An Improved Chromatography Temperature Controller

Microcontroller technology reduces cost and improves competitiveness

Jones Chromatography Ltd
Abstract

Jones Chromatography is a small privately owned company formed in 1967 and now employing 62 employees and achieving a turnover of 6.7 MEUR in 1999. The company specialises in the design, development, manufacture and distribution of a wide range of instruments, accessories and consumables for use with High Pressure Liquid Chromatography (HPLC) and Gas Chromatography systems. It also distributes related instruments.

The company’s products are applied in the medical, pharmaceutical, and research and development markets world-wide. Approximately 25% of the company’s sales of chromatography equipment are from exports. The company has sales offices in both the USA and Malaysia.

Jones Chromatography’s main expertise prior to the application experiment was in the area of formulating chemicals and reagents for the chromatography process. The company’s existing products applied electronics in the form of purchased controller units, and the company developed low complexity, typically up to 10 discrete devices, interfaces to provide power supplies or driver interfaces for these purchased controller units.

The company manufactures a wide range of bench top temperature control instruments for use with High Pressure Liquid Chromatography (HPLC) systems. Temperature control of a HPLC column is critical in obtaining chromatographic reproducibility and allows greater separation efficiencies for many applications. As the market for HPLC instruments is becoming competitive and price dominated, a market opportunity existed to provide a product with reduced cost, enhanced flexibility over temperature control, and feature enhancements to provide the product differentiation.

The rationale of the FUSE application experiment was to improve the product’s temperature regulation / cost performance and to provide extra functionality to meet this identified market need. The improved product provides enhanced user benefits in a number of areas and a available at reduced cost.

The introduction of a microcontroller device in the improved product has enabled product features to be delivered:

- Improved temperature control performance by providing:
  - The ability to provide temperature profiling over a time period extending from a few minutes to many hours, with over and under temperature audible alarms.
  - The ability to link the temperature control system into a central network to improve the process and enable greater automation. This allows continuous monitoring and would improve the long term process quality.

- Enhanced communication facilities enabling:
  - Data logging of actual process parameters for quality control and experimental analysis purposes.
  - A remote communication option via a PC modem to permit problem solving by Jones Chromatography scientists linking into the client’s system. This will provide a much higher level of customer care.
  - The ability to customise the process cycle from a remote computer.
The microcontroller performance enhancements will provide enhanced user benefits, and these have been realised whilst reducing the costs of the temperature controller by approximately 15%.

The duration of the AE was scheduled as 9 months. The application experiment was on schedule to complete within this period, but due to the impact of an unrelated business problem with the original subcontractor, this period was extended to 18 months to allow a second subcontractor to deliver the final prototype. This factor resulted in a total application experiment duration of 18 months. The total cost of the application experiment was 49 k Euro.

The increased sales expected as a result of providing the enhanced product performance will payback these development costs within 15 months. The return on investment (ROI) is estimated at 380% over three years. Including industrialisation costs, which are estimated to be of the order of 20 k Euro, this becomes 23 months and 270% respectively.

**Keywords and signature**

**Keywords**

Chromatography  
Analysis  
Temperature control  
Solvents  
Microcontroller

**Signature**

2 0141 550 0311 1 3320 1 33 UK
1. Company name and address

Jones Chromatography Ltd.
New Road
Hengoed
CF82 8AU
UK

Contact: Mr Peter Regan
Phone: +44 1443 816991
Fax: +44 1443 816552
E Mail: prr@jones-chrom.co.uk
Web site: www.jones-chrom.co.uk

2. Company size

Jones Chromatography is a stand alone company with 62 employees. In 1999 the company achieved sales of 6.7 MEUR.

3. Company business description

Jones Chromatography Ltd. was founded in 1967 and is a leading manufacturer and distributor of chromatography accessories, consumables and instruments. JCL’s own products are sold globally through sister offices in the USA and Malaysia plus a network of international distributors. The company designs, manufactures and supplies high technology products for chromatography and related analytical techniques. It also provides technical and service support. JCL operates from a 30,000 sq.ft. facility in South Wales.

The company’s product range includes equipment for chromatographic analysis and consumable items used in the preparation and analysis of samples using chromatographic techniques. Most recently, JCL has introduced a range of new Flash Chromatography products which have been specifically designed to address the fast growing drug discovery market.

As well as its own manufactured range, JCL also distributes high quality products for several leading international companies, including ISOLUTE® solid phase extraction columns from International Sorbent Technology, GC capillary columns from J&W Scientific and HPLC injectors and accessories from Rheodyne.

