

**Development and evaluation of an integrated methanol reformer and catalytic gas clean-up system for an SPFC electric vehicle.**

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## Abstract:

The aim of the project called MERCATOX was to develop and evaluate a prototype integrated catalytic methanol steam reformer and high temperature selective oxidation gas clean-up system to produce a hydrogen rich fuel for a Solid Polymer Fuel Cell (SPFC) and to meet the performance requirements (including transients) of an electric vehicle.

There were five partners in the project as follows:-

- |                                 |   |   |
|---------------------------------|---|---|
| Wellman CJB Limited (UK)        | : | Coordinator, prototype testing, integrated methanol fuel processor build and testing.   |
| ECN (NL)                        | : | Identification of catalysts for methanol reforming and combustion of fuel cell off gases and development coating techniques for applying these catalysts to metal substrates. |
| Loughborough University (UK)    | : | Development and construction of carbon monoxide selective oxidation system using coated catalyst on metal substrates.   |
| Instituto Superior Tecnico (PT) | : | Modelling of total fuel processor system and individual components, performance analysis of the system and sizing of components and their integration.                        |
| Rover Car Company (UK)          | : | Production of initial system specification and assessment of vehicle integration and manufacturing issues.  |

The design of the methanol reformer and gas clean-up system was based on a compact aluminium fin and tube heat exchanger. A methanol reforming catalyst, a combustion catalyst for burning fuel cell off-gases and a selective catalyst for oxidising carbon monoxide were coated on to the aluminium plates in the heat exchangers. This resulted in a compact unit with exceptional heat transfer characteristics.

The performance of the combustion and selective oxidation catalysts met the process requirements but the coated methanol reforming catalyst performed disappointingly. As a result, the prototype 20kW methanol fuel processor built to evaluate the system did not produce the expected volume of hydrogen rich gas at the required methanol conversion. Consequently the volume and weight targets specified by the end user could not be met. The gas clean-up unit reduced the carbon monoxide concentration from levels of over 1% to below 10ppm. Data accumulated with synthetic reformat suggests that the gas clean-up unit will meet the specified requirements at 400 l min<sup>-1</sup> of reformat.

The project has identified the requirements that the reformer and gas clean-up unit must meet to be successfully integrated in an SPFC vehicle. Based on the above results, the volume and weight of an integrated 20kW methanol reformer and gas clean-up unit would be 90 l and 92kg respectively. This is approximately double the target values specified. However, if the reformat production rate could be increased four fold, the volume and weight would meet the target values comfortably. Assuming that a more active methanol reforming catalyst is found, it is estimated that the volume and weight of a methanol reformer and gas clean-up unit for a 50kW SPFC system would be approximately 100 litres and 100 kg, respectively.

The target start-up times for the fuel processing system cannot be met at present. Nevertheless, based on heating tests with the combustion catalyst and a theoretical assessment, it is believed a start-up time of 30 seconds is attainable for the methanol reformer.

The modular nature of the design means that the device will meet the limiting dimension of height specified. The control of the complete system needs further development as does the identification of suitable valves, pumps and sensors, in particular gas sensors. However, none of these issues are insurmountable given suitable investment.

Similarly the method of construction, involving as it does, metal pressing and brazing, lends itself to mass production techniques. Again, cost targets are achievable, given suitable investment by the supplier.

The reduced performance of the methanol reforming modules was attributed to the low activity of the catalyst when coated on to the metal substrate. Whilst this could be improved by increasing the amount of catalyst in the coating, this is unlikely to overcome the fundamental problem associated with the deactivation of copper/zinc catalysts and which is accentuated in the case of coating.

The MERCATOX concept still has the potential to become state of the art for methanol reforming and gas clean-up for mobile SPFC applications. In order to realise the potential of the MERCATOX concept, a number of actions are necessary to tackle the outstanding key development issues and commercial barriers, as follows.

- Locate or develop a more active reforming catalyst that will produce high conversion of methanol and low carbon monoxide at a reforming temperature below 250°C.
- Locate cheaper aluminium substrates for testing.
- Investigate alternative substrates.
- Initiate discussions with catalyst coating specialists.
- Initiate discussions with car component suppliers.
- Initiate work on identifying control system and sensor requirements for a methanol reformer and gas clean-up unit in an SPFC vehicle.
- Build an integrated 20kW methanol reformer and gas clean-up unit to meet Rover's specification.
- Incorporate an integrated 20kW methanol reformer and gas clean-up unit in a complete stationary drive system demonstrator for an SPFC vehicle.

## 1. **PARTNERSHIP**

The partners in the project are as follows:-

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## 2. OBJECTIVES OF THE PROJECT

The aim of the project was the development and evaluation of a prototype integrated catalytic methanol steam reformer and high temperature selective oxidation gas clean-up system to produce a hydrogen-rich fuel suitable for an SPFC and to meet the performance requirements (including transients) of an electric vehicle. The prototype integrated reformer/gas clean-up unit was to produce sufficient fuel for a cell stack configuration capable of producing 20 kW of electrical power.

The programme consisted of a number of specific objectives:

- the development and evaluation of an active catalyst with high thermal stability for the steam reforming of methanol at about 225°C to produce a fuel with the lowest practical level of carbon monoxide;
- the development and evaluation of active combustion catalyst to promote the burning of fuel cell off-gas to provide the endothermic heat of reaction for the methanol reforming reaction;
- the development and evaluation of a catalyst for selectively oxidizing carbon monoxide in the presence of hydrogen, to produce a hydrogen-rich stream with a carbon monoxide content of less than 2 ppm. The operating temperature (130°C/200°C) was to be such that no interstage cooling after the reformer would be required;
- the development and evaluation of methods of applying the above active catalysts to suitable metal substrates or foams for optimum performance;
- the testing of the resulting substrates in prototype tubes installed in a suitable test rig(s);
- the design, construction and operation of an integrated, compact methanol reformer;
- the design, construction and operation of a carbon monoxide selective oxidation system operating at elevated temperatures (130°C/200°C) incorporating suitable heat transfer elements;
- integration of the methanol reformer and carbon monoxide selective oxidation system;
- the development of mathematical models for the above systems to be used as scale-up tools;
- assessment of resulting design for early exploitation in particular addressing the issues of vehicle integration, mass production and optimum cost.

Performance targets for the prototype unit were as follows and were based on practical experience of the partners existing fuel cell programmes.

