FUSE Demonstrator Document – Laboratory Impex Systems Ltd

Application Experiment 1814

Title: Design of microprocessor control board

AE abstract

Lab Impex Systems is a small company specialising in the design and supply of nuclear radiation monitoring systems, primarily to the health physics area of the nuclear industry. Many of these systems are based on the CMS-1 Continuous Monitoring Station. This product uses an expensive bought-in 68000 microprocessor board. The main objective of the experiment was to design our own board and achieve a cost saving of 50% compared to the existing design. Another objective was to develop the expertise necessary for further processor based products to be designed in-house.

The project lasted 10 months, at a cost of 35KECU, and resulted in the demonstration of a fully tested prototype. The payback time is expected to be 18 months, and the Return on Investment (ROI) 970%. The new board is now in production and the 50% cost target has been achieved. The new design is also physically smaller, and has enhanced functionality. Sales of the more competitive product have increased dramatically since completion of the experiment, and market share is expected to increase by 3% per annum. Product life is expected to be 5 years.

The design team have gained knowledge of embedded microprocessor design techniques, CAD tools for PCB design, and Surface Mount Technology. They are confident in their ability to tackle similar projects and a new processor-based product is already being planned.

A major lesson from the FUSE experiment is that with adequate knowledge and support a complex new development need not mean a high risk of failure.

1. Company name & address.

Laboratory Impex Systems Ltd
Impex House
15 Riverside Park
Wimborne
Dorset
BH21 1QU

2. Company size.

The company turnover is approximately 2.5M ECU. The number of employees is 20, with three involved in electronics development.

3. Company business description

Laboratory Impex Systems Limited (LIS) is a UK owned manufacturer of nucleonic instruments and systems for the nuclear industry, primarily for the Health Physics sector. In general, our products are used to monitor the workplace environment for radioactivity, either in the air or as direct exposure. Business activities cover sales, marketing, product design, manufacture, installation and maintenance. Our teams provide technical solutions to customer requirements using both our own in-house designed products and externally sourced products, as appropriate. We design, assemble and test systems to quality standard BS EN ISO 9001 - our certification also includes project management and technical support services. Field maintenance is carried out by service engineers located in various parts of the country.

4. Company markets and competitive position at the start of the AE.

Company markets.

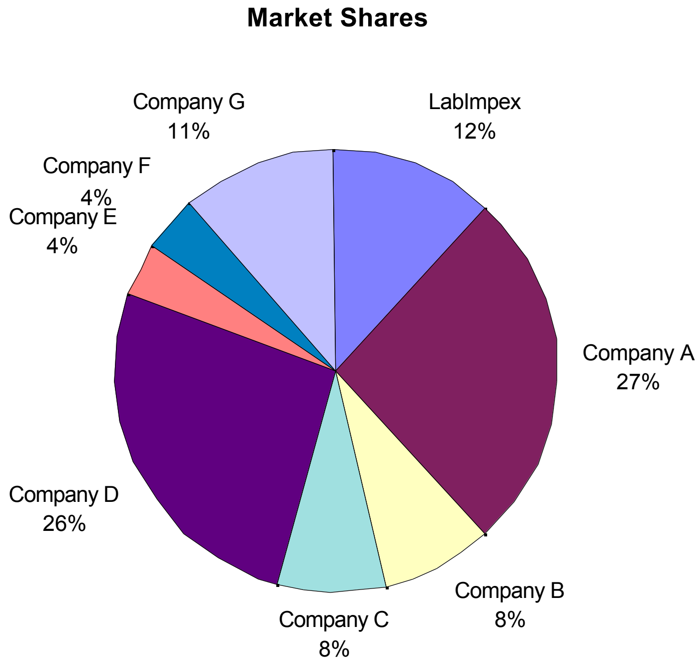
The UK market for our type of product is with Nuclear Power Plants and other large nuclear establishments, and within Nuclear Medicine. There are similar nuclear establishments in the major European countries, and further market opportunities world-wide.

