of the sustainable post-industrial age will embrace the post-Modernist view that there are as many truths as there are individuals, but will not allow this to become a deterrent to action. Knowledge and information that assist action will be valued more highly than 'truth'. In this sense the beliefs of the sustainable post industrial age will have something in common with both post-Modernist *and* industrial age beliefs.

It is important in this context to recognize that the advance of technology has not ever really been about the search for objective and immutable 'truths'. Technology in the industrial age has generally been rather less noble in its aims. It has been more about predicting and controlling narrowly defined local outcomes.

Herein lies a major difference in thinking for the sustainable post-industrial age. The desired outcomes are not narrowly defined nor local, so the results of individual action are far less predictable. Lack of ingoing predictability (as opposed to after the event explanation) has been identified in some even quite simple systems (Cohen and Stewart, 1994). Luckily, in the almost infinitely complex global context the precautionary principle suggests that full ongoing predictability is not a necessary precursor for action.

However, even in the complexity of the world we are often able to broadly predict the general direction of outcomes, at least on a 'balance of probabilities' and 'if often repeated' basis. That is, in relevant effects complexity is a much weaker driver of unpredictability than we might expect. The emergence of recognizable and fathomable simplicity from complex interactions seems to be part of the fabric of any universe that might have provided a home for us so far.

> The answer to complexity turns out to be fairly obvious, and not, in itself especially interesting: if you have a lot of simple interactors, and let them interact, then the result can be rather complicated.
>
> The interesting question is precisely the opposite, the question that most scientists never thought to ask, because they didn't see that there was a question to ask. Where does the simplicity come from? (Cohen and Stewart, 1994)

The principle of an understandable world, that things that are of relevance to us usually have emergent meaning for us, is the reason that reductionist logic can blind us to important phenomena, failing to find meaning in what looks like noise.

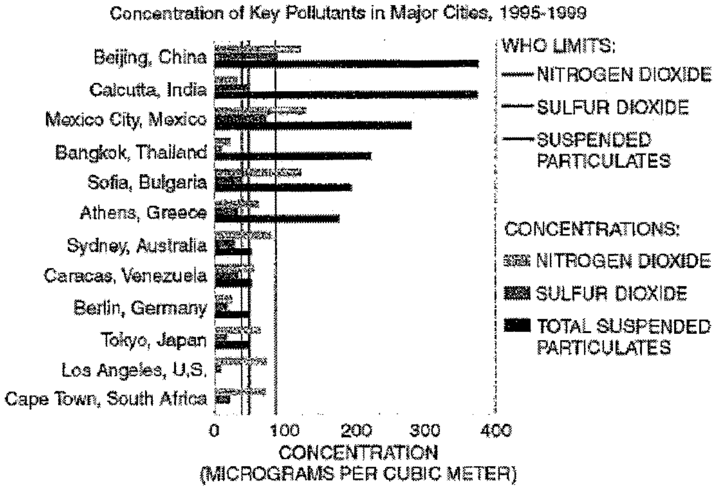

Figure 16. Pollution and poorly developed infrastructure (2.4 billion people without sanitation) threaten health and prosperity. Source: WRI, referencing WHO.

An example is the recent understanding that so-called 'junk' DNA has an organizing function that was previously missed because DNA was 'given' the reductionist role of protein templating (Cooper, 2002).

That the world has emergent meaning at the macro level is of as much philosophical as scientific importance. Indeed, in our quest for sustainability, Cohen and Stewart's suggestion that simplicity will emerge is highly significant, particularly as we acknowledge that many different outcomes are possible.

FROM NETWORKS TO PATHWAYS

Even as empathetic beings our individual powers of prediction and our actions are concentrated on 'our world as we see it'. Hence Chesterton's remark. This introduces collective complexity of action, when sustainability demands 'concerted' effort. The question becomes one of how the 'simplicity' of concerted action can arise from the complexity presented by lack of full certainty, particularly in the context of multiple constructions derived from different knowledge sets.

Fortunately that question is being answered by case studies in success. The most effective ways forward substitute the individualist, constructionist (and often adversarial) approach of the industrial era with a collectivist, 'constructivist' approach. Put more simply, we are interested in 'emergent' outcomes, or to find 'pathways through the forest' that are satisfactory and sufficient. Perhaps the attempts at this that are best known are the global environmental summits themselves, since these summits have been very helpful in elucidating principles for global action, even if not generating general agreement on the means. However, there have also been other efforts, like the US Department of Energy 'industry roadmap' exercises. Government, research institutions, industry organizations and individual businesses work together in these facilitated exercises to elucidate common goals and organize cooperative effort. Ongoing goals include sustainable development.