Efficiency	: 90% (HHV)
Start-up	: <5 seconds
Load Following	: <5 seconds
Carbon Monoxide to stack	: <2ppm
Maintenance	: Annual
Volume	: 49 litres
Weight	: 50Kg

Cost : <30 ECU/kW<sub>e</sub>

Power Output : 20kW<sub>e</sub>

The project was called MERCATOX.

### 3. **TECHNICAL DESCRIPTION OF THE PROJECT**

The work content was divided into five technical tasks, one of which was the responsibility of the partners detailed as follows:-

#### ECN

Development of metal-supported catalyst systems for the steam reforming of methanol and the combustion of hydrogen containing gas from the fuel cell and methanol/air during start-up.

#### Loughborough University

Development and construction of a compact, lightweight gas clean-up unit.

#### Wellman CJB Limited

Testing of prototype methanol reformer and gas clean-up units. Build and test prototype integrated methanol reformer and gas clean-up unit.

#### Rover

Producing the initial system specification and addressing vehicle integration and manufacturing issues.

#### IST

Systems modelling.

#### 3.1. ECN

Within the MERCATOX project ECN's main task comprised the development of metal-supported catalyst system for:

- steam reforming of methanol and,
- the combustion of methanol and hydrogen containing gas from the fuel cell.

This task was designed to realise the following objectives:

- Development of a metal-supported catalytic methanol conversion system to produce a hydrogen rich gas with a CO level of less than 0.5%.
- Development of a metal-supported catalytic oxidation system to convert hydrogen containing gas from the fuel cell and methanol into water and carbon dioxide.
- Development of a metal-supported catalytic system integrating the endothermic methanol steam reforming with the exothermic combustion of hydrogen containing gas from the fuel cell and methanol.

The content of the work to be performed by ECN consisted of the following sub-tasks.

Task 1.1: Catalyst research with respect to reforming and combustion.

- Task 1.2: Metallic substrate research.
- Task 1.3: Research into washcoat application to metallic substrates.
- Task 1.4: Application of active catalysts on to washcoats for reforming and combustion.
- Task 1.5: Performance and life testing of catalysts and catalytic systems.

Deliveries were to be catalyst samples, characterisation data, data from catalytic testing and reactors coated with catalyst.

A great deal of research effort was devoted to catalyst development and this work led to promising catalyst formulations for methanol steam reforming. However when used in coated form on an aluminium substrate on a larger scale, these formulations produced a performance similar to commercially available catalysts. As a result of this work on methanol reforming catalysts, commercially available catalysts also have been investigated. In particular the catalyst BASF K3-110 which appeared to be as active as the in-house developed catalyst. Consequently it was decided to concentrate on supplying larger structures coated with BASF catalyst.

During the first year of the project, compact aluminium heat exchangers were selected to be used as the primary reactor element for the reforming/combustion unit and the CO-removal device. Preparation methods have been developed for washcoat suspensions of the BASF K3-110 reforming catalyst and for the combustion catalyst. Calcination of the BASF catalyst resulted in lower conversion, less CO in the reformat and formation of dimethylether. In general, the suspensions appear to be more stable towards calcination at 400°C than the pure 'as received' catalyst as was deduced from methanol reforming activity measurements in ECN's micro-flow test equipment.

Catalyst coating suspensions with low viscosity and high stability have been developed that can be used to coat porous metals. Application of such suspensions on to aluminium foam parts followed by calcination at 400°C resulted in well adhering catalyst layers. The suspensions containing the combustion catalyst perform equally well as the parent catalyst. The washcoat suspensions have been applied successfully to both aluminium foam and serrated aluminium plates. Reforming and combustion reactor tubes were supplied to Wellman CJB for evaluation of the catalytic performance.

ECN's automated bench-scale test rig proved to be well suited to investigate the methanol steam reforming behaviour with BASF K3-110 in different catalytic systems.

Among the investigated catalytic systems the aluminium heat exchanger shows the highest activity due to its very good heat transfer characteristics. Mainly due to the lower catalyst load, the coated aluminium structures deactivate at a higher rate than the pure fixed-bed catalyst pellets. But the higher temperature stability of the catalytic washcoat permits the use of the heat exchanger at higher reforming temperatures that prolong its operation time. By proper temperature control 450 hours of continuous operation have been achieved for an aluminium foam at an average methanol conversion >90%. The heat exchanger catalytic system showed a hydrogen production capacity corresponding to approximately 0.5kW of electric power. It has been shown that this value can be increased to approximately 1kW resulting from a further optimisation of test conditions. Combustion of methanol with air can easily be carried out in a coated heat exchanger. Temperature rise is strongly dependent on the amount of methanol that is fed to the heat exchanger per unit of time. Results indicate that the integration of combustion with reforming is possible. Five large 5kW heat exchangers were coated with reforming and combustion catalyst, whereas the sixth one was

provided with only the catalytic combustion washcoat. These large heat exchangers were shipped to WCJB for integrated testing.

### 3.2. Loughborough University

It has been the objective of Loughborough University (LU) to design, construct, and evaluate a compact Gas Clean-Up Unit (GCU), suitable for direct thermal integration with a methanol steam reformer. The GCU will reduce the concentrations of CO, initially present in the methanol steam reformat, to levels such that reductions in SPFC performance due to CO electro-catalyst poisoning are avoided. GCU operation is based upon the catalysed selective oxidation of CO to the non-poisoning CO<sub>2</sub>. Catalyst selectivity is required to minimise the parasitic oxidation of the hydrogen. The GCU, upon integration with the methanol steam reformer, will serve as the fuel processing system for an SPFC powered vehicle. The GCU has been designed to operate in a temperature range of 130 - 200°C. No heat transfer between the methanol steam reformer and GCU is thus necessary and the GCU will be in its most compact form.

Although conventional packed bed catalyst reactors are used extensively in the chemical industry for CO oxidation, the technology is somewhat compromised for automotive applications. In addition to the larger reactor volumes often required, both significant pressure drops and poor thermal management (resulting in both reduced catalyst activity and selectivity towards CO oxidation in the presence of a large H<sub>2</sub> excess) are often apparent during reactor operation. For both increased reactor compactness, minimised back pressurisation and improved thermal management of the exothermic oxidation reaction, research at LU has focused on the direct application of a suitable oxidation catalyst to lightweight aluminium, compact and high surface area heat transfer technology.

