Compound Semiconductor Material Manufacture, Process Improvement

Thesis submitted to the University of Wales for the degree of

Doctor of Philosophy

By

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Declaration

This work has not previously been accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree.

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Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Summary

IQE (Europe) Ltd. manufactures group III/V compound semiconductor material structures, using the Metal Organic Vapour Phase Epitaxy process. The manufactured ranges of semi-conducting materials are relative to discrete or multi-compound use of Gallium Arsenide or Indium Phosphide [III/V]. For MOVPE to compete in large-scale markets, the manufacturing process requires transformation into a reliable, repeatable production process. This need is identified within the process scrap percentage of the process when benchmarked against the more mature Si-CVD process.

With this wide-ranging product base and different material systems, flexible processes and systems are essential. The negative impact however, of this demanded flexibility is a complex system, resulting in instability. Minor fluctuations in time, flow, pressure, temperature, or composition in the manufacturing process, will lead to characteristic differences in the produced material [product], when comparing the prescribed run to the actual run. The product profile changes very rapidly, correspondingly the failure profile of the process is equally as dynamic, it is essential therefore that the analysis and projected activities and actions can be identified and consolidated in a timely manner.

This project evaluates the process used by IQEE to manufacture III/V compound semi-conducting material structures and uses the business performance to identify the process drivers. One year's [1997] business and process information is used for a single iteration of the improvement cycle. These drivers are then utilised as operators and offer the critical weaknesses in the process related to performance blockages. Some of the techniques utilised in the process evaluation and cause derivation; are original contributions specifically derived for use with a multi-platform complex process with multiple cause and effect operators. A double reporting FMEA contributes a differing rank for like machines running differing products, offering a machine specific failure profile.

A novel composite of P-diagram and process flow techniques enables determination of activity influences confirming the key failure mechanism as previously identified by the business risk analysis. This project concludes by nominating the key failure mechanism accounting for 41% of the approximate 50% scrap figure identified again within the business risk analysis. The effects attributed to this failure mechanism are 2-dimensionally analysed utilising an original double operating FMEA, plotting effect to effect for the individual causes, offering a prioritised list of failure categories. The highest priority failure mode is addressed by an equipment design exercise, resulting in an overall 10% sales potential re-contribution.

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Nomenclature

ASP	Average Selling Price
BME	Blockage Masking Exercise
BRA	Business Risk Analysis
Cell	Growth Chamber of MOVPE Reactor
CoDN	Cost of Doing Nothing
CP	Centre Point
DoFMEA	Double operating FMEA
DrFMEA	Double reporting FMEA
ΔP	Differential Pressure
DXRD	Double X-ray Diffraction
EPI	Epitaxial Products International Ltd
Epitaxy	Generic Layer Deposition Technique
F.back	Feedback
FMEA	Failure Mode Effect Analysis
FoS	Factor of Safety
Global	A Derived Analysis Technique
Group III	Material from the Group III section of the Periodic Table
Group IV	Material from the Group V section of the Periodic Table
InGaAs	Indium Gallium Arsenide
InP	Indium Phosphide
IQE	International Quantum Epitaxy, IQE plc
IQEE	IQE (Europe) Ltd
IW	Impact Weighting
MA	Manufacturing Activity
MAS	Manufacturing Activity Sequence
mb	millibar
mba	millibar absolute
mbg	millibar gauge

MBE	Molecular Beam Epitaxy
MFC	Mass Flow Controller
MOCVD	Metal Organic Chemical Vapour Deposition
MOG	Manufacturing Output Gauge
MOVPE	Metal Organic Vapour Phase Epitaxy, sub set MOCVD
MTBF	Mean Time Between Failures
MTTF	Mean Time To Fail
MTTR	Mean Time to Repair
μm	micron, one millionth of a metre
OEE	Overall Equipment Efficiency
OEM	Other Equipment Manufacturer
OPE	Overall Process Effect
OPR	Overall Process Reliability
PDCA	Planning Tool - [Plan, Do, Check, Act]
PIPS	Process Improvement Problem Solving
P&L	Profit and Loss
PL	Photo Luminescence
PLi	Photo Luminescence Intensity
PoS	Probability of Success
PQC	Process Quality Control
QED	Quantum Epitaxial Designs
RfI	Rules for Improvement
RPN	Risk or Ranked Priority Number
SD	Standard Deviation
sccm	Standard cubic centimetres/min – cc/m
slm	Standard litres/min – l/m
SPC	Statistical Process Control
SPP	Schematic Process Path
URPN	Unit Risk priority number

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Chapter 1 - Introduction to Company & Technology

The general aim of this Chapter is to briefly describe the "History" of IQE (Europe) Ltd [the Company - IQEE], the "Market Sector" within which the company trades, and the basic principles of the process technology MOVPE, identify the need for improvement and define the objectives of the project.

1.1 - Company Profile

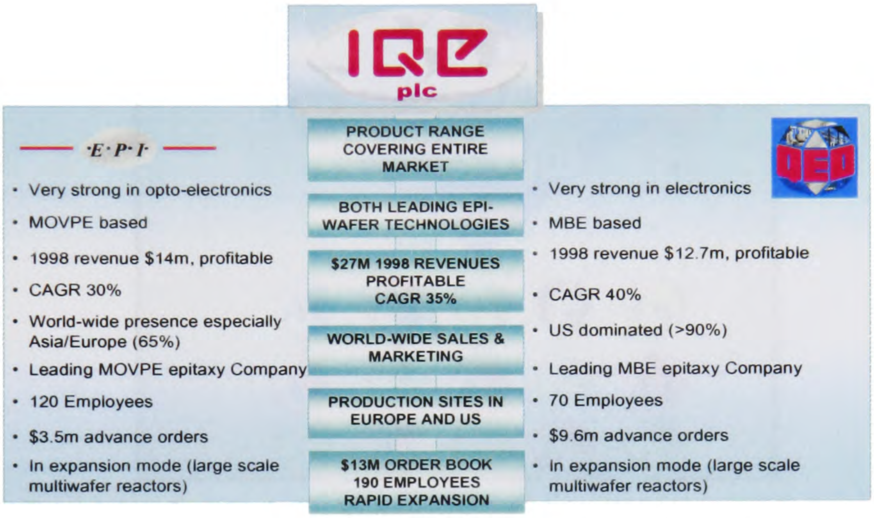
Epitaxial Products International Ltd. [EPI] was founded in 1988 as a venture capital company funded by Shell Ventures UK Ltd. Compound semi-conductor material structures, are manufactured by EPI for the electronic and opto-electronic industrial sectors, using a process called Metal Organic Vapour Phase Epitaxy [MOVPE].

Historically, EPI produced material predominately for research programmes involving a small number of international electronic companies. Currently, in excess of 80 % of its products are exported to the USA and Japan. The majority of current customers are large "Blue Chip" companies trending to more standard product lines or pilot manufacturing. IQEE is the only commercial full range MOVPE epitaxy house in Europe and one of three in the World.

The manufacturing technology has progressed from machines of single two-inch wafer capacity, to thirty-five two-inch wafers, with machines pending with a capability of up to ninety wafers at a time.

In 1999, EPI merged with a US based company, QED, specialising in manufacturing semi-conducting materials using Molecular Beam Epitaxy [MBE]. Currently a holding company owns both EPI and QED, International Quantum Epitaxy plc. [IQE]. IQE floated successfully on the European Technology Stock market EASDAQ later in 1999. EPI has been renamed IQE (Europe) Ltd, [IQEE].

Figure 1-1 is a marketing descriptor of the recently formed group of Companies IQE plc.



IQE plc

·E·P·I·

- Very strong in opto-electronics
- MOVPE based
- 1998 revenue $14m, profitable
- CAGR 30%
- World-wide presence especially Asia/Europe (65%)
- Leading MOVPE epitaxy Company
- 120 Employees
- $3.5m advance orders
- In expansion mode (large scale multiwafer reactors)

PRODUCT RANGE COVERING ENTIRE MARKET

BOTH LEADING EPI-WAFER TECHNOLOGIES

$27M 1998 REVENUES PROFITABLE CAGR 35%

WORLD-WIDE SALES & MARKETING

PRODUCTION SITES IN EUROPE AND US

$13M ORDER BOOK 190 EMPLOYEES RAPID EXPANSION

- Very strong in electronics
- MBE based
- 1998 revenue $12.7m, profitable
- CAGR 40%
- US dominated (>90%)
- Leading MBE epitaxy Company
- 70 Employees
- $9.6m advance orders
- In expansion mode (large scale multiwafer reactors)

Figure 1-1 - Marketing Overview of IQE

1.2 - Process Summary

MOVPE - "Metal Organic Vapour Phase Epitaxy"

1.2.1 - Epitaxy the Science

Epitaxy is a process used throughout the semi-conductor industry – IV [Silicon], III-V or II-VI based. The word epitaxy is derived from the ancient Greek words '*Epi*', meaning *on* or *upon* and the past tense of the verb *tienen*, meaning *arranged*. The use of the word in the semiconductor industry normally relates to an ordered arrangement of atoms on the surface of a substrate (Royer, 1928).

The substrate is the single crystal on which materials are grown atom-by-atom to build the epitaxial sandwich structure specified by the customer for each particular device type. (See Figure 1-2).

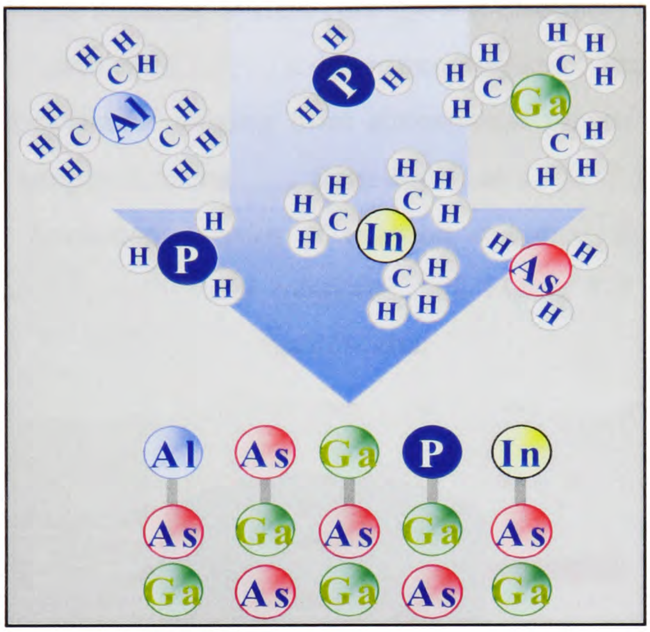


Figure 1-2 - Schematic of Epitaxial Growth

1.2.2 - Epitaxy the Process

The epitaxial process is a deposition method for materials, of a desired structure on a single crystal substrate [typically Indium Phosphide or Gallium Arsenide for III/V Epitaxy]; the material deposition can be in either, the liquid or vapour phase, Ludowise (1985) discusses the generic principles of the process technology for both horizontal and vertical tube cell arrangements.

Silicon based technology currently dominates the semi-conductor industry. Compound semiconductors; from groups III and V of the periodic table have some unique properties. It is these properties that make them more suitable in a number of applications than Silicon, for example a group III/V transistor is some twenty times faster than it's Silicon counterpart. The semi-conducting structure is grown directly onto a single crystal substrate.

The epitaxial growth takes place in a gas reaction chamber, supported upstream by a gas handling system [pre growth chamber] and an exhaust system [post growth chamber] as a downstream system. The IQEE process takes place at pressures ranging from atmospheric pressure to 100 mbar absolute, and temperatures ranging from 400°C to 1100°C. IQEE currently operates two fundamental types of reaction chamber, the linear single wafer cell and the multi-wafer rotational cell; Figure 1-3 is a schematic representation of a multi-wafer machine chamber.

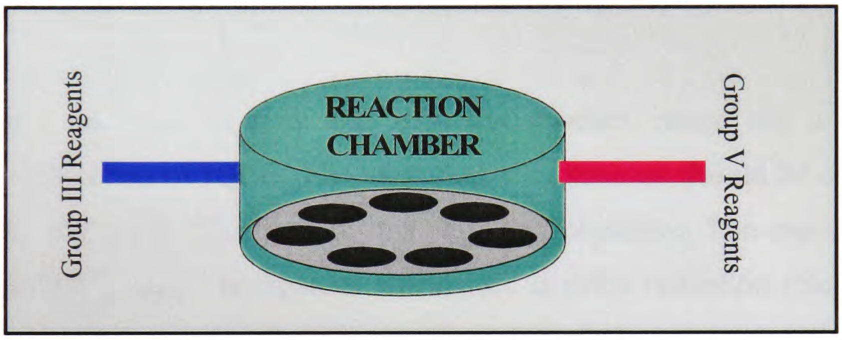


Figure 1-3 - A "Typical" Reaction Chamber Schematic

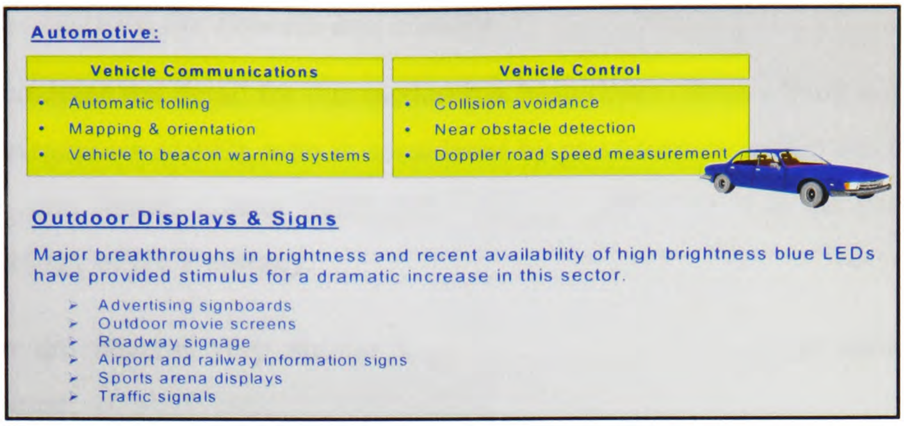
It is significant that no acknowledged or documented equipment specifications for optimising material performance, operating or maintenance procedures [O&Ms], or fit for purpose standards [FFPs] exist. Other process supporting industries assume that these typical manufacturing aids are available and mature. It is widely acknowledged that the process of MOVPE is not fully understood, Ludowise (1985) discusses this issue and Stringfellow (1999), describes the whole process as a "black box".

Many discreet failure modes currently affect the process; these can be generically categorised into several groups:

Equipment Failures
Product Compliance Failures
Process Failures

These “failures” from a business viewpoint are categorised as yield losses or scrap. The major yield losses of the process in its current form include practical engineering applications such as gas mixing and material pick up instability. The characteristic uniformity and growth chamber performance are additional, both again leading to direct non re-work failures resulting in hundreds of thousands of pounds worth of product being written off each year. As in any other business, the cost of non-deliverable product [scrap] generation will require reconciling to the deliverable sales, otherwise business failure may result.

Increasing order batch size and reducing product range are a major business objective of IQEE. The manufacturing process should be capable of supporting the implications of this company objective. The expectation of larger “Blue Chip” companies worldwide is price reduction relating to order size and longevity (economic Elasticity of Demand as defined by Anderton, 1999). To satisfy these business needs the process requires transformation into a “Dial a Wafer” turnkey process, a seemingly aggressive objective in comparison to the current situation, which is smaller batch than large-scale Figure 1-4 and Figure 1-5 detail “typical” large-scale markets.



Automotive:

Vehicle Communications	Vehicle Control
• Automatic tolling • Mapping & orientation • Vehicle to beacon warning systems	• Collision avoidance • Near obstacle detection • Doppler road speed measurement

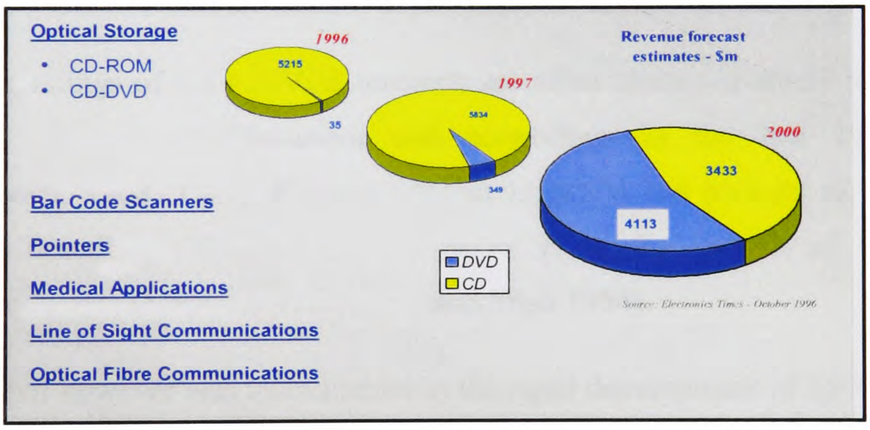
Outdoor Displays & Signs

Major breakthroughs in brightness and recent availability of high brightness blue LEDs have provided stimulus for a dramatic increase in this sector.

- Advertising signboards
- Outdoor movie screens
- Roadway signage
- Airport and railway information signs
- Sports arena displays
- Traffic signals

Figure 1-4 - "Typical" Large Scale Product Markets

Figure 1-4 offers a marketing overview into both the Automotive and Display markets that have the potential of demanding large numbers of wafers providing that the appropriate market price erosion can be achieved to displace the current "in use" technologies.



Optical Storage

- CD-ROM
- CD-DVD

Bar Code Scanners

Pointers

Medical Applications

Line of Sight Communications

Optical Fibre Communications

Source: Electronics Times - October 1996

Figure 1-5 - "Typical" Large Scale Product Markets

The optical storage market relative proportions of CD to DVD market share projections, DVD to IQEE is a critical market for the long term. Figure 1-5 offers an overview for the expected DVD:CD ratio market change.

1.2.3 – MOVPE the Process and History

The fundamental detail for this section has been drawn from a book written by Stringfellow (1999), who is considered by practitioners within the III/V compound semiconductor industry to be a scientific expert in the current technology of III/V epitaxy.