Exercises such as 'road mapping' or 'foresighting' do not require that existing beliefs are suspended, and it is both a requirement and normally inevitable that competitive interests are not suspended. Yet common goals and pathways are invariably achieved as outcomes. Individual companies and governments are then left to make progress towards those goals down the identified pathways at their own pace, alone or in combination. The force of competition means that it is

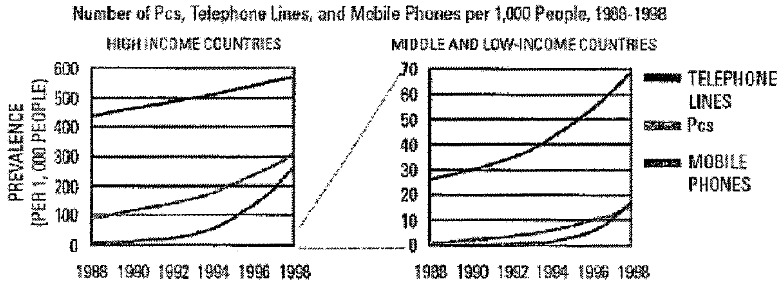

Figure 17. Infrastructure for global networking is becoming well distributed. Source: WRI, Referencing World Bank.

Table 2. Action in the face of uncertainty.

Post-Modern	Sustainable post-industrial
No objective realities	'Knowledge/information' is key
Individualistic/self-centered 'deconstruction'	Individual 'knowledge' valued, collective responsibility
Anarchy	Networks/interdependence
Chance	Pathfinding
Science/technology as 'evil'	Science/technology 'harnessed'

'I would rather discover a single fact, even a small one, than debete the great issues at length without discovering anything at all'. (Galileo Galilei c. 1640)

Table 3. The 'Laws of sustainable development'.

1. Today's problems come from yesterday's solutions	7. Cause and effect are not closely related in space and time
2. The harder you push, the more the system pushes back	8. Small changes can producing big results—but the areas of highest leverage are often the least obvious
3. Behaviour grows better before if grows worse	9. You can have your cake and eat it too—but not at once
4. The easy way out usually leads back in	10. Dividing an elephant in half does not produce two small elephants
5. The cure can be worse than the disease	11. There is no blame
6. Faster is slower	

Peter Senge: The Fifth Discipline, 1992

not long term 'sustainable' to be left behind. The result is a synthesis of the 'old' and 'new' market forces, with competition at least in part focused on more sustainable outcomes. Even at the individual business level networks that involve government, industry, research and environmental interests are being established to advise on the level and effectiveness of efforts. These initiatives often involve public reporting.

A requirement that is unfortunately often missing, even from these exercises, is truly effective pathfinding. Goals and pathways have limited usefulness if they start from some place other than where we are, if they pass over forbidden terrain, or if they do not recognize the need to equip for the road.

Potentially worse are pathways that head initially in the right direction but cannot lead to the ultimate goal. An interesting example of such a pathway is a move away from coal-based energy towards natural gas. Since combustion of natural gas also produces carbon dioxide this might at best be a stop gap measure. It is on the pathway to reduced carbon dioxide emissions, but might not be on the pathway to stopping or reversing the trend in carbon dioxide level of the atmosphere. It is 'continuing to go in the wrong direction, but more slowly'.

On the other hand, carbon dioxide sequestration technology and hydrogen from fossil fuels could create an atmospherically safe bridge to renewable energy, and therefore represent plausible steps on the pathway to the ultimate goal.

Goals that buy time are potentially valuable, but they should not be confused with steps on the ultimate path. So, there is still work to be done in the area of 'pathfinding'.

The systems thinker Peter Senge (1992) has produced a set of rules for dealing with complex interacting systems that act as a type of check list of 'avoid these things' in pathways. I have reproduced these in Table 3.

Rule 10, regarding elephants, is perhaps the most appealing when one considers the individual interests (and professions) of the post-industrial age. Like a number of amusing elephant stories it argues against purely reductionist approaches. The simplest 'root cause' solutions do not emerge from dealing with symptoms. There are elegant and relatively simple emergent ways of getting two small elephants starting with just one large one, but dissection of the original elephant is clearly not on the pathway to small elephant generation.

TOLERANCE FOR AMBIGUITY VS RESOURCE EFFICIENCY?

Some of the best business successes in chemical engineering have arisen from the approach to strategy known as scenario analysis (Van der Heiden, 1996). According to this approach business strategy emerges as a main path that is also consistent with a set of contingency plans. The contingency plans are activated when early warning signals of changed circumstances are received.

So chemical engineering has led the way in emergent approaches that recognize that there are sets of internally consistent futures that could arise. Scenario analysis requires a tolerance for dissonance and ambiguity. This balance is a good place to start (but only just a start) for sustainable development.

We can summarize the approach to chemical engineering that will best support sustainable development. Approaches based on 'imagine the world without us, so please welcome us' are industrial age. Similarly 'we're scientists so we don't need to communicate in language you can understand' is industrial age. The summary approach involves:

- science and technology—humble tool for knowledge, prediction, and control, not 'truth and glory';
- aim practical means of achieving perceived 'sustainable' benefits;
- creative emphasis—collaborative 'constructivism', not 'construction';
- breadth—global, networked;
- action—emergent, local, 'informed';
- tolerance for ambiguity—gelling, multi-scenario, not crystallizing, 'the best path through a forest of realities';
- ingoing dissonance—assisting effective action (rather than retarding efficient action), reducing 'the tragedy of the commons'.