The company continually strives to introduce new innovative products for HPLC, GC and SPE, and sees its future as being in developing its own-manufactured instruments. This provides the stability of supply, and the control over the design of the products required by its customers. It also enables the company to sell into a world-wide market.
4. Company markets and competitive position at the start of the AE

The world-wide market for High Pressure Liquid Chromatography (HPLC) equipment is enormous, estimated at 1.6 B Euro per year, with the market for products such as the 7990 Space Column Heater manufactured by Jones Chromatography at 41 M Euro.

The target markets for these products include a wide range of industry sectors including the chemical, food and drink, pharmaceutical and utility industries. The company is the market leader for such equipment in the UK, supplying approximately 30% of the UK market for this type of product. The UK market accounts for 8% of the total world-wide market.

Approximately 25% of the company’s sales of chromatography equipment are from exports. The company has sales offices in both the USA and Malaysia, which are prime export territories for the company.

In 1996, at the outset of the AE, Jones Chromatography had sales of 5.8 MEUR, with 20% exported. By 1999 the company had sales of 6.7 MEUR of which approximately 25% was exported. Growth in export sales was largely due to new Flash Chromatography products.

<table>
<thead>
<tr>
<th>HPLC Products</th>
<th>World Market</th>
<th>Company Sales</th>
<th>Company Exports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,600 MEUR</td>
<td>6.7 MEUR</td>
<td>1.7 MEUR</td>
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<tr>
<td></td>
<td>100%</td>
<td>0.4%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Space Column Heater Products</th>
<th>World Market</th>
<th>UK Market</th>
<th>Company UK Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>41 MEUR</td>
<td>3.3 MEUR</td>
<td>1.0 MEUR</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>8%</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

Fig. 1 - Market Share Data

Principal global competitors include CIL, Timberline, CERA and Alltech.

Surveys conducted at the start of the AE suggested that only 30% of HPLC systems had any form of HPLC column temperature control, and of these most were either expensive integrated temperature controllers or directly competing products which used proprietary micro controllers of varying degrees of sophistication.

The price of a typical HPLC system is in the range 15 K Euro to 35 K Euro depending on the detailed specification of the unit. The heater control system for this HPLC is normally offered by the supplier as part of the HPLC system at a cost of 3.5 –6K Euro depending on specification.

The company’s temperature control system used in HPLC applications is sold for integration into other companies’ HPLC systems, and as separate stand alone systems for end users to formulate their own system. The price range for these stand alone temperature controllers is in the range 1 to 3 K Euro, again depending on specification.

Since temperature control flexibility was seen as key feature in meeting current customer needs and in meeting the demands of an increasingly regulatory laboratory environment, there was still significant market potential for its temperature control instrument product line. The challenges in realising this
potential were two-fold:

(a) The company’s products were mature and needed to be updated to increase their attractiveness to the market. This could be achieved through the incorporation of additional functionality relevant to the demands of the market.

(b) As an own-manufactured product, approximately 95% of the market for the product line existed outside the UK. At the outset of the AE, the exchange rate of Sterling relative to the US dollar and various European currencies had reduced the commercial competitiveness of the products in these markets. The company sought to reduce the component cost of its products in order to offer better pricing to its distributors and agents.

The demand for a more sophisticated product offered Jones Chromatography an opportunity for the supply of equipment offering additional product features. Market research already undertaken by the company indicated that adding features such as improved temperature control, and RS232 communications facilities (to enable remote control, remote diagnostics, temperature logging and data analysis), would improve Jones Chromatography’s market position. Customers would react favourably to the sound technical reasons to choose the new products.

The competitive strength of the Jones Chromatography product has historically been one of quality, but as the market has expanded, the product has been regarded increasingly as a commodity product, rather than as a specialised piece of equipment. Product differentiation was therefore being sought as well as cost reduction and an image improvement by the adoption of leading edge technology.

The sales history for the integral heater units used in HPLC systems is indicated in Figure 2.

Fig. 2 - Relative Sales of Heater Units
(1995 sales = 100%)

5. Product to be improved and reasons to innovate

The major components of the Jones Chromatography HPLC system are a pump, injector, HPLC column and the detector and data system.
The heart of the system is the HPLC column. The chromatographic process involves injecting the mixture of solvent and sample into the HPLC column. Separation of the compounds occurs as the solution is pumped through the column, whilst the degree of resolution depends on the contents of the column, flow rate and column temperature. Accurate control of the column temperature is vital to achieve the desired resolution and to achieve reproducible resolution.

