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INNOVATION AS RESPONSE TO EMISSIONS LEGISLATION: REVISITING THE AUTOMOTIVE CATALYTIC CONVERTER AT JOHNSON MATTHEY

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Can environmental legislation spur innovative response? This case describes the development of the automotive catalytic converter (ACC) at Johnson Matthey (JM), a precious metals company that entered the automotive industry as a component provider. The market was unfamiliar to JM and highly competitive, but in the 1970s the US Environmental Protection Agency (EPA) introduced standards for emissions control by automotive companies well ahead of current practice. Johnson Matthew responded to the prospect of market demand for a technology that could meet the regulations. The EPA policy of technology "forcing" stimulated collaboration for innovation among companies from a variety of industries. Our case evidence shows that the key innovator, JM, achieved its breakthrough as a result of proactive R&D management by the product champion together with sustained corporate support at a high level and partnership strategies.

Key words: Automotive catalytic converter, breakthrough innovation, Johnson Matthey

A directive by the Bush administration has prevented California and other states from strictly regulating car exhaust emissions.President Obama is seeking to overturn this ruling .http://www.guardian.co.uk/environment/2009/jan/26/travelandtransport-usa

In the 1970s, when California set its own emissions controls for vehicles, a British company, Johnson Matthey, successfully seized the opportunity to develop the first automotive catalytic converter. This case history demonstrates in detail how strict emissions controls can provide business opportunities for green technologies.

1. Introduction to the Automotive Catalytic Converter (ACC)

When the first autocatalysts were manufactured on a commercial basis over thirty years ago by Johnson Matthey (JM) it was held by many automakers that the standards they claimed to meet were unachievable. Responding to the opportunity they saw in emissions regulation, JM demonstrated the effectiveness of their innovative technology and refuted the claims of US companies that new standards required by Californian regulators were unattainable. Catalytic converters soon became standard equipment in automotive vehicles and cut emissions to well below 1970s levels (Diwell, 1981). From the first two-way oxidation catalysts to today's advanced three-way catalysts, a discontinuous innovation has been followed up by a series of incremental innovations as regulations were further tightened (MECA, 2006 and Acres, 2004).

The need for a device such as the automotive catalytic converter was experienced as early as the 1940s, when problems of atmospheric pollution in large cities were traced to car emissions. The Los Angeles' basin in the U.S.A. was particularly affected as a result of ozone from on-shore winds and strong sunlight and of frequent temperature inversions, which trap and recycle polluted air (Twigg, 1999). It had been discovered by the Los Angeles County and the Stanford Research Institute[1] that combustion in the automobile engines was incomplete and that considerable quantities of carbon

[1] In the 1950s, the Stanford Research Institute wa employed by the Western Oil and Gas Association to study the air pollution problem in Los Angeles (Haagen-Smit, 1970).

monoxide, unburned hydrocarbons and NO_x were actively released. As it came to be seen that this was a major source of man-made urban emissions, the Coordinating Research Council of the automobile industry initiated research to reduce motor vehicle emissions (Haagen-Smit, 1970). Catalytic and afterburner devices were at first thought to be effective, but the systems were rendered ineffective in a relatively short time by the lead in the exhaust. Research efforts on such devices were terminated when the car industry itself started to control emissions through engine modifications (Haagen-Smit, 1970).

In 1960, the State of California assumed responsibility for reducing motor vehicle emissions (Haagen-Smit, 1970). In 1967, political pressures from the environmental lobby had resulted in Senator Edmund Muskie announcing a plan to reduce emissions from cars. The "Muskie Bill" passed by the US Congress was followed closely by the 1970 Clean Air Amendments Act, which was to be the major driving force for the reduction of emissions from cars (Acres, 2004; Twigg, 1999). These bills required that the emissions from car exhausts be reduced by 90 per cent, and highlighted the need to develop specific technologies for automotive pollution control. The approach taken by the legislators was one of technology forcing rather than a collaborative approach (Gerrard & Lave, 2005). The clean air legislation was also to apply to manufacturers exporting cars to the USA. It was appreciated that engine modifications could provide improvements to emissions, but that this was insufficient and that additional measures would be required in car models after 1975 in order to comply with more stringent Federal and Californian limits. (Twigg, 1999; Acres, 2004 and Acres interviews, 2007)

There was considerable resistance in the early 1970s from the car industry to the introduction of ACCs in the UK and the UK government did not assume any regulatory role. Nevertheless, Johnson Matthey, a British company with a US subsidiary, developed and successfully demonstrated the positive benefits of platinum-containing catalyst to clean up car exhaust (Acres, 2004; Harrison *et al*, 1981; Acres interviews, 2007). This, together with the short timescales and high penalties imposed by the US regulators led to catalytic converters becoming the preferred technology for reducing car emissions.

The ACC case has yielded numerous research and publications on technical aspects (Twigg, 1999). Little attention has been paid to the role of standards legislation and in particular the 1970 Clean Air Act Amendments in promoting this innovation, with the exception of a paper by Gerard and Lave (2005). Until now, management aspects of the ACC case have not been addressed. In this paper, we approach the issues as a case of interplay between regulation and innovative response. The story of the development of ACC at Johnson Matthey (JM) is followed by analysis of the conditions that promoted this breakthrough innovation.

The JM case provides an exemplar of ways in which established companies and complementary organizations can engage profitably in innovations within a framework provided by regulations of benefit to the natural environment. The case points to conditions internal to, and external to, the innovating firm that promote this outcome. A key enabling condition was a framework set by environmental policy which stimulated discontinuous technological advance and provided market certainty for those developing and adopting the innovation required for compliance. Gerard and Lave (2005) identified three other factors relevant to the implementation process: credible standard enforcement from the regulator, competitive pressures driving industry R&D, and uncertainty about technological development. They hold that technology forcing does not guarantee the technological breakthroughs required for significant technological shifts. The question we address is why regulations had this effect in the case of the ACC at JM.