There are several very similar classifications for the almost identical processes:

OMVPE:	Organometallic Vapour-Phase Epitaxy
MOCVD:	Metal-organic Chemical Vapour Deposition
MOVPE:	Metal-organic Vapour-Phase Epitaxy

CVD is the most general term used to describe the process (III/V, II/VI & IV) since it implies nothing about whether the resulting layer is single crystalline, polycrystalline, or amorphous.

The beginnings of the MOVPE research are often attributed solely to the pioneering work of Manasevit and co-workers in the late 1960's (Manasevit, 1968, 1969). However recent litigation has brought to light patents describing earlier forms of MOVPE to the growth of III/V semiconductors (Miederer 1962, 1963 and Scott 1954).

Manasevit however was instrumental in the rapid development of MOVPE in the early 1970s. All crystal growth processes, including MOVPE are highly complex. Early crystal growth studies were invariably empirical, giving crystal growth the appearance of a black art. Today however for simple structures it is possible to predict the outcome of each process using such tools as "In-Situ" monitoring, data logging, SPC, process modelling and "Real Time" analysis. This assumes that a full understanding of the process influences is held, for the majority of complex structures the process is still a "black box" or "black art".

1.3 - Project Objectives

It is fairly typical within the Si semiconductor industry to achieve manufacturing with less than 10% scrap. During the audited year at IQEE the scrap equated to approximately 50%, with a lost sales value of approximately £4m [see Chapter 2]. This performance when benchmarked against more mature Si industry is poor. The current approximate 50% scrap value is however an improvement over previous performance. This is as a result of some process improvement programmes. However progress on these programmes is uncontrolled, hunch driven and slow.

It is possible to initiate a "Global Process Improvement Campaign" utilising a potential of one of two strategies, "Controlled" or "Chaotic", any improvement will benefit the organisation, both have the potential of achieving the same consolidated objective, for example:

<u>Controlled</u>: following an appropriate managed and consolidated path of process evolution to achieve the optimum "Process"

<u>Chaotic</u>: to analyse by "Hunch or Guess" the out of control process and make unjustifiable/unpredictable changes to improve the "Process"

Since the company was formed in 1988, many improvements in the process have been achieved, using techniques such as:

Process SPC
Failure Mode Effect Analysis
Failure Rate Analysis

These techniques, albeit critical to a "Quality" process improvement programme, need direction, prioritising and focus. Any improvements previously achieved have been “Chaotic”. To achieve the required objectives in line with customer requirements a more controlled approach needs adopting.

A greater understanding of the techniques is needed and a “plan” derived detailing the preliminary investigation, improvement derivation paths.

The general aims of the project are to investigate the process and business performance of the MOVPE manufacturing process, and evaluate the potential for process improvement using typical, modified or novel analysis techniques.

The Aims & Objectives of the project are:

- To determine and evaluate the key variables in controlling the MOVPE process equipment
- To evaluate available analysis techniques
- To develop novel analysis techniques to identify and offer solutions to the process failure mechanisms
- Implement effective solutions to improve process capability and stability
- To derive a “Full Process Map”
- To evaluate proposed process changes

1.4 - Chapter Summaries

1.4.1 - Chapter 1 Summary

This chapter offers a précis history of IQEE, descriptions of the product range and market sectors within which IQEE merchants its custom compound semiconductor Epitaxy service.

The basic principles of the process technology, MOVPE and the general project objectives are described in this chapter. The generic complexity of the process and the need to understand and subsequently improve the process are driven by business objectives. The precise business needs for improvement are defined in Chapter 5.

The subsequent Chapter evaluates generally available quality techniques and philosophies and identifies the "key" techniques including both novel and public domain that are used within the project. These techniques are discussed against referenced work as to their suitability in standard form.

1.4.2 – Subsequent Chapters Summaries

Chapter 2 - offers the keys to the project success, a review of the history of quality as a culture, outlining and reviewing several suitable strategic quality tools. A literature review on the proposed strategic tools is undertaken and their potential discussed.

Chapter 3 - offers an understanding of the materials used, produced and derives the basic materials objectives for the process. The fundamental business metrics that enable evaluation of the process performance are discussed and presented.

Chapter 4 - offers a physical process understanding, initially describing a simple structure, enabling evaluation of the process capability and effects. Material characteristics as detailed in Chapter 3 are expanded in terms of characteristic uniformities as demands or objectives of the process.

Chapter 5 – identifies the need for improvement using raw profit & loss and failure data, this is critical to the understanding the losses and subsequently defining the areas for improvement.

Chapter 6 – in conjunction with Chapter 5, these chapters are key to the overall success of the improvement programme. The process flow is fully determined and evaluated for impact/threat. Concluding on the improvement that will have most impact.

***Chapter** 7* - offers an original definition for process improvement problem solving, operating on a typical FMEA reasoning mechanism and deriving further original modifications to the FMEA technique contributing a simple two-dimensional analysis of a complex multiple cause/cause system.

Chapter 8 - contributes an evaluation on the highest priority failure mechanism as determined in Chapter 6. An FMEA is derived for this failure mechanism and a system re-design and evaluation is undertaken.

Chapter 9 - discusses the original contribution contained within the project, describes the direct IQEE benefit and the potential developments that have been generated as a result of the project or linked sub activity.

Chapter 2 - Literature Review

2.1 - Introduction

The previous chapter offers an overview to the process of MOVPE and it's inherent complexity, sets the scene when benchmarked against the more mature Si-CVD industry. This project and adopted techniques should be controlled and be effective for use in this application. It is essential that evaluation of a process take place prior to any improvement plan derivation. This evaluation may only be effective with the appropriate selection of evaluation tools. There are currently many tools available in a quality and statistical toolbox. Hundy (1991) offers a very practical discussion on the major techniques with particular reference to manufacturing processes.

These tools/techniques require evaluation with respect to the problems to be solved, the data identified and their current and previous uses. The suitable selection of strategy, critique of appropriate techniques with respect to "Prior Art", is undertaken in this chapter. The overall objective is not novel, industrial improvement campaigns have existed for many years. However a published evaluation of the overall process of MOVPE and its operation is novel, within the process improvement context.

2.2 - History

Much has been achieved over the last 70 years in many differing cultures and industries, by application of quality programmes. Mitra (1993) discusses and quotes Feigenbaum (1983) the historical phases of quality control throughout the 20th century. A key phase in the evolution of modern quality standards was the period 1940 to 1960, termed the "Statistical Quality Control" phase (Feigenbaum, 1983), prior to which

100% inspection was more the norm. The 1960's and 70's marked the onset of the total quality philosophies.

Shewart (1931) for example writes, "the better the Quality the lower the Cost", a supporting explanation for this statement is described by Karatsu, [this quotation is an excerpt from a booklet entitled "you won't do it" produced for the UK National Quality campaign in the mid 1980's], "*as inferior products are eliminated through innovation in the manufacturing process, materials and labour as well as energy can be saved while producing the same volume of product. In addition, when a smaller volume of inferior goods are produced, machines less frequently have to be stopped for adjustment, and materials less often have to be replaced in order to produce satisfactory products, this reduces the operation rate, and so can lead to higher productivity*" also quoted by Logothetis (1994). This offers a generic scenario to be achieved via the introduction of a process improvement campaign.

Deming (1982) suggested for such a campaign a 14-point strategy, a concept breaking traditional company philosophies and focusing on change and participation. See appendix 6 for the detail of Deming's points. Each of these points has to be sorted for priority dependent upon each specific application.

The philosophy implied in Deming's points is a potential contributor to business success. The intrinsic culture for the statistical control that Deming, and Taguchi's emphasis on design (Logothetis 1994) advocate, rely on certain basic assumptions:

> That the process variables can be identified and understood
> That the process is in control [to some degree]
> That a standard product range is established

From the 14 points Deming defined, albeit proposed as a holistic approach as an overall strategy, the "most" crucial for this specific project activity that "Set the Scene" are points 1 & 5, described as follows:

> *1-Create a constancy of purpose focused on the improvement of products and services. Constantly try to improve product design and performance. Investment in research, development and innovation will have a long-term payback to the organisation.*
>
> *5-Focus on continual improvement. Constantly try to improve the production and service system. Involve the work force in these activities and make use of statistical methods, particularly SPC problem-solving tools.*

These statements endorse the objectives of focused continuous improvement with the suggestions of investment in R&D and staff. Endorsing the need for an improvement campaign to be considered as a continuous process within the normal operating practices and objectives of an organisation, not a short-term objective.

Any improvement achieved is purely a foundation for the next potential improvement step, this concept is borne out in the techniques used and developed, and is key to continued success.

Feigenbaum (1991) defines quality as "*The total composite product and service characteristics of marketing, engineering, manufacture and maintenance through which the product and service in use will meet the expectations of the customer*", and offers a definition for "Cost of Quality" or "Quality Costs".

With the complex and non-standard product range on offer to IQEE's customer base, the shipped product undergoes 100% material evaluation. This has the impact of ensuring that "What the Customer Wants, the Customer Gets", obviously at a cost. With the current "state of the art" MOVPE equipment and the need for process flexibility the consequence to the company is that the "Cost of Quality" is extremely high, with an approximate 50% process yield the confidence levels are too low to ship without full product characterisation.

By operating with a typical cost to manufacture for 1997 of £1064 per wafer, the lost cost or cost of quality may be calculated, figures detailed in Table 2-1, the data source for the failure numbers is held within the failure coding of the IQEE production databases and summarised accordingly.

Sitewide Financial Losses 1997

Fail Category	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	Lost Wafers
Total Runs	584	1254	529	473	430	1638	
Hardware	£25,296	£59,024	£51,646	£62,186	£91,698	£32,674	£322,524
Morphology	£127,534	£123,318	£22,134	£124,372	£82,212	£316,200	£795,770
Doping	£55,862	£43,214	£46,376	£23,188	£11,594	£44,268	£224,502
PL & XRD	£5,270	£338,334	£14,756	£41,106	£48,484	£160,208	£608,158
Errors	£7,378	£21,080	£10,540	£5,270	£36,890	£42,160	£123,318
Sources	£0	£5,270	£11,594	£8,432	£7,378	£3,162	£35,836
Thickness	£152,830	£9,486	£0	£18,972	£0	£3,162	£184,450
Lost Wafers	£374,170	£599,726	£157,046	£283,526	£278,256	£601,834	£2,294,558

Table 2-1 – Cost to Manufacture

The reduction and fuller understanding of the causes behind the financial implication of the listed £2.3m in lost margin is the motivation behind the process improvement objective. An overview analysis of the summary failure mechanisms that enable the data in Table 2-1 to be generated are summarised in Table 2-2.

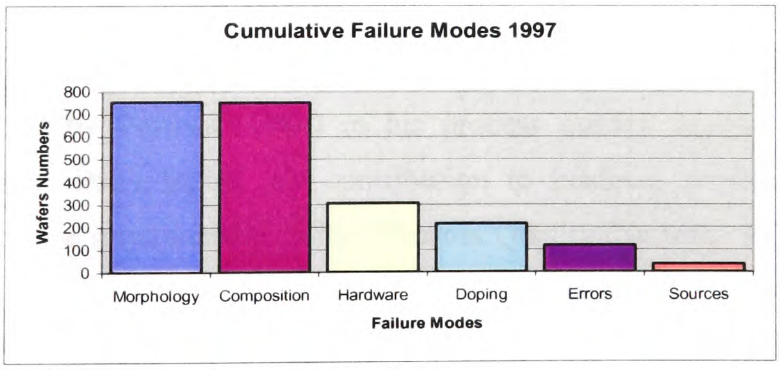


Table 2-2 – Failure Overview

The data in Table 2-2 suggests that two failure mechanisms predominate, morphology and composition, these will be further derived in Chapter 5. Table 2-1 represents the losses due to the failures, these costs will have to be supported by the business and the eventual downstream customer, the key activity to improve the process must be to reduce the overall cost by process improvement. One year's [1997] process information is used for a single iteration of the improvement cycle.

To quote from Phadke (1989) "*Delivering such a high quality product at low cost is an interdisciplinary problem involving engineering, economics, statistics and management*". This statement defines the fundamental disciplines that are required to analyse and reduce the cost of quality.

It is the basic function of identifying the variability and reproducibility in the process that will enable the outgoing product to undergo random sampling rather than total and offer the opportunity to control the process cost of quality. This will have a positive impact on the overall business performance of the company.

Quality therefore must be considered a major business management strategy as discussed by Feigenbaum (1991), encompassing the organisation as a whole. The Author defines that "*The key is that quality control must be structured explicitly and measurably so as to contribute to business profitability and positive cash flow*". The strategic requirements are endorsed by Porteus (1984) in his process quality improvement – Stanford University report, for contribution to business profitability is reliant upon the improvement of the "Process Quality Control – PQC" in a structured and measurable manner enabling additional positive contribution to customer satisfaction and cash flow. Also Black (1988) in his article reviewing quality improvement at Caterpillar using a PWAF [Plan with a Future] approach and Caudell (1997) outlining "The Quality Crusade" and offering some key comments on the strategic importance of quality. Feigenbaum (1991) also defines in his book a list of twelve key checkpoints (see A6.1 – Armand V. Feigenbaum, (1991)) for process control effectiveness, when used in pure checklist terms very few questions can be answered in the affirmative, but this also assumes that the process is fully understood.

Today, many large international corporations utilise very successful cultures that endorse the requirements for business management strategies, Motorola as an example, developed the “Six Sigma” concept during the mid 1980’s and is successful today. Sitnikov (2002) discusses the “Six Sigma Phenomena”, and details the origins, a key comment regarding the original development of the culture is that the Engineers at Motorola with their available knowledge could identify and design out the their process weaknesses. This implies again that the impacting factors on the process were understood, not necessarily at the time in control.

The key relationship conflict between current techniques, cultures and the requirement to improve the process is that an appropriate understanding of the process influences is available, whilst offering a standard range/s of products. IQEE does not have a generic process or product range. Each customer for each device category has an individual structural specification, and it is this aspect of the business profile and objective that causes this conflict. It is reasonable to suggest that once the process understanding is gained it is feasible to select a more typical culture to integrate within the organisation, such as the “Six Sigma” or “Kaizen” cultures.

Therefore one of the key objectives of this project is to offer a means to understand the process in use. It is essential for the initial business management strategy and any process improvement tools to derive an appropriate understanding of the process in use, however the techniques need developing to gain this understanding. To enable this derivation it is essential to back-engineer the typical review process.

The preliminary analysis is therefore required to be business driven, a historical analysis of data identifying business performance blockages, taking the form of a specific to IQEE analysis of the business performance enabling further derivation detailing loss categories as operators. Blockage in this situation is interpreted as a "mechanism resulting in reduced performance".

The business analysis technique selected for this project is required to offer a defensible rationale but also be capable of investigating the process losses attributable to failure mechanisms.

The inclusion of this thesis will concentrate on a singular aspect of the understanding and improvement of the process performance, the internal project for IQEE will continue.

2.3 - Review

With the objective of process improvement, any project plan must be based on some form of a practical controlled strategy; this demands the first problem solving exercise. A widely used strategic technique is the PDCA [Plan, Do, Check, Act] Cycle as described by Deming (1989). Spengler (1999) endorses PDCA as a systematic approach to quality issues using supporting evidence from Straker (1995) and Summers (1997).

This technique was originally the concept of Shewart (1931) [the Shewart Cycle] in the US during the 1930's. It was Deming however who really promoted the principle during the 1950's and is now commonly known as "the Deming Wheel" (see Figure 2-1). The flexibility of the technique is generally accepted; Meisel (1991) for example, explores a PDCA cycle for experimentation management. The PDCA principles are widely acknowledged as key and even applied within more modern cultures, Hoshin Kanry for example (Reshef, 2001), described by Stark (1998), as a systems approach to the management of change in critical business processes.

The "Deming Wheel" is a continuous improvement tool; this IQEE improvement campaign will utilise this technique as an overall framework and for this project offer a single iteration of the improvement cycle. In practice, the technique should be adopted as a continuous improvement exercise, where the general principles continue until the process can be improved no more, in practise this will continue well beyond the timescales and scope of this particular project.

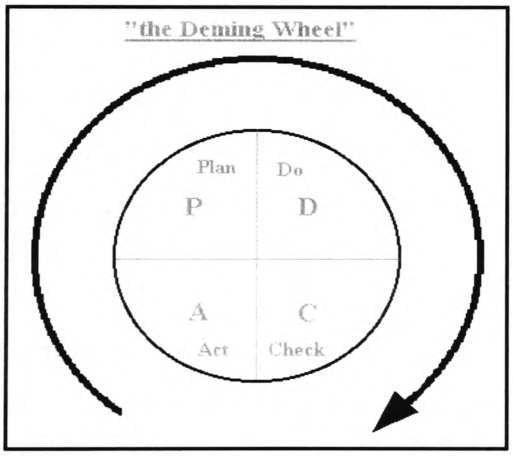


Figure 2-1 - "Deming Wheel" - PDCA

2.3.1 - PDCA: Generic Principles

- Plan – to improve the process, by first identifying what is going wrong and identify iterative techniques.
- Do – identify the changes required and wherever possible model the changes.
- Check – whether the achieved change equates to the model predictions, in addition check for further problems.
- Act – by implementing the changes in the process.

To follow through the above PDCA into the MOVPE operation at IQEE, the basic activities require further derivation and specific definition. These may be summarised into a specific project activity summary "Deming Wheel" (Figure 2-2).

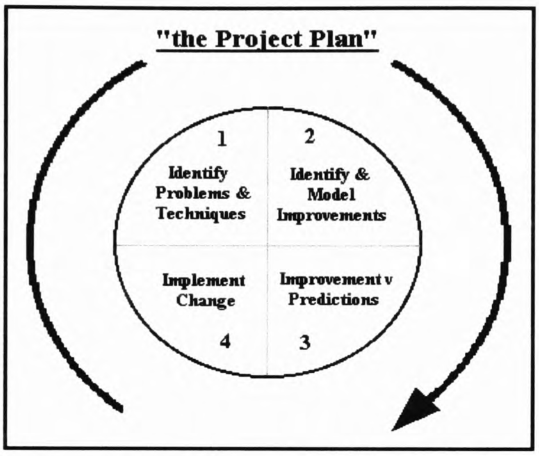


Figure 2-2 - "the Project Plan" - PDCA

This differs substantially from the PDCA defined within the "Hoshin Method", (Reshef, 2001) a "top down" deployment strategy. The generic definitions of the PDCA objectives are organisationally global, for example "Plan":

- ➢ Establish enterprise mission, vision and quality policy
- ➢ Devise long and medium term management strategies
- ➢ Collect and analyse information
- ➢ Plan the targets and the means to achieve them
- ➢ Establish metrics and procedures for checking.

