FUSE Demonstrator Document
Application Experiment Number 25744

A Miniature Pipeline Inspection Tool

*MCM Technology Size Reduction Opens Up New Exploitation Potential*

Associated TTN: Glamorgan
Abstract

The UK gas distribution network consists of 265,000 km of pipelines, which vary in size from 63mm to 1200mm diameter. The effective management of this infrastructure demands the availability of a range of high resolution, in-pipe, non-destructive testing (NDT) tools. These tools are used to detect and determine the size of significant instances of metal loss and cracks in the pipes. These results are then used to prioritise essential pipeline replacement and maintenance programmes.

Part of the BG plc group, BG Technology, employs over 600 people and had a turnover of 66 MEURO in 1997. The company supplies a range of research and technical consultancy services in gas exploration, production and transportation. BG Technology is responsible for the design, manufacture and operation of non-destructive pipeline inspection equipment for the low-pressure gas distribution market. Current electronic expertise applied in these product developments includes field programmable gate array (FGPA), microcontroller and surface-mount component technologies.

BG plc currently uses a range of in-pipe inspection vehicles, based on magnetic sensing to revalidate its gas transmission network. These devices are supplied by an external inspection company that services both oil and gas undertakings world-wide, concentrating on large diameter pipes. However existing technology prohibits the use of this type of equipment for low pressure pipes of less than 150mm diameter and is limited to ferrous materials.

The objective of the application experiment was to miniaturise the current tethered in-pipe tool to allow the inspection of currently inaccessible pipelines. This would enable pipeline inspection to take place under live gas conditions in pipe of 100mm diameter containing bends of centre-line radius equal to the pipe diameter (1D) and protrusions up to 15mm.

The technical objective of this application experiment was to use Multi-Chip Modules (MCM) to reduce the size of the electronics within the existing product, thereby reducing the overall system size.

The use of MCM technology resulted in:

- High packaging density enabling testing of smaller diameter pipes combined with more powerful data analysis.
- Increased reliability of the electronic subsystems through a significant reduction in interconnections and more versatile on board calibration and diagnostics.
- Economic benefits in:
  - Construction (reduced component count)
  - Operation through built in programmability
  - The sales area by the potential exploitation of the smaller diameter inspection market.
The Application Experiment commenced on 1st May '98, with a planned duration of 8 months. By the end of 1998, sample MCM sensors had been delivered and tested. However, additional production runs were required in order to incorporate design corrections and to provide sufficient units for the field evaluation process to be completed. The total duration of the experiment, including field evaluations, was 12 months.

The improved product is expected to provide a potential increase in sales of inspection services in pipe diameters less than 150mm. Current projections indicate that the MCM development costs of 92kEURO will be recouped after approximately 16 months of operation. The return on investment throughout the product life is estimated to be 490%.

**Keywords and Signature:**

- Gas Distribution
- Pipeline Inspection
- MCM Technology
- Electronic Packaging
- Size Reduction
- NDT (Non Destructive Test)

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1. Company name and address

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2. Company size

BG Technology currently employs 600 staff. The skills base includes approximately 200 engineers, 120 physicists and 80 chemists.

BG Technology is part of the BG plc group (formerly part of British Gas) which consists of the following:

1. Transco
2. BG Storage
3. BG International
4. Corporate Development
5. BG Technology
6. BG Energy Services
7. Property Division
8. Leasing Group

The turnover of BG Technology in 1997 was 66 MEURO, the sales of inspection services for low pressure distribution pipes down to 150mm, prior to the start of the Application Experiment were in the region of 0.5 MEURO.
3. **Company business description**

BG Technology at Loughborough provides research and technical consultancy services across the whole of the gas chain, from exploration and production, via transmission and distribution to the gas markets.

In addition to supporting internal operations, BG Technology offers a range of services in the following areas: Upstream Services, Safety and Environment, Pipeline Services, Energy Utilisation and Network Management. This includes the development, manufacture and operation of pipe inspection equipment for the gas distribution industry.

The centre is equipped with ultra modern experimental and computational facilities, which include:

1. The Chemical Technology Building, with facilities for pilot plant scale studies of gas processing and treatment, and for large-scale core flooding experiments.

2. The Pressure Test Cells, where high pressure experiments or other potentially hazardous studies can be carried out.

In addition, specialist outstation test sites are available to enable activities such as full-scale hazard testing and flow pressure calculations to be performed.

The company’s activities are in the areas of energy production and distribution, gas supply (Prodcom code 41).

4. **Company markets and competitive position at the start of the Application Experiment**

BG Technology supplies a range of research and technical consultancy services in gas exploration, production and transportation. The research performed by BG Technology operates within the following areas:

- **Upstream Services**
  - Subsurface Technologies
  - Gas Production Technologies
  - Gas Processing Technologies

- **Pipeline Services**
  - Gas Transmission Technologies
During 1998 the BG plc High Pressure Pipeline Inspection business (PII) was sold. The low pressure and non-steel inspection applications remained with BG plc. This included the original Tethered Inspection Vehicle (TIV). Both this equipment and the improved product, described here, are targeted at the inspection of low pressure, small diameter pipes.

The TIV equipment, a non-destructive inspection and testing method, developed by BG for low-pressure gas main inspection, is limited to pipe diameters of 150mm upwards. The domestic market for this type of service is limited to the small amount of suitable mains requiring inspection. In addition, operational difficulties with the system meant that the potential market for this service is declining. Sales revenue increases can be achieved either by further geographic expansion or by extending the equipment's measurement capabilities to smaller diameter pipes. Opportunities within new markets, such as Eastern Europe, are limited. This is due to the general condition of the infrastructure, which mitigates toward wholesale replacement rather than routine inspection and remediation. Therefore, sales expansion in the short term will come mainly from developments of the equipment to inspect smaller diameter pipes.