2. Johnson Matthey's Role in the Development of Autocatalysts

2.1 Introduction to Johnson Matthey

Johnson Matthey, founded in 1817 as a precious metals company, is a UK-based speciality chemicals company active in advanced materials technology. The company's core skills are in catalysts, precious metals, fine chemicals and process technology (See Figure 1 for its divisional structure). Currently, JM employs around 7,800 people in over 30 countries across the globe and its revenue in 2006 was over £4,500m.

In catalysis, JM specialised in catalyst systems for the reduction of volatile organic compound emissions from industrial processes. In the manufacture of catalysts for vehicle exhaust emissions control between 1974 and 2003, JM overtook competitors and produced over 450 million autocatalysts.

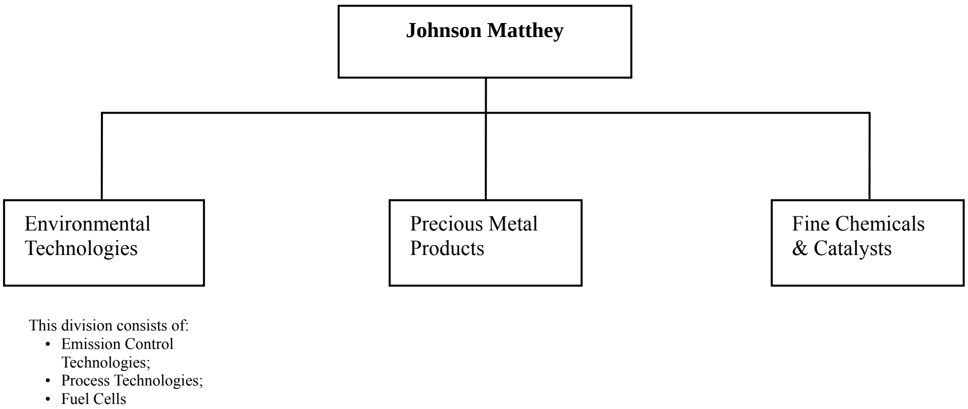


Figure 1: Johnson Matthey's Divisional Structure (Source: JM website, 2007)

2.2 Johnson Matthey's role in autocatalyst[2]

2.2.1 From a supplier to a competitor

In the early 1960s, the use of platinum catalyst for industrial application took off when Universal Oil Product Inc. in the US, set out to develop catalysis for reforming gasoline to increase the rating of the fuel, the efficiency of the engine, and the performance of the engine. JM was supplying Universal Oil Product Inc. (UOI) with the platinum for this process. Up to that point there were very limited applications of platinum catalysts in industry. Notable exceptions were the production of nitric acid and speciality chemicals.

UOI developed a platinum based catalyst for gasoline reforming and demonstrated that platinum catalysts could be viable, economical, and superior to other systems. This was the only way gasoline could be reformed at that time. This collaboration and the evidence provided by the R&D became the stimulus to JM's move into the area. Dr Leslie Hunt was the Director then responsible for research at JM. He formed a dedicated Catalyst Research Group in the UK in 1962, whose role was to provide a technical base for JM to expand its activities into the growing field of precious metal catalysts application. (Acres interviews, 2007; Acres, 2004)

Following the retirement of Dr Hunt, there was continued support from JM in the person of the Research Director, Jim Hughes and Chief Executive, Harry Brooker. A researcher specialising in catalysis, Gary Acres, was recruited to join the Catalyst Research Group in 1963 (see appendix for his biography). The group started research activities on a relatively small scale, since it was assumed that they were addressing a "niche application" by those in the company who were skeptical of the merits of

[2] This account is based on interviews with Gary Acres and his publications.

catalysts.

In the late 1960s, Acres was invited to be the Task Force Leader to take the responsibility for technology development and sales. During that time, the group was developing catalyst technology to control the gaseous pollutants from industrial applications, such as the reduction of NO_x in "tail gas" from nitric acid plants, and the destructive oxidation of odours from food processing facilities (Acres interviews, 2007; Twigg, 1999). In the following section we trace how research enabled JM to transform itself from a supplier of platinum to a competitive manufacturer of precious metal catalysts.

2.2.2 Building technical expertise

JM had been developing catalyst technology to control the gaseous pollutants from industrial applications. Based on research which included physical characterisation of catalysts, and catalysts for the control of emissions from industrial processes, three areas of technology were developed by JM which later proved to be key in establishing their competitive position in emission control technology (Acres, 2004). The first was the use of monolithic catalyst supports, the second was the application of promoted platinum-based catalysts, and the third was the preparation and characterisation of promoted platinum systems.

i) Monolithic supports

Initially there were two catalysts structures: pelleted catalysts and "monoliths". JM concentrated on "monolithic" catalysts, through which the hot exhaust gas from the engine would pass for conversion of pollutants to less harmful gases. This structure caused only a small drop in exhaust gas pressure, and its low heat capacity caused it to become hot quickly in use. Monoliths were preferred because they did not suffer the erosion problems of pellets (Twigg, 1999). However, to develop this technology, it was necessary for JM to work with companies developing monoliths. Early monolithic materials such as Dupont Torvex and 3M-American Lava in the US were commercially or semi-commercially available and provided the basis for early monolithic exhaust catalysts. However, these monoliths had been developed for relatively mild, steady state conditions. It soon became clear that early monoliths could not withstand the severe thermal and mechanical shock conditions in motor vehicles (Acres, 2004). Around that time, many different experimental monolith systems were tested. A real breakthrough came in when Corning Glass licensed monolith extrusion technology from ICI (Acres, 2004). JM adopted and developed this for industrial applications.

