# Breakthrough Carbon Capture:

## Exploiting Existing Trade-Off and Compromise Challenging Solutions from Other Sectors

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## Abstract

Despite the considerable ongoing research into a variety of pre and post combustion carbon capture and storage technologies there is concern that these programmes will not achieve the required optimal solutions suitable for timely implementation at costs that might be acceptable the consumer.

If economically viable carbon capture solutions are to be achieved within environmentally acceptable time scales then a considerable amount of paradigm-shifting breakthrough thinking may be required to support the current initiatives.

Based on the analysis of breakthrough solutions within a very large range of technological sectors this presentation offers an alternative approach that shows how recent technological innovation methodologies might be used in this arena.

The presentation specifically discusses the importance of identification and resolution of trade-offs and compromises as being the primary driving force of innovation. A number of key trade-offs present in the current carbon capture technologies are examined and suggested conceptual level solution strategies based on already known solutions to equivalent trade-offs from other sectors are proposed.

## Background

*The status of carbon capture technology cost implications and the case for considering a paradigm shift*

Within the EU there is a clear understanding that in order to meet its 20% $CO_2$ reduction (from 1990) by 2020 then in the post 2012 Kyoto period the required average 1% per year emission reduction will only be met with significant additional technology developments. It is agreed that probably one of the greatest impacts in reducing $CO_2$ emissions will be made by the introduction of zero emission fossil fuel power plants that include carbon dioxide capture and storage. Cost effective $CO_2$ capture and storage may also prove an essential element both for the production of sufficiently large quantities of hydrogen in the transition to the "Hydrogen Economy" and in the use of so called 'clean coal'. This realisation has resulted in significant EU Framework funds being directed towards R&D projects that demonstrate various technology options for the; capture, compression, transportation and storage of $CO_2$ from power plants, Table 1 provides a selection of a number of such programmes;

| Programme | Focus | Size | Completion |
|---|---|---|---|
| CO2 Sink | Full-scale underground CO2 storage test site | 18.5 MEuros | March 09 |
| Encap CO2<br>Enhanced Capture of Co2 | Precombustion tecnologies for enhanced capture of CO2 in large power plants – 90% capture rate and 50% capture cost reduction | 22 MEuros | 2010 |
| CACHET:<br>Carbon Dioxide Capture and Hydrogen Production from Gaseous Fuels | Develop technologies to significantly reduce the cost of CO2 capture from natural gas with H2 production. | 13.5 M Euros | 2008 |
| HYPOGEN | Phase 1 Feasibility Study, DYNAMIS Preparing for large scale H2 production from decarbonised fossil fuels with CO2 geological storage | Phase 1 – 7.5 MEuros<br>Overall 1.3 BEuros | Phase 1 – 2008<br>Overall 2015 |
| CO2ReMoVe, | Separation of CO2 from natural gas at oil and gas operations in the North Sea, southern Saharan desert and in Germany, followed by compression and re-injection | 15 MEuros | |
| CO2 Capture Project (CCP) | Technologies to reduce the cost of $CO_2$ separation, capture, and geologic storage from combustion sources such as turbines, heaters, and boilers. | Industry funded (50 MEuros ?) with EU support for subprojects | Phase 2 - 2008 |
| CASTER<br>CO2 from capture to storage | Esbjerg power plant<br>1 ton Co2/hour | Part of CCP | Operational since March 06 |

Table 1 – Example Selection of EU Funded $CO_2$ Capture, Compression, Storage Projects (ref 1)

(Full listing at http://www.co2captureandstorage.info/cont_europe.php)

It is clear from the project literature that there is still a diversity of opinion regarding the optimal technology and that operational costs of the alternatives are of significant concern. Current costs of carbon capture vary with the technological processes, scale and geography but are in the order of 40 to 60 Euros per tonne of $CO_2$. A typical analysis cost undertaken using the cost analysis tool GESTCO (Ref 2) has shown that storage costs could be of the order of 1 Euro /tonne and pipeline transportation is about 5 Euro/tonne (ref 3). The remaining costs (typically 45 Euros) are therefore those associated with the capture technology itself.