The complete HPLC system is reliant upon a PC to process and display the results, and (ideally) to co-ordinate the process. This is achieved by the use of serial data links to each of the controllers applied in the system.

The control system employed in a typical temperature control instrument, the MODEL 7990, was a commercially available module, purchased as a fully assembled unit and then installed into the final product by the company. This unit is treated as a ‘black box’ controller, and forms the sole component of the controller system block diagram (no block diagram description is therefore available). To achieve the required serial communications interface to a PC a separate and additional interface module is required, which increases the cost of the controller unit by approximately 25% compared to a basic controller.

The mode of operation of HPLC systems in general use is such that the equipment has a significant period of time, generally in excess of 30 minutes to stabilise as the contents of the HPLC column are stabilised by the flow of solvent before analysis commences. The response time for the temperature controller is not critical, as long as the temperature is stable within this period.

The purchased control unit was therefore a key component for the majority of Jones Chromatography's products, and accounted for 30% of the total cost of the product. This was by far the most expensive single item in the system.
The rationale for the product improvement was the need to generate product differentiation relative to competitors in a market which was becoming increasingly competitive and price dominated. It was identified that there was an opportunity for feature enhancement and with cost reduction, by the adoption of microelectronics technology.

The parameter improvements required and delivered are as identified in Figure 4 below.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Existing Product</th>
<th>Microcontroller Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy, Operating Range</td>
<td>+/- 0.5 °C 0-95 °C</td>
<td>+/- 0.5 °C 0-95 °C</td>
</tr>
<tr>
<td>Timer / Clock</td>
<td>Simple timer</td>
<td>Programmable / real time clock available</td>
</tr>
<tr>
<td>Data Logging</td>
<td>None</td>
<td>Available</td>
</tr>
<tr>
<td>Solvent sensing</td>
<td>No</td>
<td>Included</td>
</tr>
<tr>
<td>Alarm sounder</td>
<td>None</td>
<td>Included</td>
</tr>
<tr>
<td>Remote heating shut off</td>
<td>No</td>
<td>Included</td>
</tr>
<tr>
<td>Control</td>
<td>Local only</td>
<td>Local or remote PC</td>
</tr>
<tr>
<td>Display</td>
<td>Target temp. or Actual Temperature (switchable).</td>
<td>Target and Actual temp (with PC)</td>
</tr>
<tr>
<td>Cost</td>
<td>30% of total unit cost</td>
<td>15% of total unit cost</td>
</tr>
<tr>
<td>Field Servicing</td>
<td>On-site</td>
<td>Remote diagnostics by modem with PC</td>
</tr>
</tbody>
</table>

Fig. 4 - Feature comparison
6. Product or process improvement

The demands of the HPLC market for more sophisticated heating systems required Jones Chromatography to improve its existing heating system in several significant technical aspects.

In addition, in order to remain competitive in its export markets the company needed to reduce its component costs in order to offer more attractive pricing to its distributors. A survey of controllers conducted by the company had already indicated that a controller with the capabilities required could not meet the cost reduction required, and indeed would have resulted in an increased cost for the controller unit.

The introduction of microcontroller technology allowed the introduction of the following product improvements and user benefits:

- Data logging and data transfer facilities to allow the user to record the actual process cycle.
• The ability to customise the process cycle, either at the machine or from a remote computer.
• The ability to link the heater system seamlessly into a complete process and for one computer to control and monitor a number of heating systems.
• More accurate temperature profiling over an extended time period depending on the process. This time period to extend from a few minutes to many hours.
• Providing user control of output temperatures with a user interface to display the current value.
• Process recording facility to ensure that the temperature and time profiles of the process can be logged for both quality control purposes and for experimental analysis.
• Provide automatic detection of fault conditions during the temperature cycle to enable the process to be shut down.
• The ability seamlessly to link the temperature control system into a central network to improve the process and enable greater automation. This would then offer continuous monitoring and also reduce the technical skill levels of employees operating the system, which would improve the long term process quality.
• Permit remote problem solving by Jones Chromatography scientists by linking into the client’s system via a PC modem link which would enable the scientist to understand the nature of the problem prior to going on site and thereby offer a much higher level of customer care.

The block diagram of the improved system is illustrated in Figure 6 below.

![Block diagram of the microcontroller-based circuit](image)

**Fig. 6 - Block diagram of the microcontroller-based circuit**

A Platinum Resistance Thermometer (PRT) is used to measure the temperature in the oven by providing a thermally variable resistance. The output from the PRT is processed in an analogue
signal conditioning circuit, before conversion to digital format using a low cost serial, 12 bit ADC (analogue to digital converter) device.