The equipment is not sold to customers, but an inspection service is provided on a contractually negotiated basis. The pricing of these services is determined on a contract by contract basis, and depends on a number of factors: e.g.: geographic location, mileage to be inspected, reporting requirements, potential repeat business, etc.

The key market for low-pressure distribution pipe inspection is currently in the UK. Alternative suppliers of inspection services in the UK include Pearpoint, Russell Technologies, Tuboscope-Vetco and a number of smaller undertakings concentrating on the nuclear industry. Pearpoint
systems are based on the use of cameras for internal visual inspection, this is a complementary product that does not compete directly. The Russell Technologies system uses a similar operating principle, but these systems are targeting the water distribution pipeline market at present and not competing directly. The Tuboscope system uses conventional flux leakage technology (similar to TIV) and will therefore be restricted to the 150mm and greater pipe sizes.

The market opportunity for the improved system, the subject of the application experiment, is enhanced by the present lack of competition. There are currently no alternative systems on the market that can achieve equivalent performance in these small diameter low-pressure distribution pipelines. Other systems are available notably in the United States and Japan but as yet no agencies or industrial partners exist in the European market.

The limitation of the existing equipment to the inspection of low pressure pipelines with diameters greater than 150mm means that the market opportunities for the sale of pipeline inspection services is limited. The length of pipes available for inspection with smaller diameters is much greater, and the development of pipeline inspection equipment with a capability to inspect pipes down to 50mm will open up new market opportunities, especially in the areas of petrochemical plants and in power generation sites. A recently completed survey into UK non-gas opportunities indicated substantial interest, especially in the 50mm to 100mm diameter lines, as used by the petrochemical, power generation and water companies. In addition, there is increasing acceptance of the need for inspection for both reliability and regulatory reasons. The key issue to smaller diameter high-resolution inspection devices of this type is higher density electronics, allowing the advanced signal capture and processing functions to be achieved onboard.

The UK Gas distribution network consists of 265,000 km of mains pipelines of diameters greater than 50mm. Pipelines with diameters between 50mm and 150mm represent over 70% of this network. This characteristic of the UK distribution network is "mirrored" in the European and American market. The ability to address the inspection of gas pipelines in smaller pipe diameters is expected to increase the available market for the sale of inspection services by 130%.

Low pressure, small diameter in-line inspection carried out by BG plc for the 3 years prior to the AE was limited to 150mm, 200mm and 300mm tools. The estimated revenue from these operations was in the region of 0.5 MEURO. The typical cost of this service was around 20 kEURO per kilometre inspected.
5. **Product or process to be improved and the reasons to innovate**

The Tethered Inspection Vehicle (TIV) is a non-destructive inspection and testing method, developed by BG, for the inspection of low pressure pipelines such as gas and water distribution pipelines, refinery pipelines, storage terminals, loading terminals, etc. It can be used in live gas conditions and also in decommissioned pipe.

The existing TIV shown in the photograph uses the technique of Magnetic Flux Leakage (MFL) in order to inspect the pipeline for metal loss. The magnetic module of the tool contains a powerful electromagnet that transfers magnetic flux, through flexible foils, to the pipe-wall. Variations in the magnetic flux, caused by changes in the wall thickness are detected by the sensors and processed in the electronic module. The signals are then digitised and transmitted back to a personal computer (PC) and display screen via a base station. Power for the whole operation is provided by a generator at the launch site and is transmitted by an umbilical cable, which also connects the electronics module to the base station and PC.
Photograph 1: Existing Pipe Inspection Equipment

The TIV is designed for the inspection of ductile iron, cast iron and steel pipelines and is currently available in a diameter range of 150mm to 300mm.

The vehicle design consists of three separate articulated modules:

- Magnetic module
• Electronics module
• Power module.

The functional block diagram of the existing product is indicated in Figure 1.

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**Figure 1:** System Block Diagram (TIV)

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**Magnetic module**

The magnetic module contains a powerful electromagnet, which transfers magnetic flux to the pipe-wall.

The Hall effect sensors in the detector circuit detect variations in the magnetic flux, caused by changes in the wall thickness. The flux signals are then processed in the electronic module, and digitally transmitted back to the PC and display screen via the base station. The magnetic sensors are mounted on a ring between the poles of the electromagnet.

**Electronics module**

The electronics module contains several circuit boards, which provide the excitation to the sensors and process the returning signals.

The electromagnet requires a substantial direct current to generate the required flux density. This current must be monitored accurately as it dictates the actual flux within the pipe-wall. Further changes in the flux density at the detectors are consequently related to wall thickness variations.

The analogue signal inputs from the coils are amplified and filtered. They are then digitised to 10-bit resolution and combined with other digitised data relating to the system performance. This digitised information is converted into a serial RS485 data stream and sent on request to the base station, together with orientation information and the value of the drive coil current.
**Power module**

Power for the whole operation is provided by a generator at the launch site, and is transmitted by an umbilical cable, which also connects the electronics module to the PC. The cables for incoming power and outgoing data are separated within the power module. A regulator supplies power for the electronics module. The umbilical cable is released through a standard shaft encoder; the encoder produces 2 pulse trains which allow the distance the vehicle has travelled through the pipe and the direction of travel to be determined.

The analysis equipment consists of a base station interface unit and a personal computer.

The interface unit contains a 100/50Volt power supply, a direction discriminator and circuit boards for processing the signal from the distance measuring equipment. There are two serial interfaces, an input for the distance transducer, and a line out for power.

The serial data is passed to the PC, through one of its serial ports, at a rate of 38.4 kbaud. An on-board microprocessor maintains a software count of the signals from the distance transducer; the count is serialised and passed to the PC on request.