JM's Ceramic Research Group and Colors Division (producing colors for the ceramic industry) carried out experimental work to develop ceramic monoliths. The major benefit was that this provided a larger catalytic surface area and allowed better conversion efficiency and durability. A critical decision was to develop the catalyst for testing in engines, and cars. Ceramic experts were recruited to scale up the development and apply it in car engines. They selected the most stable form of alumina to use on the monolith, ensuring that JM produced the most active and the most stable catalyst among competing developments.

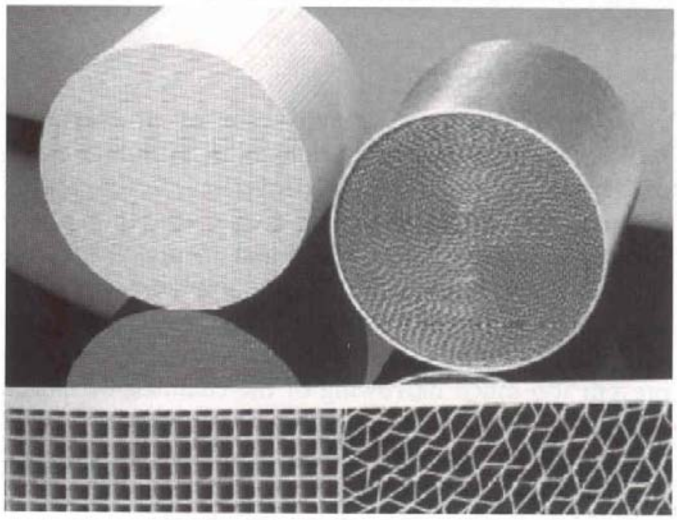


Figure 2: Examples of ceramic and metallic exhaust monoliths (Source: Acres, 2004)

ii) Coating

Alumina had been chosen to be the coating material for monolith purpose. The issue was then how to apply it to the monolith. The overall principle was to make a slurry of the alumina in water and to apply it to the monolith as a "washcoat". After coating, monoliths were dried and calcined in order to fix the washcoat to the support (Acres, 2004). There were some obvious challenges:

(a) applying washcoats to narrow channel monoliths;

(b) clearing the excess;

(c) preventing too much narrowing of the channels or even complete blockage.

The next challenge was to develop a process to coat the monolith on a continuous production line. The Catalyst Research Group passed the development to the Chemical and Colour Divisions to develop a washcoat waterfall for coating the monolith on a production scale. Blocks on continuous belts went through a cascade of washcoat, were coated and then recirculated.

iii) Metals

The Catalyst Research Group tested all metals including platinum group metals (PGMs) and the base metals, proving the advantages of PGMs over base metals. Moreover, JM had previous experience with industrial air pollution control. The most obvious choice of the active metals for exhaust catalysts was the PGM, notably platinum, palladium, or rhodium (Acres, 2004).

iv) Fuel injection—a complementary innovation

In the early stages of the development of the catalytic converter, JM's decision to concentrate on promoted platinum catalysts gave the company a distinct competitive position over other companies such as Engelhard (US) and Degussa (W Germany) which initially concentrated on single platinum metal systems. Further, early collaboration between JM and Volkswagen on the 'Beetle' car using the standard open loop fuel injection system with a rhodium/platinum catalyst demonstrated only a limited capability to reduce emissions of NO_x as well as carbon monoxide and hydrocarbons. This led to the adoption of the closed loop fuel injection system together with a rhodium/platinum catalyst for the control of all three emissions. The closed loop fuel injection systems required further technology developments in the field of on-board computers that could withstand the temperature and vibration under a car bonnet and development of low cost sensors. The diffusion of fuel injection systems and their associated new technologies was a complementary innovation important for the viability of the JM's three way catalytic innovation.

Thus, starting with "niche applications" and progressing to industrial environmental control and then the automotive catalyst, JM spent seven years building up technical expertise in the key areas and transformed itself into a competitive autocatalyst manufacturer.

3. Factors Promoting the Advance of the ACC

In addition to the technological achievements at JM, a number of other factors in the policy environment contributed to promoting the ACC. These are discussed in this section.

3.1 The development of emissions legislation

Policymakers can use a range of approaches to improve the performance or safety of consumer products. In the automotive industry, these include carrying out R&D in government research organizations, supporting commercialization of new technologies, sponsoring R&D consortia, consultative committees (which may lead to legislation) and "technology forcing" legislation setting standards higher than met by current technologies (Gerard and Lave 2005).

The US Environmental Protection Agency chose to adopt technology forcing legislation where it set an emission standard to be achieved within a certain timescale with severe penalties for non-compliance. At the time the legislation was passed there was no known technology for achieving the required standards. The political conditions that led to this approach had been formed by a breakdown in trust between the major automakers and the public. In 1965 an early consumer activist, Ralph Nader, published a report "Unsafe at Any Speed" investigating single vehicle accidents of a specific GM product (Nader, 1965). GM retaliated by employing private investigators in an attempt to discredit Nader. When this became public knowledge, GM were forced to apologise. Nader became very influential in the Environmental Protection Agency (EPA) charged with implementing the new emissions legislation. The automakers further reduced their credibility when in 1969 the Department of Justice filed an anti-trust suit alleging that the automakers had suppressed the development and diffusion of pollution control technologies (Saunders, 2002).