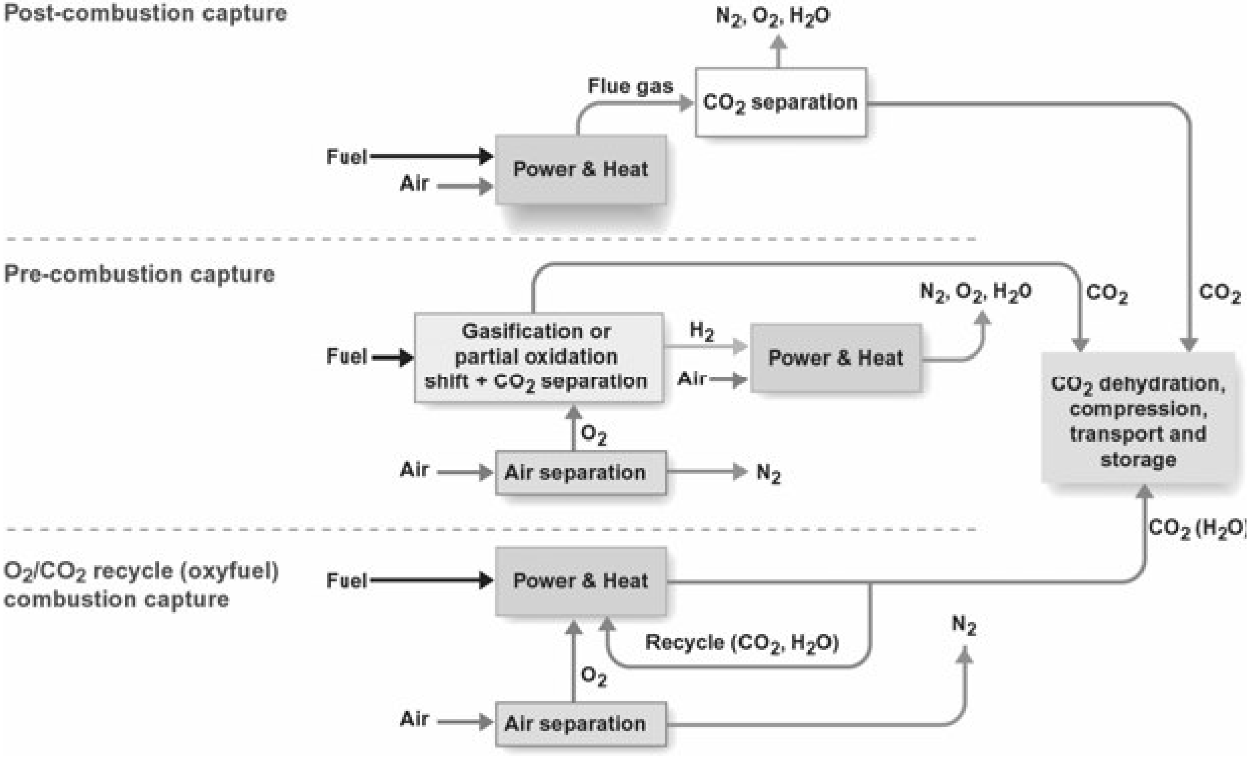
Current EU research targets for the cost of $CO_2$ capture vary from 20 Euros per tonne (ref 4) to a range of 20 to 30 Euros per tonne (ref 5). It is assumed that these targets are market derived and represent on costs that would be acceptable to the consumer. After allowing 6 Euros/tonne transport and storage this is suggesting a typical commercially realisable capture target of 19 Euros/tonne. This then is equivalent to a technology cost reduction of about 55 to 60% over current levels within a time span of as little as 3 years and up to 8 years (depending on individual programmes).

***The innovation breakthrough opportunities are therefore considered to be primarily in the area of the cost reduction of capture technology.***

In order to consider breakthrough potential a high level understanding of the current capture technologies at the concept level is required.