Our chosen market is the UK nuclear power industry, and our customers include all the major nuclear power and research establishments, and other Government Authorities. We estimate the potential UK market to be 20 -29M ECU per annum.

Competitive position at the start of the AE.

The chart below shows the competitive position and market share for all our products at the start of the experiment. The CMS range of products (CMS 1, CMS2000, SRA) accounted for 35% of our sales at the start of the experiment. Our competitors products had similar specification and performance, but had more integrated designs and were often lower in price by 5-10%.

The market is competitive in terms of both product pricing and product features. The redesigned CMS product will have a significantly lower manufacturing cost, allowing more competitive pricing. The units will be of a more compact, integrated design, offering functional improvements such as more memory, faster operation, and further digital inputs/outputs. The in-house design will also allow considerable design flexibility in meeting customers' specific requirements.



Market Trends.
In terms of new power stations, the UK industry has very low growth. The changes in East-West relations have meant a cut-back of military nuclear processing, but the sectors in which LIS operates are either stable or growing, and this picture is expected to remain the same for the next decade. We believe that by then, a rebirth of Nuclear power will have taken place.
In the longer term, within the nuclear industry there are growing and conflicting pressures to reduce manning levels and to increase operational safety. These pressures are felt in both the power stations and fuel reprocessing facilities. This means that the industry must adopt more automated and more sensitive techniques. This, coupled with our entry into the export market this year offers LIS the opportunity for further steady growth. We believe that the nuclear power industry will offer good opportunities well in to the next century.

5. Product to be improved and its industrial sectors.

Equipment and systems are supplied to customers in the following industrial sectors:

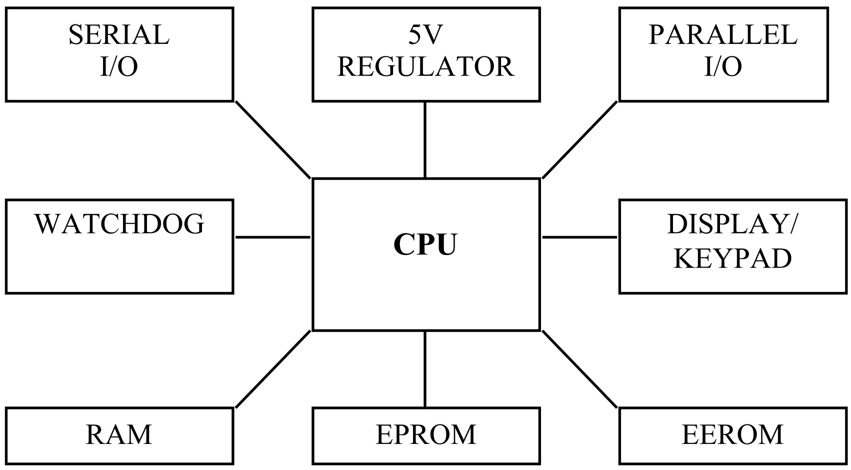
EN	:	Energy Production & Distribution
TA	:	Technical Testing & Analysis
IP	:	Industrial Process Control Systems

The product selected for improvement was the CMS-1 Continuous Monitoring Station. This is an intelligent instrument used for monitoring nuclear radiation. Its main purpose is to control one or more radiation detectors. Amplified pulses from a detector are processed by the CMS-1 and the level of radiation shown on a digital (LCD) display. Multiple alarm levels may be set and failure of a detector can also be identified.

The CMS-1 can be used either as a stand-alone radiation monitor or as a component in a distributed system. RS485 data transfer is used for communication within the system. RS232 data links are provided to pass results to other computers.

A desk-top version is also available, known as the Smart Radiation Analyser (SRA). This uses the same electronics as the CMS-1 but is used for manual operation.

The processor and much of the interface electronics are contained within the main processor card. This includes a 68000 microprocessor, serial and parallel I/O ports, RAM, PROM and E^2PROM memory and multiple high-speed pulse counting channels. A block diagram of the processor card is shown below.