The digitised temperature sensor data is applied to a PID controller algorithm in the microcontroller, and used to provide the required control outputs to regulate the temperature.

The micro controller also processes the information to provide a 4 digit LED display output. The temperature information is displayed on the front panel.

The outputs from the microcontroller are buffered to provide the control signals to two solid state relays with a load of 30VDC to control the peltier devices or heating element ( -30vdc for heating, +30vdc for cooling ). A solvent sensor input is also available to cut the power to the peltiers or heating element in the event of flammable solvent leakage.

The microcontroller also provides serial communications RS232 and 485 facilities to provide a PC communications interface capability. This facility enables the PC to provide a data logging capability, and the ability to program temperature changes for the HPLC system over time.

Alarm facilities are provided in the event of an over or under temperature condition being identified. The alarm facilities include a sounder to provide a user alert, and an error relay output to allow external instruments to be shut down.

The parameter improvements for the improved HPLC controller are identified in section 5 previously. The improved controller is illustrated in figure 7.

![Fig. 7 - New Product](image)

### 7. Choices of rationale for the selected technologies, tools and methodologies

The existing product range was based on a purchased module, connected to a number of discrete...
sub-assemblies to make up the complete temperature controller.

In many applications the use of these temperature controllers is justified. However, the purchased cost of these units can be significantly higher than the cost of the in-house assembly of a dedicated controller unit. For example, a single loop ‘low cost’ temperature controller from a large European supplier indicated a price of in excess of 200 Euros for a suitable controller. The addition of a data logging capability would have increased this cost as a separate module would have been required. After conducting this review the company realised that its twin goals of reduced cost and increased functionality could not be achieved using purchased modules, and that the introduction of several non standard features (solvent sensing alarms, integral data logging and a serial communications capability) required too many add on modules to provide a coherent solution.

The basis on which technology was selected took into account the following criteria:

- Ease of designing with the new technology and of implementing the technology to new products
- Ease of assembly, functional testing and reliability
- Ease of repairing the unit in-house
- Ease of programming the unit, both in-house and by the end-user
- Overall unit cost
- Flexibility of design and features

To implement improvements in the area of continual cycle monitoring using discrete components would have required a significant increase in the number of components, and resulted in a significant increase in component cost. Furthermore, the system would not have been flexible enough to cater for future enhancements.

ASIC technology implementations would have entailed too great a technology leap for Jones Chromatography Ltd., and would also have been a high-risk undertaking. Furthermore, the current sales volumes were not high enough to warrant the level of investment required.

FPGA implementations of the control system would be possible but was rejected because the digital control system would be more complex to design, the unit cost of the devices would exceed the microcontroller device cost, and the design tools and methodologies would be more difficult for the company to assimilate than the microcontroller methodology.

Microcontroller solutions met all the necessary criteria identified by the company. This technology solution was considered a low risk implementation route for the company. In addition, microcontroller technology provided the flexibility required for application in other company products, as well as reducing the design risk through the use of software re-programmability. The technology step was also considered a realisable, albeit significant technology jump for the company.

A wide review of microcontrollers that were potentially suitable for the identified purposes was conducted, including devices from a number of different suppliers. The selected device for this application was the PIC 16C74A microcontroller. This device selection was based on the cost-performance comparison of the device in relation to alternatives. Specifically the device was selected because it:
- Included integral ADC facilities to interface to the solvent sensor alarm.
2 K instructions, which was estimated to be acceptable in terms of supporting the code requirements
for the system.
- Adequate parallel I/O to facilitate all of the required interfaces.
- Low cost in comparison to other devices priced at that time.
- The increasing popularity of the device family in the UK which allowed the company to gain some confidence in the continued availability and support for this device in the future.

Programming of the microcontroller was undertaken using C. The development was undertaken using in circuit emulator equipment to assist in the initial error debugging process. One Time Programmable (OTP) devices will be used which will be programmed in-house with the appropriate programming tools.

The PCB assembly and testing of the unit took place in-house. Standard leaded devices were used, since the company had all the necessary assembly equipment. Furthermore, this method of assembly made functional testing using conventional test rigs and test equipment much easier. The repair route was also much easier.

A simple risk analysis was carried out on both the design and the development work plan, but also on the introduction of the new technology product into production and for its support in the field world-wide.