This method has very similar foundational demands of those previously discussed concerning "Six Sigma"; an understanding of the process variables effecting product variation is essential as a foundation for controlled and structured improvement.

2.3.2 - PDCA Exercise applied to MOVPE

2.3.2.1 – Plan: 1

The Plan for Process Improvement requires the process problem/s to be defined and understood. Once the causes of the specific process problems are identified then solutions can be identified and appropriate plans derived and prepared for implementation. Typical strategies and cultures should be adopted here, however; "Six Sigma" for example is based upon a generic understanding enabling the process to be mapped using such techniques as Taguchi using "Design of Experiment" [DoE] strategy. This DoE strategy is a successful technique (Masters, 1999), and is quoted by Orszulik (No Date) as a method of investigating interactions between variables. It would be an option to fully exercise the process via DoE across all of the differing platforms and all of the differing process's, however again it is unknown what in the process effects what in the product, suggesting a subsequent use for the tool rather than immediate. To operate today would require the DoE requirements to include changing all of the basic machine control as well as process variables [a large number of iterations and immense cost]. In recent years however, many thousands of runs have been carried out and for each run a lot of data collected, offering no direct return. If this data were to be organised or operated and successful, it may negate the initial need for additional experimentation for the initial stages.

In contrast the Kaizen strategic style is more business process orientated, Keen (1999) summarises Kaizen typically as:

"the implementation of kaizen reflects a radical commitment to an entire way of operating that requires floor-to-ceiling change in management, work, manager-worker relationships, discipline, decision making, and the organization of knowledge, that transforms an organization into a federation of problem solvers. Continuous improvement treats every

variance from target as a problem to be solved and everyone as a responsible contributor".

The key query with the process and business profile of IQEE is whether the process is mature enough to support this type of culture. The answer has to be positive, with the caveat that the underlying process requires evaluation in the small batch mode [today] in preparation for larger scale manufacturing and company wide cultural change [tomorrow].

To gain this understanding of the overall process performance particular evaluation techniques will need to be utilised. It is defining/constructing these evaluation techniques that is the single most critical activity to the success of this project. This will entail the evaluation of the MOVPE process used to manufacture compound semi-conducting material structures. This can be achieved by identifying the potential strengths and weaknesses of the process using (SWOT Analysis, Mind Tools, 1995/8) a generic analysis tool that can be used in many applications as a preliminary decision-making tool.

Many examples exist for SWOT [Strengths, Weaknesses, Opportunities, Threats] analysis, a typical exercise carried out for the University of British Columbia by de Bruijin (2000), considering the organisation and effective service levels of the Library function, Jensen (1995) identifies and utilises SWOT to consider personal evaluation.

When undertaking a process overview, to identify the potential strengths and weaknesses of the technology, the primary question is "where do you start?" The practical starting point is to review the available data; there is normally data suggesting that the process requires improvement; this can take the form of customer feedback, low profitability, high scrap rates etc. Mears (1995) offers an example in his book as a reason for improvement being customer complaints rising chronologically [a "sole monitor"], however this may in real terms, when plotted to the number of satisfied orders be a reducing percentage. It is therefore key that any decisions made on improving the process are holistic, quickly satisfied and robust. Most companies, including IQEE have a vast amount of historical performance data buried in the profit and loss [P&L] summaries.

Utilising this data, it may be easy to quantify the need for improvement within an overall business management strategy. This data will require evaluation using a technique that identifies an outcome in terms measurable qualitative dimensions rather than those typical to a normal P&L account. Evaluating the output variables of such an analysis as financial risks to the business or business risks.

The proposed method for carrying out the business analysis is a business risk analysis of the process, identifying the major "blockages" in the business performance. The specific "MOVPE Risk Analysis" will require a detailed summary analysis of readily available data, the most process specific business information that is produced by the company, is circulated on a monthly bases as business unit data for its management team.

Business risk analysis is typically used in one of two ways, i/-as a comparative economic prediction tool for evaluating change and investment impact/risk on cash flow on modelling of company, (Financial Training Partners, 1999 and Mills, 2001) or project profit and loss accounts (Angelelli, 1997 and Harris, 2000), or ii/-as an evaluation technique in "Disaster Recovery Planning" (Business Continuity, 2001). Angelelli (1997) seems to offer the most appropriate interpretation, however, using the principle as a sensitivity analysis for financial modelling but not as a technique as a means of reviewing process failure losses, BRA is described in this recent paper as a *"cost and schedule evaluation technique which* *quantifies risk and offers a defensible decision-making rationale".* The expectation of using a form of business analysis [BRA] is an outcome that identifies the business impact hierarchy for failures, which differs to other current interpretations.

The business risk analysis will identify a set of key failure modes, these will be reality checked using a standard MTBF [Mean Time Between Failures] principle as a technique to quantify the anticipated failure rate against time for each effect. This MTBF will however be a mixed function of both hardware and process failures offering a mean time between "Business Failures". Thus offering a priority as a function of the mean time per machine type and overall that can be evaluated against the BRA. De Bruijin (2000) describes a typical MTBF analysis in its standard form, operating on generic process effects. A singular major weakness with using MTBF is identified by Bergman (1994), raising the issue that as equipment ages it may be expected that the plant MTBF reduce accordingly, however this may be a key failure effect, and therefore making MTBF an ideal tool for a compound semiconductor improvement programme. This basic form of analysis could be used in differing forms throughout this improvement programme, as a medium to "sort data" into a hierarchical form. In certain instances a typical Pareto Analysis sorting technique may be utilised, as detailed by Juran (1988) and well summarised by HCI (2001), as a key technique for resolving the dilemma of deciding which activity should take priority? One crucial advantage of this rule is that it is quick to assimilate, however it must not be considered to be a scientifically accurate estimate of priorities. In summary the available information should include the largest failure mechanism as identified by a business risk analysis and the most frequently occurring failure offered by the MTBF technique.

To proceed with the overall investigation a core technique-enabling analysis of the failures that are blocking business performance is required.

This analysis must be capable of identifying the failure of the system from the downstream process effects; a good bottom up technique is therefore required. Vandenbrande (1998), comments on such a technique. His claim for this technique is that it is "*a stepwise approach to quantifying the effects of possible failures, thus allowing a Company to set priorities for action*". This technique is Failure Mode and Effects Analysis, normally referred to as FMEA.

Gilchrist (1993) describes FMEA as, "a systematic method of seeking out potential causes of failure before they become a reality", to derive a qualitative process improvement path. FMEA as described also by Stamatis (1995) is an extremely powerful tool; "*The fundamental cornerstone of FMEA is the need to improve. It is this need that becomes the impetus for change. Change in this case can be modifications, improvements, and/or a complete change. The idea that the FMEA proposes is not revolutionary; it is a simple yet systematic methodology used to approach problems, concerns, challenges, errors and failures, to seek answers for improvement.*" The principle is quoted, as simple; in reality the overall principle is very flexible and could be modified to suit a complex situation.

The history of FMEA, (Kinetic, 1999) discipline and technique was developed in 1949 by the US military as a reliability evaluation technique. Yang (1997) claims that the typical FMEA oversimplifies a system into the binary states of success and failure.

Using an FMEA technique it may be possible to analyse the results by processing the resulting data from the business risk analysis through to effects by identification per platform [Manufacturing Unit] as manufacturing blockages, prioritised by the financial losses and the MTBF.

However FMEA in a standard form appears unsuitable for direct use in this analysis of the MOVPE process for several reasons:

1/ - the Failures within the MOVPE process are multiple causes and multiple effects. This multiplication effect may be defined easily if reversing the FMEA principle: each effect may source from many causes, and subsequently these causes may result from many differing failure mechanisms. Attempting to identify these relationships within the classical FMEA is very complex and time consuming, it is possible, however with the potential of the effects changing with each product type and the product type lifetime in manufacture being small it is essential that the technique used concludes quickly. Price (1998) summarises FMEA "*usually only considers single failures in a system*".

2/ - FMEA is a technique used for predicting cause/effect relationships, predominately in the design (Skewis, 1985) or R&M stages for a system/s, for this process improvement programme, a lot of data exists that show the effects of failures. FMEA also may be operated on historical data, the inverse of the norm, working back from effect to failure mode. This will entail feeding the FMEA by back-engineering the process failures to identify the currently unknown grouped causes from a business risk analysis (this is developed in Chapter 5)

3/ - This programme of work will encompass multiple processes, although the equipment and process is generically all MOVPE, the equipment base and the run processes [product lines] differ. There are a few industrial specific [general process related] interpretations of FMEA as defined by Trahan (1999) and Whitcomb (1994), where both papers discuss the implementation of FMEA in Semiconductor Manufacturing including component fabrication. Traham considers "reducing risk in a Fab"; whilst Whitcomb, considers "FMEA System Deployment in a Semiconductor

Manufacturing Environment" the process considered however is linearly integrated. The process of III/V MOVPE is a vertically integrated process rather than linear as used in the Silicon semiconductor industry. Linear activities, are carried out in sequence and potentially on very differing equipment, each step is individual, whereas the compound semiconductor vertical replaces the Si semiconductor linear steps with one operation.

Some specific similarities occur however, as discussed by Stamatis (1995) in his chapter entitled "FMEA and the Semiconductor Industry". His evaluations for FMEA again revolve around the Silicon semiconductor Industry. It is the Structures to be grown that define the complexity of the process; a Si component typically undergoes 250 process steps in series, whereas an III-V structure can undergo 500 process steps within the epitaxial growth.

A huge amount of prior art exists for the development and improvement of the structures and modifying the fundamental process variables to accommodate material structures and characteristics. No qualitative evaluation exists however for the global handling of the process.

Investigations into FMEA prior art also suggest that no direct technique exists to support a multi cause x multi effect complex FMEA, [further derivation is discussed in Chapter 6] with no direct boundary limits using historical data. Price (1998) confirms this, where the authors in this paper define an FMEA for multiple failures. The considered multiple failures however define series multiple rather than compound multiple. Sankar (2000) in their paper go some way to offering a hierarchical "Multi-Effect" technique, however linked causes and multi-causes are not considered. The differences here lie in the fact that with MOVPE an effect may have up to twenty differing causes and those causes again numerous linked generic failure modes. Hawkins (1998), discuss the analysis of complex engineering systems, the definition here of a complex system is two closed loop control system, in comparison to evaluate the failure mode potential for an MOVPE reactor some one hundred control systems are harmonious. Multi-Purpose Casual Reasoning is defined by Bell (1992) for application with complex systems. The applications detailed by Bell describe an application where numerical operators can be applied to replace the normal requirements for "Expert data" operators in a typical FMEA, however to derive an algorithm the system and or component failure mechanisms require definition and understanding. This differs to Russomanno (1992), who defines an expert system to assist the design process for FMEA operation. This system could be used for multiple failures, as the FMEA is operated by the expert system [XFMEA], providing the expert system is appropriately configured. However an expert system for the MOVPE process is potentially the only way qualitative process problem solving on a 24hr 7-day basis may be achieved. In 1998 IQEE set an objective of developing an intelligent expert system specific to the III/V compound semiconductor process of MOVPE. This work was initiated as a part of the evaluation work of this project, the basic background for this, can be evaluated from Michael (1999), for the background, and Richards (2001) for the system modelling.

A specific FMEA based technique therefore requires developing to be capable of identifying the generic failure modes, relative to multi-platform evaluation and weighting. How these relate to the operation and where the responsibility for the failure lies [for example, error, calibration, environmental etc.] will require additional investigation.

Development of additional overview and analysis techniques should be involved in the improvement of decision making, resulting in a "reasoning mechanism" that is directly appropriate to the process. Much research has been carried out investigating the trade-offs between multiple objectives

(Vincke 1989, Yu 1985 and Barber 1999). To quote Barber (1999), "*For manufacturing environments in general, alternative solutions may not be enumerated and high uncertainty may be involved*". It is essential therefore that that all activities and the impact and influences on the overall company objectives are identified, the primary evaluation step is to identify the key contributing activities.

A full understanding of the manufacturing activities details will be required, using a process flow diagram as typically detailed by Kolarik (1995), with the potential influences on the process that each component or activity will have. Caudell (1997) briefly outlines a similar principle. These techniques however require additional analysis to review the specific influences and/or impact that each activity imposes upon the holistic process. Utilisation of a typical system P-diagram with signal to noise factoring, as detailed by Phadke (1989), solves the influence quandary. The classical P-diagram technique ["P" standing for Process or Product] is typically used when supporting Taguchi techniques in the treatment of static optimisation techniques [factorial organisation]. Examples of this is include i/ a "Wheatstone Bridge" robust design exercise using the Taguchi system of quality engineering as detailed by Dixon (1999) and ii/ a modified "P" diagram and signal to noise ratios using Taguchi methods in a conference Keynote presentation by Taguchi (2000). The classical P-diagram however has the potential of offering an extremely flexible and powerful means of organising process effects, influences and outcomes from either a component or organisational viewpoint. The standard technique however will require modification to enable multi-input evaluation of a series activity, each with differing signal to noise [SN] factoring and influences all independent of each other, offering amplification or damping effects on the overall output, Belavendram (1995) discusses and emphasises the criticality of the SN ratio on the output evaluation of the analysis. The general use of the P-diagram will require supporting with general analysis tools to identify the activities and their influences; the tools used are generically similar to those developed by Bertalanffy in 1936, known as "General Systems Theory" as described by Begley (1999) referencing Gillies (1982).

Improving the process will require some fundamental problem solving and decision-making activity. To remove any uncertainty and ensure consistency, the decision-making should not be based upon rule of thumb [heuristic decision-making] or simplistic reasoning. Kim (1991) discusses the reasoning behind complex decision making and defines an objective of "*to better identify the nature of difficult problems, model their modes of resolution, and explore how they may be supported by intelligent tools*" and concludes with a statement that "*knowledge based systems can be used in various ways to enhance both the effectiveness and the efficiency of decision making*". Kim's concluding advice will be used to operate a decision making tool for the Process Improvement plan.

A reasoning mechanism will therefore require definition. The concluding benefits should include the identification and prioritisation of the essential variables and potential improvement paths for the MOVPE process, equipment. Effective solutions to improve process capability and stability will also need detailing enabling achievement of the full business potential of the process.

2.3.2.2 – Do: 2

The exercises and techniques as listed within the "Plan" section will be operated using data available for the process and business for the year 1997. As many data sources as possible will be collated and evaluated, reducing the potential impact of contaminated data. The techniques defined in section 2.3.2.1 – Plan: 1 should be used with the available data culminating in a series of prioritised detailed manufacturing blockages. The detail of which will outline the process problems and their independent impact upon the whole performance.

2.3.2.3 – Check: 3

Verification of the resulting recommendations is essential, the current data sources have some potential of conflicting data, and as such multi-handling of the same data using differing techniques will prove useful as a comparator. Any change to process variables can cause the product to change specification and also incur major expenditure. It is essential therefore to use dual monitors to enable re-conciliation of the projections prior to any proposed changes. This will involve comparison of derived variables from differing techniques:

Hard data Evaluation
Business risk analysis
Resulting FMEA analysis

The resulting development work of this project should have an impact on the potential business performance of IQEE and the way the process is currently utilised. The supporting evidence for this is presented using normalised "Multivariate Statistical Process" data; Weighell (2000) discuss the typical handling of such data. This in turn should result in a more cost-effective process and enable IQEE to deliver the "Customer Ideal", namely [a safe, identical product, each time, to an identical specification and performance, at an affordable price].

2.3.2.4 – Act: 4

The anticipated improvement in business performance, should offer major cost reductions in manufacturing which can be both, passed on to the customer and enable IQEE to support large volume orders effectively whilst maintaining profit. The prospect of addressing additional electronic and opto-electronic device markets that the current process is not suitable may also be achieved.

Any derived benefit to the group III/V compound semiconductor manufacturing process will offer a step forward, transferring IQEE's process technology toward a more production style of process with the appropriate reliability and repeatability requirements.

The actual modification of the process may require some system re-design. For this the typical DFMEA [Design FMEA] will be used for evaluation purposes, and will follow a typical review process similar to that defined by Montgomery (1996). The resulting operators within all of the FMEA, derived RPN's and subsequent techniques will be operated and supported by spreadsheet or database operation, this will enable quick and accurate algorithm operation and comparison. This will compare favourably with the comments and conclusions of Kukkal (1993) and their operation of databases for automating FMEA exercises.

The cyclic involvement of the PDCA technique is infinite and will be used in a continuing process improvement plan. This project however will follow a single cycle of the exercise. Recommendations for further development and improvement beyond the single cycle will be included within section 9.5 - Developments.

2.4 - Techniques & Sequence

The success of this project relies upon the use, derivation and modification of several very common, key "Quality Tools", some of which may require novel interpretation to meet the needs of the overall project, a complex manufacturing process improvement for compound semiconductor material manufacture using the MOVPE process.

The generic framework for the project relies on a general technique known as PDCA [Plan, Do, Check, Act], the Deming Wheel. Within each of the four listed activities additional techniques are used to support the objective of each section.

The majority of novel and standard techniques will be undertaken within the planning stage, where the first activity in the plan stage is to execute a partial SWOT analysis of the process, defining the strengths and weaknesses. This identifies the generic opportunities for improvement pre-analysis, and defines the key variables that are used to conduct an investigation into the failure modes of the process.

Standard FMEA may be used resulting in a generic hardware failure pack defining the potential causes of any identified effects. This analysis should be generic to the process failures modes on a site wide basis within IQEE, however many differing products are run using differing equipment, running differing processes. A modified FMEA may have to be developed and used, to derive specific to each manufacturing platform the cause and effect relationship.