The proposed product improvements are aimed at opening up new market opportunities by removing the diameter limitations of the current equipment. Market opportunities for the sale of pipeline inspection services, with the current equipment, are limited to 150mm diameter upwards. The length of pipes available for inspection with the smaller diameters is much greater. The development of pipeline inspection equipment with a capability to inspect smaller pipes will open up these new market opportunities.

### 6. Description of the product improvements

The objective of this application experiment is to improve the Tethered Inspection Vehicle (TIV) so as to enable the equipment to be utilised in the non-destructive testing (NDT) of smaller diameter pipes.

The parameter to be improved by the product development is the reduction of tool size in order to provide a minimum pipe diameter capability of 100mm, down from 150mm.

This development requires the miniaturisation of the electronics and sensor assemblies to allow the equipment to negotiate pipes of 100mm nominal diameter and, more importantly, to enable the equipment to negotiate the internal pipe geometry at bends (one diameter bend passing capability) or at the pipe entry. This requirement is illustrated in Photograph 2, where the existing electronics package is shown next to a 90 degree, 1D bend: i.e. a bend that has a centre-line radius equal to the diameter of the pipe.
Photograph 2: Illustration of Pipe Diameter Constraint
The reduced diameter of the equipment requires a modification of the magnetic principle behind the system. The smaller volume available means that the flux produced by an electromagnet will not be large enough to provide an efficient inspection of the pipe under test. BG Technology have demonstrated that the measurement of remote field eddy currents (RFEC) and the processing of the sensor signals to detect changes in both the amplitude and phase, allow differences in pipe wall thickness to be accurately determined. The change to an ac excitation of the magnetic field in the RFEC system has been demonstrated to provide the required NDT information in pipes below 150mm diameter. Appropriate choice of excitation frequency will also permit the inspection of both ferrous and non-ferrous metallic pipes. This is an additional benefit since not all pipes in the target markets are constructed of steel or cast iron.

The systems block diagram for the improved tethered vehicle (hereafter termed the RFEC equipment) is shown in Fig 2. The RFEC equipment consists of several modules connected together to form an articulated assembly capable of movement through the pipe.

![System Block Diagram](image)

**Figure 2: System Block Diagram**

Each sensor ring contains 24 sensors mounted around the circumference of the sensor module. Each sensor consists of 200 turns of wire on a former of dimension 28mm x 8mm. The sensor assembly is constructed so that the sensor coils are near the surface of the pipe. The suspension units allow the sensor rings to compress so that the unit can accommodate variations in the inner diameter of the pipe at joints etc. This means that the sensor assembly has minimal space for mounting the electronics circuits, constraining the available circuit board area to 14mm x 6mm per sensor when allowance is made for cable connections.

The signal processing requirements for the RFEC equipment can be summarised as follows. The analogue signal level received from the sensor coil is greater than 140µV. This signal is a continuous tone at a frequency of between 10Hz to 1kHz, the actual frequency being optimised for pipe diameter and material. The received signal is pre-amplified, bandwidth limited using a frequency selectable, microprocessor driven, band-pass filter. The filtered signal is then used as
the input to the subsequent amplitude and phase processing circuits. The inspection performance specification requires a specific spatial frequency along the pipe, this translates to a data output requirement of a single sample every millisecond. To produce this data reduction, the sensor signals are analogue to digital converted and a microprocessor used to perform the time averaging.

The phase difference between the sensor signal and the excitation reference signal is extracted using a digital counter circuit in the microprocessor. This information is combined with the amplitude information, and transferred via an I²C bus to a central communications node located in the electronics module.

The resolution required from the amplitude and phase processing systems is 12 bits to enable subsequent processing algorithms to achieve the required defect sensitivity.

The device technology needed to accommodate the functions outlined above must conform to the following outline specification:

Space Requirements: 6mm(wide) x 14mm(long) x 8mm(high) (Double-sided circuit board)

Processing Requirements: 12 bit analogue to digital conversion
12 bit counter
I²C bus output
microprocessor to filter and average 12-bit data sufficiently fast for 1ms sampling

Analogue Channel Specification:
(Each channel)
- amplitude 140µV rms minimum.
- Frequency Continuous tone, range 10Hz - 1kHz selectable.
- Linearity less than 1 lsb deviation.
- Long term drift unimportant (removed by set up self calibration procedures).
- Short term drift less than 1 lsb drift between each channel per hour.

Sample Rates: 1 output sample every 1ms (approximate maximum rate).
The capability to inspect both ferrous and non-ferrous pipelines is a key feature of the improved system, allowing a wider range of pipe materials in varying locations to be inspected. (e.g. stainless steel process plant pipework)

The ability to add features like this, whilst at the same time reducing the minimum diameter of pipe that can be inspected, constitutes a major advance. This could not have been achieved without the use of MCM technology.
7. Choice and rationale for the selected technologies, tools and methodologies.

One of the crucial factors in the selection of an appropriate component technology for the RFEC vehicle application area is the restricted space available for the processing of the sensor signals. Mechanical tests to evaluate the space constraints indicated an available circuit board area of 6mm(wide) x 14mm(long) x 8mm(high). Other factors that influenced the selection of an appropriate component technology were the anticipated volume of components to be used and the design risks and flexibility associated with the technology choice. The number of units required was a minimum of 500 units, this would cover the demand for 48 sensors for a minimum of 10 units and associated spares.

The functions to be performed by the sensor processing circuitry include:

- Pre-amplification
- Bandpass filtering
- Analogue-to-digital conversion at 12-bit resolution
- Sample averaging
- Phase measurement to 12-bit accuracy.
- Interfacing to a central node via a communications bus.