## CO2 Capture Technologies

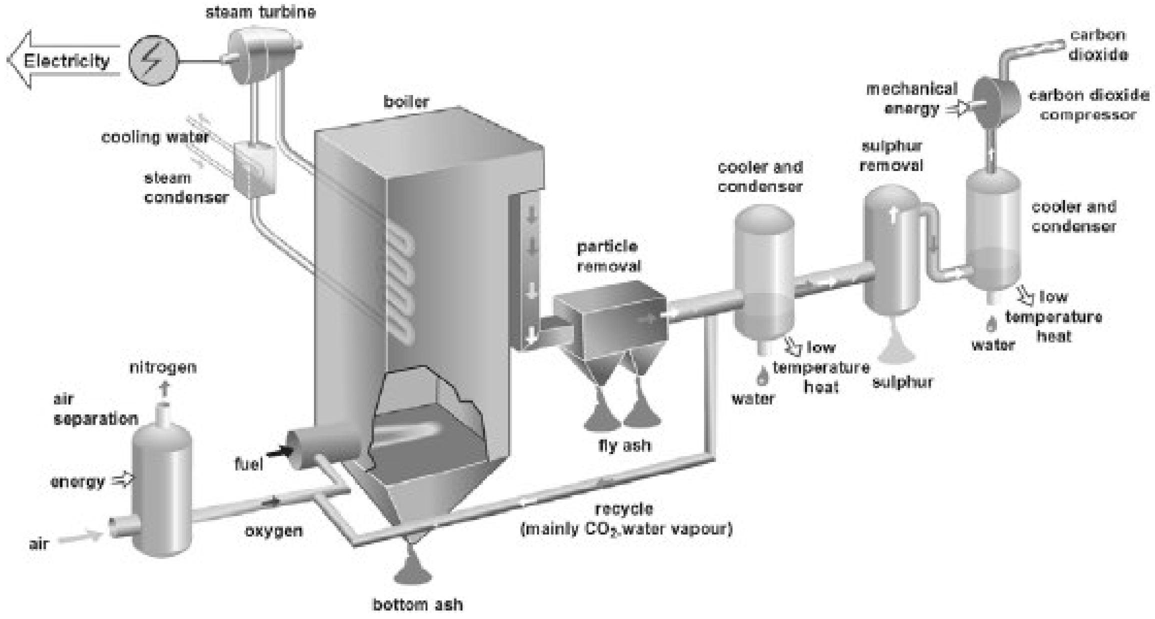
A useful overview of capture methodologies is provided in Reference 6 ;



Some of the methodologies are described in outline detail below;

### *O2/CO2 Recycle*

In the O2/CO2 recycle process, the fuel is combusted with almost pure oxygen that has been mixed with recirculated flue gas. The recirculation serves to moderate the combustion temperature. The resulting flue gas from the process is a practically pure stream of $CO_2$ and water, the later being separated by condensing.

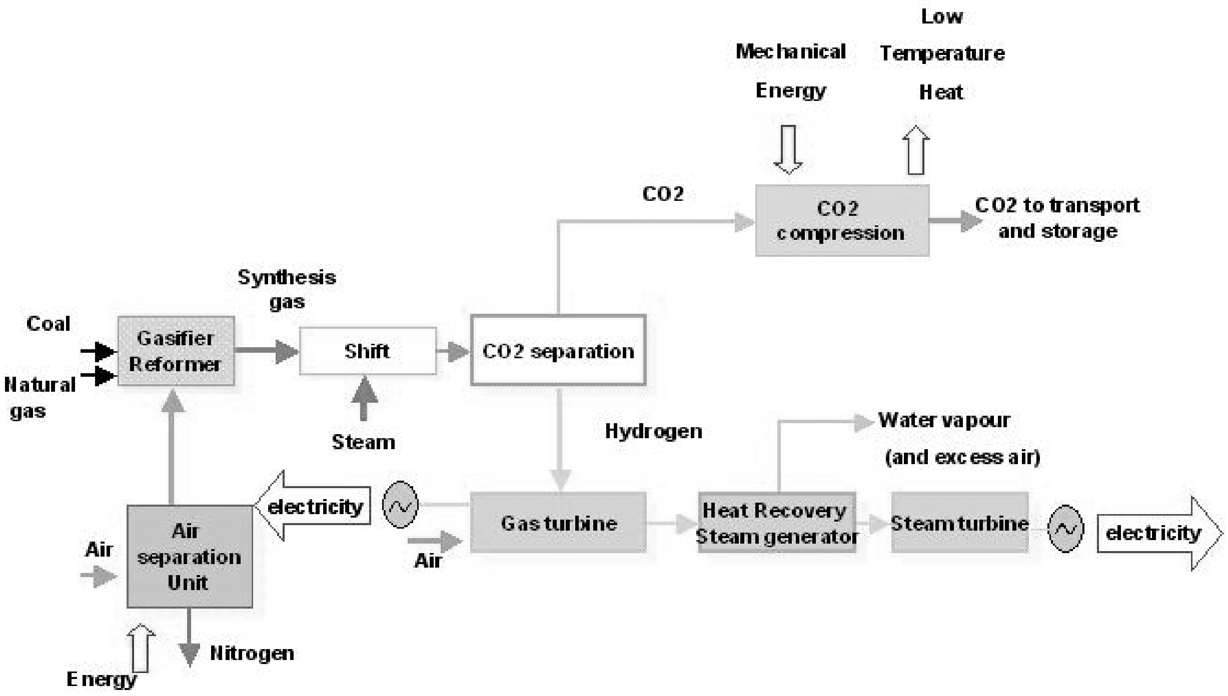


O2/CO2 Recycle Process (ref 6)