Loughborough University (LU) designed, constructed and evaluated a gas clean-up system (GCU). The GCU selectively oxidises carbon monoxide (CO), present in the fuel stream which is produced by the steam reformation of methanol. The reactor design is based upon the catalyst washcoating of high surface area heat transfer technology. Compact fin heat exchanger technology, was identified as being the most suitable for the GCU application. (The technology identified was also subsequently being utilised in the reformer design.) Based on such design features, a compact, lightweight reactor with considerably improved thermal management and response characteristics, compared to conventional packed bed technology was demonstrated. Catalyst screenings carried out by LU at micro-reactor, bench scale and reactor prototype stages of development identified a platinum - ruthenium (Pt-Ru) catalyst mixture as being the most suitable for CO oxidation in the GCU application. A 1 litre dual stage GCU was successfully demonstrated in reducing CO concentrations from 0.7% in the reformat fuel stream to ⇔ 12ppm and 2ppm under wet and dry fuel conditions respectively. Operation of the 1 litre GCU was performed with synthetic reformat flow rates equivalent to approximately 5kW<sub>e</sub>. The GCU supplied to Wellman CJB Limited consists of 2 x 2 litres compact fin heat exchangers, washcoated with the Pt-Ru catalyst. The GCU has an optimum operating temperature of 150 - 160°C and is thus suitable for direct thermal integration with a methanol steam reformer. Laboratory assessment of the reactor performance at LU, using synthesised methanol reformat, found it to be capable of reducing CO concentrations from 0.7% → ⇔ 10ppm (flow rates equivalent to approximately 20kW<sub>e</sub>) and 2% → ⇔ 10ppm (flow rates equivalent to approximately 10kW<sub>e</sub>). The physical specifications of the MERCATOX GCU developed by LU for integration with the methanol steam reformer are given thus:

- Total Reactor Volume : 3.7 litres
- SPFC Power Equivalent : ca. 20kW<sub>e</sub>



- Total Reactor Mass : 5.0 kg

### 3.3. Wellman CJB Limited

The experimental programme at WCJB consisted of three main activities - the evaluation of coated foams in tubes, coated heat exchangers and the build and testing of the prototype integrated system.

#### 3.3.1. Coated Foam in Tubes

In June 1996, ECN delivered four prototype aluminium reformer tubes for testing. The aluminium foam substrate inside the tubes was coated with different loadings of methanol reforming catalyst. These tubes were evaluated in a test rig built by WCJB.

The overall performance of the tubes was disappointing in terms of methanol conversion and deactivation. All the tubes demonstrated an initial sharp fall in reformat output. Although the rate of fall decreased after about 4 hours, the trend continued over 150 hours intermittent operation. This fall in reformat production was attributed to deactivation of the catalyst. The carbon monoxide level in the reformat was typically 0.3%.

ECN also delivered three combustion tubes similar to the prototype methanol reformer tubes except that the aluminium foam was coated with combustion catalyst of varying degrees of activity. The tubes were installed in a simple test rig which enabled simulated fuel cells off-gas and air to be combusted. Additionally, methanol/air mixtures were combusted to investigate the potential for fast start-up from cold. Both tests demonstrated that reforming temperatures could be reached in the aluminium foam within 120 seconds. Using methanol/air mixtures, there was a delay of thirty seconds before temperatures started to rise which was caused by methanol absorbing onto the combustion catalyst.

#### 3.3.2. Coated Heat Exchangers

WCJB and ECN purchased a number of small compact plate and fin heat exchangers made of aluminium. The volume of these heat exchangers was 0.5 litres and hence were designated HEX 0.5.

A programme of tests was undertaken at WCJB using HEX 0.5 compact heat exchangers. These were coated by ECN with reforming and/or, combustion catalyst. The object was to demonstrate the viability of using catalyst coatings on adjacent side of the corrugated plates within the heat exchanger. In addition, the possibility of using a thermal fluid as an intermediate heat transfer medium was investigated.

WCJB initially tested a HEX 0.5 unit with methanol reforming catalyst on one side and combustion catalyst on the other in a test rig. After 40 hours, accumulated in 6/7 hours of continuous running, the methanol conversion rate slowly deteriorated. The carbon monoxide content remained constant at around 0.3%.

A similar test using a thermal fluid as a heating medium also showed a similar performance deterioration.

#### 3.3.3. Integrated System

Despite the disappointing performance of the 0.51 reformer modules, it was decided to assemble and test the 20kW prototype methanol reformer and gas clean-up unit. Even with a derated performance valuable information could be obtained about the performance of the

gas clean-up unit and the heat transfer characteristics of the complete unit.

Based on recommendations made by IST, the methanol reforming section of the integrated system was built up of a number of compact heat exchanger units of 0.5 litre (HEX 0.5) and 5 litre (HEX 5) volume. Prior to assembling the system, each unit was individually tested. The units used, their function and size were as follows:-

Methanol Reforming	HEX 5 (a) (b) (c) (d) (e)	Reforming/ Combustion
Steam generator/ vaporiser	HEX 5 (f)	Combustion
Methanol/water vaporiser/ superheater	HEX 0.5 (a)	Combustion
Reformate cooler/heater	HEX 0.5 (b)	No coating

The methanol reforming units were supplied in two batches by ECN. HEX 5 (a) and (b) were supplied initially followed by the remainder. ECN experienced some difficulty coating the larger units and HEX 5 (c) (d) and (e) were coated using an improved technique.

The HEX 5 units were individually tested in a rig that also incorporated the superheater, HEX 0.5 (a) and steam generator/vaporiser HEX 5 (f).

The reformer, vaporiser, superheater and methanol heater/reformate cooler were integrated with the gas clean-up unit built by LU which was connected to the reformate leaving the reformate cooler/methanol heater.

The performance of the integrated reforming unit did not meet the specification in terms of volume because the reformate flowrate produced was approximately 25% of the required flowrate. Depending on how the complete SPFC system is operated, the required flowrate of reformate is typically 20 l min<sup>-1</sup> kW<sup>-1</sup> (although lower figures have been quoted). In the integrated test, four HEX 5 units produced typically 100 l min<sup>-1</sup> which is the equivalent of 5kW of electrical power.

### 3.4. Rover

Rover has considered vehicle integration and volume manufacture.

#### 3.4.1. Vehicle Integration

An important feature of the reformer and fuel cell system in terms of its integration within the vehicle is the time response requirement for start-up and transient load following. The potential limitations of the reformer/fuel cell in this regard were addressed by the concept of a 'parallel' design, where the start-up and transient demands of vehicle traction would be met principally by a conventional traction battery, with the reformer/fuel cell providing steady state power. An electrochemical battery will also allow the vehicle to capture energy during braking. Clearly, however, there is a need to balance the time response of the reformer/fuel cell against the size of the traction

battery so that the latter can be minimised. These considerations led to the primary specification requirements given below.