The poor public image of the automakers in turn lead to a 'bidding war' between President Nixon and Senator Muskie resulting in escalating severity of emissions regulation. Muskie introduced a bill in 1969 to introduce a set of standards that were consistent with current technology and emissions standards (Gerard & Lave 2005). Nixon responded with a target reduction for 1975 but with a research target of 90% reduction by 1980. Muskie responded with a bill setting the requirement of a 90% reduction of the 1970 standard by the 1975 model year. This bill was passed by congress and came into law on the 31st December 1970. The Muskie bill further required that any extension to the timing or relaxation of the limits would have to be approved by Congress rather than, as was the normal case, delegated to the EPA (Forswall and Higgins, 2005).

The task imposed on the automakers was to reduce emissions by 90% in three and a half years. The development and launch programme for a vehicle, with known technology, varies between 2.5 and 7 years dependent on the scale of the change. Most manufacturers can only change one model range at a time so that meeting the legislation on a business as usual basis was not feasible. The manufacturers were faced with prisoner's dilemma-type options: If no one met the standard all might be exempted since the government could not close down the US auto industry. If two of them could but one could not the government might penalize the one that could not. If the Japanese importers, who were more advanced with combustion technology, could comply but US manufacturers could not, it would not be politically viable to allow imports to dominate the market and US manufacturers might hope to avoid the costs of compliance.

Further dilemmas followed Department of Justice allegations that findings on emissions control technology had been suppressed. The issue arose as to which company had concealed know-how. If no company knew of any technology to meet the standard, all were politically safe, providing they had invested sufficient resource in trying to find out. If some other agency (the EPA for example) had a viable solution, the car producers might be forced to adopt it, with expensive on-costs. These strategic games could have resulted in a policy impasse. It is in this area that the interventions of JM were pivotal in promoting catalyst technology.

3.2 JM incentives to develop the automotive catalytic converter

JM identified an unmet environmental need – improvement of Californian air quality - as providing the rationale for market entry into the area of auto exhaust catalysts. In the 1950s, regulations stipulated that HC and CO emissions be reduced by 70% and 57% (Acres, 2004). Some American companies put effort into developing catalytic systems but were unable to do so while leaded fuel was in use. Moreover, companies in the car industry were not enthusiastic about fitting "add on" devices manufactured by others and were more interested in using engine modifications (Acres, 2004). To the car industry's relief and the disappointment of the catalytic converter industry, which had spent millions of dollars developing and promoting their systems, the California standards were initially met without the use of catalysts. JM was aware of this outcome and had not taken part in these efforts. In the 1960s, the Catalyst Research Group of JM was concentrating on controlling emissions from industrial plants, and in the meantime, they "kept an eye" on developments in the US (Acres, 2004). There pollution continued to increase, notably in California, as the number of cars on the road increased.

When in early 1971 the Amendments to the Clean Air Act was published and legislation requiring the elimination of lead in gasoline, JM had to decide whether to shift its efforts on the development of catalysts to applications in the automotive industry.

Multiple factors were considered by JM's Board and the Catalyst Research Group including resistance from the car industry, competition and the feasibility of platinum applications. The approach to be taken to promote the use of platinum as the preferred catalyst approved by the board was as follows:

(i) Monolithic catalyst supports would be used;

(ii) Based on previous experience, promoted platinum catalysts would be developed to compete with existing base metal systems;

(iii) Engine tests would be carried out in cooperation with Ricardo Consulting Engineers Ltd to meet cold start requirements of the US legislation.

Launch of full-scale production was planned within three years, provided these primary aims were achieved (Acres, 2004 and Acres interviews, 2007).

3.3 Relationship with the US Environmental Protection Agency (EPA)

JM had to persuade the EPA that the technology worked and was affordable, and had to do so against the interests and advice of the big US car manufacturers. To do this, they had to gain the confidence of the EPA and overcome the opposition of the US car makers.

In the early 1970s, there was still considerable resistance from the car industry to the use of catalysts for emission control (Acres, 2004). This is particularly evident in the UK where companies such as Rolls Royce, Jaguar, and British Leyland had significant American export business (Acres, 2004). Nor was the UK government supportive.

However, car companies were required by the EPA to demonstrate that they had made a determined effort to meet the 1975 model year standards. In 1972, the EPA held the first of several hearings in Washington. Car companies such as GM, Ford, and Volvo who were requesting a one year delay presented their cases. Also subpoenaed were other car companies together with major oil and catalyst interests, including JM's subsidiary in the US—Matthey Bishop Inc.

The US car industry spokesmen claimed that the required standards could not be met. Unknown to them, JM and its American operation, Matthey Bishop Inc., were able to demonstrate to the EPA prior to the hearings that JM, with engineering support from Ricardo Engineering Consultant Ltd., had already met the forthcoming 1975 standards and could meet the 1976 standards. In 1973, the EPA had visited JM in London to find out the progress in the development of catalytic converter. EPA was particularly interested in the work JM had done with Ricardo on cars with American specification. When the results were presented at the EPA hearing, they were received with great interest, and were reported in the American and UK press as a challenge to the car industry's case.

The EPA rejected the US car companies' request and asked them to evaluate JM catalysts. As a result of the EPA hearings the focus was changed from looking at a wider range of technologies to concentrating on the catalyst design. This then required developing as a product, engineering into the whole US vehicle range, manufacturing at high volumes and finally converting the US gasoline supply chain to unleaded petrol. This would obviously take far longer than the original target timescale and the EPA started slipping the targets and introduction dates in line with the speed at which this new technology could be introduced.

It was a great advantage to JM that it had a US subsidiary, Matthey Bishop Inc. Through this subsidiary, JM approached the "big three" automakers in Detroit—Ford, GM, and Chrysler and was able to demonstrate the platinum based autocatalyst to Ford and Chrysler, which provided the basis for a collaboration. GM however, did not want to collaborate. They were convinced that they could make a base metal catalyst work and they chose a "pelleted" catalyst structure rather than the monolith.