The reported challenges involved with the O2/CO2 recycle approach relate to individual process efficiencies that contribute to the overall efficiency of power generation. Current research is looking at alternative methods of oxygen separation (eg metal oxide doped ceramic membranes, ref 4 SP5) and ways of recovering the low temperature process heat.

### *Pre Combustion Capture*

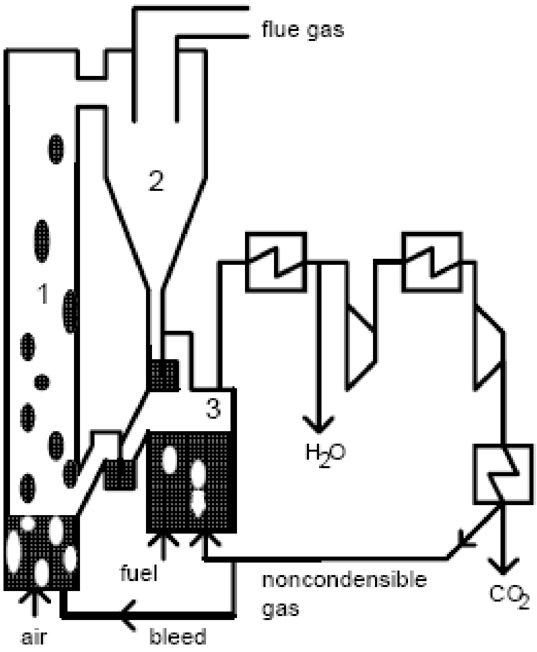
Using oxygen and steam, the fuel (natural gas or solid fossil fuels) can be separated into $CO_2$ and $H_2$ through the so called “water gas shift” reaction. $CO_2$ / $H_2$ separation can be enabled through the use of, for example, vanadium membranes with ultra thin palladium layers (Eltron membranes ) or so called ‘hydrogen transport membranes’. The hydrogen generated is directly used for power generation with gas turbines or even fuel cells. This so called IRCC (Integrated Reforming Combined Cycle) process has its analogue for solid fossil fuel in the IGCC (Integrates Gasification Combined Cycle).



Pre Combustion Water Gas Shift Process (ref 4)

An alternative pre combustion technology is chemical looping, in which the combustion oxygen is transferred to the fuel via an intermediate metal oxide that acts as an oxygen carrier (eg refs 7, 4 SP4)

Fuel reactor: $4MeO + CH_4 \rightarrow 4Me + 2H_2O + CO_2$
Air reactor: $4Me + 2O_2 \rightarrow 4MeO$



### *Post Combustion Capture*

This area focuses on making cost effective improvements to the already used solvent based $CO_2$ absorption systems through the development of new solvents (amines) and system optimisation. As such this approach it very applicable to application on existing power plants although it decreases the efficiency of generation by 15-25% and currently increases the power cost up to 50%. Alternatives that are under consideration include using the calcium cycle, cryogenic separation, membranes or solid adsorbers. The calcium cycle uses quicklime as the capture medium which then yields limestone which can be subsequently reheated so releasing its stored $CO_2$ and producing quicklime for re-use.

At the Elsam coal fired power station pilot a post combustion absorber based $CO_2$ capture unit has been installed within a pilot plant as part of the Castor project (ref 8). The flue gases are directed to an absorber, where they are mixed with a solvent. The solvent captures the $CO_2$ ("enriched") since it has a greater affinity with $CO_2$ molecules than with the flue gas constituents (eg nitrogen). The $CO_2$ trapping efficiency is reported to be nearly 90%. Solvent regeneration is undertaken through heating to 120℃, in order to break the bonds between the $CO_2$ and the solvent, so that it can be reused within the system.