<b>Issue</b>	<b>Parameter</b>	<b>Value</b>
Response Times	Start Up	<5s
	Transient Response	<5s
Size Limits	x dimension	700mm
	y dimension	350mm
	z dimension	200mm
Volume	Total system	49 litres
Weight	Dry weight	50kg
Output Power	Fuel Cell output power	20kW
Efficiency	Methanol to H <sub>2</sub>	>85%
Cooling	Medium	Liquid
	Temperature	<80°C
Ambient Temperature	Maximum	+40°C
	Minimum	-20°C

The package envelope and weight target is shown in the previous table. The height is the critical dimension for the system package. All other dimensions are flexible. The output of the project is targeted to be packaged within these constraints or show a level of design feasibility which demonstrates that the package is achievable in the second design phase.

The MERCATOX prototype reformer must demonstrate a potential compliance with the Ultra Low Emission Vehicle (ULEV) limited defined by the Californian Air Resource Board CARB. Relatively conventional gasoline fuelled internal combustion engine vehicles can comply with this legislation. To be competitive in the market from 2000 onwards, the vehicle should either comply or show potential compliance with the EZEV emission limits. It is anticipated that an internal combustion engine in a series hybrid could meet these limits.

These targets are detailed below:

Emissions as a Function of Energy Consumption: Based on an energy consumption of 150Wh/km (or 0.241kWh/mile).

	<b>Hydrocarbons (ii) (HC) grams per kWh</b>	<b>Methanol (CH<sub>3</sub>OH) grams per kWh</b>	<b>Carbon Monoxide (CO) grams per kWh</b>	<b>Oxides of Nitrogen (NO<sub>x</sub>) grams per kWh</b>
<b>ULEV</b>	0.166	0.033	7.04	0.829
<b>EZLEV</b>	0.0166	0.0033	0.704	0.0829

The vehicle will have a number of individual systems and sub-systems, most of which need some form of local control. The vehicle control hierarchy uses a central Vehicle Management Unit (VMU) to control and co-ordinate the vehicles systems according to both the drivers demands (i.e. torque demand) and the vehicle status (i.e. battery state of charge low). Communication using a CAN Bus allows a wide range of information to be easily accessible by remotely packaged system components.

The table below should be considered as the maximum service requirement for a reformer system. Every effort should be made to produce a service free system.

<b>Service Task</b>	<b>Interval</b>
Minimal Operator Inspection	Monthly
Minimal Garage Servicing	1 year or 10,000 miles
Significant Garage Servicing	5 years or 50,000 miles
<ul style="list-style-type: none"> <li>Major component replacement</li> </ul>	

The 'production' vehicle reformer system and its components should be manufactured in such a way that the failure rate of the system at the point of delivery to the car manufacturer is zero. Failures in operation should be kept as low as possible.

The vehicle reformer system is expected to last the life of the car. This is quantified below:

<b>Parameter</b>	<b>Value</b>
Operating time	>5000 hours
Calendar life	>10 years
Vehicle mileage	>100,000 miles

The principle behind cost target setting is that the complete vehicle will need to be competitive with a conventional internal combustion engine version. A fuel cell powered car can be expected to achieve lower exhaust emissions and better fuel economy than the conventional product, but these are not attributes that customers normally consider to be high on their list of requirements when making a purchase. Therefore the fuel cell car will need to 'sell itself'

by offering attractive features (quietness, refinement, etc.) and be competitively priced.

On this basis, therefore, all of the systems that replace the internal combustion engine + gearbox + exhaust (reformer, fuel cell, battery, power inverter, drive motor and gas clean up) need to be under the typical 1000 - 2000 Euro cost of a 50 - 70kW commuter car power train.

The cost portion that can be allocated for the reformer and gas clean-up can be only estimated when seen against the complex technologies of the other systems, an estimate of 30% of the total power train cost is proposed. For an equivalent 20kW<sub>e</sub> system the volume cost target is 30 Euro per kW<sub>e</sub>.

### 3.4.2. Volume Manufacturing Technology

The two principle areas of consideration that determine the manufacturing task are firstly the bought out materials, components, sub-assemblies, etc. and then secondly the processes/assembly techniques required in the manufacturing plant. Both of these are, of course, directly influenced by the engineering of the product design itself and the choice of suppliers, especially for the more critical components. Hence the need that is now recognised universally within industry to link the design and manufacturing technologies, even at the very early stage of the design of a new product.

#### 3.4.2.1. Bought-out Items

The raw materials required are not difficult, consisting principally of aluminium plate, tube and bar for the main structure of the reformer, gas clean up unit and the mounting structure. For the internal components of the system the aluminium plate is corrugated.

The most significant sub assembly task is the catalyst coating of the reformer and gas clean-up plates with different catalyst materials. These processes of coating by passivation and other techniques are standard within industry, although generally carried out by small specialist suppliers on a low volume basis. However no significant difficulty is seen in moving to high volume, apart from the need for investment in capital plant and factory space.

A significant number of expensive, specialist components are required - pumps, control valves and instrumentation (flow, pressure, temperature). Some of these will need to be able to handle high temperatures and also some to withstand the corrosive effects of methanol. To lessen the difficulties of supply availability and cost, the potential to use existing automotive components has to be considered. A first appraisal shows that this will not be easy as most of the flow levels are much smaller (≈100ml/min.) than conventional automotive use and the temperatures are generally higher. In addition the high volume part of the automotive industry has little experience with methanol. These issues are all capable of resolution, but it may require a large investment by the supplier companies to meet the economies of scale that will be required.

Finally the control system will be a specific design and a dedicated manufacture, however it will consist of well known electronic devices and assembled onto standard pcb and housing, so no particular problems are foreseen.

### 3.4.2.2. Manufacturing assembly and test

No large issues are expected here, the reformer and gas clean up units themselves are assembled by a well established diffusion bonding process, which can be readily brought to a high volume level.

The rest of the manufacturing processes involve standard practices of metal handling and fitting of sub-assemblies, pipework and thermal insulation material. All of these are quite capable of being placed in a high volume environment with the right level of manufacturing engineering applied to assembly line layout and work-in-progress handling.

The test facilities will require a good level of investment because there is a number of services to be provided - fuel, air, oxygen, hydrogen, water, electrical, cooling and gas analysis equipment all mounted in a purpose designed assembly.

The design of this system does not present any significant technological challenges from a volume manufacturing viewpoint. However the need for significant investment is foreseen, especially by sub-assembly and component suppliers in order to reach a level of supply volume and low cost that will be necessary to ensure commercial success.