8. Expertise and experience in microelectronics of the company and the staff allocated to the project

Jones Chromatography’s main technological expertise was focused in the chemistry of chromatography, especially in formulating chemicals and reagents for chromatography.

Jones Chromatography’s electronic expertise was limited to the selection, assembly and commissioning of various purchased controller modules into the company’s chromatography equipment. In addition, the company had some prior experience of low complexity design using a small number of discrete analogue and digital components for power supply modules or specific interfaces for the controllers to meet specific functional requirements of the system.

Prior to the application experiment the company had no experience in designing, developing or manufacturing complex digital circuits using discrete or complex digital devices, and had no experience of hardware or software design for microcontroller based systems.

The company allocated the following staff to the application experiment:

**Technical Manager:** This individual possessed a Masters degree in Chemistry and approximately 18 years experience in industry, but had no prior experience in electronic design.

**Design Engineer (1):** This individual possessed a technician level (non graduate) electronics qualification in electronics, and had over 10 years experience. However, this individual had no experience of microcontroller hardware or software design.

**Design Engineer (2):** This individual had over 10 years experience in high level software development for PC applications, but had no electronic design knowledge or experience.
9. Workplan and rationale

The programme of work undertaken during the application experiment is discussed in this section. A Gantt chart is also included which describes the planned and actual work programmes for the application experiment.

The company allocated a development team to support the knowledge transfer activity. The company’s Technical Manager and design engineers were involved in the formal training and then in subsequent phases, as defined below.

The major activities conducted during the application experiment were:

**Specification**
The specification phase involved the company engineer and manager, working with the subcontractor, in developing a specification which took full advantage of the capabilities of the microcontroller. It also included reference to other people in the company to ensure that their needs were understood and that they recognised the implications of the new technology, not just in terms of its requirements, but also its facilities and capabilities. The choice of microcontroller device was made by the subcontractor after a review, not only of the requirements of the AE, but also of possible future expansion of requirements.

**Hardware Design**
The subcontractor then led the design phase, both hardware and software, with the close involvement of the company engineer, whose objective was not to become an expert designer, but to be able to direct changes to hardware and software, with a good appreciation of the methodology and implications.

**Hardware Build and Test**
The hardware build and initial testing and de-bugging was led by the subcontractor with the involvement of the company engineer, as part of his product familiarisation. This experience would become useful to him in the event of teething problems during initial production or subsequently in the field. Design modifications were made as necessary to achieve the intended functionality.

**Test Equipment Design**
This was primarily a company task, which involved designing special purpose equipment for the functional testing of both the prototype control board and the product at the production stage. It was carried out by the company, but with the involvement of the subcontractor to ensure that there was agreement upon the use of this for product acceptance testing as defined in the initial specification.

**Software Design**
Software structure design and coding was carried out by the subcontractor, but the company engineer designed the algorithms and needed to become competent to make small changes himself, without recourse to the subcontractor, so his involvement was correspondingly greater. He also needed to be involved with the design of the diagnostic software in order to be able to make full use of it as a product diagnostic facility as well as for the printed circuit board (pcb) alone.

**Software Testing and Modification**
This was carried out with closer involvement of the company engineer than the earlier software design, for the reasons given above.
**Functional Testing**

This was carried out by the company engineer with minimal involvement of the subcontractor and ended with a final review to confirm that the product had achieved its specification.

**Technical Management**

Throughout the AE, technical management remained the responsibility of the company Technical Manager. This task was complicated by the subcontractor ceasing trading during the course of the AE. A new subcontractor was found, who picked up where the other had left off and the AE was completed satisfactorily, albeit with an extension to the original programme length.

The resources applied to the application experiment are identified in Figure 8 below. This table also identifies the split in the subcontractor costs and those incurred with the second subcontractor after the necessary change in subcontractor.

The second contractor was provided with an operational circuit board and software listings (but no source code) completed by the original subcontractor on their appointment, together with the specifications developed to date. However, the program had to be re-coded and evaluated by the second subcontractor. Additional software development training was also supplied.