The range of technologies considered for this application included:

a) Discrete analogue device processing
b) Analogue ASIC implementation
   with programmable logic digital support circuitry
c) Mixed signal ASIC implementation
d) Analogue 'tile' array ASIC with microcontroller or DSP back-end processing
e) An MCM implementation using discrete Surface Mount Technology (SMT) analogue devices and a chip-on-board microcontroller.

The first option considered for this application experiment was the use of a conventional packaging solution. This was to mount a microcontroller and an EPROM memory on one side of the circuit board, and then use a very small footprint SMT operational amplifier, a rms to dc converter integrated circuit, a switched capacitor filter, a comparator, three 4-bit digital counters and a 12-bit analogue-to-digital converter (ADC) mounted on the other side of the 6mm x 14mm circuit board. In addition, the need for several relatively large capacitors for the filtering and rms to dc averaging filter would require a significant circuit board area, and the total space was greater than that available. An MCM implementation of the total circuit was also not feasible because of the excessive number of discrete components and die types required for the implementation. The discrete device solution was therefore rejected.
The use of a dedicated analogue ASIC to perform the amplification, rms to dc conversion, switched capacitor filtering and zero crossing comparator for each sensor channel was considered. The major obstacle to implementing these circuits in an analogue ASIC was the small number of devices required (a maximum purchase quantity of 1000 units). This factor limited the number of foundries prepared to undertake the fabrication of the ASIC, and this in turn limited the number of subcontractors prepared to undertake the design. This factor was particularly important in the rejection of the mixed signal ASIC solution. The costs and risks associated with the lack of design flexibility of the ASIC implementation were greater than that for an MCM solution. The design subcontractors contacted for the ASIC solution advised the consideration of an analogue tile array ASIC.

The use of analogue tile array ASICs allows the integration of the amplifier, filter and comparator circuits. The analogue-to-digital converters, phase processing circuitry, and serial data transfer functions are not solely analogue functions. The majority of these processes could be performed using programmable logic, microcontroller or digital signal processing (DSP) devices. Analogue tile array ASICs can provide greater design flexibility but the small production numbers for this application again restricted its adoption.

As a microcontroller device incorporates the majority of the required peripherals, it was decided to examine an MCM implementation. By mixing discrete small footprint SMT devices with bare die construction it was possible to create a design based on the following blocks:

i. SMT operational amplifiers for signal amplification
ii. SMT support circuitry for signal conditioning
iii. A bare die switched capacitor filter
iv. A 12-bit analogue-to-digital conversion in bare die
v. A bare die microcontroller incorporating timers for phase determination and serial data transfer.

This system configuration allowed the data averaging and sampling functions to be implemented by software algorithms operating in microcontroller code. This feature removed the need to use a rms to dc converter circuit with its associated large value capacitors.

The use of a microcontroller to perform the averaging and sampling functions and the corresponding reduction in complexity of the support circuitry enabled the use of very small surface mount discrete amplifiers. The analogue to digital conversion is performed using a serial ADC device which is available in bare die form. Amplification filtering is also performed in a bare die microprocessor controlled device. The size reduction achieved by this strategy allowed conventional small footprint devices to be used for the amplification circuit and certain signal conditioning functions.

Investigations into microcontroller bare die availability were conducted through the Europractice MCM group at National Microelectronics Research Centre, Cork, Ireland and using
commercial organisations in the UK. These indicated that a number of types of microcontroller were readily available in the required volume for this application, thus confirming the feasibility of this design approach. The application experiment then proceeded on this basis. The selected sub-contractor was involved at an early stage in order to confirm the final circuit board layout.

It is difficult to persuade a microcontroller manufacturer to provide a ROM mask for only 500 units. Therefore, to maximise design flexibility, an external EPROM or microcontroller with an in-circuit programmable ROM was the preferred solution. The device chosen was the PIC16C73A.

The low risk, flexible design capability and reasonable cost estimates for this solution resulted in the MCM packaging option being selected as the preferred technology route.

The subcontractor selected to assist in this application experiment, Custom Interconnect Limited (CIL), had prior experience in the production of circuit boards incorporating both SMT (Surface Mount Technology) and bonded, 'glob topped' bare die. CIL were to package known good die on to the circuit board, and jointly develop probing and test equipment to access the circuit board contacts. This test equipment would also permit the in situ programming of the EPROM memory device.

The development included the following phases:

i) Testing of the SMT packaged circuits using standard packaged microcontrollers connected to the circuit board via an adapter interface. This testing is designed to eliminate circuit board errors prior to the chip-on-board packaging implementation thereby avoiding expensive reworking.

ii) Programming of the EPROM memory and the subsequent testing of the MCM assembly using the probes and test equipment developed by the company. Communication to the microcontroller is via the serial data link.

iii) Field evaluation testing conducted using samples of different pipes to establish the correct operation of the MCM assembly.

CIL were to produce 2 sets of 10 prototype units for the test programme. This would allow for microcontroller program modifications after laboratory or field trials as required.

The microcontroller software was developed using the C programming language. A low cost ROM emulator was used facilitate the debugging of the code developed using the standard packaged microcontroller. A number of diagnostic routines were implemented in the software. These included a facility to confirm data link integrity between the central processing node in the RFEC equipment and the microcontroller, using predetermined test messages.
8. **Expertise and experience in microelectronics of the company and the staff allocated to the project**

The electronics skill team at BG Technology has 20 engineers with experience in the design and production of electronic circuitry based on both discrete device analogue and digital design techniques. The methods of implementation include multilayer and flexirigid PCBs, in conjunction with surface-mount and through-hole devices. EDA design tools available include the Zuken-Redac Cadstar integration suite for design capture. There is a very limited PCB layout capability. In addition, the electronics engineers at the company use tools supplied by programmable device manufacturers such as Xilinx. They also have design experience in the use of UV and electrically erasable FPGA devices. The company does not currently utilise the simulation facilities available within the design tools.