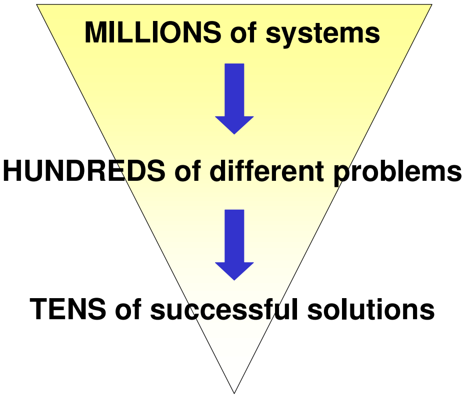
## Breakthrough Solution Methodology

The carbon capture problem is still in many ways in its infancy. Nevertheless there is no doubt that progress is being made, and certain breakthroughs in, for example, so of the membrane technology have created step-change improvements.

Step-change breakthroughs have been the focus of extensive programmes of research that has considered a considerable number of case studies (ref 9). These case studies have been gathered from a broad spectrum of technology and scientific disciplines, primarily through the reverse engineering of solutions found in the global patent database, but more generally through the detailed examination of any form of true innovation.

One of the aims of this research has been to establish whether there are repeatable patterns and therefore reproducible solution archetypes within innovation. In essence, the objective has been to uncover the so called “DNA” of breakthrough innovation itself. Perhaps surprisingly, some very distinct patterns began to emerge in even the very early stages of the research, in fact in the first 50,000 or so innovation exemplars. The subsequent analyses have in some senses merely served to re-enforce and refine these initially identified patterns.

The research has highlighted that there is a considerable amount of re-inventing the wheel taking place across different disciplines: a problem identified and solved in one industry sooner or later appears and is solved in another. Frequently, because the two industries tend to use different terminology, the two solutions are derived completely independently of one another. The extent of this ‘re-inventing the wheel’ phenomenon is suggested below:



At the present time, around 95% of all attempted innovations will fail for one reason or another. Reverse engineer the failure and there are almost as many ways to get things wrong as there are failures. Study the successful innovations, on the other hand, and firstly, there is considerable overlap in terms of the types of problem being tackled (strength versus weight being one such classic archetype). Secondly, and perhaps more surprisingly, the research reveals that there are just a very few ways of deriving successful solutions.

One of the key characteristics of a step-change ‘breakthrough’ solution is that it involves the identification and challenge of some form of trade-off or compromise. Breakthroughs thus tend to occur when problem solvers refuse to accept the compromise, to continue with the previous example, that higher strength must equate to higher weight. When a problem solver finds a way of simultaneously increasing strength and decreasing weight, we have the basis for breakthrough. Likewise, when we increase strength and decrease cost, or increase strength and use less material, the status quo has again been challenged. Breakthroughs happen, in other words, when problem solvers stop looking for the ‘optimization’ solutions, and start looking for the ones that seek to ‘eliminate’ the trade-offs.

Some of the most significant breakthroughs occur when existing solutions from one industry are translated into another. Think for example of the Dyson vacuum – which takes a well known industrial separation process and translated it into a domestic cleaner. Or the more recent Sanyo ‘zero-detergent’ washing machine, which likewise transfers a well known industrial cleaning means (in this case ultrasound) from one discipline to another. An effective heuristic here is to think of someone who has a more extreme version of your problem since they are likely to have already identified a solution. The main difficulty in making these kind of connections is that it is not always easy to make the cross-industry analogies and connections.

Step change breakthroughs also tend to follow distinct and repeatable patterns. Jumps that occur in one industry are also very likely to occur in others. These patterns occur because inevitably when we make one step change advance to solve one problem, sooner or later another problem arises, and that this problem eventually also has to be solved.

If these findings are true – and we can only aim in this paper to intrigue readers enough to want to explore further – then there are some significant potential implications for the carbon capture problem. One of those implications is that someone, somewhere has already solved the problem. Another is that the patterns of evolution of other solutions can help point the direction that current carbon capture technologies can be expected to follow. Both of these implications are simultaneously huge and difficult to believe.

## Application of SI to Carbon Capture

By way of a crude demonstration of the potential, it is possible to focus on an aspect of a carbon capture problem and examine what emerges. As described in the previous section, an important characteristic of a breakthrough solution is that it identifies and challenges a trade-off or compromise. There can be little doubt that there are significant unresolved compromises in and around the carbon capture arena. At the highest level, these may be seen as a conflict between knowing how to sequester carbon and how much it will cost to achieve that aim. Challenging a conflict at this kind of abstract macro-level is likely to prove inconclusive, and so it is frequently helpful to zoom-in and look at some of the contributing factors to this overall cost-capability conflict.