Block diagram of existing processor card

A photograph of the CMS –1 product is shown overleaf.

CMS-1 Continuous Monitoring Station

6. Description of the technical product Improvements

The processor board, which contains the majority of the CMS-1 electronics, is not a Lab Impex product. It is a high cost bought-in board. By designing our own replacement board a number of important benefits are achieved including:

- 50% cost reduction
- Direct control of production
- Reduced board size
- Enhanced functionality

Because the CMS-1 is a successful established product range it is essential that the new board is interchangeable with the previous one. The design objective was to produce a replacement board with full compatibility as follows:-

- No change to existing firmware
- No change to electronic interfaces
- Minimum change to physical mounting/wiring

Functionality improvements include:

- 5v only operation
- Increased memory capacity
- Use of flash EPROMs

Synchronous serial expansion bus
3 channel digital to analogue converter
Discrete digital inputs and outputs

These new features do not affect the standard CMS-1 application but provide for future enhancements. A summary of the design specification of the new board (now known as the Sapphire Card) is shown in the table below.

Processor:	C68HC000FN16 or MC68HC001FN16, PLCC Package
Speed:	16Mhz
Memory:	512k Byte RAM 512k Byte Flash EPROM
Counters:	10 Channels minimum
Serial Ports:	At least 4 channels. One RS232 and one RS485 the other two RS232,485 compatible
Digital I/O:	8 inputs, 8 outputs, expandable, 5 volt logic, with option of 12 volt switching
Analogue I/O:	3 channels of 12-bit analogue output (0..5v)
Serial I/O:	3 wired bus, to control analogue i/o and other peripherals if and when required
Display/Keypad:	V1A to drive CMS-1 display/key pad with the possibility of having circuitry on the processor board itself, enabling direct driving of displays
Power Supply:	12 volts DC nominal, an on-board DC - DC converter will provide 5 volt logic power
Mounting:	Standard 3 U rack mount (i.e. with holes for card ejectors). Also, holes for flat mounting
Environment:	0..50C, option of -25..+ 75C for external use

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

Processor choices were limited by the requirement for firmware compatibility. An updated version of the 68000 processor (68HC001) was selected as it is available in a small PLCC package and is 100% assembly code compatible.

Use of surface mount technology (SMT) for the majority of components was dictated by the requirement to minimise the board size. The high complexity led to the need for a multilayer PCB (six layer). This also had the benefits of reduced noise and cross talk.

For the circuit design a PC-based schematic capture package was used. This allowed automatic generation of a net list and provided high quality schematic drawings. Circuit simulation was considered, but rejected due to the complexity of the design and the required timescale The net-list was supplied to a PCB layout bureau who translated it to the required format for their CAD system. Assembly of the prototype surface-mount PCBs was subcontracted to a local contract assembly company Newring Electronics Ltd., who also provided advice on designing for surface-mount assembly.

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

LIS has a long history of system design for the nuclear industry, and has built up considerable expertise in nuclear metrology. Design capability covers electronics, software and mechanical design. Manufacture of sub-assemblies is subcontracted, with final assembly and testing being carried out in-house.

Since 1991 most of the electronic sub-assemblies have been designed in-house. These have mainly consisted of digital and analogue interface boards. These are single or double sided PCBs with discrete components and low level analogue and digital ICs. Circuit schematics have been produced manually, and PCB layout subcontracted to an external bureau.

A significant level of firmware development expertise has been built up, based around the bought-in 68000 board, but no micro processor circuitry has been designed by Lab Impex. An objective of the project was to develop the knowledge and experience of embedded microprocessor design. This will allow other processor based products to be designed in future.

Two engineers were involved in the design of the new product. The experiment was managed by a Principal Engineer, with considerable previous project management experience, and design experience of hardware and software design, including general microprocessor work. The detailed design and testing was carried out by a design engineer with previous microprocessor hardware design experience. He was recruited shortly before the start of the experiment.