Process flow analysis may be undertaken using a function of a classical P-diagram technique operating a signal to noise relationship, to identify the activity influence and process flow techniques. The manufacturing process of MOVPE is a complex activity, the supporting activity and infrastructure to define, program, machine set-up, material measurement and evaluation has to be functionally as complex as the practical process. This complexity renders the operation of a standard P-diagram analysis extremely difficult to handle. The P-diagram technique, with hierarchical derivation however offers a sound basis for derivation of a complex technique.

2.5 - Chapter Summary

This chapter offers the basic plan for the project success, a review of the history of quality as a culture, outlining an overall quality strategy as the means to improve and evaluate as a business management strategy. The Shewart cycle is selected and defined as the overall structural tool for the process improvement process.

Many generic acknowledged quality tools are evaluated for suitability and potential, justification in use, and a literature review are undertaken. The potential of evaluating process performance using typical profit and loss financial data, in an original business risk analysis, offering a real interpretation on impact, justification and prioritisation relative to business performance, but linking with the failure modes.

FMEA is introduced as a diagnostic and prioritisation tool, the intrinsic difficulties of using this technique in a complex situation are evaluated relative to prior art; suggesting that no specific technique is currently available to satisfy the independent analysis. Requiring a technique development to satisfy the objective, of evaluating multiple processes with common mechanisms

A process mapping technique is described using a mixture of both process flow and P-diagram techniques, utilising the signal, noise, and control factors from the classical P-diagram and superimposing the influences in flow chart form. The offered combined technique may have the potential of fully mapping the influences of each activity, on the holistic process.

The techniques as defined in this chapter, their practical application and subsequent analysis are developed and used later in Chapters 5 and 6.

The subsequent chapter sets the scene for the technology and defines what has to be achieved by the process of MOVPE to satisfy its day-to-day requirements with respect to material capability.

Chapter 3 - Compound Semiconductor Summary

3.1 – Introduction

The preceding Chapter defines the plan and tools that are to be used in the overall improvement programme for the process. This Chapter defines in basic terms, a background description of the materials, materials technologies and includes the evaluation techniques [characterisation] of the grown materials. To enable evaluation of a process for improvement and derivation of a controlled improvement programme, it is essential that an overview of these issues are presented and understood. Based upon the number of hardware configurations that have to be modified to satisfy the process requirements for each differing product type, increase the capability normally results in increased complexity. Recent experiences contribute a general heuristic statement, that the "flexibility of a process is directly proportional to its complexity". The influence of each of the topics discussed within this chapter offer to the overall complexity of the issue of "Process Understanding and Improvement".

3.2 - Products & Materials

A commonplace word that is in daily use is "semiconductors"; this describes a group of materials without which our lives would be significantly different today. It is therefore essential to the project to answer a critical question:

What is a Semiconductor?

Many definitions exist for the term semiconductor; this is functionally relative to the science base from which the interpretation emanates, for example Material Science, Electronic Engineering, IT Theory, for typical differences see Academic Press (1996) and Techtarget (2000). The definition that appears to substantiate the basic principles is the Microsoft Encarta (1999) definition. This definition with additional interpretation is:

Any material, in either liquid or solid phase with the ability to conduct electricity more readily than an insulator, but less readily than a metal at room temperatures, is a semiconductor. Typical metal conductors such as Copper, Silver and Aluminium have excellent conductive properties. Insulating materials such as diamond and glass have extremely poor conductive properties.

Temperature has a major effect on the conductivity of pure semiconductors, at low temperatures the material behaves as an insulator, at high temperatures the material behaves as a conductor. The introduction of light or impurities to the material can also change the conductive properties of semiconductors. Semiconductor conductive performance can approach that of metals under certain conditions.

The most common semiconductors include elements and chemical compounds typically:

Silicon
Germanium
Selenium
Gallium Arsenide
Indium Phosphide
Zinc Selenide
Lead Telluride

The single most critical property of these materials is their retrograde insulating ability, as the material temperature increases the conductivity increases also. In a pure form for example Silicon is non-conductive, the outer or valence electrons of an atom are paired and shared between atoms, making a covalent bond that holds the crystal together. The valence electrons are "non mobile"; the material therefore is incapable of conducting electrical current. Introduce heat or light energy and excite these valence electrons such that the bonds are broken, the valence electrons are then “free” to conduct current.

What is a typical “End Product”? [Semiconducting Device]:

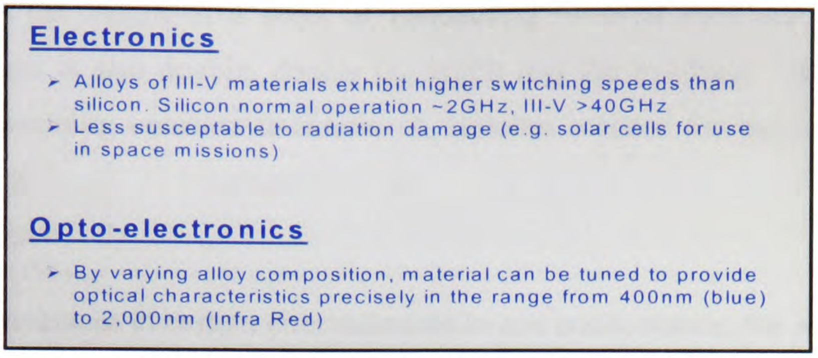
A transistor is a typical device manufactured using semi conducting materials. These are devices that are generally, operated at ambient temperatures, the materials used thus require doping [minute quantities of foreign elements/impurities are added], resulting in an abundance [n-type] or drought [p-type] of “free electrons”. The combination of both n & p type materials can result in a diode being produced.

Connect this diode to a battery p side to the battery +ve and vice versa. Electrons are repelled from the battery –ve terminal and pass unimpeded to the p region, which lacks electrons. Reverse the battery to material relationship, the electrons arriving in the p material can only pass to the n material with great difficulty, as the n material is already full of free electrons, the current is therefore almost zero.

As previously discussed, IQEE is a manufacturer of Group III/V compound semi-conductors. A secondary question now arises:

Why III/V Semiconductors?

Silicon albeit by far the most commonly used semiconductor has some fairly major limitations, the advantages of using alloys of III-V or II-VI are identified, see Figure 3-1.



Electronics

- Alloys of III-V materials exhibit higher switching speeds than silicon. Silicon normal operation ~2GHz, III-V >40GHz
- Less susceptable to radiation damage (e.g. solar cells for use in space missions)

Opto-electronics

- By varying alloy composition, material can be tuned to provide optical characteristics precisely in the range from 400nm (blue) to 2,000nm (Infra Red)

Figure 3-1 - Fundamental Material categories

IQEE concentrates on mixing elements from Groups III & V and achieving an alloy with similar properties to that of a standard Group IV semiconductor [Si], with compositional and structural variation the broad band of required devices may be achieved. Stringfellow (1999) discusses the basic principles of MOVPE.

One of the company's original objectives was to become the world leading custom epitaxy house. This objective is satisfied at a cost, the business of manufacturing the most complex opto-electronic and electronic material structures on a small scale stretches the business, the staff and the process equipment beyond their practical limits.

3.2.1 - Material Properties

Resistivity

The physical effect that opposes the flow of electrical current through a conductor [and by Ohms Law-the voltage across it] is the Resistance. Resistivity is expressed in terms of Ohms per cubic centimetre [at 20°C].

Resistivity is a materials property. If a material is moulded or shaped so that it has specific dimensions: it then takes on the property of resistance. [Resistance is a function of the material, its dimensions and temperature]. The Sheet Resistivity of a material is measured in Ohms per square.

Double the length of a sheet of conducting material then the resultant resistance is also double, double the width and the resultant resistance is half, assuming constant thickness. A 500ohm resistor for example, is a string of 5 x 100 ohms/square in series. For typical material resistivities, see (Figure 3-2).

It is convenient in certain circumstances to use conductance, the reciprocal of resistance.

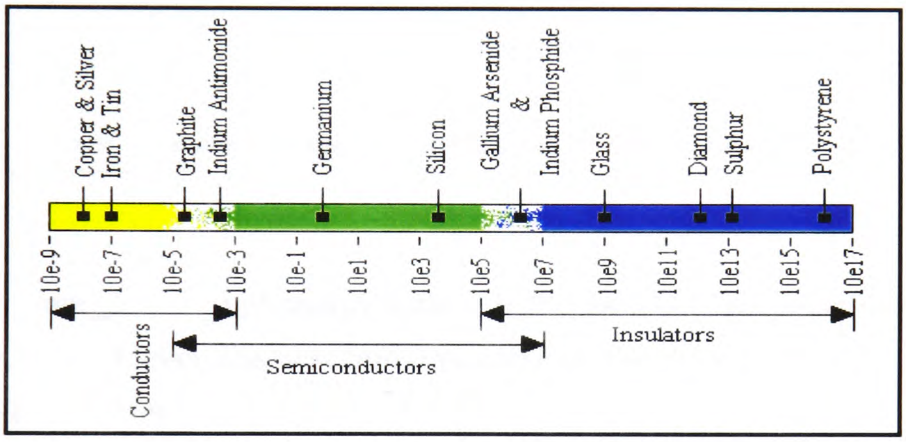


Figure 3-2 - Material Resistivity Comparison

Conductivity

The material property, that describes the ability to pass an electric current through a material. Conductance, as previously stated is simply the inverse of Resistance [G=1/R]. All materials are relative conductors; the definition between conductors and insulators is relative to degree rather than a physical effect. The concern here is with the "outer" or valence electrons of an atom. It is convenient to consider the atoms and hence electrons collectively, referencing to the valence Band.

This valence band has a particular energy level associated with it; these levels are described in Figure 3-3. The differences between the Ec & Ev plots in Figure 3-3 are known as the "Energy or Band Gap".

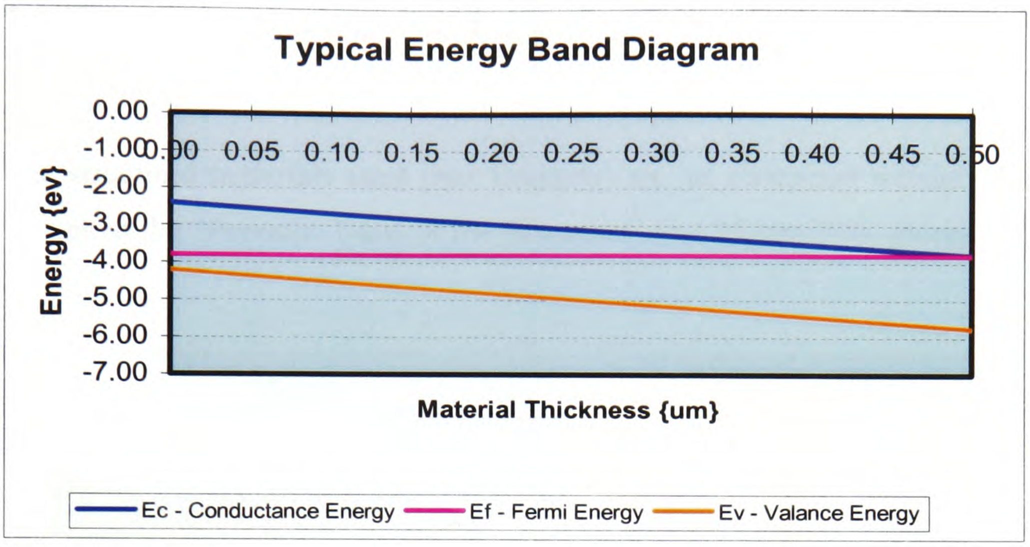


Figure 3-3 - Energy Band Diagram

If an atom gains enough energy [heat or light], the electrons "jump" up to a new, discreet level. The next convenient level is the conduction band. Once an electron transfers to the conduction band, it becomes "free", mobile.

It is evident that the easier it is for an electron to "jump" to the conduction band, the easier it is for the material to allow a current to flow, or conversely, the lower the resistance and resistivity.

The gap between the conduction band and valence band is the band gap and normally measured in Electron Volts [eV]. A small band gap allows electrons to cross easily [Conductors]. If the band gap is large, it is difficult for the electrons to cross [Insulators], unless conductive materials are introduced [Dopants]. Materials where the band gap is in between the two electrical definitions are called semiconductors. There is a direct relationship between the band gap of a material and its wavelength. Some common materials are listed in Table 3-1

Material	Sn	Ge	Si	InP	GaAs	GaP	C Diamond
Band gap eV	0.08	0.67	1.12	1.35	1.42	2.26	5.4
Wavelength um	15.5	1.85	1.11	0.92	0.87	0.55	0.23

Table 3-1 - Relationship Comparison

The structural materials used [not Dopants] are all contained within two groups in the "Periodic Table of the Elements" (see Figure 3-4), groups III & V.

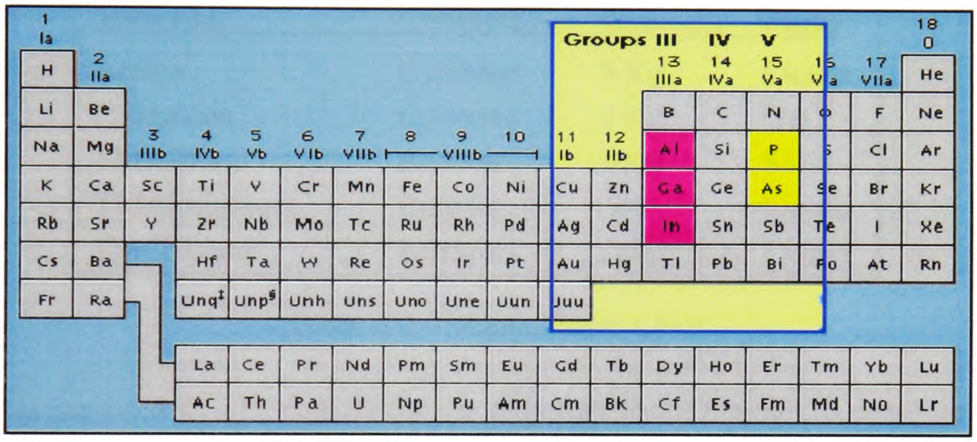


Figure 3-4 - Periodic Table of the Elements

Silicon as a material is found in Group IV of the table, a compound semiconductor is manufactured as a functional mixture for a group IV for example an III/V, an II/VI etc. In the groups IIIa and Va [columns 13 & 15] the "full set" of materials that are used by IQEE in the manufacture of compound semi-conductors can be found: -

Group III –	Aluminium Gallium Indium	*Group V –*	Arsenic Phosphorous
Dopants -	Can be found all over the periodic table Silicon Zinc Selenium Ferrocine Carbon Magnesium		

The source materials are not used in the direct form listed, for example: -

Arsenic – As used as Arsine - AsH_3
Phosphorous – P used as Phosphine - PH_3
Indium – In used as Tri-Methyl Indium - $In\ (CH_3)_3$ - TMI
Aluminium – Al used as Tri-Methyl Aluminium - $Al\ (CH_3)_3$ - TMA
Gallium – Ga used as Tri-Methyl Gallium - $Ga\ (CH_3)_3$ - TMG

The available type of source and the form are different (See Table 3-2) for the differing material groups also.

Material	**Container**	**Quantity**	**Form**
Arsine	Cylinder	3 Kg	Liquid
Phosphine	Cylinder	3 Kg	Gas
TMIndium	Bubbler	200g	Solid
TMAluminium	Bubbler	200g	Liquid
TMGallium	Bubbler	200g	Liquid

Table 3-2 - Source Form Chart

It is essential to understand how the materials listed interact as compounds in the final product and the growth process. The materials in their source form change state in the process. The molecular bonding of the source materials "break down" when heated above each material specific "cracking temperature", thus releasing the material in the required form. For example when AsH3 is heated above 450°C the As-H bonds fail releasing the As [Arsenic] for use within the process [Pyrolysis], the transportation details are discussed by Pena-Sierra et al (1991).

For Example: -

Injected into the Cell is: $H_2 + AsH_3 + TMI + TMG$

Each of the material compounds listed can be broken down or "Cracked" at a specific temperature, into its source elements.

Equation 1: $H_2{+}AsH_3{+}In\ (H_3)_3 \Rightarrow 120°C{+} \Rightarrow InAs + H_2 + C_2H_6$

Equation 2: $H_2{+}AsH_3{+}Ga\ (CH_3)_3 \Rightarrow 120°C{+} \Rightarrow GaAs + H_2 + C_2H_6$

These are approximate determinations

The epitaxial growth is initiated by allowing the group V material, AsH_3 in this instance to be introduced to the cell below its “Cracking Temperature”, for two reasons.

1 – To protect the group V material in the Substrate, by maintaining a group V overpressure in the cell the group V material in the Substrate is prevented from being driven off during cell “Warm Up”.

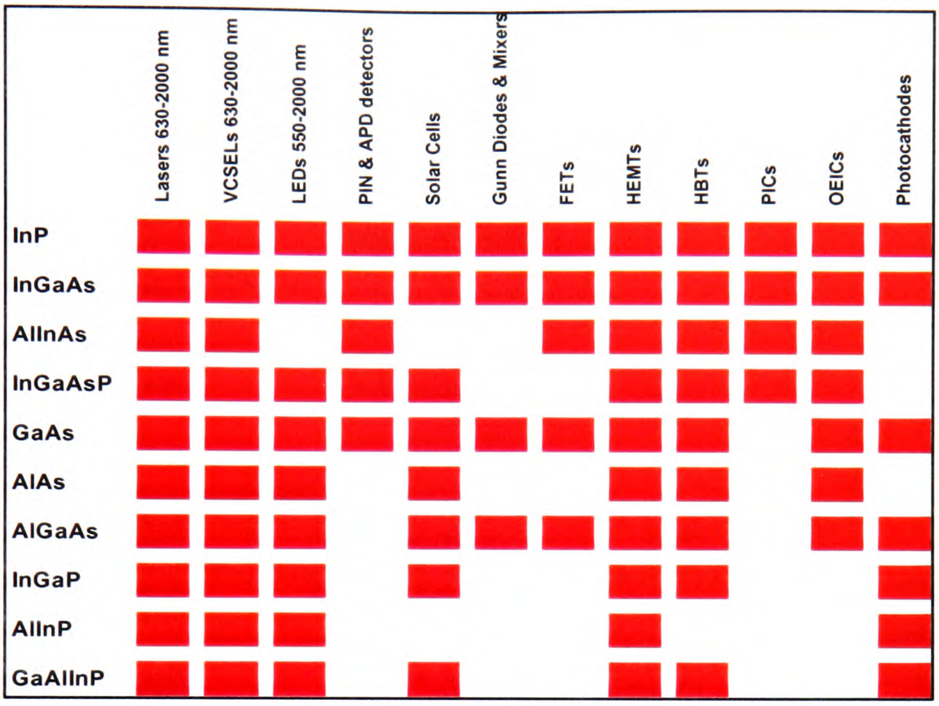
2 – To condition the cell and its components, to seal in any particular materials being “driven off” from the previous run (parasitic deposition). Commonly known as the Cell Memory Effect.