The best outcome for us will not necessarily be found along the pathway that we can most easily construct. Emergent solutions are better, but require humility. They also require knowledge, courage, authority, determination and honesty.

A simple example of an emergent solution that meets human, business and sustainable development needs is the Eraring coal washery (Dunphy *et al.*, 2000). The washery operates in the context of a town that 'needed' to construct a long ocean outfall for sewage disposal. The washery could not obtain enough water for its needs. It was only when the interested parties, including those having concern for the local environment, came together to discuss regional needs that the solution of the washery constructing a sewage treatment plant, taking the treated effluent as washery feed water, emerged. A water catchment and distribution system, an outfall deposition system and the discharge of raw sewage into the environment were avoided.

Another lesson in the effectiveness of emergent outcomes for technological advancement is found in 'people power'. In the limited circumstances where this has been engaged it has allowed a pace of development that has exceeded that which has been available by most traditional means, producing better outcomes in shorter times.

The best examples are to be found in the successes of Linux server technology, and Danish advanced wind turbine technology (capturing 55% of the global market against competition from NASA), but there are also examples in the development of agricultural machinery. These are examples of the 'open systems' approach, where the users influence the development of the system (Hall, 2002; Douthwaite *et al.*, 2002, Unpublished data).

The basic proposition is that a large and diverse interest group of willing participants having various initial 'orientations' coupled with a central 'pathfinding' team can produce a very fast evolutionary effect towards a goal. An essential feature of this approach, termed 'learning selection' is that a poorly developed concept having practical promise passes through iterative stages of novelty generation, selection and promulgation.

The 'father of chaos' and population modeller, Robert May (Matthews, 2002), reflected on the success of promulgation of his work in the biological sciences, compared with the successes of later theories. He concluded that a simple and humble promise having recognizable utility that can be further customised by others was an essential ingredient.

A challenge for the profession is to bring active networks to the pathfinding teams to better enable rapid, evolutionary approaches to sustainability.

CHILDREN OF THE INDUSTRIAL AGE

The birth and history of chemical engineering is so closely associated with the history of the industrial age and its surviving bureaucratic organizational forms that the profession is best thought of as co-evolved. It is not surprising that we are earmarked as specialists, and often stereotyped into roles and contributions accordingly. Our skills and training are acquired via formalized, specialized education, and often via specialized experience in particular industries. We are often selected for roles on the basis of functional and industry specialization.

Our formal training prepares us to make a primarily reductionist, deductive and deterministic contribution. For the most part our role has been to combine and adapt existing individual unit operations to suit the technical purposes of market driven corporations. In an industrial age this has been the 'place' of the profession, as strengthened by its own successes.

As an example of this success, the role of the extractive metallurgist was increasingly supplanted by chemical engineering in the late twentieth century. In part this was because the metallurgical profession was already specialized into a smaller subset of the chemical processing industries (mining and smelting), and because it attempted to specialize even further, into separate mineral processing, hydrometallurgy and pyrometallurgy emphases. The more broadly based chemical engineering profession presented more options for the participation of individuals in industry, and greater potential for solving broadly defined problems. So in the industrial age chemical engineering has avoided the main dangers of being too specialized, a good starting point.

In the 1997 Presidential Address to IChemE, Professor Bridgwater reflected on the strengths of the chemical engineering profession as ready to make a crucial contribution (Bridgwater, 1997):

> Chemical engineers know much about how to cope with processing and with systems, and how to deal with uncertainty. Indeed the role of the chemical engineer is becoming more vital in society... We know how to take relevant information, incorporate it with best practice—having due regard to economics, safety and the environment—to yield both a process and a product that takes account of life cycle analysis and satisfies the needs of the community.

However, with the focus of industry in the early twenty-first century swinging fast towards sustainable development we must heed the words of Lew Platt (former CEO Hewlett-Packard): 'Whatever made you successful in the past, won't in the future' (Peters, 1997). Which is not to say that we shouldn't build on our strengths—just that some of the things that have made us strong can contribute weaknesses in a new context.

There is no reason to expect that the drive to specialization that has been the backbone of self-organizing societies since the dawn of civilization will cease. However, for an existing profession there is the need to adapt to meet new needs if the profession itself is to be sustainable. In the twenty-first century, greater individual specialization means a greater emphasis on networking for problem solving. We move from a strong emphasis on complexity arising from deterministic simplicity (synthesis of unit operations approach) to include a greater emphasis on:

- simplicity arising from probabilistic complexity and diversity of influence;
- better model of behaviour, next generation operations;
- inclusive, constructivist, emergent solutions;
- inductive 'transfers' to/from collaborators;
- as much emphasis on 'pathfinding' as destinations;
- scenario-based—uncertainly is no excuse.

WHAT NOW FOR CHEMICAL ENGINEERS?