Prior to the experiment, LIS had no experience of 68000 microprocessor hardware design, the use of CAD tools such as schematic capture/layout, or the design of surface mount assemblies.

9. Work Plan and rationale.

The table below shows the proposed workplan produced at the start of the experiment.

		Month									
Task	**Task Description**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Workpackage 1 Management										
1	Project management	X	X	X	X	X	X	X	X	X	X
2	Dissemination									X	X
	Workpackage 2 Specification										
1	Feasibility study	X									
2	Technical specification	X									
	Workpackage 3 Training										
1	Microprocessor design training	X									
2	OS-9 software training				X						
	Workpackage 4 Design										
1	Design investigation	X									
2	Circuit design –phase 1	X	X								
3	Final circuit design			X	X						
4	PCB design information				X						
5	PCB layout				X	X					
6	Firmware driver design					X	X				
	Workpackage 5 Evaluation										
1	Prototype production			X	X	X					
2	Test planning				X	X					
3	Prototype testing					X	X				
4	Rework						X	X			
5	Final testing							X	X		
6	Install in CMS-1								X		
7	Evaluate CMS-1								X	X	

The project was planned and carried out in a number of phases.

1. Feasibility Study

From the outset, sales staff were involved to define future product needs. Characteristics of the bought-in processor board were studied and essential requirements defined. These included features necessary for compatibility with current products. Desirable improvements were also considered, but constraints of cost and board size limited the addition of new features.

A formal report was produced and reviewed by engineering, sales and management staff.

2. Design Specification

Results of the feasibility study led to the production of a design specification. This was inevitably similar to the old board but several enhancements were added without seriously affecting the cost. These included -

Use of flash EPROM for on-board programming
Addition of a synchronous serial bus
Addition of analogue outputs
Inclusion of 5v power regulator

3. Circuit Design

Design of the board was carried out jointly by 2 Lab Impex design engineers. One was recruited for the project because he had previous experience of 68000 microprocessor design. In-house training allowed this knowledge to be transferred to other engineers including test/service technicians.

The board was partitioned into subsections and a schematic produced for each one. A PC based CAD system was used for design entry. The complete design covered 10 A4 pages.

Several design reviews were held during this phase to check for compatibility with the specification. A third party designer (a consultant) provided additional training and guidance, and he reviewed the schematics at various stages, as an additional check for errors.

4. Prototype Construction

An information package including schematics, net-list and component details was compiled. This was supplied to a CAD bureau who translated the net-list into their required format. The translated net -list was rechecked against the schematics. A list of layout requirements was also compiled including physical and electrical constraints. The layout density was high and required both manual and automatic routing. 6 layers were necessary to achieve the requirements. Modifications added at a late stage caused significant additional work and cost.

A prototype board was produced and components assembled by hand.

5. Testing and Evaluation

The first prototype was found to have some design errors. The board was made to function but could not be fully tested. The errors were corrected, the PCB layout updated and a second prototype produced. This board was fully functional.

A design verification test schedule was produced to check all aspects of the board. For some tests, special assembly level test code was written. All these tests were successful.

Final evaluation was carried out by fitting the board into one of the Lab Impex existing products. One minor change was needed to the standard software to cure a problem with the digital I/O. The standard production test was carried out and all the tests passed.

Deviations from workplan.
The actual workflow generally followed the original workplan, except for the following –

1. The actual effort required for the project is summarised in the table below, and was significantly less than the original estimate. Due to the project generally progressing well, less management time was required than estimated, and the tasks of FUSE reporting and dissemination were also less than expected. The use of a consultant to provide design support, and to check the design at each stage proved very worthwhile, resulting in very few design problems, and this significantly reduced labour for the design and evaluation stages.

2. In an attempt to reduce the time to market, the PCB layout task was commenced before the design requirements were finalised. However, later changes, although fairly minor, caused over significant additional layout work, due to the high board density. (This was in addition to the later PCB rework following prototype testing). In future we would wait until 100% of the design information was available.