One such aspect might be seen to involve the membranes used in the pre-combustion hydrogen – carbon dioxide separation concepts. According to recent patents granted in this area (ref 10) a key conflict with these membranes is a parallel desire to have a high membrane surface area (in order to assist in the ability to transfer the hydrogen from one side of the membrane to the other), and, knowing that the vanadium or other equivalent materials required to act as the membrane material are expensive, to minimise the amount of material required.

Although the specifics of this particular membrane material are unique to the carbon capture problem are unique, the generic high-surface-area-versus-minimum-amount-of-material conflict is not. Many other industries and problem solvers have had to tackle this generic problem. When we study what these people have done, even though the specifics of their particular situation may again be unique, what the research reveals is that they have all used a relatively small set of strategies to successfully challenge the trade-off.

That list of strategies includes the following:

1) segment the expensive material into smaller pieces
2) incorporate asymmetries into the system
3) incorporate composite material structures
4) incorporating 3-D curvatures into the membrane design
5) apply high frequency vibrations

Clearly these strategies are generic. Asymmetry, for example, could mean a whole series of different things. Fortunately or unfortunately, depending on your perspective, only someone with some domain knowledge of the hydrogen separating vanadium membrane is likely to know how asymmetry may help to solve the problem. An outsider familiar with the general strategies may be able to make suggestions like differential thickness of membrane or different porosities or different sizes of porosities or protruding surfaces, but they cannot know if or how any might help to solve the specific problem.

On the other hand, one of the other things the non-domain specialist can do is to go back to the original source of the general strategies – in this case a patent database – and to use the words suggested in those strategies as search words.

By way of a demonstration of this procedure, we might take the unlikely sounding ‘apply high frequency vibrations’ idea and use that as a way of focusing a search on where others have used it to solve a surface area versus amount of material problem.

Conducting such a search within the specifics of the vanadium membrane reveals nothing – suggesting that this strategy has not yet found its way into this sector. Searching more generally, however, reveals that it is frequently used in other areas. These areas include catalysis in the petrochemical and pharmaceutical sectors and fuel spray nozzles in both jet engine and automotive. These sectors contain the same area-versus-amount-of-material conflict, and that the incorporation of ultrasound or similar ultrasonic fields have been extremely effective in improving effectiveness.

Clearly the authors here have little domain knowledge about vanadium membranes, and therefore little detailed knowledge about the likely efficacy of incorporating some kind of ultrasonic or other high frequency vibration to the specific problem. We do, on the other hand, have some knowledge of the catalysis and fuel spray nozzle problems and we do know that ultrasound can deliver a thousand-fold improvement in performance.

We also know that as soon as we solve one problem, another problem is going to arise. Typically this next problem is expressed as a ‘yes, but…’ statement. Usually by the domain experts. ‘Yes, but’ is frequently used as a way of halting discussion of a solution direction. In the systematic innovation methodology, however, knowing that certain problems always follow others, we can be reasonably certain that whatever the new contradiction created by the ‘yes, but..’ is, someone somewhere will also have solved that new problem. Applying ultrasonic vibration to a delicate vanadium membrane sounds like it will present a fatigue and component life problem. But then we’re not the only people to have had to tackle what is now a new “vibration-versus-life” conflict.

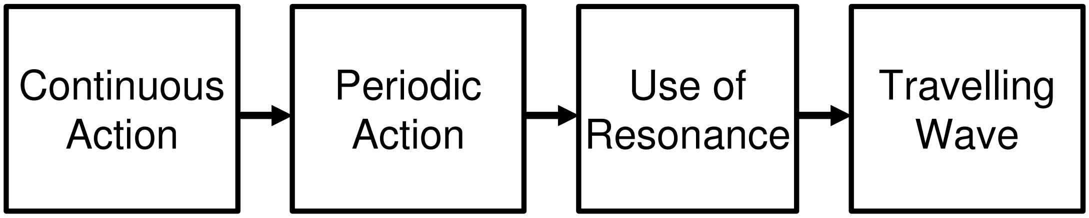
Which in turn is intended to imply that whatever other conflicts we might be able to find in and around *any* aspect of the carbon capture problem, someone, somewhere has already been thinking about how to solve that conflict.