## 3.5. IST

IST's modelling activities were fivefold:

- Basic system simulation.
- Reformer modelling.
- Modelling the gas clean-up unit.
- Dimensioning and integration of components.
- Performance analysis of the system.

### 3.5.1. Basic system simulation

A system model was developed with the objective of analysing the effect of thermally integrating different components. Individual energy balances were performed to define the flow and heat streams in the system. A number of assumptions were made about the performance of individual components. It was assumed that the cathode off-gas was cooled to condense water for recycling back to the reformer. Heat exchangers were required between the reformer and gas clean-up unit and the gas clean-up unit and the fuel cell.

The model was used to predict the impact of system efficiency of component arrangement and integration and to provide data for heat loads and flowrates for individual sizing.

Variations in system efficiencies were determined for the basic case of no water or heat recovery through to the maximum water and heat recovery. The system efficiency calculated ranged from 32.5% to close to 35%.

### 3.5.2. Reformer modelling

IST reformer modelling commenced with an overview of the kinetic parameters derived from data provided by ECN. This was followed by modelling the aluminium foam tubes and the Chart Marston heat exchangers. This was achieved by considering the heat and mass transfer characteristics of the two configurations. Practical tests were undertaken to estimate values for these parameters. The resulting simulation enabled the prediction of hydrogen conversion and methanol production.

### 3.5.3. Modelling the gas clean-up unit

IST had difficulty determining a suitable chemical model description for carbon monoxide selective oxidation in the presence of hydrogen. Mechanisms postulated in the literature did not produce results that agreed with data from LU. Consequently IST developed their own approach. They considered a constant reaction rate for the consumption of carbon monoxide for variable fuel rates at constant temperature. The results predicted by this approach showed a measure of agreement with LU's data for temperature distribution.

### 3.5.4. Dimensioning and integration of components

The calculations for predicting volumes of the plate and fin type heat exchangers were done using the LMTD method which requires the knowledge of the inlet and outlet temperatures for the hot and cold fluids. This method is suitable for the steam generator and the superheater but in the case of the reformer, reaction kinetics are also a factor. These considerations resulted in a reformer volume of five HEX 5 heat exchange units being required. Similar size predictions were made for the steam generator (0.5 l), methanol/water superheater (5 l) and methanol heater/reformate cooler (0.5 l).

On the combustion side, consideration was given to the best flow pattern for the gas stream that is to be combusted. The object was to meet the heat requirements of each vessel but also to keep the combustion temperatures below an acceptable value. The model suggested that the combustion stream should flow initially to the steam generator, then the superheater and finally to the reformer. This arrangement leads to higher temperatures in the evaporator, a more uniform set of maximum temperatures in each component and improves the system efficiency as the exhaust gas temperature is decreased.

### 3.5.5. Performance analysis of the system

A calculation for the start-up time for a 20kW system was determined by considering the operating temperature of each component and estimating the thermal inertia. This analysis predicted that the reformer could be raised to reforming temperature in under 60 seconds. In order to meet the start-up time targets, some form of energy storage will be required.

## 4. **RESULTS AND CONCLUSIONS**

The performance of the integrated reforming unit did not meet the specification in terms of volume because the reformate flowrate produced was approximately 25% of the required flowrate. Depending on how the complete SPFC system is operated, the required flowrate of reformate is typically 20 l min<sup>-1</sup> kW<sup>-1</sup> (although lower figures have been quoted). In the integrated test, four HEX 5 units produced typically 100 l min<sup>-1</sup> which is the equivalent of 5kW of electrical power. Therefore the volume of the methanol reforming section, based on the integrated system testing results, will be

80 litres. Alternatively, the reformat production rate will have to increase from 25 l min<sup>-1</sup> to 80 l min<sup>-1</sup> if the reformer volume is to be 25 litres as predicted.

The quality of reformat was acceptable in that the gas clean-up unit was able to accommodate the carbon monoxide and methanol levels at the flowrate produced. LU testing on synthetic reformat suggests that the gas clean-up unit would have difficulty reducing the high carbon monoxide levels exiting the reformer at higher flowrates.

The ultimate goal for the reformer is to produce reformat at the required flowrate at the highest methanol conversion and with the lowest carbon monoxide level. The prime reasons for the reduced performance is thought to be low catalyst activity resulting in low conversion and the well known tendency for copper/zinc catalysts to deactivate. Contributory factors may be insufficient catalyst or poor uniformity of the coating on the HEX 5 units. However the latter does not appear to have been a problem with the combustion catalyst.

Testing done in parallel at ECN and WCJB on HEX 0.5 units did not produce identical results. WCJB's results were disappointing compared to those obtained at ECN. The major factor causing the difference in results was believed to be ECN's use of nitrogen in the vaporised feed which may suppress the deactivation process. The catalyst loading on the smaller HEX 0.5 unit is greater than on the HEX 5 units. This means that the rate of deactivation would be accelerated in the case of the larger units. Whilst the deactivation process can be slowed down by working at temperatures up to 300°C, the margin between the operating and safe working temperature of aluminium is reduced. The quality of methanol being used was also highlighted. ECN used a grade of methanol specified as a higher quality than the technical grade (BS506, Part 1, 1987) used by WCJB. By changing to AnalaR grade, WCJB obtained a better performance but deactivation was not eliminated. The subsequent analysis of AnalaR and technical grade methanol by GC-MS revealed identical composition and no organic contaminants. It therefore seems possible that any contaminant causing the performance variation observed at WCJB is inorganic and could be introduced during the bulk filling of drums in which the methanol is supplied. This contamination may be typical of that to be found in a methanol infrastructure.

The corrugated plate and fin heat exchanger demonstrated exceptional heat transfer performance which leads to good control characteristics and fast response. The temperature of the methanol reforming and vaporiser units could be raised to a suitable temperature for hydrogen production in around 30 seconds which is a substantial step forward for steam reformers.

The gas clean-up unit performed satisfactorily in the integrated test although only at 25% of its rated capacity. The levels of carbon monoxide and unreacted methanol exceeded the specification yet the device reduced carbon monoxide to acceptable levels and appeared unaffected by the present of methanol. Insufficient running time was achieved to confirm these initial observations. Similarly, due to the reduced output of the methanol reformer, performance data at higher flowrates was not obtained.