At this point, no “Metals” are present in the process; growth will not therefore take place. The Group IIIs are then introduced at the specified Growth temperature.

The materials in equation 3 are a typical example of a resulting ternary structure -

Equation 3: $H_2 + As + In + Ga \Rightarrow \mathbf{InGaAs} + H_2 + C_2H_6$

This describes a single component in an overall structure; the principle however is identical. Many types of “device” are grown utilising these materials and this process, to offer some form of capability identification the following (Figure 3-5) chart is used to describe the overall potential. It is evident from Figure 3-5 that the product and material matrix grouping range is very broad. One material is listed for each structure type, this is typically the definition of the “active” layer of the structure, and the overall structure may contain many of the listed materials.



	Lasers 630-2000 nm	VCSELs 630-2000 nm	LEDs 550-2000 nm	PIN & APD detectors	Solar Cells	Gunn Diodes & Mixers	FETs	HEMTs	HBTs	PICs	OEICs	Photocathodes
InP	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
InGaAs	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
AlInAs	🟥	🟥		🟥			🟥	🟥	🟥	🟥	🟥	
InGaAsP	🟥	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥	
GaAs	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥
AlAs	🟥	🟥	🟥		🟥			🟥	🟥		🟥	
AlGaAs	🟥	🟥	🟥		🟥	🟥	🟥	🟥	🟥		🟥	🟥
InGaP	🟥	🟥	🟥		🟥			🟥	🟥			🟥
AlInP	🟥	🟥	🟥					🟥				🟥
GaAlInP	🟥	🟥	🟥		🟥			🟥	🟥			🟥

Figure 3-5 - Product / Materials Mix

The company had an objective to rationalise the product and customer base of the business. This rationalisation allowed the company to focus its business and resources into a less widespread device spectrum. The resulting benefit of deriving an understanding on, process, device and structural performance that will transfer IQEE's business from that of world leading custom epitaxy house to that of worlds largest epitaxy manufacturer.

The objective set by the organisation in 1997 was "to establish 8 key products with world class manufacturing capability for each, and develop the appropriate marketing to ensure a high take up by the customer base".

A product strategy for the eight key product lines was defined and is listed in Figure 3-6.

Product Sector	Key Product	Reactor No	Market Drivers	Material Group	Current Status
1	Visible LED's	4	Integrated Displays, discrete LED's for signalling, outdoor displays, automobiles, traffic information systems	GaInAsP	EPI has a well establishhed visible technology base, requires relationship development with customers and equipment development
2	Visible Lasers	5	Digital Video Disk, Bar Code Readers, CD-ROM, medical applications, pointers,	AlInGaP	EPI has a well established AlInGaP technology and an increasing understanding of Lasers. In a good position to be a major supplier, equipment utilisation a performance blockage.
3	Visible VCSEL	4	In development but potential to replace Laser Diodes for DVD	AlInGaP	EPI, the Worlds first and currently only supplier
4	AlGaAs Laser	3	CD-ROM, Laser Printers, Fax etc.	AlGaAs	EPI has excellent technology, some process stability issues
5	AlGaAs VCSEL	1	CD-ROM, computer communications- replacing AlGaAs edge Lasers	AlGaAs	EPI only current World Supplier, has excellent technology, some process utilisation issues.
6	AlGaAs HBT	1-4	Mobile Telecoms, direct broadcast TV, GPS systems	AlGaAs	EPI taking the opportunity to break into large volume market.
7	InP Detectors	6-2	Optical Fibre Telecoms, Instrumentation, Sensors	InGaAs	EPI is currently dominating the InP world market, uniformity and stability issues are allowing Japanese competition to gain foothold.
8	InP Emitters	2-6	Optical Fibre Telecoms, Instrumentation, Sensors	InGaAs	EPI has been a dominant supplier , needs to develop a more stable and uniform LED/Laser product.

Figure 3-6 - Product Priority Chart

The listed, “Large” volume devices “Rely” on the process of MOVPE. IQEE is now in a product technical position to be capable to support most of the markets and supply the best and cheapest material in the world. The major hindering factors now revolve around physical process issues.

3.2.2 - Process Impact Summary

All process’ need to be evaluated, using business, quality and fit for purpose metrics. Typical metrics include:

Profitability
Downtime
Failure Rate
Mean Time between Failures
Process Yield

Critical features of "growing" materials with a complex specification are the large numbers of systems in use at any one time. The larger the numbers of systems in use the lower the probability of success. Requiring machines to have a broad materials and product base requires flexible systems. This requirement also increases the probability of failure. Both system and process problems are frequent, and a major downtime consumer is "Problem Solving".

Each year, resources are consumed, in product related problem solving. The majority of these problems are complex process control issues that growing material to evaluate.

To evaluate a process inconsistency or problem it is essential that the material selections support derivation of the problem. To achieve this objective a complex material system is required, in a simple structure. Grow a layer of pure GaAs on a GaAs substrate; the material crystallinity should be identical [on match], (Stringfellow, 1999). Any changes from expectation would therefore be difficult to detect. The material grouping nomenclature is as defined in Table 3-3: -

2 Materials Compound – Binary	- i.e. GaAs
3 Materials Compound – Ternary	- i.e. InGaAs
4 Materials Compound – Quaternary	- i.e. InGaAsP

Table 3-3 - Material Compound Options

To appreciate the previous comments regarding complexity and flexibility on probability, the following paragraph titled "Nutrient Injection" describes the operation and the impact on probability of the number of materials and systems compound.

Nutrient Injection

A "typical" Grp III nutrient TMG, is sourced in a bubbler (see Figure 3-7), the material is "Picked Up" from the storage vessel [Bubbler] by holding the source material at a specific vapour temperature and pressure. Hydrogen is passed through the bubbler at a specific flow, which is controlled by an MFC [Mass Flow Controller]. The accuracy of this "pick up" activity is a function of four variables:

- Source MFC Accuracy & Stability
- Temperature Accuracy & Stability
- Pressure Accuracy & Stability
- Bubbler Stock Balance

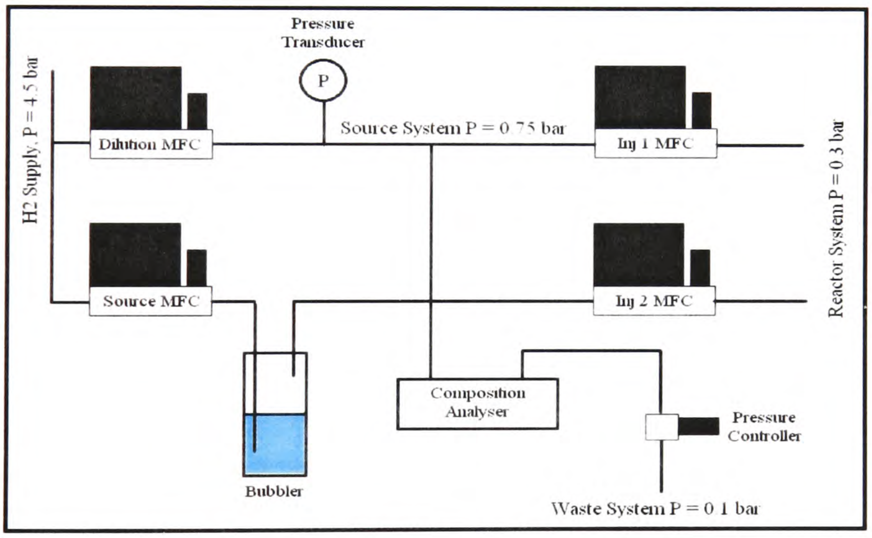


Figure 3-7 - Bubbler System "Nest"

The H_2 source flow with nutrient content is then mixed with an additional H_2 supply, [the dilution] controlled by an additional MFC. This mixed flow is pressure controlled to maintain the bubbler pressure; an allowance on total flow is made for pressure balancing [spill].

The mixture is injected into the growth chamber via two additional injector MFC's, either or both may be switched to the cell simultaneously. An additional variable now exists affecting the "mixture concentration", prior to injection into the run line and eventually the growth chamber [Cell], the actual operating accuracy for the full operating scale.

Any operating range offset and instability will affect all downstream operations unless variation harmonises in opposing directions. If all MFC's are operated within the optimum range with a 1% set point variation, the probability of success for the system (see Figure 3-8) will be (see Figure 3-9):

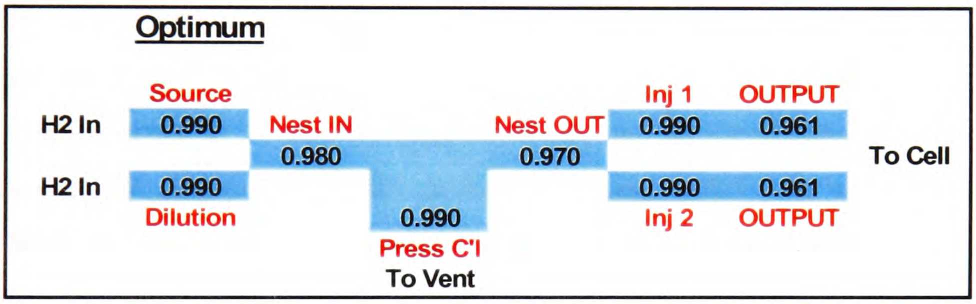
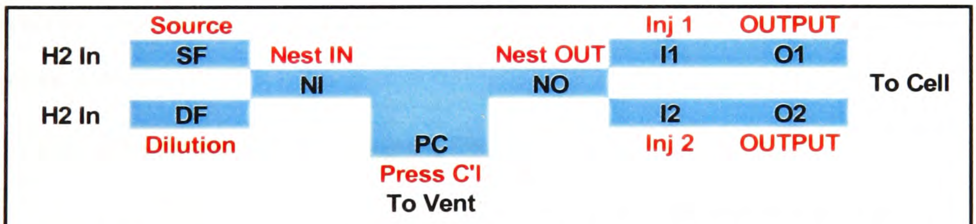


Figure 3-8 - 1% Optimum Range



Probability of Actual Flow achieving Desired Flow O1=((SF*DF)*PC)*(I1*NO)
Probability of Actual Flow achieving Desired Flow O2=((SF*DF)*PC)*(I2*NO)

Figure 3-9 - Generic Range Calculator

<u>Single Source probability of success = 0.961 for each Injector MFC</u>

From Figure 3-9 a 3.9 % error is the best that can be achieved for a structure using a single source, grp III and a grp V in a binary structure. If more unusual and complex structures are to be considered, for example ternary, and quaternary these may additionally include duplicate sources for higher growth rates:

	Binary	**Ternary**	**Quar'ry**	**High GR Quar'ry**
Grp III Potential Probability	**0.955**	**0.912**	**0.870**	**0.831**

Four-grp III source lines, flow structure has a 0.83 probability of achieving target specification, with flows operating within the optimum range.

Returning to the problem solving discussion:

Utilising a quaternary structure with an unstable process, there would be too many potential variables to analyse the problem effectively. It is necessary therefore, to run a material system and structure, which is complex enough to enable stability issues to be identified, yet simple enough to allow subsequent problem solving techniques with a high confidence of effect identification.

A typical ideal structure and material system for this is an InGaAs PIN/Opto-detector. Duplication of this structure in a different material system, AlGaAs for example would enable the identification of Indium related issues.

Looking for Issues with: -	Datum Run	Secondary Run
Al	AlGaAs	InGaAs
Ga	AlGaAs	AlInAs
In	InGaAs	AlGaAs
P	InGaAs	InGaP
As	AlInAs	AlInP

The mentioned typical structure, an InGaAs PIN, a three layer structure grown on a InP substrate, with an 0.5 μm buffer layer of InP grown directly on the substrate with "n" type doping. The second layer to be grown is a 3.5 to 5 μm [typically] ternary layer of InGaAs undoped, using the background doping of the material itself [intrinsic doping] with a capping layer again of InP 0.5 μm thick, doped this time "p" type. From the layer-doping characteristic, it can seen that the derivation of the descriptor PIN, the doping profile from the top of the structure is:

Capping Layer	- **P** type	InP
Active Layer	- **I** intrinsic doping	InGaAs
Buffer	- **N** type	InP

Any variability in the following parameters:

Growth Pressure Control
Growth Temp Control
Temperature Bath Control
Mass Flow Control
Group III Material Pick up Performance [In - TMI]
Material Pressure Control

will cause some variation from the specified product requirement, any one or multiple of the quoted variances may show the same characteristic deviation from specification. For binary material growths, any of the quoted variances, have the potential of giving rise to thickness variation only. The material "grown" is the same as the substrate layer with only one metal organic [group III], for example InP grown on InP substrate.

When ternary or quaternary compounds are involved, "lattice mismatch" is the major effect of process stability (Ryan, 1998). InGaAs for example is a constituent group of InAs and GaAs both with lattice constants, as the material composition changes the overall crystallinity and material quality changes. Compositional uniformity for InGaAs is discussed and detailed by Cureton (1991) including references to material quality.

One of the measurements of material quality is the resulting material composition, relative to grown material and substrate. A customer typical specification for this variance is +/- 500 PPM. Reducing this range to +/-

250 PPM, being an objective that will require reactor cell re-design and both flow control and gas mixing improvement. The accuracy of this material positioning and crystallinity relies predominantly upon the accuracy of the "material mixture" injected into the reaction chamber and the gas flow distribution within.

A typical example of variation impact on specification:

> ***For InGaAs, a typical TMG pick up flow is 200 sccm, + 1 sccm of TMG will shift the material composition -1000ppm***

To conclude: 0.5 % flow instability will meet the customer specification limits, 1 % is the manufacturer single quoted component quoted accuracy [twice the customer specification limit]. It is typical for up to thirty "Mass Flow Controllers" [MFC's] to be used in any one layer.

Taking the single example of flow control, the probability of success can be summarised as:

Single MFC performance - 0.990 **(+/- 0.5%)**
MFC Nest single Output – 0.961
7 x Nests in Use, Overall – $0.961^7 = 0.757$
20 x Others Flow Controls – $0.99^{20} = 0.818$

<u>Cumulative Probability of Flow Control = 0.619 = 62% Success Rate</u>

This assumes that the equipment operates at the design limit issued by the manufacturer. Practical interpretation of product suggests that flow controllers operate at somewhere between 0.9975 and 0.995.

Re-working the above with 0.995 not 0.990

Single MFC performance - 0.995 **(+/- 0.25%)**
MFC Nest single Output – 0.980
7 x Nests in Use, Overall – $0.980^7 = 0.869$
20 x Others Flow Controls – $0.995^{20} = 0.905$

<u>Cumulative Probability of Flow Control = 0.786 = 77% Success Rate</u>

And for 0.9975

Single MFC performance - 0.9975 **(+/- 0.125%)**
MFC Nest single Output – 0.990
7 x Nests in Use, Overall – $0.990^7 = 0.993$
20 x Others Flow Controls – $0.9975^{20} = 0.951$

Cumulative Probability of Flow Control = 0.887 = 89% Success Rate

This approximates the process losses due to flow control instability within the range 77% and 89%, and assumes that all variability is working against the overall product specification simultaneously. The precise impact of the losses due to flow control will be dealt with later in Chapter 5.

3.3 – Material Measurement

Material structures are “grown” using the MOVPE process to a given recipe, structural specification and characteristic performance. The activities involved in determining these characteristics of the grown material are generally known as characterising the material.

Once produced, the structure designed to have precisely defined optical, electrical and physical characteristics, it is necessary to “Prove” that the material does have those specified attributes. Some of the determining measurements are destructive techniques and others not, therefore some measurements are performed on the deliverable wafer, whilst other destructive measurements are implied from test pieces within the same growth run.

The specific characterisation that is required for each structure will be a function of the final device performance, for example: a transistor will not be capable of luminescing [emitting light] but a laser will. The typical characteristics that are measured for general device structures are listed below.

The Layer ***Thickness*** & the Uniformity

The *Morphology* - Surface Texture and Defect Density
The Material *Composition* & the Uniformity
The Material *Impurity Level* - Intrinsic or Doped
The *Electrical Type* of Impurity Atoms - n or p
The *Mobility* of Holes or Electrons through the Material
The *Compositional Purity - Crystallinity*
The Emitted *Wavelength/Band gap* & the Uniformity
The Compositional *Strain* - Tensile or Compressive

The links between the measurement characteristic, the technique and whether direct or implied measurements are listed in Figure 3-10.

Measurement Characteristic	**Measurement Technique**	**Destructive Test**	**Implied Meassurement**
Thickness	Alphastep or Ball Lap	Yes	Yes
Morphology	Laser Particle Counts	No	No
Coimposition	X-Ray Diffraction	Possibly	Sometimes
Impurity Level	Electrical Profiling	Yes	Yes
Impurity Type	Electrical Profiling	Yes	Yes
Mobility	Hall Effect	Yes	Yes
Crystallinity	X-Ray Diffraction	No	No
Wavelength/Bandgap	Photoluminescence	Possibly	Sometimes
Mechanical Strain	X-Ray Diffraction	No	No

Figure 3-10 - Measurement Matrix

3.4 – Chapter Summary

This Chapter offers an understanding of the materials used, produced and derives the basic materials objectives for the process, describing the complexity of achieving the ternary and quaternary material compounds.

The fundamental business metrics that enable evaluation of the process performance are discussed and presented; these metrics are the basic operators within the business risk analysis undertaken in Chapter 5. The problem solving challenges are briefly described, and detailed in an example of a probability of success [PoS] of a typical hardware set up.

The produced material assessment or characterisation measurements are listed; these highlight the potential number of variables that are involved in the evaluation to confirm compliance to specification of the grown material.

The following chapter offers a practical description of the criticality in the process and some process operating systems.