3. The planned OS-9 software training was not carried out, due to the supplier defaulting several times, and the lack of an alternative supplier. The training was intended to enable testing of some of the enhanced features of the microprocessor board. Fortunately, this was finally achieved by test code written in assembler, and there was no significant project delay. The formal microprocessor training was replaced by self training, as described in Section 10.

4. Initial problems with the CAD schematic capture tool, due to the complexity of our design, delayed this task by several weeks.

Workpackage	First User planned effort person days	First User actual effort person days	Subcontracted tasks	Planned subcon cost KECU	Actual subcon cost KECU
1. Management	31	15	none	-	-
2. Specification	9	10	none	-	-
3. Training	12	10	Microprocessor training OS9 training	2.0 1.8	See text See text
4. Design	127	100	Design support PCB layout + later rework	2.1 2.5	1.66 3.35
5. Evaluation	139	83	Prototype manufacture + assembly – 2 stages	0.373	1.5

Totals	318	218		8.773	6.51

10. Subcontractor Information

Suppliers/subcontractors were selected for their demonstrated expertise in the relevant areas. Aero-Physics are a design consultancy with many years experience of designing microprocessor systems for industrial and other applications. They had in fact supplied Lab Impex with the previous control card product. They were employed by Lab Impex to give informal training and design support on the specific design issues relating to microprocessor control cards, and to provide valuable assistance in confirming that the specific requirements of Lab Impex had been integrated into the final design. They appreciated and supported the need to transfer knowledge to our design team and a good working relationship was established. In addition to providing training and design support, they checked the detailed schematic design, and identified several problems which were then rectified before prototype manufacture. However, responsibility for the design remained firmly with the First User.

Bournemouth University was selected as our TTN, and they monitored the progress of the project via a series of visits, and via our monthly progress reports. The monitoring visits were an opportunity to discuss any problems, although the project generally proceeded well. In addition to acting as our appointed TTN, the university was originally selected to provide formal training on microprocessor hardware design. However, LIS subsequently had the opportunity to recruit a design engineer with some experience of designing microprocessor systems. The formal training was therefore replaced by self -training by the new engineer on 68000 microprocessor hardware design techniques, followed by in-house training of other design and production staff. This method proved successful in practice, but would not be generally applicable to other companies.

11. Barriers perceived by the company in the first use of the AE technology

The major factors preventing the Company from embarking on this development were considerations of cost and risk. The development cost was estimated as 40K ECU plus the cost of production, significantly more than any other PCB designed by Lab Impex. There were also risks associated with the simultaneous introduction of several new technologies, and this might lead to cost over-run or even failure. The design of a complex microprocessor board had not been attempted before, and there was no guarantee that it would be successful. It was planned to make first use of CAD tools, although in order to minimise the risk, this was restricted to schematic capture. First use was also to be made of Surface Mount Technology and multi-layer PCBs, and this would mean identifying and evaluating new suppliers, since existing suppliers did not offer these services.

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

Financial concerns were eased by the availability of partial funding from the FUSE scheme. Most of the estimated development cost, up to working prototype stage, was covered by the scheme.

Technology risk was minimised in several ways during the development. Microprocessor design knowledge was acquired by recruiting an engineer with previous 68000 experience. In-house training spread this knowledge to other technical staff. An experienced external consultant (Aero-Physics) was used to supplement this knowledge, and to independently check the design schematics. Critical parts of the circuit were prototyped and tested, and formal design reviews were held throughout the project.

CAD tools had not been used in-house before, and it was decided to minimise the risk by restricting their use to schematic capture, and to sub-contract the PCB layout to an experienced bureau. The use of simulation tools was also considered, but these had not been used before, and it was felt that with such a complex design, it might be difficult to achieve a reliable model of the system and obtain useful results. In-house use of PCB layout and logic simulation tools would however be considered on future designs.