IST produced recommendations for the sizes of the major components in the reforming section and the burning of fuel cell exhaust gas in series through the units requiring heating. The time taken for heating the units to a suitable temperature for reforming was predicted. With the exception of the methanol reforming unit performance, these recommendations proved to be accurate. IST also predicted that the temperatures generated in the vaporiser and superheater by burning fuel cell off-gas and excess air were approaching (and in some configurations exceeding) the acceptable operating temperature for aluminium. Consequently, it is possible that these components will have to be manufactured in another material.

LU has developed a gas clean-up unit that has performed satisfactorily. However, the current design uses a thermal fluid as a cooling medium although it is possible in an integrated design, this feature could be eliminated.



Based on the results of testing the larger reformer units, the volume and weight of the 20kW system is estimated to be as follows:-

	<b>Volume l</b>	<b>Weight kg</b>
Methanol reformer	80	80
Steam generator	5	5
Vaporiser	0.5	1
Reformate cooler	0.5	1
Gas clean-up unit	4	5
<b>TOTAL</b>	<b>90 l</b>	<b>92 kg</b>

This is twice the target volume specified by Rover. If the performance of the methanol reformer units could be improved four fold, the volume is estimated to reduce to 30 l and the weight to 32kg, which would be substantially better than the target.

The following table shows the target power densities and specific powers for MERCATOX and the USA Partnership for a New Generation of Vehicles (PNGV) and compares the actual and predicted results for the MERCATOX project.

	<b>Targets</b>			<b>Actual</b>	<b>Predicted</b>	
	MERCATOX	PNGV		MERCATOX (20kW)	MERCATOX	
		Year 2000	Year 2004		20kW	60kW
Power Density kW/l	0.4	0.6	0.75	0.22	0.66	0.6
Specific Power kW/kg	0.4	0.6	0.75	0.22	0.625	0.6

It should be noted that for an operating pressure of 4 bar, the aluminium construction will have to be strengthened resulting in a weight and volume increase.

An area of concern is the operational temperature of the methanol reforming units. As ECN has noted and WCJB has observed, the decline in activity of the methanol reforming catalyst can be mitigated by raising the reformer temperature. In practice, this has been raised to 300°C which reduces the safety margin for the use of aluminium. Although the melt point of aluminium is 660°C, when used at pressure, temperatures greater than 300°C will weaken the structure significantly. It is therefore imperative that the reforming reaction takes place at 250°C or less. This would seem unlikely to be achieved with copper/ zinc/aluminium catalysts typified by BASF K3-110 used by ECN. It is interesting to note that Daimler Chrysler recently signed a collaborative agreement with BASF to develop improved methanol reforming catalysts. There have been a number of recent catalyst developments for methanol reforming that suggest improvement is possible. These include the use of zirconium oxide with copper (Royal Military College of Canada, Daimler Chrysler) and Exxon's development of a catalyst that is claimed to produce negligible carbon monoxide. If the operation temperature cannot be reduced, the use of an alternative metal/alloy as a material of construction would need to be considered. The use of stainless steel for example, would result in an increase in weight by a factor of 2 to 3. A significant change in volume is unlikely.

The volume of a conceptual fuel processor for a 50kW<sub>e</sub> SPFC system is 200mm(h) x 650mm x 800mm. The volumes of the individual sections were determined from the predictions made by IST for the 20kW system. The basis for the shape was determined by the packaging criteria supplied by Rover for the 20kW system.

IST sized the components using the LMTD method to determine heat transfer characteristics which required knowledge of the inlet and outlet temperatures. The heat transfer coefficients were derived from practical experiments with HEX 0.5 units. In the case of the reformer, kinetic calculations were completed for a range of reformer temperatures and conversions. These results were combined with the heat transfer calculation to produce an estimate of the reformer sizes for each case.

The fuel processor for a 50kW<sub>e</sub> SPFC system will be approximately three times the weight and volume of the 20kW system. Some saving in size should be achieved by using a fully integrated process design with interconnecting of the major components achieved by the use of internal channelling. The only external connections will be for feedstocks in, reformate and exhaust out and possibly a cooling circuit. The internal configuration will be based on a plate and fin heat exchanger design or similar.

Rover has commented that this type of construction poses no major impediment to mass production although investment will be required by motor components suppliers. A similar comment applies to the development of components for the control of the fuel processor. Components such as flowmeters are available in the motor industry but the use of methanol and the scale and nature of the parameter to be measured (e.g. gas detectors) present technical challenges. Again, Rover comments that solutions are possible given the correct level of investment.

Rover's specification calls for specific emission levels to be met. An accurate assessment at this time would require periods of continuous operation preferably with a fuel cell in the loop. A number of rudimentary tests using the foam tubes and the integrated test rig provided some information. Negligible hydrocarbons, methanol, oxides of nitrogen or carbon monoxide were detected in the exhaust gases during normal running. On the integrated test rig, hydrogen was detected in the combustion exhaust and the low oxygen concentration of the gas at the exhaust. This could be eliminated by good design.

The specification for the project defines the market segment which is targeted for the end product, viz. an SPFC passenger vehicle. However, because the design is modular, larger units can be constructed to meet the requirements of buses, locomotives and ships.

It is also possible that with a change of substrate material, higher temperatures could be achieved which would allow different feedstocks to be used, such as gasoline. Natural gas would also be an option opening up possibilities in the stationary power market.

Based on the work done at ECN, the following conclusions can be drawn:-

- A great deal of research effort has been devoted to catalyst development. This work has led to promising catalyst formulations for methanol steam reforming. However, when used in coated form on an aluminium substrate on a larger scale the catalyst produced a performance similar to commercially available catalysts. A small loss of performance after a few hours initial operation was apparent. As a result of this preliminary work on methanol reforming catalysts, commercially available catalysts have been investigated. In particular the catalyst BASF K3-110 appeared to be as active as the in-house developed catalyst. Consequently it was decided to concentrate on supplying larger structures coated with BASF catalyst.
- Calcination of BASF catalyst K3-110 results in lower methanol conversion, lower CO concentration in product and formation of dimethylether (creation of acidic sites). Calcination of suspensions containing BASF catalyst has a less

pronounced effect on methanol conversion and CO production but presence of boehmite leads to ether formation.