We thus present the thoughts in this paper not to propose any specific solutions to the carbon capture problem, but rather to suggest to the domain experts that if they can identify the critical trade-offs and compromises, there exists a considerable database that suggests someone somewhere has already been thinking about and has solved a similar problem.

## Concluding Thoughts

Research suggests that all systems evolve in only a relatively few number of pre-set patterns (of which so far we have found 37). In the preceding section, we have explored how a vanadium membrane may make a number of step-change jumps in order to resolve a particular (surface area versus amount of material) conflict. Clearly this is not the only conflict to surround the design of this component. While we may not necessarily know what all of the other conflicts might be, we do know what the trend patterns are likely to look like.

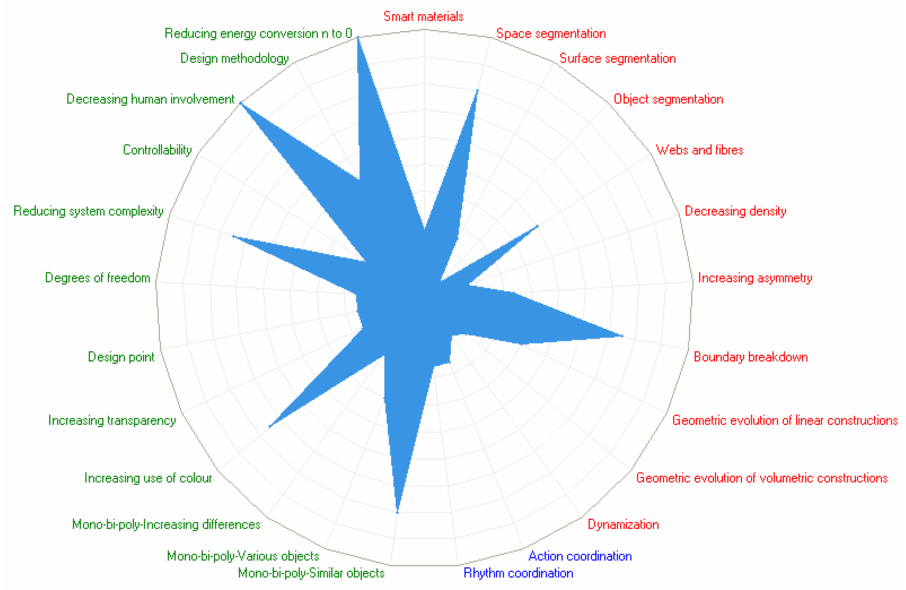
The figure below illustrates one of these pre-set patterns. It is a trend that describes how actions that start off as continuous are likely to advance to incorporate pulsations, and that the frequency of these pulsations is likely to increase up to a point where a resonant frequency of some form is found.



Looking at the vanadium membrane patents on the US patent database it would appear that the current designs are currently at the first stage of this progression "Continuous Action". Should the ultrasonic vibration idea turn out to be practically viable, then the system will make the predicted jump to the second or third stage of the trend.

The 'yes, buts' that might prevent the system advancing along this particular trend are in turn likely to be solved by one or more jumps along any of the other (36) step-change trend patterns. A useful thing to do is to therefore is to make the same sort of comparison as described for the pulsation trend above and to map where the current membrane designs reside along these other trends. The figure below illustrates the results of this analysis for a typical state-of-the-art membrane. Each of the spokes on the radar plot represents one of the step-change trend patterns. The shaded region then represents how far along each of those trends the current designs have evolved.

The meaning of each of these trend patterns and the current position of the membranes along each is beyond the scope of this paper (see reference 11 for more details on the trend patterns). What is important to register here is the amount of un-shaded white space on the plot. This un-shaded area gives an impression of how many step-change advances observable in other industries have not yet been made in the vanadium membrane sector. In all this white space (or 'blue ocean' to use the fashionable vernacular) represents around 45 jumps that have not yet been exploited.



Whether these jumps represent a sufficient advance to make carbon capture via the vanadium membrane route an economically viable proposition remains to be seen.

Meanwhile, it is our belief that a trend pattern analysis of components in other candidate carbon capture technologies will reveal similar levels of untapped potential, and thus open the possibility that at least one will get us where we need to be.

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