<table>
<thead>
<tr>
<th>Work Package</th>
<th>Planned Company Resources (person days)</th>
<th>Actual Company Resources (person days)</th>
<th>Planned Sub-contractor Costs (KEuro)</th>
<th>Original contractor 1 Costs (K Euro)</th>
<th>Sub-contractor 2 Costs (K Euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
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<td>10</td>
<td>1.5</td>
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<td>Technical Management</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>150</strong></td>
<td><strong>174</strong></td>
<td><strong>18.5</strong></td>
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<td><strong>Total Subcontractor Costs</strong></td>
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<td></td>
<td></td>
<td><strong>20.7</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Fig.8 - Planned and Actual Resources for the Application Experiment**

The actual and planned work programmes are indicated in Figure 9 below.
Fig. 9 - Gantt Chart comparing planned and actual timing of activities
The variance in the work programme leading to an extension in the duration of the application experiment was solely related to subcontractor problems. The initial design subcontractor effectively ceased trading well into the application experiment for reasons not relating to this project. This subcontractor difficulty resulted in a significant disruption the progress of the project because for some time after this event the subcontractor insisted that the final deliverables would be provided and that the subcontract would be completed. This prevented the transfer of the remaining work to an alternative subcontractor until such time as this possibility was evidently no longer credible. This factor, together with the time required to select and assign a second subcontractor to assist in the finalisation of the application experiment created a significant delay in the application experiment.

The variances in the resources applied to the application experiment were a consequence of the subcontractor difficulties described above, and required:

- Additional technical management effort to resolve the issues related to the delivery of the original subcontractor’s deliverables, and in managing the second subcontract deliverables in compressed time scales.
- Additional evaluation effort to assess the status of the delivered prototype provided by the initial subcontractor, and the evaluation of the final prototype as originally planned.

The other variances in company resources from that originally planned were minor.

The knowledge development process involved formal training in microcontroller technology and development, and on the job training and knowledge development achieved as part of the joint development process conducted with the selected subcontractors.

10. Subcontractor information.

The selection criteria for the design subcontractor required for the product development included the following criterion:

- Demonstrable success in developing low cost controllers for industrial products.
- Successful trading over some years to provide confidence in their capability and continuing availability to provide the support required.
- Reasonably local to the company, so as to be able to provide flexible access and technical support facilities.

The initial subcontractor met these criteria, and was identified through personal links achieved at a local business club. This subcontractor company was a five person, electronic design consultancy, and had extensive experience of designing embedded microcontroller systems along with designing the interface electronics for a whole range of devices. The subcontractor was also located relatively close to the company’s site.

Unfortunately, for reasons not associated with the AE, the subcontractor effectively ceased to trade before the completion of the AE. This necessitated the identification and selection of an alternative subcontractor to complete the AE with the consequent hand-over of information.

The second subcontractor company, Mytron Design Limited, also met the previously identified criteria. This subcontractor was a four person electronic design consultancy, and very experienced in the design and development of microcontroller based industrial control systems. The company was also able to start the work without delay, and completed the development very satisfactorily. Mytron
Design were supplied with an operational circuit board and software listings (but no source code) completed by the original subcontractor on their appointment, together with the specifications developed to date.

Mytron Design established a good rapport with Jones Chromatography, and this enabled them to deliver a system compliant with all of the original AE objectives.

With both subcontractors, there was a written design specification and a purchase order. The company defined that the ownership of the design documentation and the related intellectual property rights were owned exclusively by the company.

The deliverables did not, however, specify that all up-to-date documentation and source code should be delivered with each delivery of prototype parts, although it was required to complete the contract. In the event, the first subcontractor effectively ceased trading during the application experiment for unrelated reasons. The work up to that point had been satisfactory. This subcontractor continued to maintain that he could complete the contract on an extended time-scale. This was not viable, but it was necessary to respond in a reasonable manner before cancelling the initial subcontract. Nevertheless, the AE was successfully completed in its entirety.

11. Barriers perceived by the company

The main activity of Jones Chromatography Ltd. was the manufacture and supply of the reagents, glass particles and the chemical formulations associated with the process of HPLC analytical chemistry, along with the assembly of HPLC systems, and as a consequence, the majority of employees were chemists. The company’s instrument design capability was limited to mechanical design and simple electronic design.

However, the company was aware that technology was moving fast and that it needed to leapfrog the competition. To achieve this, the company needed to take on board the opportunities offered by the introduction of microelectronics. This was a major barrier to the company, since understanding of electronics, particularly in the area of microcontroller design, specification and software development was very low.

Technical barriers included:-

- limited electronic technical management capabilities
- low electronic design and development capability
- low software development capability
- lack of knowledge in planning microcontroller based projects
- learning curve – the technical risk was seen to be too high because of the time it would take to bring enhanced electronic products to market and given the lack of knowledge of how to manage efficiently an electronics project of this nature

The company’s perception of electronic system development, based on its previous experience, was one of high risk. The company’s perceptions of the potential costs of taking on board this new electronic technology were that costs would be too high, and this was seen to be a major barrier. Additionally, it was thought that the project would inevitably have an extended time-scale, which would further increase costs. These perceptions of high risk provided significant barriers to adoption.
12. Steps taken to overcome barriers

A significant element in overcoming the barriers associated with the adoption of microelectronics by the company was the feasibility study undertaken to generate the FUSE application experiment proposal. This study, conducted in association with the subcontractor and TTN, provided the company with a higher level of awareness of microelectronics and resulted in a lowering of the perceived uncertainties of economic payback, development risks and development time-scales.