- Calcined BASF catalyst *coatings* are more active than the calcined catalysts and offer a better stability towards temperature excursions.
- The combustion catalyst is very active in the combustion of methanol even in the presence of water. Suspensions containing combustion catalyst perform equally well as the parent catalyst.
- Catalyst coating suspensions containing 22 wt% of solids, 4-6 wt% of urea and catalyst/ boehmite ratios of 4/1 have a very low viscosity and high stability and can be used to coat porous metals. Application of such washcoat suspensions of the BASF K3-110 reforming catalyst and the combustion catalyst onto aluminium foam parts leads to well adhering catalyst layers after calcination at 400°C.
- Aluminium heat exchanger parts need to be oxidised in air at 550°C to generate an oxygen-rich surface layer that acts as a key to washcoat adhesion. Application of washcoat suspensions of the BASF K3-110 reforming catalyst and the combustion catalyst onto the aluminium heat exchanger substrates has been demonstrated successfully.
- Among the investigated catalytic systems for methanol reforming the aluminium heat exchanger shows the highest activity due to its good heat transfer characteristics. The small heat exchanger catalytic system shows a hydrogen production capacity corresponding to approximately 0.5kW of electrical power. Increasing temperature and feed gas flow rate for methanol steam reforming has led to a hydrogen production potential corresponding to > 600 l/min at high methanol conversions (> 95%). Mainly due to the lower catalyst load, the coated aluminium structures deactivate at a higher rate than the pre fixed-bed catalyst pellets. But the higher temperature stability of the catalytic washcoat permits the use of the heat exchanger at higher reforming temperatures that prolong its operation time. By proper temperature control 450 hours of continuous operation have been achieved for an aluminium foam at an average methanol conversion > 90%.
- In the range of 1.1 - 2, the steam/methanol molar ratio has no strong effects on the reforming performance of the heat exchanger. Operating the heat exchanger under conditions of high flow and high temperature with periodic temperature cycling does not lead to excessive losses in activity over a period of 5 days. Deactivation rate is only marginally higher when compared to continuous operation. The methanol steam reforming performance of coated heat exchangers is determined predominantly by the quality of the applied washcoat. The specific design of the aluminium heat exchanger is of less importance.
- Combustion of methanol can easily be carried out in a coated heat exchanger. Above 100°C the methanol is fully converted into carbon dioxide and water, below this temperature methyl formate is formed in quantities which depend on the temperature. Temperature rise is strongly dependent on the amount of methanol, which is fed to the heat exchanger per unit of time. In agreement with the thermodynamical reaction enthalpies hydrogen yields a much lower rise in heat exchanger temperature than the combustion of methanol.
- In contrast to the combustion of hydrogen, combustion of methanol is delayed by a short time due to adsorption on the catalytic coating at low starting temperatures. This delay time can be decreased significantly by preheating the heat exchanger to temperatures above the boiling point of methanol. Combustion of hydrogen could be used for this purpose. The adsorption of oxygen on the washcoat at room temperatures (or lower) prior to the supply of the methanol/air feed interferes with the combustion of methanol. The heat exchanger temperature rise per unit of time appears to be linearly dependent on the feed gas flow rate.

- Results indicate that the integration of combustion with reforming is possible.

Based on the work done at Loughborough University, the following conclusions can be drawn:-

- In order to fulfil the criteria of the MERCATOX programme, Loughborough University (LU), have developed and evaluated a compact and lightweight gas clean-up system (GCU) for the selective oxidation of carbon monoxide present in reformed methanol fuel stream. The design and construction of the GCU has involved the critical assessment of a number of potential catalyst formulations for selective CO oxidation and heat transfer technologies suitable for catalyst washcoating and ultimately GCU automotive applications.
- Catalyst screenings have been performed at the micro and bench scale reactor level. The most promising catalyst formulations have subsequently been applied to heat transfer substrates for further evaluation. A formulation based upon platinum and ruthenium was ultimately selected by LU for use in the final GCU reactor design.
- The use of aluminium compact fin heat transfer technology was used in the final GCU design on the basis of its lightweight, compactness (high surface area per unit volume) and excellent heat transfer characteristics.
- The GCU reactor supplied to Wellman CJB Limited for evaluation with the methanol steam reformer is based on a dual stage reactor design. Each reactor is of 2 litres (2.5kg) in volume and the process stream chamber is washcoated with the platinum - ruthenium catalyst formulation. Each reactor is supplied with its own regulated air supply for CO oxidation. Each reactor has approximately 1 litre available for reaction of the fuel stream with oxygen and 1 litre for reaction cooling via the re-circulation of heat transfer fluid. A reactor thermal management sub-system, for isothermal operation, has been designed by LU for use with the GCU. The optimum reactor operating temperature is 150 - 160°C, this is in accordance with the original reaction specifications of 130 - 200°C. No inter-stage cooling between the reformer and GCU should therefore be necessary.
- The GCU has been evaluated at LU using synthetic reformat fuel rates of up to approximately 20kW<sub>e</sub> (SPFC power output). The reactor has successfully demonstrated that CO concentrations can be reduced from at least up to 2% to ⇄ 12ppm.
- Preliminary GCU response trials, regarding fuel flow rate changes, have shown that due to the high thermal transfer efficiency of the reactors no transients in the reactor temperature appear to occur. Losses in catalyst activity and selectivity should therefore be minimised. CO outputs have been maintained below 20ppm during such dry fuel trials. A more extensive evaluation of the GCU response capacity was planned upon integration with the methanol steam reformer.
- The MERCATOX GCU has a volume of 4 litres and has demonstrated that at fuel flow rate equivalents of approximately 20kW<sub>e</sub>, CO concentrations (typically produced by a methanol steam reformer), can be reduced to <20ppm. The GCU is therefore believed to be one of the most compact reactor technologies for its particular application. It is recommended that future improvements in reactor design should focus on air cooled rather than oil cooled system. The oil cooled design requires external high temperature pumps and radiators to dissipate the exothermic heat of reaction. This in turn may compromise the reactor somewhat for vehicle installation. Future GCU design should therefore focus upon the production of an air cooled system, which includes the reactor modules, manifolds, valves and cooling fans within a single unit. Similar physical specifications to the MERCATOX GCU should still be targeted.