How to summarize this discussion for the chemical engineering profession? We will need to participate in society in more creative ways, in the types and focus of the innovations that we contribute, in the rate at which we can innovate, and in the means by which those innovations are generated. Our contribution has shifted more to that of options provision than problem solving, since the more important problems are not ours alone to solve.

We must be specialized, but bring a broader view via networks. We can continue to be self interested, but recognize that the interests of others affect what our interests are in ways that by ourselves we cannot understand. Our context is now set by markets and governments and informed by NGOs and the public.

We can expect that the organizations that seek our services will evolve gatekeeping systems that demand greater networking ability and tolerance for ambiguity. Consultants and technology developers in services firms and advisory organizations will dominate our ranks rather than direct employees of individual chemical producing firms. To be successful we must be able to 'bring the network with us' as a service.

We face some major challenges on the path to sustainability. Developing scenarios call for seemingly contradictory paths to be pursued simultaneously, e.g. hydrogen from fossil fuels and the development of renewables technology are both 'right' for greenhouse gas abatement. Shared understanding of this type of ambiguity is essential for pathfinding; and there are many paths to be found:

- clean water for all, land and water for irrigation without salination/desertification, fertilization without eutrophication;
- recycling *and* biodegradation of plastics and paper;
- resource extraction without waste piles.

Recycling and waste elimination come with particular challenges, firstly with design to enable ease of component separation, and then with the direct pursuit of industrial synergies, where waste can be incorporated into inputs to other processes, generating value.

We are already seeing the influence of the new forces at work on our profession. For example, leading educational and research institutions, such as Oxford University (Oxford University Department of Engineering Science, 2002), have introduced sustainable development priorities in chemical engineering education, focusing on hydrogen as fuel, emissions reduction, sequestration, photovoltaics and life cycle analysis.

An initiative of the World Resources Institute is the *Beyond Grey Pinstripes* (World Resources Institute, 2001) ranking system for post-graduate business education, emphasizing sustainable development. The leading proponent so far appears to be the University of Michigan's Sustainable Development MBA. Other institutions have already followed, providing opportunities for professional engineers to participate in the processes and networks that arise.

For the most part we have probably not gone far enough in preparing engineers for the environment that they will be working in, which includes the post industrial social environment. The dilemma for undergraduate teaching is how to provide a thorough specialist engineering education, as continues to be needed, while also preparing engineers to make innovative contributions to emergent outcomes in networks. The aim is to prevent specialization from becoming demarcation and social marginalization. My predecessor in this lecture pointed to this same challenge (Sargent, 2002).

The answer to this may well in itself be emergent. We can and should start out the way in which we wish to finish. Sustainability should be an objective of all professions. The social sciences and business schools have already developed systems for dealing with non-deterministic, emergent behaviours in complex, dynamic and human systems. Networking with these schools in cross-functional syndicates via case studies and project work having sustainability objectives will provide both specialist training and skills in obtaining emergent outcomes. This approach will also emphasize the importance of decision making in the absence of full certainty, the value of patterns from other environments, and 'learning by stories'. Some universities are already blazing trails in this direction. The Institution should encourage all to do so.

As a profession, we must celebrate approaches that result in emergent outcomes (rather than just outcomes). It is certainly not the case that chemical engineering is so lacking in diversity of approach that there will be no present examples to choose from. Because perceptions are reality, these symbols are important to the attraction and leadership of people having the skills we need.

To the extent that our profession influences primary and secondary education we can continue to reinforce that we value skills in physical sciences but be sure to point out that these will not be sufficient. For real success we prefer that these skills are accompanied by breadth, as indicated by other creative and co-operative activities.

In the final analysis the choice for us as a profession is the one that has always been there—between providing merely a useful set of skills or also contributing to the leadership and decision making of the societies in which we operate.

For chemical engineers this means adding a new yoke to that of our industrial age heritage. The challenge of sustainability will be supported by our traditional skills, but it will not be met by more efficiently doing what has led to success so far.

Our contribution along traditional lines is continuing, with improvements in many measures of success. These results suggest an energetic and skilful profession whose services will be needed in meeting the challenge of sustainability. There are also signs that we have recognized the need for change, and we are responding to the new forces at work.

Yet have today's practising engineers absorbed the meaning of sustainability to the point that they can offer leadership? Will next year's new graduates be better prepared for the challenge?

To me, a sustainable future for chemical engineering as an identifiable and energetic profession built on traditional strengths and recognizing new challenges seems reasonable, . . . but not quite.

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ADDRESS

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Danckwerts Lecture – PowerPoint Presentation

TEN YEARS OF SUSTAINABILITY: WHERE DO WE GO FROM HERE?

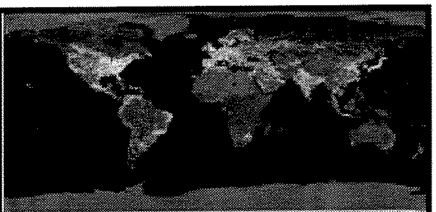
R. J. BATTERHAM

Chief Scientist of Australia
Chief Technologist, Rio Tinto Limited
Vice President, The Institution of Chemical Engineers

The Bruntland definition

Sustainable development means the advance of human prosperity in a way that does not compromise the potential prosperity and quality of life of future generations.