The engineers in the electronics area have specialist skills that support the company's technology capability and ensure it remains the forefront of the international gas industry. The company’s electronics capability includes the design of microprocessor-based circuits and the design of operational software for these devices. The use of hybrid packaging technology has been employed to achieve the high circuit densities required for applications in pipeline inspection vehicles. Hybrid analogue devices have been developed for analogue signal processing and pre-conditioning. These devices implement functions such as active filtering and complex frequency translation. Specialist subcontractors produced these hybrid circuit layouts to specifications prepared by the company.

One Graduate Engineer and one Engineering Technician worked on the electronics design for the inspection vehicle. The Engineer alone worked on the MCM program and wrote the operational software. The Technician carried out most of the build work and some of the electronic circuit design. Neither had previous MCM or bare die experience and neither did the project manager. All had prior experience of electronic design and build projects. At design reviews, they had the opportunity to seek independent audit of circuit designs by fellow engineers from other projects, albeit none of them with MCM experience.

9. **Work Plan and Rationale**

The tasks performed during this application experiment are detailed below. A risk assessment was carried out which gave rise to the following issues:

- **Die Availability in small quantities**: contact with the Europractice MCM group and with the selected subcontractor provided guidance on available devices. The risk was minimised by the selection of a subcontractor with experience in supplying low quantity MCM modules.
- **Once designed, the hardware would be more difficult to alter than with a conventional printed circuit board.** A check was made using a physical space model with a prototype
vehicle to verify that there was clearance for all the devices on the MCM when negotiating bends and obstructions.

- One-time-programmable devices were specified for the microprocessors and these were to be programmed in situ on the MCM. In the event that errors were made in programming, a complete module might be lost. Design effort was expended to provide simplified test software to validate the hardware at the preliminary integration stage to ensure that software errors did not mask or create hardware errors.

- An incorrectly placed die might result in the loss of the complete module. To limit this risk initial batch samples were kept very small to enable the hardware to be verified before further modules were manufactured.

The work programme adopted is described below. The related resource requirements, and variances are summarised at the end of this section. The scheduling of these tasks in the work program is illustrated in the attached Gantt chart.

**Task 1 Systems Requirement Specification**

This involved the detailed functional and electrical system requirements for the sensor-processing unit within the RFEC equipment. The important physical dimensions, shape and mounting arrangements for the circuit board and the connector requirements for the circuit board were also defined at this stage. The mechanical drawings, showing details of the volume available for the MCM modules were sent to the subcontractor to determine the maximum allowable board area.

The outline board was tested in-house to ensure its bend passing capability, with the existing sensor module, in order to determine the volumetric space available. This involved extensive laboratory tests and regular meetings between the mechanical and electronics teams. The subcontractor emphasised the importance of optimising the space used, so a more thorough investigation than planned was carried out.

**Deliverables:** Systems Requirement Document Issued.

**Task 2 Systems Design**

This task involved the confirmation and finalisation of the systems design architecture and identified the major components to be used in the final circuit. The systems design architecture could not be confirmed and finalised until the Die Availability Review (Task 3) was completed. This was conducted with advice from the subcontractor and took longer than expected.

The MCM system design covered the following issues:
a. Method of connection to the MCM  
b. The mechanical arrangement and fixing method  
c. The provision of test probing points for use during the manufacture stage.  
d. Encapsulation methods.

   Deliverables:  System Block Diagram available  
                   Major Components List approved.

Task 3       Die Availability Review

The confirmation of the die availability and the acceptability of the die footprints for incorporation into the final circuit board area were undertaken by the subcontractor. The company engineer developed a general awareness of die availability.

BG Technology was unable to procure the prototype quantities of bare die itself, so it was necessary to get CIL to assist with this task. The minimum order quantity was also a problem, but CIL had greater leverage in this area. Despite enlisting the help of Europractice, the subcontractor was found to have far greater leverage for buying microcontrollers and microprocessors cheaply in small volume. Because of these difficulties, this task over-ran significantly.

   Deliverables:  Availability and Die Packaging Data confirmed.

Task 4       Circuit Design

This involved the hardware design for the processing circuit and the selection of component types (including passive components) and values. The aim was to minimise the board space requirements while achieving the required functionality.

The completion of the circuit design was carried out by the BG Technology engineer and reviewed by electronics experts. The size of circuit implementation was determined and found to fit with volumetric requirements.

   Deliverables:  Circuit Schematic Diagram Issued

Task 5       Circuit Simulation
The analogue circuitry was simulated to ensure that the system gain and frequency response requirements could be achieved using the component values selected. The company engineer conducted this task concurrently with Task 4 - Circuit Design. Measurements were also made with the prototype vehicle to confirm these values and previous in-house research on the RFEC technique in pipelines was reviewed to ensure suitable parameters had been selected.

Deliverables: Circuit Verification Results.

Task 6 Circuit Design Review

This task involved the detailed review of the circuit design and the components selected, prior to circuit board layout. This was to ensure compliance with the layout design rules defined by the subcontractor. In-house electronics experts assisted with this task, in collaboration with CIL, to ensure the circuit design was tailored to the needs of MCM technology. Minor modifications were suggested to improve the design. These modifications were incorporated into the design by the company engineer.

Deliverables: Approved Circuit Design
Component List Defined.

Task 7 Circuit Board Layout

This task involved the layout of the prototype circuit board using CAD tools. The schematic of the circuit was entered into the CAD system by the BG engineer and this was converted into a proper circuit board layout by CIL. A BG policy decision had been made that work of this nature was to be contracted out. The test requirements (Task 9) were also considered and test points were added to ensure manufacturing tests could be applied.

Deliverables: Accepted Circuit Board Layout Design.