Based on the results from the test programme at WCJB, the following conclusions can be drawn:-

- The target volume and weight for the methanol reformer and gas clean-up system have not been met. In order to meet the more demanding PNGV requirements, a four fold increase in reformat production is required.
- In order to achieve a four fold increase reformat production, a more active catalyst will be required. This catalyst should produce the required performance at 250°C maximum with a carbon monoxide content of maximum 1% (typically 0.5%).
- Assuming a more active methanol reforming catalyst is found, the volume and weight of a methanol reformer and gas clean-up unit for a 50kW SPFC system will be approximately 100 litres and 100kg respectively. This would meet the PNGV goals for an on-board fuel processor for the year 2000.
- The quality of methanol has an effect on the reforming catalyst performance and operational lifetime.
- Methods of coating aluminium substrate with active catalyst have been developed. Coating techniques were developed successfully for methanol reforming, combustion of fuel cell off-gases and methanol/air and selective oxidation of carbon monoxide in the presence of hydrogen.
- The gas clean-up unit performs according to specification in the 5kW<sub>e</sub> range using real reformat. Using simulated reformat, this performance is within specification at 20kW<sub>e</sub>.
- The heat transfer characteristics of the Chart Marston compact heat exchangers are excellent.
- The target start-up time of <5 seconds cannot be met at present. However, based on tests and a theoretical assessment, a start-up time of 30 seconds for the methanol reformer is attainable.
- Gaseous emissions from the exhaust of the system are very low, based on the rudimentary tests carried out. Levels of contaminants quoted in Rover's specification are negligible. However, some excess hydrogen has been detected.
- In terms of other fuel processor developments around the world, MERCATOX has the potential to become state of the art. This assessment is based on volume, weight and speed of response data generated in this project.

Based on the work at IST, the following conclusions can be drawn:-

- A model for a PEM fuel cell system was prepared and used to optimise the system efficiency. This model was continuously used during the project to set the operation conditions for the system components. This model approach was not initially foreseen in the work programme but it was identified as necessary in order to develop the reformer and GCU for the expected conditions in a PEM fuel cell system. The system efficiency considering 52% voltage efficiency can be increased from 32.7 to almost 35% by adding components. These values were obtained using considerable values for the parameters of the components, rather than assuming optimum values not yet achievable.
- The original project work programme was based on the development of a detailed model for the reformer and gas clean-up unit. For the reformer detailed numerical models were developed for the aluminium tube and the plate finned heat exchanger. The numerical model for the aluminium tube was validated with measured temperature profiles and was used to characterise the temperature distribution in reforming tubes. For the plate finned heat exchanger the calculated transversal gradients were very small leading to a one dimensional representation of each channel.
- For both reactor configurations, experiments were carried out to characterise heat and mass transfer. For the aluminium foam an effective conductivity of 4

W/mK was determined, while for the plate finned heat exchanger the convection coefficients were lower than suggested from the literature. For mass dispersion effective values were found showing an increase with air velocity with larger values for the aluminium foam. The parameters for the reforming kinetics were derived from data from ECN.

- For the GCU the modelling was limited to due to the complexity of the phenomena. Nevertheless global kinetic rates were derived, enabling to estimate the outlet temperature and CO concentration for specific catalysts and mixtures in the feed. The temperature profile is calculated considering constant parameters allowing for the use of an analytical expression.
- Based on the plant model the components were dimensioned assuming their construction to be made on standard plate finned heat exchangers. This allowed to define the arrangement of the components to test the MERCATOX system. The modifications made compared with the initially assumed plant reduced the expected system efficiency to 31.7%.
- For the defined reformer, start up time calculations were performed leading to the conclusion that the best option would be the use of clean reformat to heat the system within half minute until the operating temperature. This can be reduced starting the reformer at a lower temperature and increasing the peak temperature in the components.
- For ideal steady conditions of the reformer the numerical model of the plate reformer was used to describe temperature profiles within the different units, allowing to verify that the staging option from the dimensioning was good. Further the use of co-flow in all the units was found to lead to a better reformer conversion that using counter-flow in some units. The actual performance of the final system was lower than anticipated and reduced reaction rates had to be considered in the model to allow for the calculation of rather uniform temperature profiles as observed in the test experiments.

Based on Rover's assessment of the technology, the following conclusions can be drawn:-

- The design of this system does not present any significant technological challenges from a volume manufacturing viewpoint. However the need for significant investment is foreseen, especially by sub-assembly and component suppliers in order to reach a level of supply volume and low cost that will be necessary to ensure commercial success.
- Further work is required on the development of the control system and sensors for a methanol reformer and gas clean-up unit for an SPFC hybrid vehicle.

In order to realise the potential of the MERCATOX concept to become state of the art for methanol reforming and gas clean-up for mobile SPFC applications, we recommend the following actions as necessary to tackle the outstanding key development issues and commercial barriers.

- Locate or develop a more active reforming catalyst that will produce high conversion of methanol and low carbon monoxide at a reforming temperature below 250°C.
- Locate cheaper aluminium substrates for testing.
- Investigate alternative substrates.
- Initiate discussions with catalyst coating specialists.
- Initiate discussions with car component suppliers.

- Initiate work on identifying control system and sensor requirements for a methanol reformer and gas clean-up unit in an SPFC vehicle.
- Build an integrated 20kW methanol reformer and gas clean-up unit to meet Rover's specification.
- Incorporate integrated 20kW methanol reformer and gas clean-up unit in a complete stationary drive system demonstrator for an SPFC vehicle.

5. **EXPLOITATION PLANS AND EXPECTED BENEFITS**

The MERCATOX project was specifically targeted at an SPFC electric passenger car. Whilst not achieving the technical targets specified, MERCATOX project represents a considerable step forward in on-board fuel processing technology. All other 'state of the art' fuel processors are unable to meet the specification for start up and response times, weight and volume. With the possible exception of start up time, MERCATOX has the potential to meet the specific density and power targets set by the US government PNGV programme for the year 2000.

The technology could also be used in other areas of transportation from buses to locomotives. The principle of coated catalysts on metal substrates using different materials and catalysts could be extended to process other feedstocks, such as natural gas, gasoline, diesel etc. This would open up the stationary power and military markets to this type of technology. Markets outside of fuel cells include process intensification.

All major car manufacturers have fuel cell development programmes for vehicles. As part of these programmes, the development of fuel processors is prominent. At the present time, most manufacturers are considering methanol or gasoline as the preferred feedstock. Currently, methanol seems to be emerging as the preferred choice with Daimler Chrysler, Ford and Ballard actively investigating the possibility of a methanol infrastructure with the oil companies.

Several major car manufacturers are forecasting marketing a fuel cell vehicle by the year 2004. The market potential is enormous. For example, Rover/BMW estimate that in Europe by 2002, the potential market will be for 40 million vehicles per annum.

None of the partners intend to apply for patents in respect of their activities, relying on confidential know-how to protect their technological expertise. The chosen route of exploitation is to move forward to a stationary demonstrator incorporating fuel cells, drive train, electric motors etc. combined with the fuel processor. The technology will be offered to a number of end users as Rover/BMW does not place a high priority on the use of on-board reformers, preferring to concentrate on liquid hydrogen. However, prior to this, some effort will be concentrated on looking at alternative methanol reforming catalysts. If a group can be assembled, it is likely that there will be a proposal for further JOULE funding.