Technology Barriers - Production
To avoid the introduction of errors at the PCB layout stage, a computer generated net list was supplied to the layout company. This was automatically translated into the format used by the CAD layout system. The translated net list was then 100% manually checked.

Our existing suppliers for PCB layout and for board assembly did not have the necessary facilities for this board so new third party suppliers were carefully evaluated and selected. The PCB layout company and the PCB manufacturer selected had extensive experience of complex multi-layer boards. The company used for prototype assembly was already producing high density surface mount boards for other customers and had all the necessary equipment in-house. Working closely with these suppliers ensured that the design requirements for efficient manufacture were met.

13. Knowledge and Experience Acquired

The experience gained from this project has increased the expertise of the engineers involved and the company’s ability to successfully manage a high technology development project. Knowledge of embedded microprocessor design and interface techniques has been acquired; design and project management methodology has also improved.

In-house training in Microprocessor/interface design and schematic capture (Easy PC) was arranged, to ensure that the acquired knowledge was distributed within the design team. Test/service engineers were also trained and have been successful at fault finding the new boards. Use of the PC-based schematic capture tool allowed the design to progress in a controlled and documented way. Despite an initial problem with the tool, due to the size and complexity of our design, we now have experience of the benefits of CAD and will consider adding tools for PCB layout and simulation on future projects, in order to further reduce the design risks.

The feasibility study and creation of a design specification ensured that the project was well defined. Frequent design reviews, and the regular FUSE reporting requirement ensured that the project was closely monitored and design issues resolved at an early stage.

The software driver training could not be provided by Aero Physics as planned. This was needed to test the enhanced features of the board. It was found that these could be tested with simple code written in assembler.

On the manufacturing side, close liaison with both PCB layout and assembly companies allowed a better understanding of their constraints and problems, especially relating to surface mount technology. Another SMT design has been completed since the FUSE project.

14. Lessons Learned

A major lesson from the FUSE project is that with adequate knowledge and support a complex new development need not mean high risk of failure. This development has been seen as a great success. It has been an important step which will lead to other technically complex products. We believe that the design of microprocessor based circuits can now be handled within our own design department.

Use of the schematic capture package (Easy PC) proved to be a great benefit. Unfortunately the size of the design (10 A4 pages of schematics) led to problems. Although they were eventually resolved, it was felt that this low-cost package was more suitable for smaller designs. Also the non-standard net list format meant that the PCB layout company had to translate it, which could have been a source of errors.

Part of the evaluation necessitated the design and construction of an interface card. This allowed the memory to be loaded directly from a PC.

Because it was only a development tool it was hand wired. Unfortunately it proved unreliable and could have delayed the project. The cost of producing a PCB for this board would have been justified, as it would have been more reliable and a spare unit could have been produced at very low cost.

The PCB layout density was very high. Also there were many physical constraints including connector designation and track routing. Under these circumstances, apparently minor changes at a late stage are difficult and costly to implement. In future, PCB layout will not be started until 100% of the design information is complete.

A surprisingly large amount of time was spent evaluating and selecting components. The flash EPROM market was very volatile at the time. Issues of cost availability and compatibility were changing rapidly during the project. More time will be planned in future developments for this activity.

15. Resulting product, its industrialisation and internal replication

Following the successful application experiment a number of other engineering activities were necessary. These included producing full production documentation for board assembly and testing.

The manufacture of the board will continue to be subcontracted to a specialist supplier, who will be responsible for the procurement of the bare PCBs, as well as the assembly and test. A special production test jig has been built, and test programs in EPROMs developed. This simplified the test procedure so that it could be carried out by the board assemblers. The assemblers will supply a test results sheet for each completed board. The first batch of 50 boards has now been produced and the first instruments delivered to customers.

Board repair, including any field returns will be carried out by our service staff who have the basic tools necessary for surface mount components, and who have been trained in the necessary techniques. Any major repairs will be passed to our suppliers.