Task 8 Software Requirements Specification

This task defined the functions to be performed by the microcontroller's software programme, including the definition of the signal averaging, data reduction and diagnostic procedures. It was performed entirely by the company.

Deliverables: Software Requirements Defined
Task 9  Test Requirements Specification

This task defined the test requirements for both the MCM assembly testing and the field evaluation testing. It was performed entirely by the company.

Deliverables:  Test Requirements Document Issued.

Task 10  Test Equipment Design

This task involved the development of a test jig to test the MCM assembly, including the development of a probing system to allow connection to the EPROM device for programming purposes. The MCM manufacturing Test Jig was developed by CIL and the development Test Jig was completed by the company engineer.

Deliverables:  Test Jig Available
              Test Equipment Available.

Task 11  Microcontroller Code Development

The development of the C Code to perform the microcontroller's software requirements tasks was conducted by the company engineer.

Deliverables:  Object Code for Integration Testing

Task 12  PCB Production and Procurement

This involved the procurement of the base circuit board, photoplotting and the production of printed circuit board tooling to produce prototype boards. The task was performed entirely by the subcontractor. The first two prototype MCM sensor units were received from CIL somewhat later than expected due to problems with the printed circuit board subcontractor and the availability of resources at CIL.

Deliverables:  10 Prototype Circuit boards Available.

Task 13  Initial Circuit Testing
This task involved the population of the prototype circuit board with SMT components only, and the use of a ROM Emulator system to test the hardware/software and to prove the SMT circuit.

Preliminary tests performed by the company engineer on the two units, using the MCM Manufacturing Test Jig, indicated that the phase acquisition system conformed to the test specification. However, there appeared to be a problem with the amplitude circuitry. One of these units could be successfully programmed while the other unit would not. This task took priority over the Microcontroller Code Development (Task 11).

The company visited the subcontractor in order to review the MCM circuit testing and discussed the evaluation tests that should be performed. Three more prototype units were delivered by CIL. After some further investigation, two problems with the MCM units were identified. A device selection problem and an incorrect offset were both rectified.

Deliverables: Software Accepted
Circuit Board Layout Proven.

Task 14  Software Amendments

This task involved the revision of the programme code to eliminate design errors identified during initial circuit testing (Task 13).

Deliverables: Final Software Code Registered.

Task 15  Direct Die Attach

This task involved the attachment of the bare die to the reverse of the SMT circuit board. The task was undertaken entirely by the subcontractor.

Deliverables: 10 assembled prototype MCM boards.

Task 16  Microcontroller Programming

This task involved the programming of the bare die EPROM using test probes designed by the subcontractor with the proven object code.

Deliverables: 10 Programmed Prototype MCM Boards.

Task 17  Circuit Testing
This task involved the circuit testing of the prototype MCM boards using the test equipment. The functional and electrical performance of these prototype units was demonstrated and the circuit board errors corrected.

Deliverables: Tested MCM assemblies

Task 18 Circuit Layout Corrections

The circuit board layout errors identified during the functional testing of the circuit (Task 17) were rectified. The revised drawings were then used to produce fully functional MCM modules.

Deliverables: 30 Prototype MCM Modules.

Task 19 Evaluation Test

This task involved the final evaluation of MCM modules in the final equipment assembly by the use of representative samples of different pipes.

Deliverables: System Evaluation Test Results

Task 20 Technical Management

The Technical Management task involved the provision of guidance on the technical implementation, risk management, and project management to the application experiment.

Deliverables Project Management Plans

Task 21

(i) MCM Training was provided to the company engineer. This included training on the different MCM packaging options available, the available laminate options and dedicated training on the chip-on-board design and implementation rules. The training was provided by CIL.

(ii) Test Training involved the training of the company engineer on the test methods used on MCM assemblies and on the specific issues related to testing of the final assembly.
The major work package costs (in person days) to individual tasks are described in the following table.

<table>
<thead>
<tr>
<th>Work Package</th>
<th>Tasks</th>
<th>Planned Effort (person days)</th>
<th>Actual Effort (person days)</th>
<th>Sub-Contractor Costs (KEURO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
<td>21</td>
<td>8</td>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>Specification</td>
<td>1,8,9</td>
<td>25</td>
<td>35</td>
<td>2.5</td>
</tr>
<tr>
<td>Design</td>
<td>2,3,4,10</td>
<td>52</td>
<td>72</td>
<td>11.25</td>
</tr>
<tr>
<td>Software Coding &amp; Integration</td>
<td>11,14,16</td>
<td>33</td>
<td>33</td>
<td>-</td>
</tr>
<tr>
<td>Evaluation</td>
<td>5,6,13,17,19</td>
<td>45</td>
<td>55</td>
<td>5.1</td>
</tr>
<tr>
<td>MCM Layout &amp; Build</td>
<td>7,12,15,18</td>
<td>13</td>
<td>17</td>
<td>6.0</td>
</tr>
<tr>
<td>Technical Management</td>
<td>20</td>
<td>25</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>201</strong></td>
<td><strong>253</strong></td>
<td></td>
<td><strong>28.35</strong></td>
</tr>
</tbody>
</table>

The major deviations in the work programme and resources required to finalise the development were related to two major problems:

1. **Difficulties in obtaining the selected die:** This problem, although considered a risk factor, had been considered manageable because of assurances from a number of die suppliers. However, the actual response by these suppliers was less than satisfactory. This required a great deal of additional company and subcontractor effort to identify suitable devices in suitable minimum order quantities.