3.4 Scaling up rapidly for mainstream car manufacturing

It was one thing to provide and prove the concept, another matter to scale up production to meet demand by car manufacturers for catalyst supplies stimulated by the EPA hearings. JM proved able to develop a viable production process and scale up output to meet the demand. JM protected its technology by patenting various elements of the technology, including the rhodium-platinum system, and continued research on further improvements to the technology.

As legislation was increasingly tightened and required significant reductions in NO_x, further innovations were developed at JM. The three-way catalyst together with electronic fuel injection was provided on most American cars by 1982. This led to the adoption of three-way catalyst technology in most countries, as we know it today. (Acres, 2004)

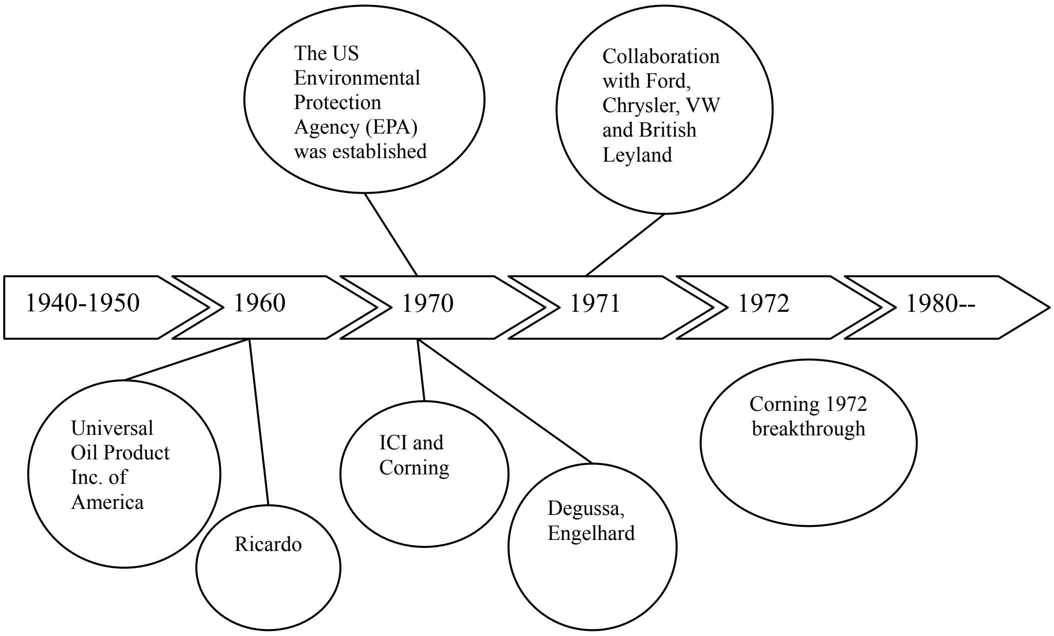
4. Participants in the Development of the ACC

Table 1 provides a time line of the development of the ACC.

Figure 3 provides an overview of the participants in these developments, from the perspective of Johnson Matthey. Though Johnson Matthey played a key role in the development of the ACC, this was only achieved in conjunction with other players with a variety of skills and capabilities, who came together from many industries. They were provided with incentives to do so, whether willingly or unwillingly, by the Clean Air legislation which removed large elements of uncertainty from future market demand.

Table 1: Chronological development of automotive catalytic converter (JM website, 2007)

1950s	1960s	1970	1971	1972	1975	1976	1977	1980s
Work by Dr Arie Haagen-Smit at the California Institute of Technology proved that automotive exhaust emissions were a major source of photochemical smog in Los Angeles	In 1965, the US Motor Vehicle Air Pollution Act set the first federal emission standards to control pollution from automobiles. Targets were met without catalysts; JM set up Catalyst Research Group, with competition from Engelhard and Degussa later on	The US EPA was established and US Congress passed a major revision of the Clean Air Act (1970 amendments); Agreement to phase out lead in gasoline in the US from 1972 onwards; JM carried out research with Ricardo and Corning.	JM filed a patent covering the use of a rhodium –promoted platinum catalyst to control NO_x and other compounds; JM approached car companies such as Ford, Chrysler, and GM	**Corning** developed ceramic support for catalyst monoliths; JM proved to EPA that US emissions regulations could be met using rhodium-platinum catalyst; JM was competing with Engelhard, and Degussa, etc	The first cars fitted with oxidation catalysts reach the showroom in the US; Unleaded gasoline was widely available	Japanese vehicle emissions standards to control HC, CO and NO_x came into effect.	US Clean Air Act amendments agreed to tighten emissions standards further from 1981 onwards.	To meet the strict NO_x limits under the amended Clean Air Act, more sophisticated 'three-way' catalytic converters were introduced in 1981; Vehicle emissions regulations were introduced in Australia and Germany



Car companies: Ford, Chrysler, GM, VW
Competitors: ICI, Degussa, Engelhard Corporation, Umicor, and Delphi
Supplier: Corning (ICI)
Partners: Ricardo

Figure 3: Participants in the developments of ACC

5. Discussion

Although JM were presented by events with an opportunity for the development of autocatalyst, JM's success in the automotive catalytic converter was not just a matter of luck. They were facilitated by progressive emissions legislation, but they were alert to the opportunities inherent in regulation of emissions. Their experience in, and commitment to, the area, their scientific expertise and rational approach to innovation, and identification of the market opportunity all played an important part. They built on their existing competence in catalytic technologies for heavy industry to develop a product for the car industry and tested their device under real conditions throughout the R&D process. They worked effectively with partners. JM's approach and efforts in environmental R&D, demonstrated the effectiveness of their technology and undermined the claims of US companies that standards required by regulations were unattainable. As a foreign component provider offering new competition, they exemplify the forms of competition that drive industry R&D, as discussed by Gerard and Lave (2005). EPA legislation reduced uncertainty regarding demand for the product, but JM's monitoring of the industry was also needed. The automakers had been arguing that meeting the emission standard was impossible. The EPA had established credibility and shown its intention to enforce the new emission standards. By publicizing advances made by JM, they reduced information asymmetry and persuaded the automakers to make the necessary R&D outlays to meet the new standards.