In addition, the application experiment directly addressed the problem of lack of technical knowledge by providing a structured approach to formal training, technical support and knowledge-transfer from the subcontractor. By working closely with the subcontractor, the associated project management skills and technical skills were acquired in an ordered fashion. This allowed the company to assume a level of control over the development programme which was needed to increase confidence amongst the company’s management.

The risk barriers were diminished by conducting the FUSE application experiment in a controlled environment, with technical and managerial support from the TTN monitoring the experiment. This additional level of support made it possible to, in principle, be more assured of adhering to programme time-scales, and to control associated costs. These factors convinced the company that a microelectronics development could be undertaken successfully by the company with the support structures identified.

The effectiveness with which these barriers were addressed can be measured by the company’s ability to replicate the microcontroller application even before the AE product was in series production.

13. Knowledge and experience acquired

At the start of the application experiment, Jones Chromatography’s electronic design expertise was limited to the design of relatively simple discrete analogue and digital circuits, and the in-house assembly and test of the controller systems. The company therefore anticipated the development of the following skills:

- Technical management and project planning expertise in microcontroller product design.
- Project/product specification skills.
- Component selection, including microcontroller device selection.
- Selection of the correct technology for the application.
- Design and development of microcontroller interface electronics.
- Embedded processor software design, coding and debugging.
- The experience of testing a microprocessor-based system.
- Design verification and validation methods to be applied during the software development cycle.

At the end of the project these skills have been acquired by the company, through the technical support given by Visible Sound and Mytron Design, as design subcontractors and by the TTN:
14 Lessons learned

The company has learned the following lessons from its first application of microcontroller technology:

• The specification was able to include a number of alternative strategies for a variety of contingencies, with an ability to select the required strategy. This was useful for events such as the conditions under which power to the heaters would be cut. The flexibility of microcontroller technology can be applied at the specification stage to leave some options open is useful, but the full consideration of the subsequent cost and implementation difficulties should be appreciated.

• The PCB design and layout could have been completed sooner in the programme had it not proved difficult to obtain all the detailed information required on the specification of the PT100 sensors. Practical advice on system design incorporating this sensor was obtained by the use of a technical forum on the Internet. This proved to be an useful facility, and should be considered by other first users if other technical advice is required.

• The use of test equipment which was a modified version of existing production test equipment, meant that a comparison could readily be made between functionality and performance of the microcontroller version and the existing controller version. This also facilitated the production of a final production test specification. This methodology of testing is a strategy suggested for others to consider.

• The limitations of standard test equipment is sometimes overlooked when implementing new product developments. During the application experiment, the accuracy and consistency of the microcontroller based system required a more accurate, precision resistance box than was available to simulate the PT100 sensors in the test equipment. Such issues are easily overlooked, and a detailed assessment of test equipment needs is suggested.

• The facility provided by the use of a high level software language and modular design methods in implementing additional features at low cost was evident during the application experiment. This extended to the ability to accommodate the use of another processor in the possessing additional facilities in the device family without any significant delay. The ability to increase significantly the perceived added value for the customer in such a flexible manner by the provision of additional features and functionality achieved in software was notable.

• With the benefit of hindsight, a regular staged transfer of source code and hardware design records from the subcontractor was required. This would provide increased secuiry for the company, and would have made the task of re-sourcing to another subcontractor much more straightforward when difficulties arose. This mechanism is advised for others considering subcontracting microcontroller product developments.
15. Resulting product, industrialisation and internal replication

The result of the project was the successful development of a low cost high functionality controller which is enabling the company to further develop its existing products and offer better pricing to its distributors. The prototype testing confirms that the prototype device meets its technical requirements.

The tasks remaining to be completed as part of the industrialisation process for the controller are the:

- Final trials in a representative ‘field’ environment, durability and stability testing. (Months 1-3)
- Finalisation of PC interface software development. (Months 1-4).
- EMC certification. (Month 5)
- The partial redesign and styling of the 7990 HPLC range to accommodate the new microcontroller and the new features and user interfaces it provides. (months 5 – 7)
- Product preparation, including the definition of production tooling, production test equipment, and production and service instructions. (months 7-8)
- Production staff training. (Month 8)
- Market launch preparation, including publicity data preparation. (Months 8-9)

The costs of industrialisation are estimated to be of the order of 20 k Euro.