Chapter 4 -Process Equipment

4.1 - MOVPE System Introduction

The basic principles of the process are common across all machine formats [platforms] whether single or multi-wafer. Recipes of materials for each layer are prepared within the gas handling system and bypass the growth chamber until required by the master recipe to enter the growth chamber, this activity runs the gases to vent whilst preparing the flows for each layer.

In a simple structure (see Figure 4-1), the layer recipe may be required to change three times, and be established for in excess of 30 minutes. In a structure that is more complex, layers may be established for 10 seconds and have many hundreds of discrete layers [VCSEL]. The demands on the switching and control mechanisms are far more intense in the more complicate structures. The criticality for homogeneity and clean interface/interrupts remains the same whatever the structure.

The prescribed individual layer recipe flows are transported to the growth chamber using a carrier flow of H_2. Each of the differing "base" flows are transported separately [Group III, Group V, Dopant], it is therefore critical that the specific recipe components all enter the growth chamber at the same time [unless by design], accounting for density, pipe work and flow differences.

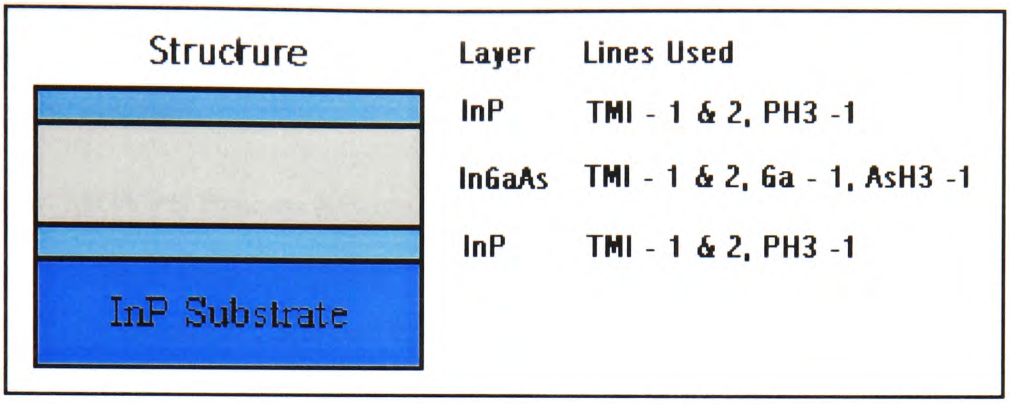


Figure 4-1 - Layer Switching Schedule

Although the physical and engineering principles of MOVPE for both single and multi-wafer machine types are the same for the gas handling systems, the "Cell" gas injection principles are very different, for justifiable reasons.

For the single/dual wafer cells, the gas flow is injected into one end of the chamber (Tischler, 1990); the mixing can be achieved using cell injection design utilising typical Reynolds number evaluation. Depletion effects are compensated for with tube design, with the exhaust gases emerging at the other at a much-increased velocity. The full set of materials for the reaction enters the cell together following mixed injection. There is a heated zone of susceptor exposed to the gas flow prior to substrate, enabling the nutrients to heat and crack effecting pre-deposition prior to the layer growth on the substrate.

For the multi-wafer cells [7-35 wafers/run], the gas flow is injected into the centre of the chamber and radially ejected over the surface area of the chamber. This is to allow the Grp V material to be pre-heated prior to mixing with the injected Grp IIIs. The Grp IIIs typically crack at lower temperatures than typical Grp Vs. Pre-deposition occurs in this arrangement as for the single wafer machines. The flow compensation for separating the nutrient materials, ejection device design [Injection Nozzle], compensates for depletion and radial de-acceleration flow dynamics and wafer rotation.

4.2 - MOVPE Process Effects

4.2.1 - Basic Process Effects

4.2.1.1 – Reaction Chamber Effects

The preceding section mentions the generic differences between the two differing cell types in use. The characteristics that affect the performance of the differing cell designs are generically the same but the detail differs. Typical considerations for cell performance are:

- Gas Flow Dynamics
- Longitudinal Depletion Effects (Single Wafer only)
- Radial Depletion Effects (Multi Wafer only)
- Thermal Boundary Layer
- Gas Velocity Boundary Layer
- Rotation Gas Flow (Multi Wafer only)
- Nutrient Residence Time
- Rotation Speed (Multi Wafer only)
- Gas Path Streaming
- Susceptor Thermal Uniformity
- Susceptor Absolute Temperature
- Cell Nutrient Cracking Efficiency

These characteristics may affect the capability and the material properties within the process.

Example: For certain doping materials a 10°C temperature variation over the susceptor surface will vary the doping uniformity by a factor of 10 [1E17 to 1E18].

The depletion effects are controlled by the cumulative H_2 carrier flow, if this varies by 10% run to run then the composition of the material will shift in excess of 1000 ppm across a wafer.

4.2.1.2 – Gas Handling Effects

The characteristics that affect the performance of the differing cell designs are generically the same but the detail differs. The gas handling has subtle differences required to support the basic cell differences. These differences are fundamental injection lines to the cell. Typical considerations in gas handling system performance are:

- Gas Flow Pick Up Performance
- Gas Flow Mixing
- Gas Flow Control
- Gas Pressure Control
- Gas Temperature Control
- Flow & Mixture Stability
- Flow & Mixture Repeatability
- Gas Flow Switching Stability
- Gas Path Streaming

These characteristics will also affect the capability and the material properties within the process.

Examples:
If the nutrient switching produces a pressure transient the grown interface will be poor, affecting the device performance.

The pressure control of the "Source Vessels-Bubblers" is critical. If these pressures vary then the amount of material "picked-up" will vary, changing the composition of the grown material [$\Delta m = \rho A C$].

4.2.1.3 – Effects Summary

Linking the effects of both cell and gas handling, which potentially cause the compositional, crystallinity and interfacial quality of the manufactured material. The following matrices Table 4-1 and Table 4-2 have been constructed linking the process cause and the corresponding product effect (see Table 4-1).

Gas Handling Effects :	**Poor Compositional Quality**	**Multi Compositional Material**	**Poor Material Interfaces**	**Irreproducible Compositions**	**Unpredictable Compositions**	**Non Uniform Characteristic**	**Uncontrolled Uniformity**	**Uncontrolled Doping Level**	**Growth Rate Unpredictable**
· **Gas Flow Pick Up Performance**	■			■	■				■
· **Gas Flow Mixing**	■	■	■	■	■				■
· **Gas Flow Control**	■	■	■	■	■	■	■	■	■
· **Gas Pressure Control**	■	■		■				■	■
· **Gas Temperature Control**	■	■		■	■			■	■
· **Flow & Mixture Stability**	■	■	■	■	■			■	■
· **Flow & Mixture Repeatability**				■	■				■
· **Gas Flow Switching Stability**			■						
· **Gas Path Streaming**	■	■	■	■	■	■	■	■	■
Reaction Chamber Effects :	**Poor Compositional Quality**	**Multi Compositional Material**	**Poor Material Interfaces**	**Irreproducible Compositions**	**Unpredictable Compositions**	**Non Uniform Characteristic**	**Uncontrolled Uniformity**	**Uncontrolled Doping Level**	**Growth Rate Unpredictable**
· **Gas Flow Dynamics**	■			■	■			■	■
· **Longditudenal Depletion Effects**						■	■		■
· **Radial Depletion Effects (M Wafer)**						■	■		■
· **Thermal Boundary Layer**								■	■
· **Gas Velocity Boundary Layer**	■		■			■	■	■	■
· **Rotation Gas Flow (M Wafer only)**	■		■	■	■	■	■	■	■
· **Nutrient Residence Time**	■		■	■	■	■	■	■	■
· **Rotation Speed (M Wafer only)**	■		■	■	■	■	■		■
· **Gas Path Streaming**	■	■	■	■	■	■	■	■	■
· **Exhaust System Condition**	■			■	■	■	■	■	■
· **Susceptor Thermal Uniformity**	■		■	■	■	■	■	■	■
· **Susceptor Absolute Temperature**	■		■	■	■	■	■	■	■
· **Cell Nutrient Cracking Efficiency**	■		■	■	■	■	■	■	■
· **Susceptor Thermal Transfer Rate**	■		■					■	■

Table 4-1 - Effect Summary Matrix

The matrices in Table 4-1 and Table 4-2 have been constructed from a mixture of sorting data from failed runs and comparing to process logging data, linking cause to effect and generic understanding of component, system performance and duty.

The practical use and impact of information of this type (Table 4-1) will be used to support development of a standard FMEA exercise in Chapter 5, as defined by Stamatis (1994). Its value also includes derivation to OCAP and basic fault logic for internal expert system derivation.

4.2.2 - Other Process Effects

Excluding the specific "material issues" such as composition, crystallinity and purity, many other properties exist that are controlled by the fundamental machine design and the principle in which the process is operated and controlled. These can be grouped into the following categories:

- Generic Inner Wafer *Uniformity* [W2W] of:
    - Thickness
    - Composition
    - Doping
    - PL Intensity
    - Crystallinity
- Generic Inter Run-Wafer *Uniformity* [R2R] of:
    - Thickness
    - Composition
    - Doping
    - PL Intensity
    - Crystallinity

The two-listed uniformities are the variation of the listed characteristics across each wafer, the mean relationship of the individual wafer within each run and are typical grown material evaluation characteristics. The uniformities are measured typically as a function of the percentage variation within the wafer excluding the exclusion zone, typically 2mm off the wafer radius.

The system attributes that control the process uniformity are grouped into 4 fundamental groups.

Group 1 – Thermal Profile and Uniformity of the growth zone (susceptor)
Group 2 – Thermal Gradient of the Growth Zone through Volume
Group 3 – Gas Flow Dynamics of the Growth Volume (cell)
Group 4 – Rotational Speed of the wafer surfaces

An effect summary derived from and similar to Table 4-1 can also be produced for these specific effects (see Table 4-2).

Reaction Chamber Effects :	Compositional Uniformity	Doping Uniformity	Interfacial Uniformity	Inner Run Uniformity	Thickness Uniformity	PL Uniformity	Crystallinity Uniformity
· Gas Flow Dynamics	■	■			■	■	■
· Longditudenal Depletion Effects	■	■			■	■	■
· Radial Depletion Effects (M Wafer)	■	■			■	■	■
· Thermal Boundary Layer	■	■	■			■	■
· Gas Velocity Boundary Layer	■	■	■			■	■
· Rotation Gas Flow (M Wafer only)	■	■				■	■
· Nutrient Residence Time	■	■				■	■
· Rotation Speed (M Wafer only)	■	■	■	■	■	■	■
· Gas Path Streaming	■	■	■	■	■	■	■
· Susceptor Thermal Uniformity	■	■	■		■	■	■
· Susceptor Absolute Temperature		■	■		■	■	■
· Cell Nutrient Cracking Efficiency	■	■			■	■	■

Table 4-2 - Chamber Effects Summary Matrix

4.2.2.1 – Inner Wafer Uniformity

To assist in defining the concept of these non-uniformities an example will be used. The thickness non-uniformity of a longitudinal cell describes the process and the potential.

The thickness uniformity of a linear cell measured on a 2" diameter wafer on a typical structure is thickness mapped by measuring 3 linear measurement and 2 lateral measurements either side of the central linear measurement, as detailed in Figure 4-2, this is a typical industry standard measurement technique.

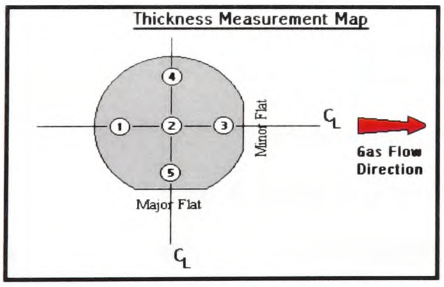


Figure 4-2 - Thickness Measurement Map

The longitudinal thickness uniformity of a grown wafer along the centre line is denoted by measurements numbered 1,2 and 3. The following chart

(Figure 4-3) denotes the typical thickness trend but exaggerates the actual process non-uniformity, and is derived from a six run sequence of like product measuring the five-point thickness and a five point x-ray map for each "B" denoted wafer (Table 4-3), (see Appendix 7 – Data Analysis for further derivation).

	InGaAs M.Match ppm						**Layer 2 Thickness**					
Run No	**B-X01**	**B-X02**	**B-X03**	**B-X04**	**B-X05**	**X - Average**	**B1**	**B2**	**B3**	**B4**	**B5**	**T - Average**
8.2076	440	134	-149	236	519	236	5.14	5.04	4.94	4.92	4.83	0.2
8.2077	338	134	0	204	511	237.4	5.06	4.98	4.82	4.85	4.83	0.24
8.2078	471	181	0	220	684	311.2	5.08	4.9	4.87	4.91	4.79	0.21
8.2079	379	141	0	189	566	255	4.99	4.94	4.89	4.87	4.75	0.1
8.2080	487	149	0	220	644	300	5.19	5.1	4.98	4.95	4.82	0.21
8.2081	306	204	0	291	589	278	5.11	5.02	4.91	4.93	4.77	0.2
8.2082	409	275	0	330	644	331.6	5.14	5.07	4.96	4.94	4.81	0.18
Average	**404**	**174**	**-21**	**241**	**594**		**5.10**	**5.01**	**4.91**	**4.91**	**4.80**	

Table 4-3 - X-Ray & Thickness "5" point data

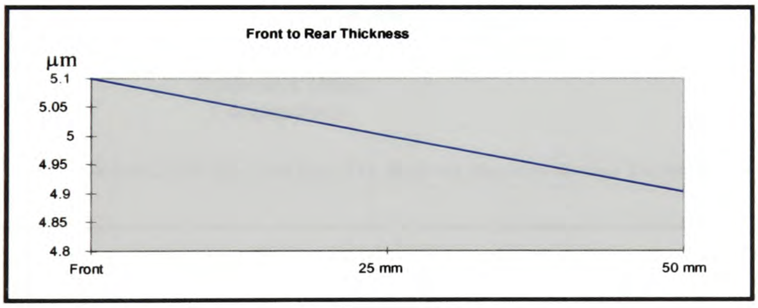


Figure 4-3 - Longitudinal Thickness

The lateral thickness uniformity of a grown wafer along the centre line is denoted by measurements numbered 4,2 and 5. The following chart (Figure 4-4) denotes the typical thickness trend but exaggerates the actual process non-uniformity.

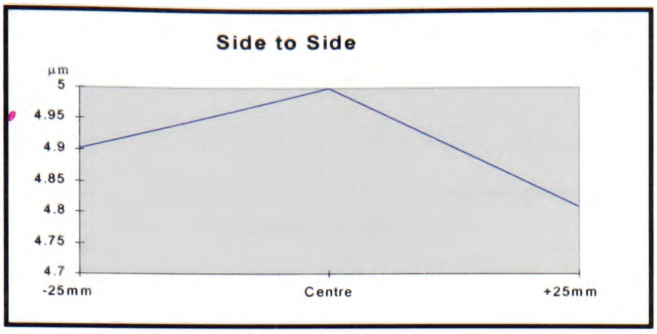


Figure 4-4 - Lateral Thickness

The presented data (Figure 4-3 & Figure 4-4) are values for a structure with a planned overall thickness of 5 µm. A three dimensional representation of the layer thickness is shown in Figure 4-5.

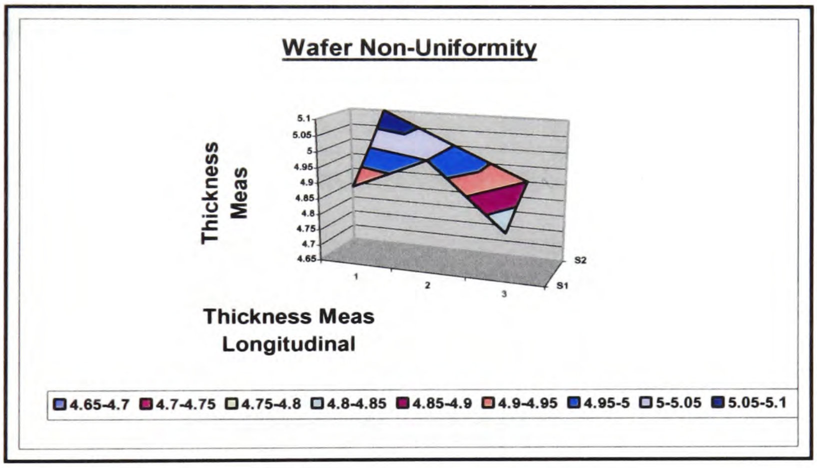


Figure 4-5 - 3D Uniformity Map

Both the longitudinal and lateral characteristics may be controlled by cell design and flow dynamics.

The same characteristics however on the Multi-Wafer rotational cell are completely different. For primary process evaluation the cell it is essential that a Non-Rotational regime be adopted, otherwise understanding the "averaged" results may be extremely difficult to de-convolute. Centre to edge averaged data looks very similar to the longitudinal data on a linear cell.

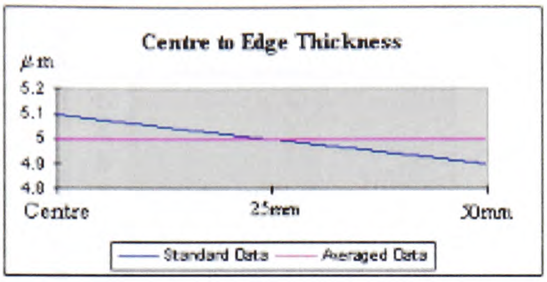


Figure 4-6 – Centre to Edge Data: Averaged

The expectation for a Radial Rotational cell from a starting point of the longitudinal cell would be an average of the two uniformities Figure 4-8 as presented in Figure 4-6 & Figure 4-7.