Rio and 10 years



By nearly universal agreement, those grand aspirations have fallen flat in the decade since that summit. Little headway has been made with … climate change or loss of biodiversity.

The Economist, July 2002

Any progress has been due to:

- more decision-making at local level
- technological innovation
- the rise of market forces in environmental matters

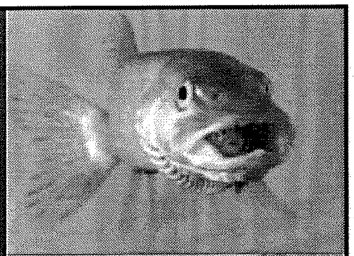
The Economist, July 2002

The London Communique

To use our skills to improve the quality of life: foster employment, advance economic and social development, and protect the environment.

This challenge encompasses the essence of sustainable development. We will work to make the world a better place for future generations.

GK Chesterton's world, reasonable but not quite



- A 10 year Scorecard
- Our post industrial age
- Creativeering

10 year Scorecard : efficiency

INDUSTRY	YEARS	EFFICIENCY GAIN PER UNIT OUTPUT	
EU chemical industry	1985 to 1996	34%	L E S S
US chemical industry	1974 to 1998	43%	
European paper industry	1975 to 1997	50-80%	E N E R G Y
European and Canadian paper industry	1990 to 1998	10.5%	
Steel industry: 10 OECD countries	1971 to 1991	20%	

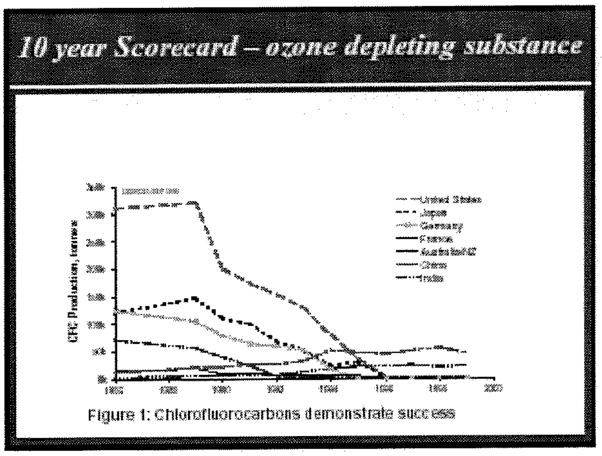
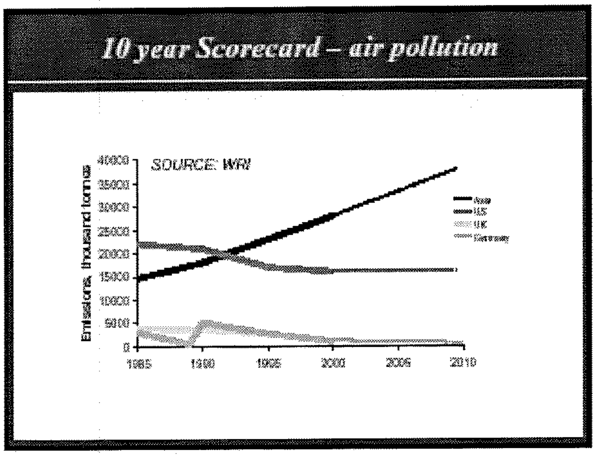