Thus JM, previously a "metal bashing company" not only made the move into the growing field of precious metal catalysts application, but also identified the opportunity for autocatalysts by monitoring the evolution of new legislation and technology development in the US and relating these to JM's existing competence and experience. In doing so they overcame considerable challenges summarized below.

5.1 Finding and working with lead customers/users and with other partners and suppliers

The automotive supply chain is very difficult for outsiders to penetrate particularly in the area of new technology. Forming collaborative partnerships was a critical strategy. Ricardo, a major UK engine consultancy, not only carried out bespoke projects but also had their own research interests; they were a critical partner in establishing entry level credibility. JM approached and worked with European car makers including VW Rolls Royce and British Leyland for demonstrating, testing and supplying autocatalysts. This gave them an expertise base without involving them in the strategic struggles taking place between the three big US car producers, and provided a basis for sustained collaboration.

It was because JM's expertise was in precious metal catalysts that they outsourced the specialist development work to experts in other fields. For testing the catalytic converter, Ricardo Engineering Consultant Ltd. provided engines, cars and testing technology, while JM provided the catalytic converters. JM also worked on the monolith support with suppliers who included Corning Glass and 3M-American Lava.

5.1.1 Foresight and long-term commitment

As early as 1962, the Research Director, Dr Leslie Hunt had foreseen the potential of developing applications for precious metal catalysts and set up the Catalyst Research Group. This support was continued by the Chief Executive and Research Director following Dr Leslie Hunt. Not only was there extensive investment in test facilities since an early stage and on-going investment in R&D afterwards, but resources were also deployed in a flexible way. These factors had equipped JM with the capability to innovate and enabled them to seize the opportunity when it came. A strong incentive for JM to develop the catalyst technology was the prospect for the technology to have other applications in industrial processes even if it were not introduced to the car industry.

5.1.2 Building on competence in catalyst technology

Building on its experience in catalyst technology for heavy industry, JM was systematic in developing the ACC, selecting technologies and materials on the basis of sustained research, as in the case of pelleted vs. monolith catalyst support, and base metal vs. precious metal.

Another essential factor in building on the competence in the technology was the ‘community of practice’. Within JM, there was active and close collaboration among the Catalyst Research Group, Ceramic Research Group, Colour and Chemical Divisions, and good relationships with the Board. Some of the resources at JM had been scattered to subsidiaries or operations around the world but connections were retained.

5.1.3 Key individuals accorded discretion

In the development of the automotive catalytic converter at JM, certain individuals played critical roles, and were given the scope to do so. The “technology champion” was Gary Acres. With a background in chemistry, Gary Acres was recruited to join the Catalyst Research Group of JM in 1963, later becoming a task force leader of catalyst research in the late 1960s and the Research Director in 1974 (until 1985). Gary Acres contributed to JM’s development of the catalytic converter in the following ways:

(i) He provided experience and expertise in the technology;

(ii) As the leader of the Catalyst Research Group, paying attention to and anticipating technical developments in the regulatory environment in the US from the 1960s;

(iii) He prepared JM to meet requirements by using his professional and personal network inside and outside the UK, and by collaborating with top executives in the company and partners such as ceramic experts at JM and Ricardo Engineering Consultant Ltd.

There was sustained support from the top of the company for this innovation even when prospects were uncertain. As early as the 1960s, Dr Leslie Hunt, the Director responsible for research at JM, decided catalysts would be a major future activity for JM. He formed a dedicated Catalyst Research

Group in the UK in 1962, the role of which was to provide a technical base for JM to expand its activities into the growing field of precious metal catalyst applications. Following the retirement of Dr Leslie Hunt, there was continued support from Jim Hughes, Research Director, and Harry Brooker, Chief Executive. Harry Brooker was initially skeptical about JM's competence in the area. Gary Acres knew Harry Brooker socially through JM's cricket club. Gary Acres approached the CEO and explained that the Catalyst Group had, on his initiative, been developing catalysts for industrial applications. After further review and discussion, Harry Brooker approved JM's involvement in the development of the automotive catalytic converter. With support from top management, even when threatened with litigation, JM remained steady in the pursuit of this innovation.

5.1.4 Intellectual Property and Patents

During the early stages of contract negotiations for the supply of catalysts to car manufacturers, it came to the notice of these potential customers and JM that the US engineering company, Englehard, claimed the ownership of a 'base' patent describing the use of a monolith, alumina and platinum metal catalyst for the control of emissions from motor vehicles. If valid this claim to a base patent was a potential 'show stopper' for JM, despite its own patents. After discussions with Corning and some car companies, Harry Brooker decided to challenge the validity of the patent on the grounds of prior publication of the claims. The final outcome was that Englehard decided to grant free licenses to JM and others, thus resolving the IP situation.

5.2 Taking advantage of the proactive role of the US Environmental Protection Agency (EPA)

The technology forcing strategy adopted in the US lasted a relatively short time, born of the public relations disasters of the automakers in the late 60's. By the time of the 1973 oil crisis, public appetite for forcing the automakers to produce more expensive and less economical vehicles was severely reduced. However while it was in place, the strategy favoured advances in component technologies with rapid impact, to the benefit of the JM technology. The EPA sought out innovators rather than accepting dominant car manufacturers' views on what was technically possible. They progressively tightened emission legislation to provide motivation for the development the catalysts technology and stimulated an innovative response from the private sector. The EPA was able to reduce information asymmetry by targeting and publicizing a promising technology (Lewis, 1996 and Marino 1998). The

EPA was not swayed by lobbying in the US challenging the viability of their new standards, but kept informed on the latest ACC developments and sought out an innovative company elsewhere.