2. **Under test conditions, the original MCM units demonstrated a poor yield and erratic operation.** This required additional time to identify the cause of these problems. The problem was eventually traced to the supply of a variant of the correct bare die device from the supplier, with slightly different performance characteristics. Finding a source of the correct devices, plus some minor design corrections incurred some additional delays. A single MCM unit performance was sufficient to confirm the functional performance within the original timescale. Unfortunately, the low yield meant that the final evaluation of the complete system could not take place, as too few operational units were available.
Figure 4: Planned and Actual work Programme
10. Subcontractor Information

BG Technology undertook a detailed survey of the market to identify a sub-contractor with the following characteristics:

- Previous knowledge of bare die packaging
- Proven expertise in sourcing and supplying bare die devices
- Previous assistance to other first user companies in acquiring MCM design knowledge.
- UK based, if possible, to ease the transfer of information and maintain good inter-company communications.

After this survey, the company selected Custom Interconnect Ltd (CIL) to be the subcontractor. CIL has experience in custom design and manufacturing, covering many different technologies from ceramic hybrids, chip-on-board and surface mount technologies to both high- and low-temperature flexible circuits.

The selected subcontractor had a proven track record of working with many well known U.K. companies. This provided BG Technology with the confidence that a successful outcome would result.

The subcontract with CIL was organised to provide several staged payments linked to the work plan. The phasing of these payments is outlined in the table below:

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Design</td>
<td>8%</td>
</tr>
<tr>
<td>Die availability Review</td>
<td>3.5%</td>
</tr>
<tr>
<td>Circuit Design</td>
<td>4.5%</td>
</tr>
<tr>
<td>Circuit Design Review</td>
<td>4%</td>
</tr>
<tr>
<td>Circuit board Layout</td>
<td>12.5%</td>
</tr>
<tr>
<td>Test Equipment</td>
<td>6.5%</td>
</tr>
<tr>
<td>Photoplot, pcb’s</td>
<td>7.5%</td>
</tr>
<tr>
<td>Assembly of 9 off units</td>
<td>15%</td>
</tr>
<tr>
<td>Micro programming</td>
<td>1.5%</td>
</tr>
<tr>
<td>PCB and part procurement</td>
<td>15%</td>
</tr>
<tr>
<td>Build and Test 30 off</td>
<td>11%</td>
</tr>
<tr>
<td>Training</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 1: Sub-Contract Payment Plan

The above payments were made upon acceptance of each deliverable by the company. The ownership of the designs resides with the company.
The working relationship with the sub-contractor was generally very good. This was an important factor in the success of the project. Only through the sub-contractor were the company able to source bare die at acceptable prices and with reasonable minimum order quantities.

The sub-contractor’s terms and conditions of sale were accepted by the company and in practice, these did not give rise to any problems. Industrial and Intellectual Property Rights for the circuit design rest with the First User, who was required by the sub-contractor to indemnify them against any infringements.

11. Barriers

The company had no previous technical management skills or design expertise in the area of MCM or the use of bare die. The company encountered several barriers during the adoption of MCM technology:

**Knowledge Barriers:** The company had no appreciation of the potential of MCM technology in this application. There was also no knowledge of the suppliers, issues associated with bare die implementation, or the manufacturing stages of any MCM solution. Indeed, the initial solutions proposed by the company included the use of higher power DSP devices or analogue ASIC devices, both of which would have been inappropriate. These knowledge barriers meant that the use of MCM technology appeared to be a high-risk solution.

**Psychological Barriers:** BG Technology operates as a separate accounting (trading) entity within the BG group. This means that the usual financial concerns affect managers in the organisation. Therefore, in terms of technology choice, the adoption of low risk, well understood technology is the preferred approach. This conservatism is influenced by the high visibility of the application experiment in the company as the result of internal budgeting, organisational and commercial concerns. The psychological barrier for adopting new technology on such projects is therefore high.

**Financial Barriers:** Whilst the company is a profitable organisation, the normal imperatives of budget accountability and trading profit targets pertain as in any small organisation. The psychological and technical risk views from a management perspective would pre-dispose the company to avoiding MCM adoption for the first time.

12. Steps taken to overcome the barriers and arrive at an improved product

The issues related to knowledge barriers were overcome by the initial involvement with the Technology Transfer Node (TTN). The initial technology selection discussions with the TTN provided the introduction to this process, introduced the Europractice MCM and related
information and provided some cost estimates for the technology implementation. This process eventually resulted in a detailed project proposal. The discussions with the subcontractor during this process involved confirmation and finalisation of the system architecture and the major components to be used in the final circuit.

The knowledge barrier was overcome by the provision of training and support from the subcontractor who was consulted throughout the application experiment. This close involvement with the subcontractor, who had ten years experience using this technology, was invaluable.

The technology development support, enabled by FUSE, was a crucial factor in overcoming the psychological barriers. By providing a visible demonstration of the technology support mechanisms, the fear of failure was significantly reduced.

The elimination of the perception of high risk made the investment in the technical solution more attractive. The FUSE application process provided an independent assessment of the investment in MCM technology. This further reduced the perception of technical risk.

13. Knowledge and experience acquired

This application experiment has allowed BG Technology to gain knowledge and expertise in several interrelated areas during the specification, design and evaluation of the MCM-based improved product. At the end of the application experiment the company had gained knowledge and experience of:

• Technical and project management of MCM developments.
• Processes for identifying bare die availability.
• Systems partitioning to accommodate limitations imposed by die availability.
• Achievable circuit board size reductions using MCM based technology.
• Available MCM technologies and the potential applications for these.
• Chip-on-board attachment techniques and methods.
• Circuit board layout design rules for MCM chip-on-board implementations.
• Testing constraints and methods to be applied in MCM circuits.
• MCM subcontractor management and liaison.
• Comparative costing of MCM assembly and traditional circuit board assembly methods.

The mechanisms by which knowledge and expertise was transferred into the company took several forms. The company engineer attended training courses on the different MCM packaging options available, the available laminate options and chip-on-board design rules and implementation. The training was provided by the subcontractor.