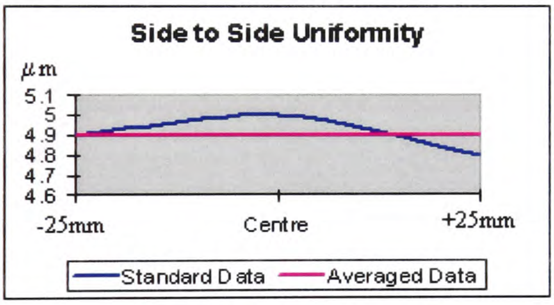


Figure 4-7 - Lateral Data: Averaged

Using the data from the previous two tables, a chart (Figure 4-8) defining the effect of rotation may be derived. This assumes cell characteristics average with rotation. This needs comparing to the actual data (Figure 4-9) uniformity when rotating; this data is not sourced from a five-point thickness map, but by measuring the wafer thickness as a strip across the wafer in steps of 2mm:

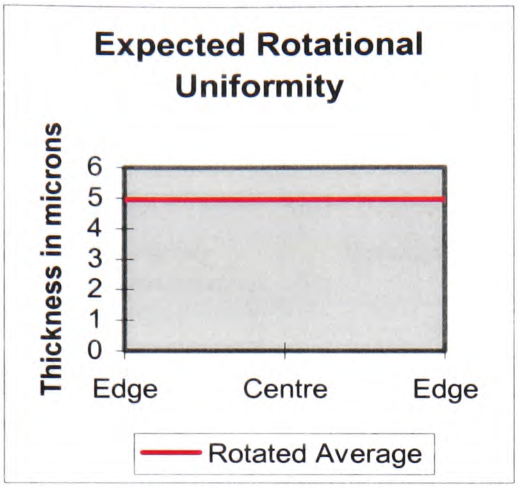


Figure 4-8 - Expected Uniformity

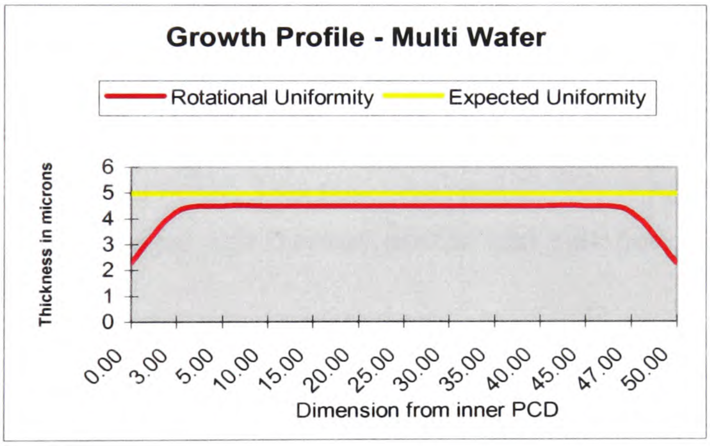


Figure 4-9 - Uniformity Comparison

The actual uniformity differs from the expected. At approximately 5mm from the edge the thickness grades to 0.5 the expected thickness. The overall thickness is some 10% below expectation.

To enable evaluation of the potential causes of the differences between expected and the actual thickness uniformity it is essential to compare (Figure 4-10) both to the uniformity on a non-rotated wafer in the multi-wafer machine.

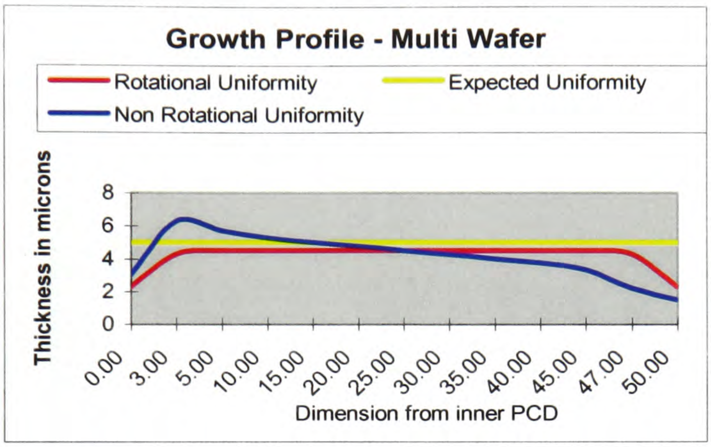


Figure 4-10 - Overall Uniformity Comparison

The rotational uniformity is an absolute geometric mean of the non-rotational thickness profile. This non-rotational profile is again affected by cell component design, cell thermal profile and cell flow dynamics, see Figure 4-10.

The primary objective of rotating a wafer is to average the growth uniformity characteristics, i.e. thickness, wavelength etc. The basic principle is effective (Frijlink, 1991); the improvements therefore need to be evaluated on a non-rotation platform.

To determine the direct effects within the cell, the overall profile variation will need to be evaluated in discreet functional components. By partitioning the non-rotational profile into 3 zones (Figure 4-11) it is possible to analyse the effects. Each of these zones may be control via a function of cell geometry, gas dynamics and thermal profile. Frijlink, 1991 discusses the growth depletion effects in his paper.

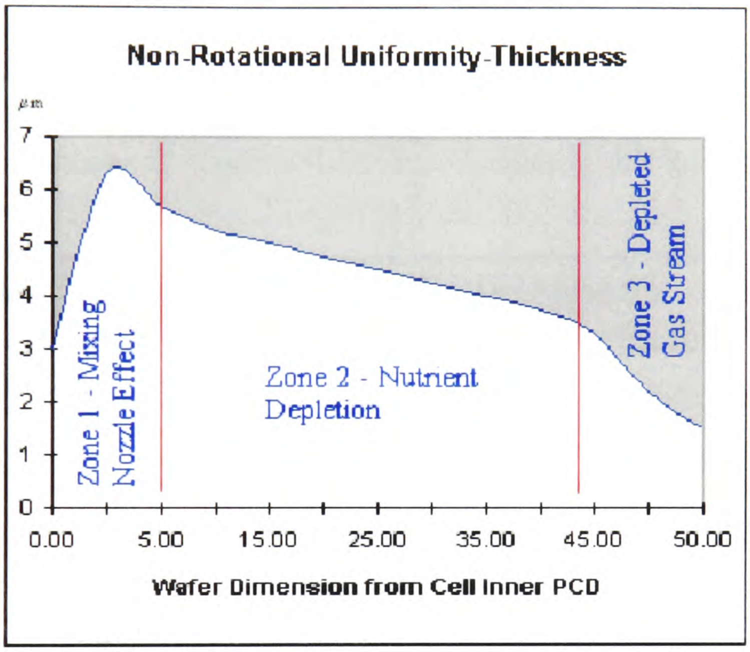


Figure 4-11 - Effect Zoning

4.2.2.2 – Zone 1 – Mixing Nozzle Effect

The linear growth profile in this area is a predominate function of the nozzle to susceptor geometry, the wafer to nozzle geometry and the gas carrier flows. This relationship is described in the following diagram (Figure 4-12). The nozzle is the component that separates the two nutrient flows [Grp V & III] and distributes the gas. The geometry and ejection velocities are critical to the shape and position of Zone 1 as discussed by Frijlink et al (1991). The basic relationship between the nozzle and other cell components is schematically described in Figure 4-13.

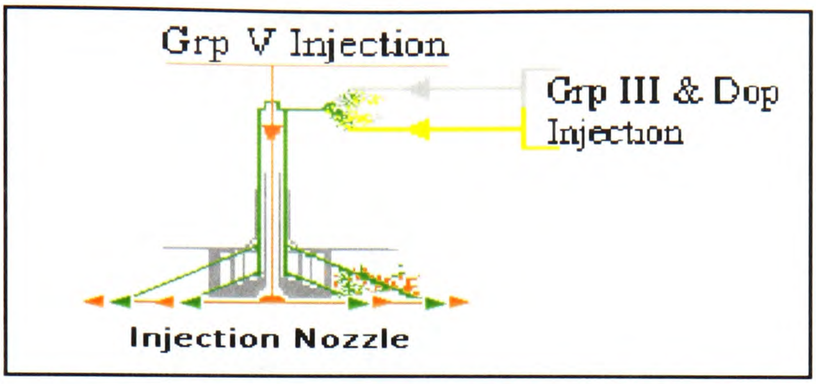


Figure 4-12 - Gas Distribution Nozzle

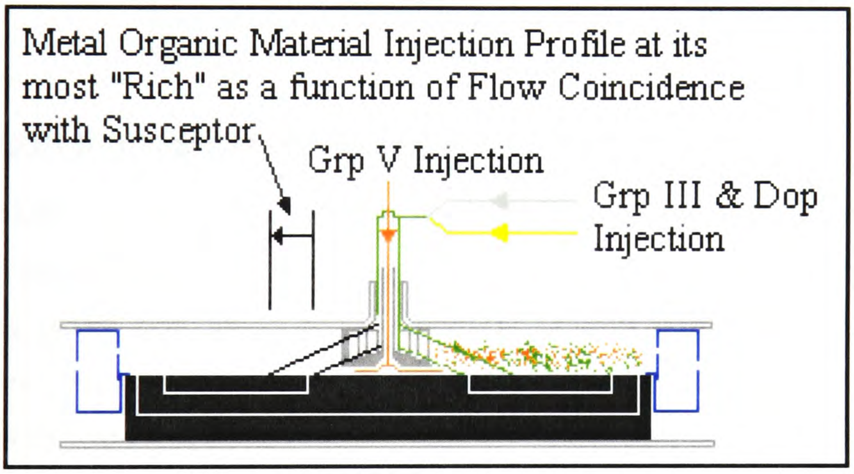


Figure 4-13 - Nozzle/Cell Relationship

4.2.2.3 – Zone 2 – Nutrient Depletion Effect

This zone is affected by three major growth components:

a – Radial Gas Velocity Reduction
b – Grp III & V Depletion through Growth Zone
c – Thermal Contact Efficiency, Substrate to Susceptor

a – Radial Gas Velocity Reduction

All of the gases, both carrier and nutrient are injected into the cell from the nozzle, which is located centrally to the growth zone. The exhausting gases are extracted around the edge of the growth zone. (See Figure 4-14)

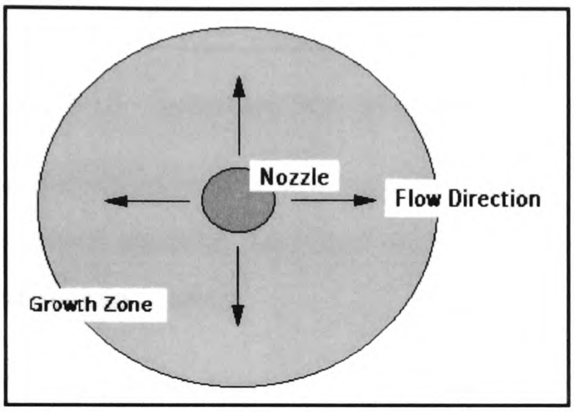


Figure 4-14 - Nozzle/Growth Relationship

b – Grp III & V Depletion through Growth Zone

At growth zone entry the "nutrient materials" are at a specific percentage of the overall flow. The carrier flow is hydrogen this does not incorporate into the grown material, as do the nutrients. As growth progresses through the zone the nutrient percentage of total flow reduces. As the overall amount of Grp III material reduces the growth rate reduces. This affects the growth relative to time; the thickness grown per unit time therefore reduces.

c – Thermal Contact Efficiency, Substrate to Susceptor

The surface temperature of the substrate will be affected by the quality of the contact with the susceptor (see Figure 4-15).

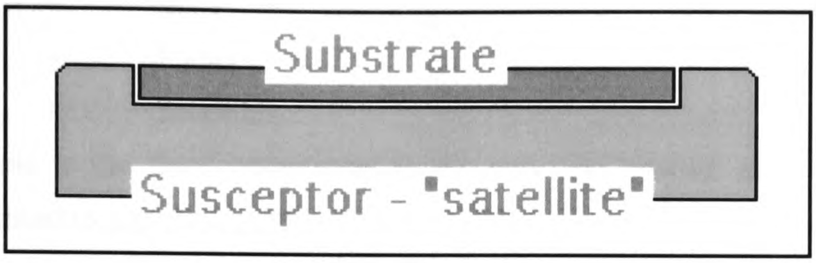


Figure 4-15 - Substrate/Susceptor Relationship

The single biggest contribution to compromise the contact between the two is the previously grown material deposited on the susceptor in the major and minor flat and clearance areas.

4.2.2.4 – Zone 3 – Gas Stream Depleted Effects

This is the next step on from Zone 2-b depletion; at this stage the nutrient materials are exponentially decreasing. By increasing the carrier flows this zone can be eliminated, the cost to the process however is high. To reduce this zone to zero effect on the wafer the carrier flows have to be increased to a level where the growth rate in Zone 2 is reduced dramatically. As the growth rate reduces the required overall process time increases. A trade off is required therefore between overall process time and maintaining the depleted growth zone due to this effect within the exclusion zone of a delivered wafer.

When the susceptor is rotated at a suitable speed the three zones are averaged into the profile previously shown. All of the Inner Wafer Uniformities are influenced by the same parameters as the discussed thickness.

4.2.2.5 – Inter Wafer Uniformity

The primary factor controlling the wafer-to-wafer uniformity is the rotation and rotation relationship of the components within the cell The Susceptor is manufactured from graphite and is a three-component assembly.

Base
Planet
Satellites

The base is the fixed component in the cell; the rotation gas flows are transmitted to and through this component. The temperature monitoring for the cell is embedded into the body of the base. The gas foil rotation and bearing surface for the planet is located onto the upper surface (see Figure 4-16).

The planet is the primary rotating component. Sitting on the top of the base and rotating. This component also acts as the holder and rotating base for the wafer holders or satellites (see Figure 4-16).

The satellites are the holders for the substrates. The satellites are recessed to match the substrate thickness. The satellites can contra-rotate relative to the planet rotation (see Figure 4-16).

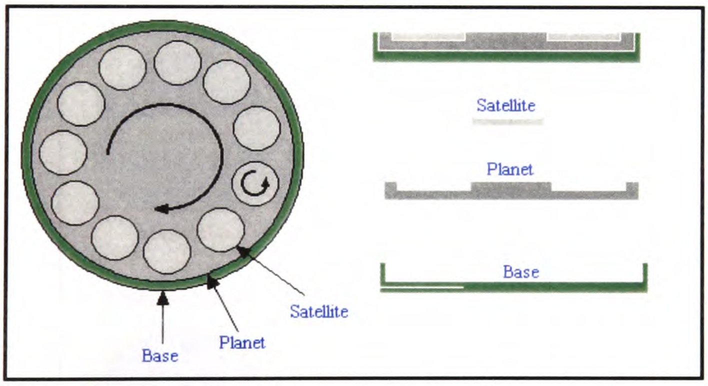


Figure 4-16 - Susceptor Assembly

The generic uniformities wafer to wafer [W2W] are affected greatly by the rotation speed of the planet and the inner wafer uniformity by the satellite rotational speed.

The only other contributor is the wafer contact quality. The primary effect that compromises the contact thermal efficiency is the flat growth areas.

The satellite wafer area is circular, for a 2" wafer the recess is machined to 51.2 mm diameter. The substrate is circular in section with two machined flats, major and minor, denoting "cut" and facilitating handling.

On a 2" substrate the flats have chord lengths thus:

Major – 16+/-2mm
Minor – 7+/-1 mm

The susceptor is not changed each run, the growth that is laid during the previous run in the uncovered chord included area is on the satellite. The next run is loaded with the flats in potentially differing position (see Figure 4-17). This could potentially result in the substrate being lifted on one side, by the height equivalent to the previous growth thickness.

The above and the relative satellite rotation speeds will have a major effect on the uniformity of each wafer within each run.

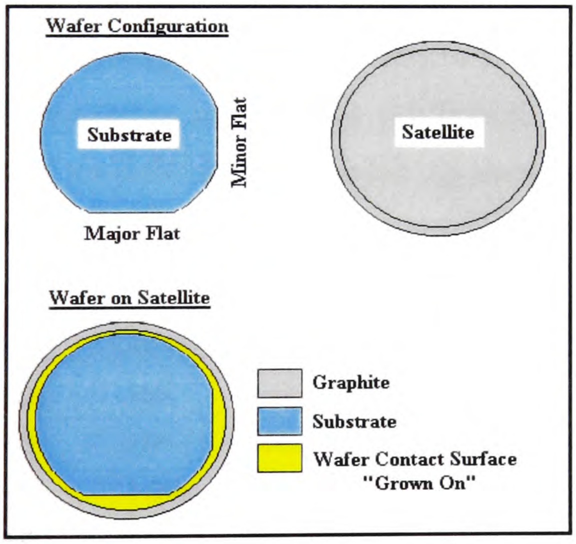


Figure 4-17 - Substrate/Substrate Arrangement

The above and the relative satellite rotation speeds will have a major effect on the uniformity of each wafer within each run.

4.2.3 - Basic Process Systems

4.2.3.1 – Nutrient Gas Diversion

The general background to the material recipes, their derivation from the device structural specifications, i.e. InGaAs, is previously discussed. It is crucial therefore that the material diversion from to the "vent line-waste" to "run line-cell" relationship is understood and that the "switch" to "cell" time and swept/dead volume must be controlled to a minimum. Switched flows can vary for each line from 2 to 1500 sccm, the differing material densities also vary for a given composition, and the prescribed flow for fixed volumes must enter the growth zone simultaneously if structurally required. In a non-assisted flow state some flows could take up to, 5 minutes to establish from divert time [swept pipe volumes]. The functional process relies on a constant flow for each material ported to/from cell; by using Hydrogen [H_2] as a carrier or push gas for all constituents, a constant flow can be achieved.

The process has a growth rate of typically 4.5 μm/hr. The material constituents are diverted to and from the cell [run & vent lines see Table 4-4] as required by the differing semi conducting compound requirements.

For Example:

Layer No	Activity	Material	To Vent	To Cell
4	Cooling	N/A	AsH_3, TMI, TMG	PH_3
3	Growth	InP	AsH_3, TMG	PH_3, TMI
2	Growth	InGaAs	PH_3	AsH_3, TMI, TMG
1	Growth	INP	AsH3, TMG	PH_3, TMI
0	Heating	N/A	AsH_3, TMI, TMG	PH_3

Table 4-4 - PIN Layer Schedule

To achieve the typical growth rates required for manufacturing, several sources each with two injection points may be required to be used, therefore increasing the functional complexity of the basic structure. This is functionally dependant upon:

Growth Pressure
Source Operating Pressures
Cumulative wafer Surface area per run
Source "Pick Up" Efficiency
Gas Mixing Performance

The list above suggests that the maximum number of three materials switching at any one time. On a large area multi wafer machine, this translates to up to nine gas lines porting at the same time.