The new standard approved by the EPA required manufacturers to make changes to designs for the mainstream market, rather than in market niches, leading to rapid development of a global market for the autocatalytic converter. The size of the market was known to them through their operating subsidiary in the US. JM made the decision to enter the US market when the new regulations were confirmed.

6. Conclusion

The story of the automotive catalytic converter is again highly topical in view of impending changes to directives by the Bush Administration preventing California and other states from setting emissions standards higher than those enforced by the Federal authorities. New regulations will be designed to elicit responses from environmental innovators. A historical case shows that this is possible, providing evidence of how such an objective has been achieved.

This case has received surprisingly little attention in the management research literature. In revisiting it, we learned much from participants, while the technical literature provided us with an account of the technology and a history of the automotive catalytic converter. This enabled us to examine the management dimensions of JM's entry into a new market and to propose which key factors enabled JM to succeed in this field. The autonomy of a research group within the company and the authorization provided for them to engage over a long period in responsive and flexible deployment of resources, with support from top management, was essential for their innovation. An effective regulatory framework was equally critical. Even given these favourable conditions, the challenge of entry into a highly competitive sector in which the innovator had no prior experience was formidable and success required ingenuity and persistence by project champions, partnership arrangements and support from the top of the company. Whether this kind of innovative entry by an established company into an expanding market would be possible under conditions where Boards and managers are pressed to show short term returns on investment is an open question. Yet environmental innovations require technological initiative together with supportive conditions of the kind found here.

This case study provides an exemplar of "technology forcing policy" as a source of innovation

(Gerard and Lave 2005). Complementary advances by companies in related industries (fuel injection technology, monolith design) were required to make this innovation possible. The case of the ACC illustrates the interplay between innovation by regulators and complementary companies responding to the demand created by more stringent regulatory standards.

Appendix A: The technology of automotive catalyst converter

1. The chemistry of emission control

A catalytic converter has no moving parts. The technology involves a very small amount of catalytic metal—e.g. platinum, and rhodium—applied to acres of surface area contained within a stainless steel canister (MECA, 2006).

The three major pollutants in exhaust gas are hydrocarbons (HC), oxides of nitrogen (often called NO_x) and carbon monoxide (CO). During the early days of research on car exhaust catalysts, a simplistic approach was taken, and the first legislation demanded only the removal of hydrocarbons and carbon monoxide (Acres, 2004 and MECA, 2006). Therefore, the reactions in the first generation of catalytic converters (two-way converters) were also simple (MECA, 2006, Acres, 2004 and Twigg, 1999). Fairly quickly, early legislation was tightened and by 1976 it appeared that NO_x control would also be required (Twigg, 1999). Chemical reactions that could remove NO_x were considered (Acres, 2004). This could be achieved by setting off the following reactions:

$$2CO + 2NO \rightarrow 2CO_2 + N_2$$
$$HC + NO \rightarrow CO_2 + H_2 + N_2$$

$$2CO + O_2 \rightarrow 2CO_2$$
$$HC + O_2 \rightarrow CO_2 + H_2O$$

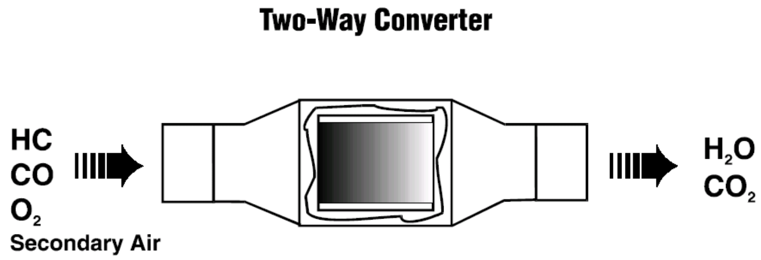


Figure 1: Two-way Converter (Source: MECA, 2006)

In the early 1980s, further research and technology progress had enabled consistent catalytic performance, and the use of platinum/rhodium (Pt/Rh) catalysts to simultaneously control all three pollutants—HC, CO and NO_x (Twigg, 1999, Diwell, 1981, and MECA, 2006). Thus, the concept was named the "Three-way Catalyst" or TWC (Twigg, 1999).

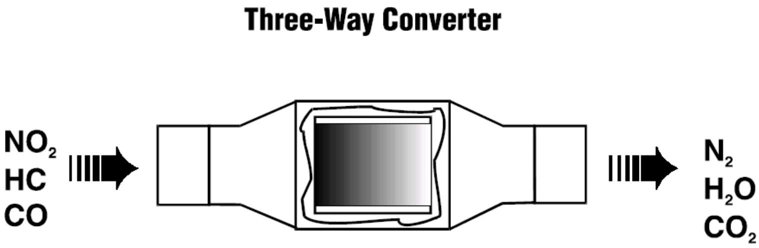


Figure 2: Three-way Converter (Source: MECA, 2006)

Table 1: The Three-Way Catalyst (Source: Acres, 1980)

						Clean Exhaust:
Carbon Dioxide		Carbon Monoxide	$CO+O_2 \rightarrow CO_2$ $CO+NO \rightarrow CO_2+N_2$	➡ ➡		Carbon Dioxide
Nitrogen	+ Polluting Gases	Unburnt Fuel	$HC+NO \rightarrow CO_2+H_2O+N_2$	➡	Clean Exhaust	Nitrogen
						Oxygen
Oxygen		Nitrogen Oxides	$HC+O_2 \rightarrow CO_2+H_2O$	➡		Water

Early TWCs had a narrow operating air:fuel range over which all three pollutants were removed and were only effective with closed loop electronic fuel injection. From 1980s ACCs were almost universally fitted to cars sold in the U.S.A. Since then, much effort has been directed towards improving catalyst performance. Today, TWCs are able to work in sophisticated engine systems (Twigg, 1999). In countries where car ownership is rapidly increasing, such as in China and India, legislation has been put in place requiring the use of TWCs on all new passenger cars.