The application experiment has allowed BG Technology to gain knowledge, for the first time, in using MCM technology to integrate the electronic circuitry in its pipeline inspection equipment.
The acquisition of the technical management skills and design expertise has resulted in a clear increment in capabilities. This will provide the company with the means of developing more versatile and lower cost products in the future. The experiment has allowed the company to overcome a major technology barrier and will enable its future products to address new markets.

14. Lessons Learned

The main lessons learned were:

The experience of the subcontractor was very helpful at the design stage of the project. The subcontractor emphasised the importance of correct mechanical connections and mounting to the success of the project. This meant that the system requirements specification took a little longer than planned.

The majority of semiconductor manufacturers seem to concentrate on discrete devices rather than ICs. They were also reluctant to release, or did not have available, any information on die function for any of their devices. They were interested only in part numbers. This is less useful to the designer than knowledge of the die function.

The minimum order quantity was also a serious problem and, without help from the subcontractor, it would have been impossible to secure the required quantities of bare die. Europractice were unable to help with this matter. Bare die suppliers in the U.K. are not meeting the requirements of small scale development products, due to the high minimum order quantity they impose.

An important lesson here is that working through the subcontractor to source bare die was very successful. This strategy should be considered by other MCM first users.

The introduction of test points into an MCM unit is important. The subcontractor emphasised the importance of test points on the circuit board layout to the company as a means of performing yield tests on the MCM units. The test points were very useful for evaluating the problems encountered subsequently.

The company developed a good working relationship with its MCM supplier, CIL. This working relationship was crucial to the success of the application experiment. The subcontractor was able to resolve the supply of bare die and support the company when dealing with suppliers. Simple contractual terms and conditions would not necessarily have delivered the same flexible approach.
15. Resulting product, its industrialisation and internal replication

The prototype MCM units are now operational but need to be fully evaluated prior to the product being used for commercial pipeline inspection work.

The project priority is to build and assemble the subsystems necessary in order to test the MCM units when they arrive from the subcontractor. The appropriate vehicle software will also be developed before testing in the assembled units. Programming of the MCM units can then take place before final evaluation of the MCM modules in the integrated equipment assembly. The demonstration of the MCM system will involve the detection of defects in a pipe and subsequent signal processing. The complete vehicle requires 48 MCM sensors. These units are expected in Q1, 1999.

The evaluation process for the prototype inspection equipment must be exhaustive to demonstrate compliance with gas industry requirements, including test in the field under live gas conditions. This evaluation process will require at least 9 months to complete, and will include trials, data analysis, and technical review activities prior to acceptance. This evaluation process will therefore, be on-going for the whole of 1999.

The complete costs for the industrialisation process will be 330 kEURO.

So far, only one "production" unit has been ordered, but the intention is to develop a service for small diameter pipeline inspection, nationally and internationally, rather than to manufacture inspection vehicles for sale.

The acquisition of an MCM design capability will also allow the technology to be applied to other commercial developments by the company, generating long-term economic benefits.


The exploitation route for the improved equipment is expected to be based on the sale of inspection services in low pressure lines, rather than the sales of the equipment. The price for an inspection service is influenced by several factors including site survey results. Typical inspection charges are in the range 10,000 to 20,000 EURO per week for the inspection team (depending on situation, terrain and other special factors. In one week a team will inspect several kilometres of pipe. The inspection process achieves an average of 500m of survey work in one run.

Initial exploitation is expected to be based on a single inspection team surveying around 50km per annum. Without this development the inspection work with the existing small diameter,
system is expected to reduce by 20% per annum due to lack of innovation restricting the range of potential applications.
The estimated survey potential for small diameter pipes in the UK and European market is at least 900 km per annum. In the medium term, the development of American and Far East markets will mean that the potential market size will increase fourfold. The results of this market exploitation opportunity are illustrated by the following graph:

Figure 5: Relative Increase in Sales (1998 = 100%)

Further sales development will occur in the application of the inspection equipment. This will include the use of the inspection tools for cast iron pipelines of almost the full range of diameters requiring inspection, and in applications areas where other non-magnetic pipes must be inspected. This commercial exploitation of the improved RFEC equipment is expected to generate sales equivalent to the addition of 5 extra equipment teams starting in 2000, and resulting in a doubling of sales revenue by 2004.

The additional profit per inspection team during the first year of operation results in a payback period of approximately 16 months. From the FUSE investment of 92kEURO, the expected return is 490%.

Note that the increased sales in 'units' cannot really be considered, as the First User is selling an inspection service, which makes use of the revised product. It is important to note that the figures shown in the graph represent external sales only. The provision of services for the BG internal distribution pipeline is the subject of a different commercial analysis based on internal project assessment procedures. The value of this activity is not included in the table, but it is expected to be of a similar level to the external sales.

17. Added value to the portfolio and target audience
The added value in this AE lies in the best practice exhibited in the company’s relationship with its sub-contractor. The achievement of success despite the extremely low production volumes (initially only 48 units plus spares) required a great deal of determination and team-work.

This application experiment will be of interest to a wide-ranging audience including the following:

- Companies in engineering/manufacturing sectors looking to adopt MCM technology for the first time.
- Companies who manufacture existing electronic products and who are looking to reduce the physical size of their product through the introduction of MCM technology. These could include companies working in the field of data logging, pipeline inspection, petrochemical, water, gas and telecommunications.

The application experiment provides best practice guidance in subcontractor selection and management for MCM product developments. It covers die selection and sourcing issues for low volume MCM manufacture and in testing and programming one-time-programmable microcontrollers embedded into MCM units. The best practice lessons will be of value to all companies considering the adoption of MCM technology in low volume applications.