As for the costs of industrialisation, it is estimated that 2-3 person months of additional labour were required, plus the costs of the test jig and components mentioned above. It was not necessary to re-design the instrument case, as the Sapphire board was designed to be compatible with the existing case, although the Sapphire board is considerably smaller than the old one.

The small size of the Sapphire board has led to the conception of further new products which would not have been possible with the original board.

Another processor-based project has been proposed and is being evaluated. This will use one of the PIC series of microcontrollers to add distributed intelligence to some of our interface products. The experiences of the FUSE application experiment will ensure the success of this project.

16. Economic impact and Improvement in competitive position.

Marketing Decisions

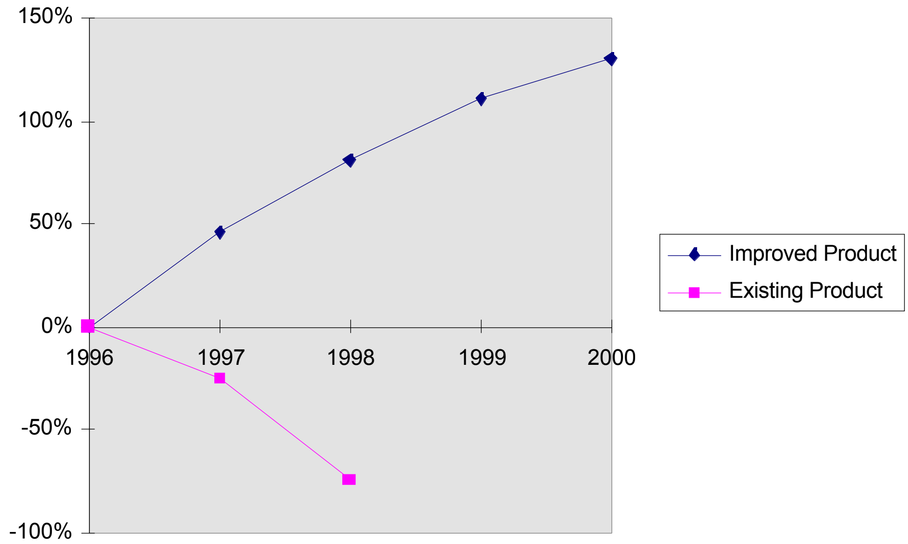
Within the nuclear industry, the lead time from enquiry to order is typically between six and 18 months, although it can be as long as ten years. In June 1996, two months into the experiment, the Sales & Marketing Department therefore took the decision to reduce the price of the current CMS range of products, based upon the final target price for the new processor card. The risk to the company was that if the experiment were unsuccessful and we had to continue using the current imported processor board, then the original units would need to be supplied at very much lower margins. The management consensus was that this risk should be taken, and steps were put in place to take advantage of the more competitive pricing for the CMS range of products.

Towards the end of ‘96, since the project was proceeding to plan, the decision was also made to include the new processor board into other projects, particularly within a new development being undertaken in 1997 for an Automatic Sample Changer. The result of these early decisions has been a dramatic increase in orders received since the early part of 1997.

Competitive Improvement

The Continuous Monitoring Station CMS-1), Smart Radiation Analyser (SRA) and CMS 2000 Unit (Continuous Air Sampling) were all ordered for the first time this year with the new “Sapphire Card”, including a major system installation in the UK. The more competitive pricing, making the difference between winning and losing orders, has produced a marked improvement in sales, almost an unbelievable improvement, over the previous year. The graphs below contrast the predicted % decline in sales of the existing product without any improvements, with the actual and predicted % increase in sales of the new improved product. Based upon our current sales level, we should recover the costs of the experiment within a payback period of18 months (time to recover development costs from profit on new sales). In addition, we predict that our market share will increase by 3% per annum up to the year 2000.