To date, more than 500 million vehicles equipped with catalytic converters have been sold worldwide (MECA, 2006).

2. Catalyst structure

One of the first considerations in fitting vehicles with catalysts was how to support the catalyst in the exhaust system (Acres, 2004). The vehicle exhaust environment is one of the most demanding found anywhere in the world of industrial catalysis. Vehicle exhausts which feature high temperatures (up to 1000 ℃), vibration of the exhaust system, and pulsations from the engine, etc (Acres, 2004; Diwell, 1981).

Initially two catalyst structures were tested: pelleted catalysts and "monoliths". At first a pelleted support was used as many catalyst designers came from a background in industrial catalysis where this technology was used (Acres, 2004 and Twigg, 1999). Pellets had the advantage of a naturally high surface area upon which to support the catalyst.

The other structure is the monolith. Before the advent of exhaust legislation, work was under way on monolithic "honeycomb" supports for industrial pollution control (Acres, 204). In a monolith, the catalyst volume is a single structure with many small open channels running along its length, as in a honeycomb (Twigg, 1999). At first, monoliths proved to be unable to withstand the severe thermal and mechanical shock conditions which prevailed in motor vehicles exhaust systems (Acres, 2004). But later on, improvements were introduced and today, monoliths are the basis of all autocatalysts, and typically have 400 cells inch^{-2} (Twigg, 1999).

3. Coating

Unlike pellets, the intrinsic surface area of monoliths is too low for adequate dispersion for such metals as platinum (Acres, 2004; Twigg, 1999). It was necessary to develop a high surface area coating to increase the surface area. Many materials had been ruled out, among other reasons, because of the tendency to oxidation under the exhaust conditions, poor ability to survive the severe hydrothermal exhaust conditions and high price (Acres, 2004). Alumina (Al_2O_3) emerged as the ultimate choice for monolith coatings, also known as washcoats (Twigg, 1999).

4. Choosing the active metals

Base metals and precious metals (platinum group metals, PGM) were both considered. Because of the perceived cost of the PGMs, considerable effort was exerted, particularly by car companies, to develop base metal catalysts (Shelef *et al*, 1968). However, the base-metal-only system was found to have three fatal drawbacks (Acres, 2004):

Firstly, they were often supported on alumina to provide raised high surface areas, and there is a tendency under high temperature conditions for raised surfaces to be eroded.

Secondly, the light-off temperature for base metal catalysts was considerably higher than for Platinum Group Metals. This is important because the key US test cycle involved starting the vehicle from cold.

Third, and the most important issue for base metal catalysts, was the high level of sulphur in gasoline. Such base metals were found to be particularly prone to poisoning by sulphur. In comparison, although PGMs can also be poisoned by sulphur, the effects are much more subtle than with base metals.

Combinations of platinum and palladium and particularly platinum and rhodium had the best light-off temperature characteristics Therefore, from a practical point of view, it was necessary to coat washcoated monoliths on a large scale with accurately controlled amounts of mixed platinum group metals. (Acres, 2004)

Thus, it turned out that the technology in which JM had built up core competencies was the most appropriate for developing the ACC.

Over the years, JM has moved and expanded plants, and opened Autocatalyst Technology Research Centres globally to enhance the capability of R&D and production in order to meet market need.

Appendix B: The ACC at ICI

The following account is based on interviews with two ex managers at ICI in May 2007: *Dennis Dowden*, Senior Research Associate and *Sid Andrew*, Research Group Manager.

ICI started work on autocatalysis with experience in certain catalysts but without expertise in the most important parts of the field. They had actually developed the monolith catalyst support and produced related patents. ICI also had joint research activity going on with British Leyland.

ICI spent millions of pounds on development. But the choice as to whether to use base metals or precious metals had to be made before there was adequate evidence. ICI chose base metals with which they were more familiar and which were much less costly but which proved to be inadequate to meet the technical requirement.

ICI was aware that JM had experience in precious metal catalysts, but did not want to deflect profit to JM by outsourcing to them. This proved to be a short-sighted view of the situation particularly in view of complementary technologies emanating from the two companies. JM worked with Corning in the US, the company that had licensed ICI's monolith technology used for the ACC. According to Gary Acres, JM would have preferred to work directly with ICI than with Corning which licensed the monolith technology from ICI.

Appendix C: Brief Biography of Prof Gary Acres

Prof. Gary Acres is a graduate of Nottingham University. Following 5 years with the UKAEA at Harwell, he joined the catalyst research group of Johnson Matthey in 1963, becoming Director responsible for R & D operations from 1974–1985 and following, Director, Corporate Development until 1994 when he retired from full time employment.

Since then he has held a number of advisory roles and is currently a Consultant to Johnson Matthey on fuel cell and related activities. He is Chairman of the Grove Fuel Cell Symposium and the first Chairman of the European Fuel Cell Group. Since 2000, he has been a Royal Academy of Engineering Visiting Professor on Sustainable Development at the University of Birmingham.

His awards include the Queen's Award for Technology and the MacRobert Award for the development of automobile emission control catalyst systems.

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