Figure 1: Chlorofluorocarbons demonstrate success



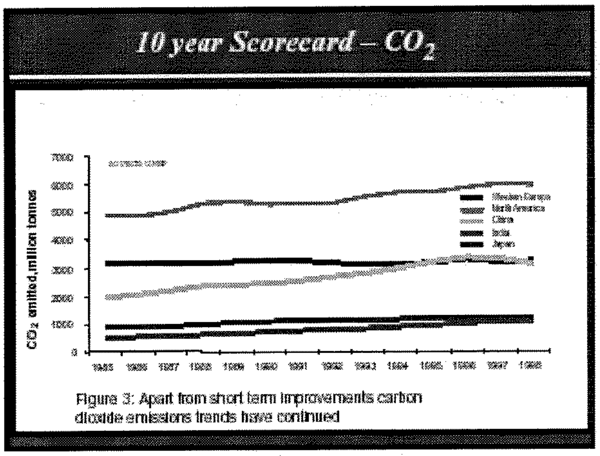
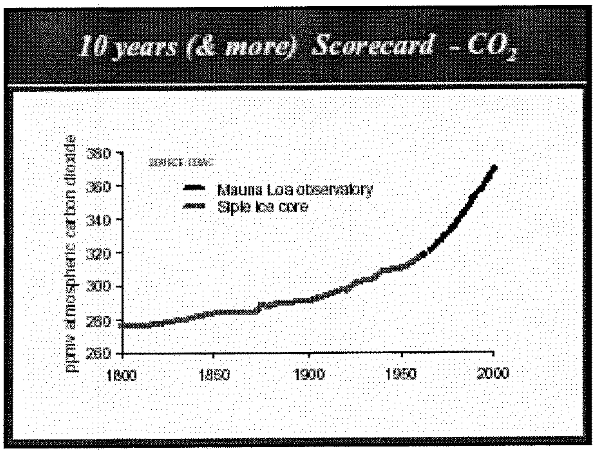
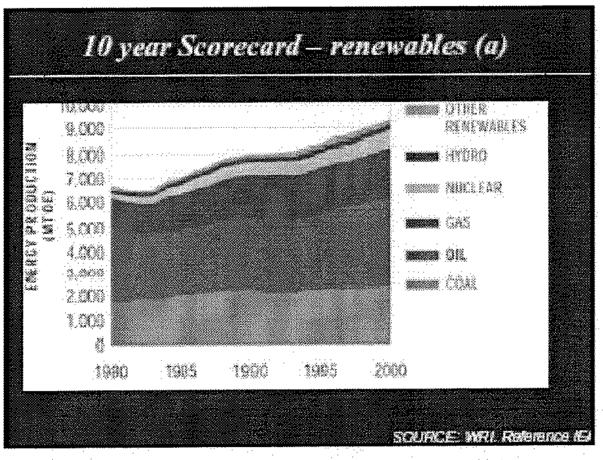
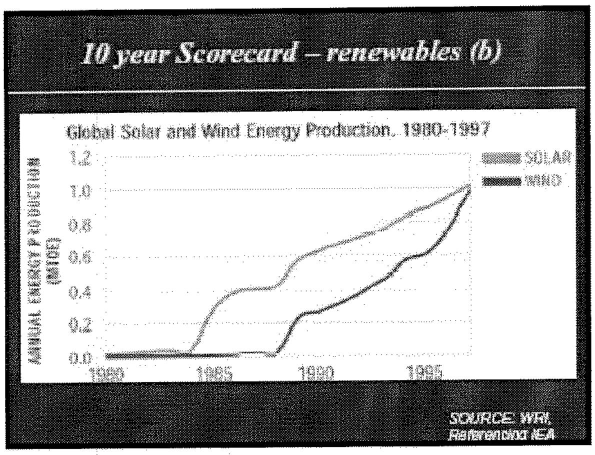
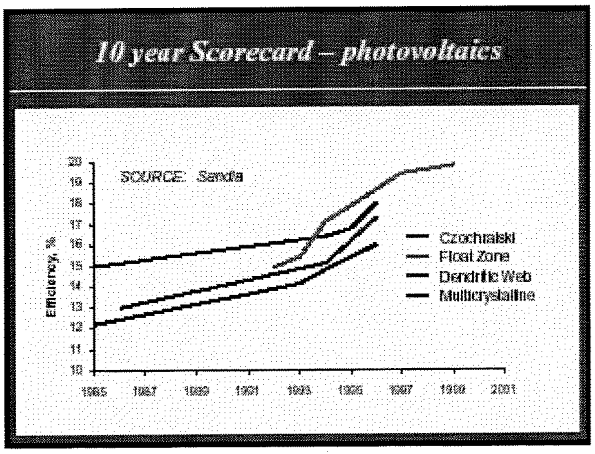


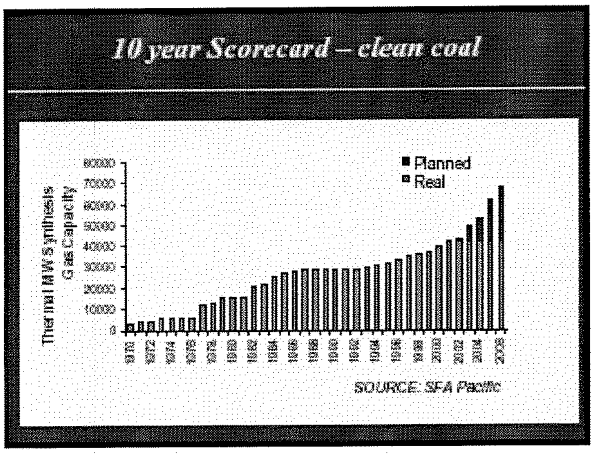
Figure 3: Apart from short term improvements carbon dioxide emissions trends have continued