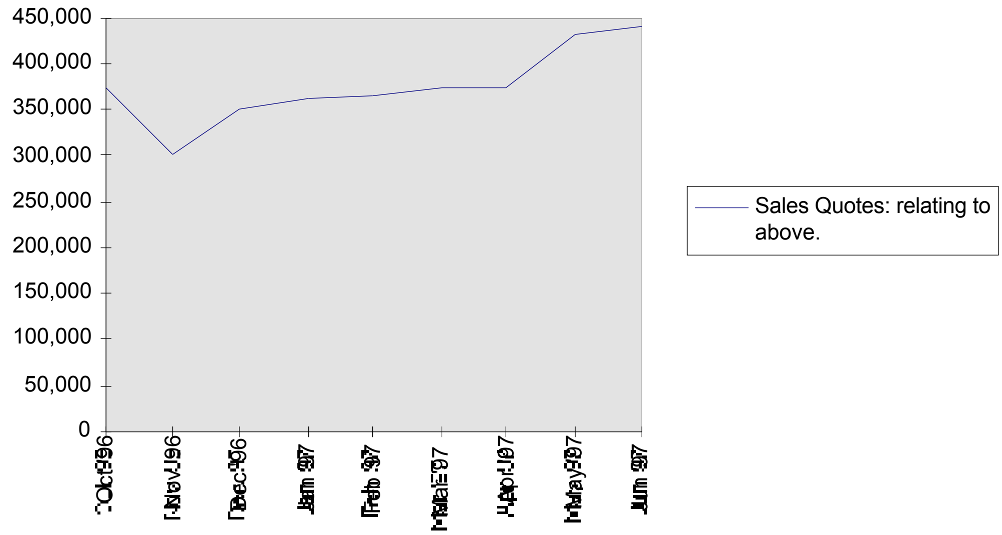
Change in Sales



In addition to the dramatic increase in sales, our current level of enquiries and quotations is also rising, as shown in the twelve month rolling average graph shown below.

The lifetime of the product is expected to be 5 years, during which time various improvements and enhancements will no doubt be introduced. Over this period, the Return on Investment(ROI) is expected to be 970% (total profit during product lifetime/costs of development).

Rolling Average Year to June '97



Exports

We entered the export market for the first time via Europe during 1997, and achieved some early success. We are now exporting to several

European countries, and expect export sales to reach 6.6% of total sales this year Additional sales personnel will be employed to assist with the export task.

Long Term
Plans are being prepared to produce new products which extend the product range that we are able to offer to our now, world-wide customers. For example, the decision to include new Sapphire Cards in the Automated Sample Changer has assisted in securing three major orders for this new product. Customer contact and support in the UK will be increased, and we believe this will assist the improvement in orders achieved by our more competitive position.
Further, opportunities in the UK with the British Government are now presenting themselves because many UK manufacturers of nuclear instruments are fast being taken over by foreign companies, allowing the remaining UK companies the chance to become major government suppliers, in a market which was previously difficult to enter.
Our long term growth forecast can be achieved, we believe, via our more competitive position in the market. Our forecast is to double the value of our sales by the year 2000 and this is dependent upon success in the export market.

17. Target Audience for Dissemination

Applications of microprocessor technology are very diverse. Suppliers of products into most industrial sectors could benefit from the lessons of this project. Our main motivation was product cost reduction. Equally important in many situations is the inherent flexibility offered by a microprocessor solution.

The results of this experiment will be of interest to any company wanting to design an embedded microprocessor product. Our success should convince such companies that the risks can be minimised and the technology mastered. There is no doubt that the recruitment of an engineer with some experience of microprocessor system design significantly contributed to the success of the project, and this option may not be available to other companies. However, other aspects of our workplan and experiences should be of interest to other companies, for example –

- the overall emphasis on training
- the training of other staff within the company, including production, test and repair staff.
- the use of consultants for design support and design verification.
- the approach to sub-contract assembly and test.

The demonstrator should be of interest to companies within the following Prodcom sectors –

3320 *Instruments and appliances for measuring, checking, testing, navigating and other purposes.*

33 *Medical, precision and optical instruments, watches and clocks*

30 *Office machinery and computers.*

29 *Machinery and equipment*

34,35 *Transport equipment*