These development tasks will be undertaken starting in the autumn of 2000. The delay in the finalisation of the temperature controller has been caused by the need to apply the engineers with familiarity in microcontroller technology to the development of a microcontroller based system for the company’s flash chromatography product range. This recently introduced product range is exhibiting almost a 100% per annum sales growth for the company, and the economic payback for the microcontroller adoption in these systems necessitates its priority. This replication involves the development of a microcontroller based Gradient Former (a device for managing solvent mixing and delivery) for use in flash chromatography instruments.

This replication has been undertaken as a direct result of the knowledge gained during the project, and this product development would have been unlikely to happen without the experienced gained during the application experiment.

The company plans to introduce the new controller system for the temperature control instruments in Quarter 1, 2001.

16. Economic impact and improvement in competitive position

The product improvement will provide the following user benefits:

- Provided added value to the existing product range by increasing the feature count.
- The new controllers with their serial control offers full system integration features for the customer.
- Data logging of actual process parameters for quality control and experimental analysis purposes.
- The ability to provide temperature profile control over a time period under PC control offers the ability for the HPLC system to undertake more demanding applications.

The availability of a low cost, high functionality temperature controller will therefore produce the following economic benefits for the company:
• Increase the profitability of the company through the replacement of a high cost component in its previous product line. A cost reduction of approximately 15% has been achieved by the application of microcontroller technology to replace the bought-in controller module.

• Improve the company’s prospects of penetrating other geographical markets. Unfavourable exchange rates and the availability of similarly priced local products previously formed a barrier to penetration of European and other overseas markets. The ability to offer lower priced, feature-rich products will make the product far more attractive to potential export partners.

• Improve prospects for penetrating other related market segments.

• Prolong the life cycle of these products by the addition of new, flexible design features.

• Enable the production of heater instruments appropriate to the ‘combinatorial chemistry’ market. Leading drug discovery departments in pharmaceutical companies are now using combinatorial chemistry as the technique of choice for producing biologically active compounds. Part of the process involves performing many reactions in vial reactors using instruments similar to the HPLC column temperature controllers discussed above. The specific requirements of this could not have been addressed with existing technology.

• The implementation of microcontroller technology has also reduced the threat from HPLC systems with integrated temperature control systems. A significant part of the company’s business (approximately 35%) came from sales to other instrument manufacturers of temperature control instruments, which they market as part of their complete HPLC systems. This business was at risk from the trend towards fully integrated temperature control instruments on the basis of cost.

The factors identified above have enabled Jones Chromatography to improve the competitiveness of the product. The combined impact of these factors on company sales is illustrated in Figure 10. Figure 10 also indicates the impact of the introduction of microcontroller technology into a Gradient Former for the flash based chromatography in 2000.

Using the sales forecast shown above in Figure 10 for the temperature controller alone results in a payback period for the costs of the microcontroller system development of 49 K Euro of approximately 15 months from the start of series production. The Return on Investment (ROI) is approximately 380% over a projected product life of three years. Taking into account the costs of industrialisation, which are estimated to be of the order of 20 k Euro, these figures become 23
months for the payback period and 270% for the ROI over three years.

The impact of the replication involving the gradient former device however, reduces the forecast for payback period and increases the potential ROI significantly. The payback period is reduced to 6 months and the ROI is 1509% over the same period.

17. Summary of best practice and target audience

The company has exhibited best practice in the specification process, and in the utilisation of microcontroller technology to improve the company’s competitive advantage through added value and feature improvement. This AE provides best practice experience in the development of test methods based on existing production test equipment. The application experiment also demonstrated best practice in knowledge and skill transfer, in that the company has immediately started an internal replication project.

The results of the application experiment will be of interest to companies in a large target segment, including the following industrial sectors:

- Technical testing and analysis 3320
- Pharmaceuticals 2440
- Industrial process control systems 3330

Since Jones Chromatography had in place at the start of the AE a certain amount of in-house electrical assembly expertise, one of the main areas of interest has been the process and experience of "jumping the technology barrier" from discrete electrical devices to assembling an embedded microcontroller system.

The target audience therefore includes the Managing Directors and Technology Managers of organisations in the identified industrial sectors operating with a low level of awareness of microelectronics.