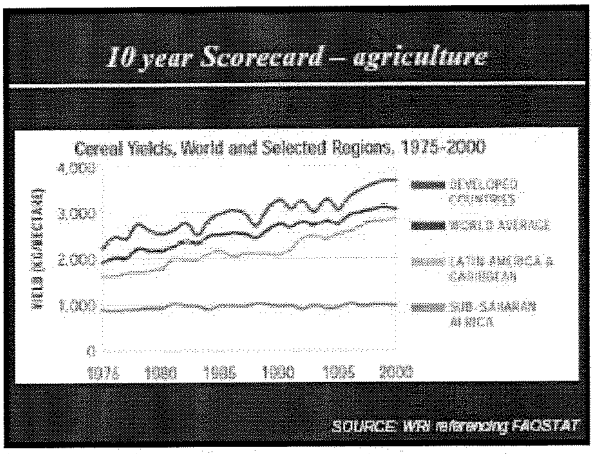


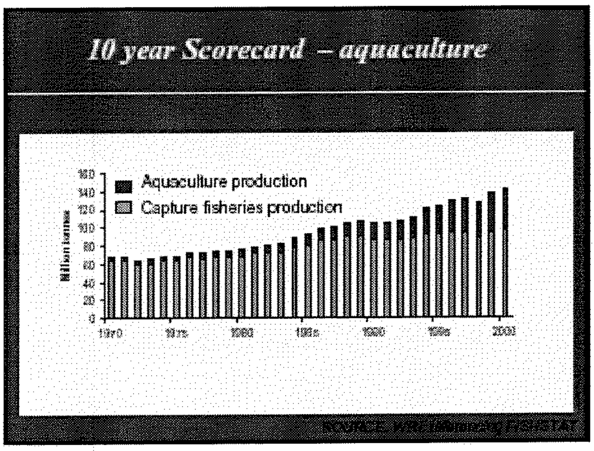


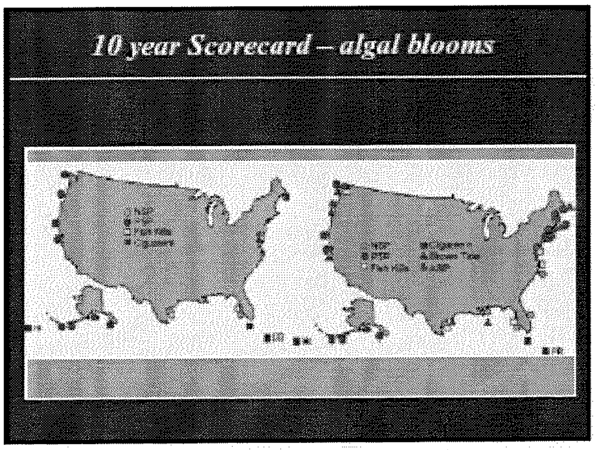

10 year Scorecard – renewables (b)
Global Solar and Wind Energy Production, 1980-1997
ANNUAL ENERGY PRODUCTION (MTOE)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
SOLAR
WIND
1980
1985
1990
1995
SOURCE: WRI, Referencing IEA


10 year Scorecard – photovoltaics
SOURCE: Sandia
Efficiency, %
Czochralski
Float Zone
Dendritic Web
Multicrystalline

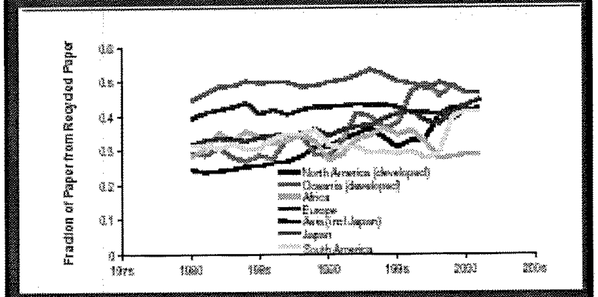

10 year Scorecard – clean coal
Planned
Real
Thermal MWS synthesis Gas Capacity
SOURCE: SFA Pacific


10 year Scorecard – agriculture
Cereal Yields, World and Selected Regions, 1975-2000
4,000
3,000
2,000
1,000
0
1975
1980
1985
1990
1995
2000
SOURCE: WRI referencing FAOSTAT


10 year Scorecard – aquaculture
Aquaculture production
Capture fisheries production
Million tonnes
1970
1975
1980
1985
1990
1995
2000

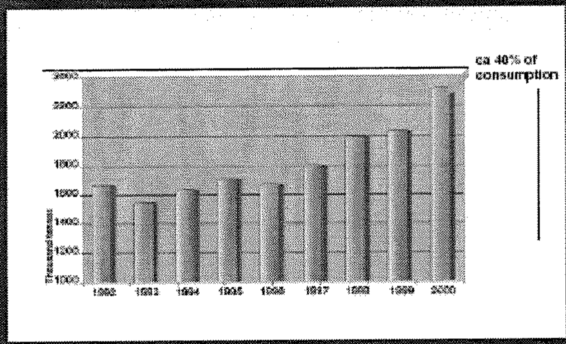

10 year Scorecard – algal blooms

10 year Scorecard – paper recycling



SOURCE: FAOSTAT after WRI

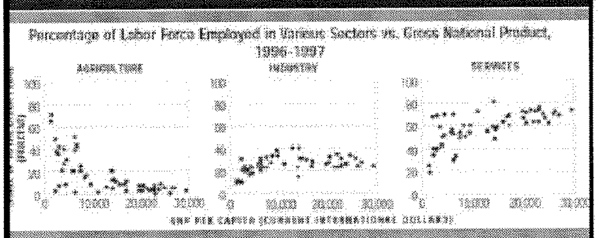
10 year Scorecard – aluminium recycling



The new market forces

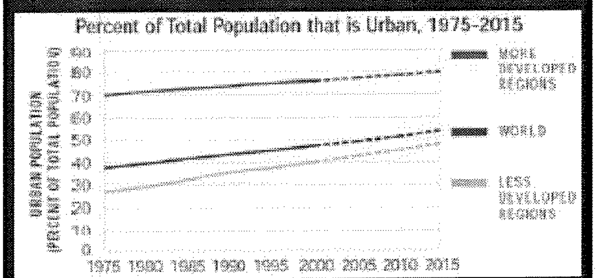
- Social funds that invest in corporations based on social and environmental criteria.
- Shareholders' expectations of improved and environmental performance.
- Voters' expectations of commitment to sustainable and development. Government support aligned with and commitment to certain programs.
- Alliances between business groups, global interest bodies and organisations of governments, each aimed at emergent outcomes that meet the needs of all parties.

Post industrial services age



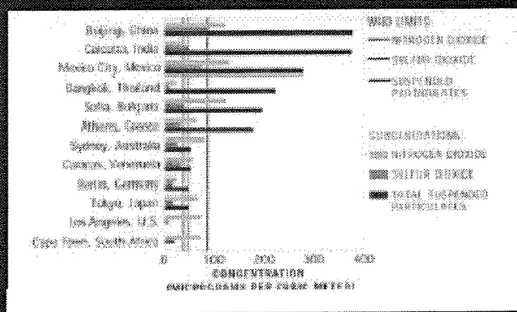
SOURCE: WRI referencing World Bank

Post industrial urban age



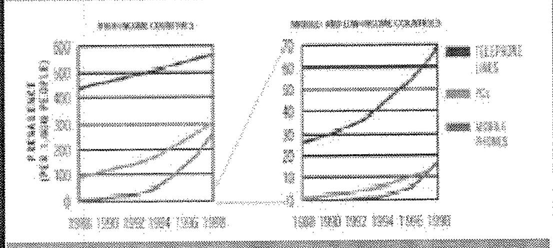
SOURCE: WRI, Referencing UN

Post industrial human age



SOURCE: WRI, referencing WGO

Post industrial information age



SOURCE: WRI, Referencing World Bank

Post Modern v *Post Industrial*

Post Modern	Post Industrial
No objective realities	"Knowledge / information" is key
Individualistic / self centred "deconstruction"	Individual "knowledge" valued, collective responsibility
Anarchy	Networks / Interdependence
Chance	Pathfinding
Science / technology as "evil"	Science / technology harnessed"

Chaos or creativeering?

The answer to complexity turns out to be fairly obvious, and not, in itself especially interesting. If you have a lot of simple interactors, and let them interact, then the result can be rather complicated.

The interesting question is precisely the opposite, the question that most scientists never thought to ask, because they didn't see that there was a question to ask.

Where does the simplicity come from?

Cohen and Stewart

Laws of the Fifth Discipline

1. Today's problems come from yesterday's solutions
2. The harder you push, the more the system pushes back
3. Behaviour grows better before it grows worse
4. The easy way out usually leads back in
5. The cure can be worse than the disease
6. Faster is slower
7. Cause and effect are not closely related in space and time
8. Small changes can produce big results-but the areas of highest leverage are often the least obvious
9. You can have your cake and eat it too – but not at once
10. Dividing an elephant in half does not produce two small elephants
11. There is no blame

Peter Senge: The Fifth Discipline, 1992

The chemical engineering approach

Science and technology: Humble tool for knowledge, prediction, and control, not "truth and glory"

Aim: Practical means of achieving perceived "sustainable" benefits

Creative emphasis: Collaborative "constructivism", not "construction"

Breadth: Global, networked

Action: Emergent, local, "inform"ed

Tolerance for ambiguity: Gelling, multi scenario, not crystallising, "the best path through a forest of realities", ingoing dissonance: assisting effective action (rather than retarding efficient action), and reducing "the tragedy of the commons".

A new, "emergent" approach

Examples

- Wind turbines (beat NASA)
- Linux (taking on Microsoft)
- Pacific Power (Eraring)

Sir Robert May

The deeper challenge

The voyage of discovery is not in seeking new landscapes but in having new eyes.

Marcel Proust

Where to? "Creativeering "

Context: development that reduces "the tragedy of the commons", leading rather than following regulation.

Options rather than solutions: innovative, increasingly "emerging" from constructivist approaches.

Employer: consultant organisation, NGO or large corporation

Emphasis: network, collective, collaborative

Some challenges

Emission free energy;

Clean water for all, land and water for irrigation without salination / desertification, fertilisation without eutrophication;

Recycling and biodegradation of plastics and paper; and

Resource extraction without waste piles.

Qualifying education (Tertiary)

Social sciences

Specialisation, not demarcation

Collaborative case studies & projects

Physical science and technology (including ecological and environmental)

Finding simplicity in complexity (eg the Eraring case study)

Business training

People learn best through stories

Finally

To me, a sustainable future for chemical engineering as an identifiable and energetic profession built on traditional strengths and recognising new challenges seems reasonable,

.... but not quite.