The component gases therefore, have to be diverted in and out of cell accurately and rapidly with the pressure transients minimised (see Figure 4-18). A typical value for a 2-litre diversion, is approximately 3mbar with a balancing system (see Figure 4-20), without, the differential could exceed 150mbar. Detail of the gas diversion manifold valves is described in Figure 4-19.

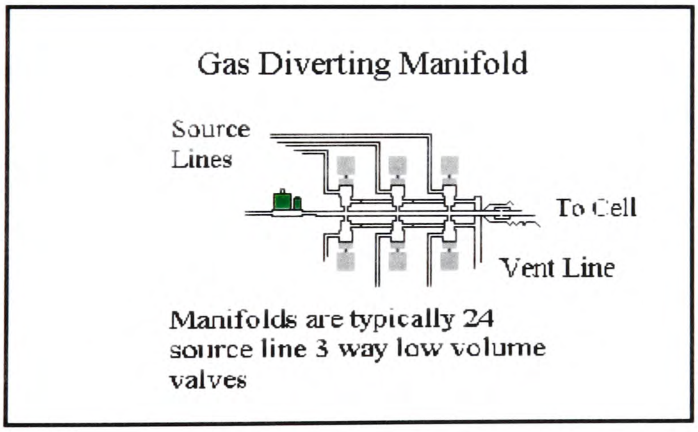


Figure 4-18 - Gas Diverting Manifold: Schematic

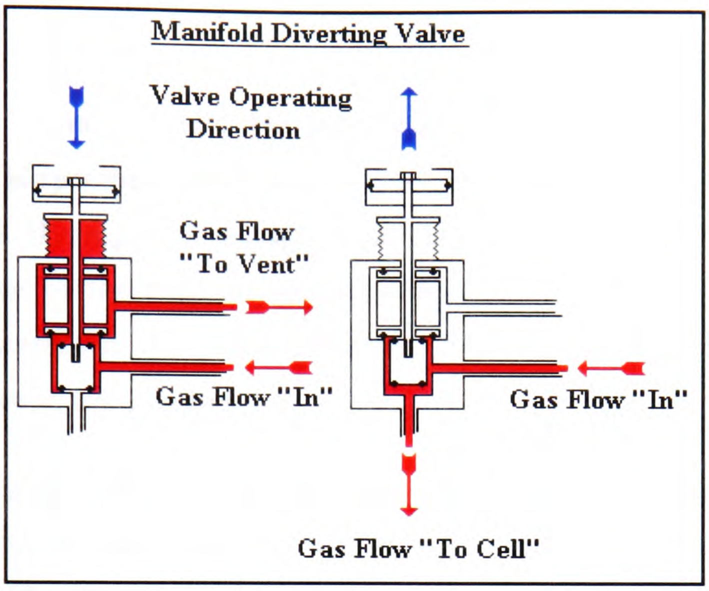


Figure 4-19 - Manifold Diverting Valve 3 Way: Schematic

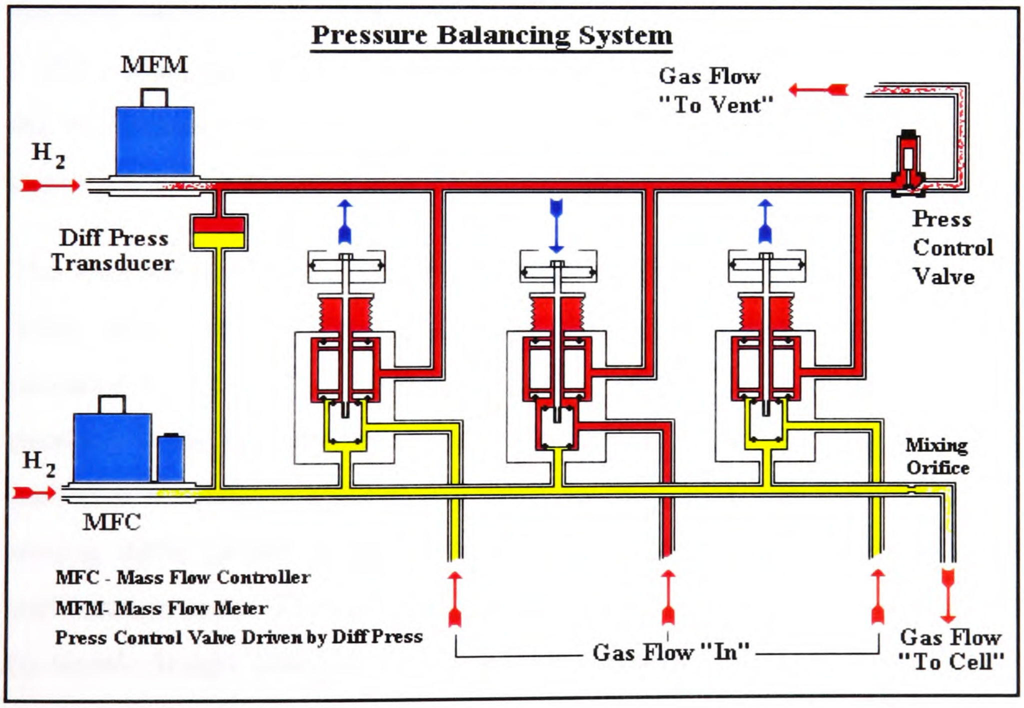


Figure 4-20 - Manifold & Pressure Balancing Detail

4.2.3.2 – Carrier Gas

Hydrogen [H_2] has been quoted as the carrier, pick up and mixer gas for all of the constituent materials. The gas is readily available as semi-conductor grade that is specified with a purity of 99.995 %. The amount of Oxygen still in the Hydrogen is enough to dilute the photo-luminescence [PL] performance of the material and impurities such as Silicon will act as doping materials in the intrinsic material, affecting electrical and optical performance of the material.

By diffusing the Hydrogen through a heated membrane manufactured from a compound of Palladium and Silver, the purity of the gas in use is enhanced. This technique reduces the amount of free Oxygen amongst other materials and improves the purity by a factor of 10, to 99.999995%. This typically takes the dew point of the incoming Hydrogen from approximately 5°C to less than -110°C [unable to measure less than – 110°C, using current commercial gas Hygrometer technology], improving the PL intensity by a minimum factor of 10. This Oxygen removal has a major impact on the performance of opto-electronic devices such as Lasers.

The hydrogen is presented onto the heated [250°C] diffuser membrane at 20bar, and is delivered to the machine gas handling system at typically a pressure of 5bar. The hydrogen conduit system is maintained at this pressure to the primary "Mass Flow Controllers". The carrier gas with the included nutrients enters the cell from the manifold, the requirement for mixing differ greatly whether the machine is a linear cell or multi wafer cell arrangements. The cell gas mixing for a multi-wafer cell is controlled by nozzle design, however for a linear cell arrangement it is critical that the design of the injection system maintains a specific Reynolds number [Re.<2000]. This Reynolds number minimum dictates whether the gas entering the cell has reached a "turbulent" state. If so the gas can be considered to have mixed, this Reynolds number can either be achieved by be design of the quartz tube throat (Moerman et al, 1991) or by physical manifold design (Mason and Walker, 1991).

4.2.3.3 – Pick up Gas

Some of the raw material sources in use, typically Al, In and Ga are supplied to the process from small stainless steel containers that are connected to the machine directly. A "pick up" gas is passed into the steel container (known as a "Bubbler" see Figure 4-21), and is forced by pipe work layout through the raw material. The Hydrogen input is via the "Dip Leg" resulting in bubble formation.

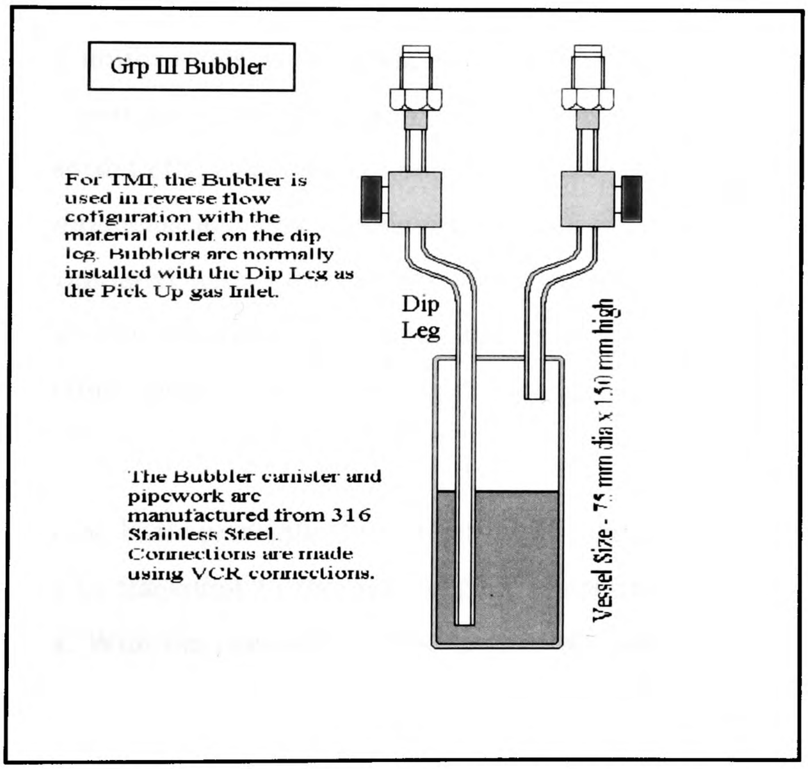


Figure 4-21 - Bubbler: Schematic Cross Section

Hydrogen is used as the "pick up" medium; it is flowed through the material stored in the bubbler. The bubbler is maintained externally at some temperature between -10 and 40°C, depending upon vapour conditions of the material stored in the bubbler. The pressure in the bubbler is controlled precisely; volumetric flow is directly proportional to pressure change, varying the "Pick Up" characteristic and the expected source material flow rate.

4.3 – Chapter Summary

This chapter offers a physical process understanding, initially describing a simple ternary structure, a three-layer PIN structure encompassing a ternary layer, enabling evaluation of the process capability and effects. The detailed outcome and effects detailed are used within the effect matrix for the FMEA exercise in Chapter 5.

Material characteristics as detailed in Chapter 3 are expanded in terms of characteristic uniformities as demands or objectives of the process. Layer thickness is used as a typical example of uniformity and control, with detailed cause and effect discussion upon the impact of certain key process variables/components and their operational objectives. Two basic layouts of cell are compared within this uniformity discussion, the linear and the radial rotation cell. The potential process effects of gas flow dynamics are introduced within this chapter, for process, material source and uniformity impact.

Armed with the basic principles and effect detail discussed in this chapter it is possible to transition to the next step in understanding the need for improvement. With the principles of the technology detailed to be able to understand the "Full Process Cycle", the complexities and the fundamentals of the process requirements.

The following Chapter utilises the background knowledge offered on the process from this Chapter and uses the detail as failure types within the overall business risk analysis. The knowledge offered here enables the cause to be derived from some of the material failure characteristics. For example, although a material may be rejected due to composition being out of specification, the cause may be any number of hardware issues but typically flow control of a nutrient.

Chapter 5 - Process Performance

5.1 - Introduction

For a service, technology based Company [no generic product base] to succeed, its fundamental objectives should include: maintaining a technological lead and customer satisfaction. It is usual for customers to want "Higher Performance", "Better Quality", "Lower Price" and a "Shorter Lead Time", if these cannot be satisfied, competition could flourish and if so, eventually customers and business are no more.

A major requirement in maintaining a "technological lead" successfully is to fully understand the capabilities, strengths, weaknesses and performance of the process. Evaluation of the process performance for the MOVPE process has not been previously documented. Equipment manufacturers do issue "Cost of Ownership" calculations, which when analysed are operationally extremely weak and include too many assumptions.

Evaluation of the overall process is undertaken within this and the subsequent Chapter, utilising the tools as described in Chapter 2, the material characteristics detailed in Chapter 3 and process characteristics detailed in Chapter 4 are all combined, enabling analysis.

5.2 - Equipment Performance Evaluation

5.2.1 – Process Performance Analysis

There are potentially many ways of analysing performance relating to a process and its operation, the SEMI Standards E10; E35 & E79 (2000) offer substantial derivation. Many factors or metrics may be analysed offering an indication how each impacts relatively on the overall performance. These factors will vary in "Potential" impact on the process performance. A typical; list of such factors is detailed in Table 5-1.

Cost to Manufacture
Reject Rates
Product Device Performance
Product Statistical Process
Failure Modes
Characteristic Stability
Mean Time between Failures
Process Uptime/Downtime
Manufacturing Efficiencies
Reliability Statistics

Table 5-1 - Typical Manufacturing Metrics

The initial objective of this project is to identify a set of measurable variables, within the "Process" that are critical to the overall performance of the process. It is also critical to the overall impact of the projects success in improving the process to derive a suitable technique, enabling the identification of the following process characteristics (see Table 5-2):

Strengths
Weaknesses
Capability

Table 5-2 - Impact Metrics

The potential benefit of this project will result in Table 5-3:

Improved:	Process Design
	Process Control
	Equipment
	Utilisation
	Profitability
	Organisational Support
	Process Efficiency
	Process Reliability
	Staff Training

Table 5-3 - Benefit Potentials

The precise impact upon the above process variables is purely supposition, until the analysis and improvement work is undertaken. Initially a top-level investigation requires initiation; this top-level investigation will need to identify the "Primary Direction" for the investigation process. It is essential that the variables used in such an evaluation easily identify the impact of the strengths and weaknesses of the process. Evaluating the available data by using the strengths and weaknesses of the business are the top-level operators. The data source is readily available as the information on each process unit is published on a monthly basis for the management team involved at IQEE. A standard SWOT [Strengths, Weakness', Opportunities & Threats] analysis technique (de Bruijin, 2000 as discussed in Chapter 2) would work on this business information, however the first part of the analysis identifying the strengths and weakness will cascade to additional SW analysis. A technique based upon a typical SWOT analysis requires modification purely around business performance data. This will take the form of a business risk analysis. A business risk analysis in this application differs from other interpretations for profit, loss and disaster recovery (Financial Training Partners, 1999, Mills, 2001, Angelelli, 1997, Harris, 2000 and Business Continuity, 2001), and is used as a technique to identify and qualify the variables that have a major impact upon the business performance of the process for the company.

A "Business Risk Analysis" is required to be carried out including indices that control the overall business performance of each process unit. Figure 5-1 offers a percentage distribution of the cost profile of the operation. The Substrates, Reagents and Factory Materials are the critical variable charges involved in the process, these are directly dependant upon the order profile and the experienced process yield.

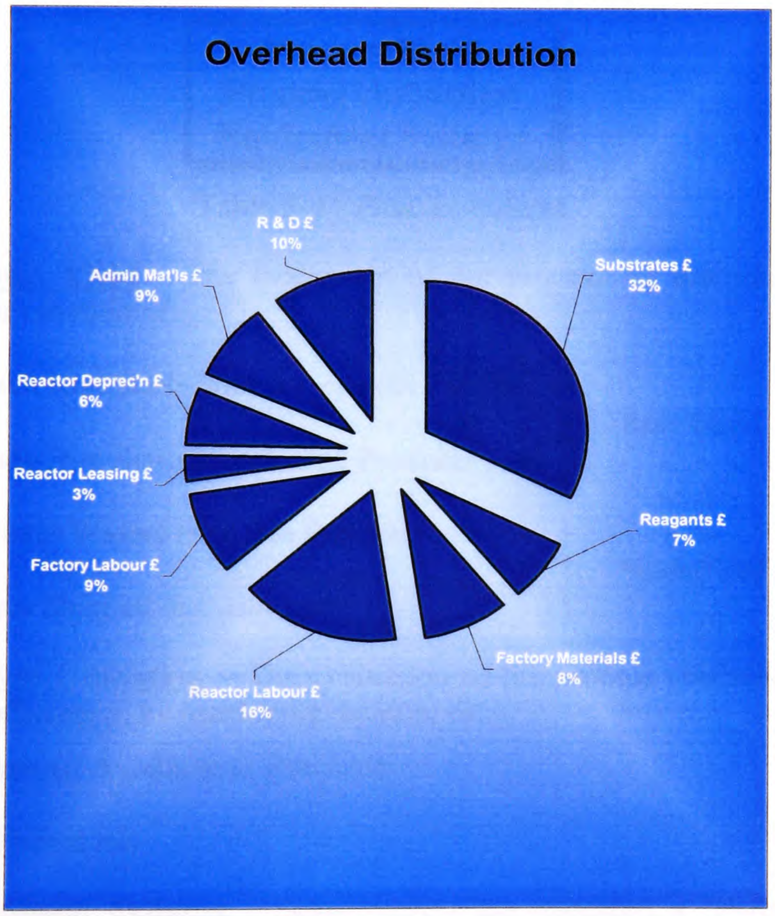


Figure 5-1 - Financial Overhead Distribution

The balance of the charges are considered for this exercise to be "Fixed Overheads", these charges are distributed across the number of deliverable wafers, the critical influences on the deliverable wafer numbers are yield, wafer production rate [run rate] and machine uptime. The run rate and uptime have again major contributing influences, the available time for production and the utilisation of this available time.

Based upon the critical influences discussed the processes indices listed in Table 5-4 have been selected as the initial operators, indices such as these are initially defined within such standards as SEMI E35 200 (2000):

Process Yield
Process Utilisation
Equipment Failures

Table 5-4 - Process Indices

Process Yield – The evaluation of the process by measuring either the ratio of:

Growth Run Starts with Acceptable Product]
to] - Run Yield
Growth Run Starts with Failed Product]
or
Substrate Wafers Issued to Process]
to] - Wafer Yield
Wafers Shipped to Customers]

Process Utilisation – The evaluation of the process equipment use efficiency, by measuring the ratio of:

Equipment Available to Run time
to
Total hours run

Equipment Failures – Failed wafers are allocated a "Failure Code", this code if appropriate is allocated to a specific equipment failure mechanism. The failed wafers therefore can be analysed for specific equipment failure mechanisms.

5.2.1.1 – Data Summary

During 1997, approximately 2500 wafers were scrapped due to one or more failure mechanism [approx 50% of all wafers grown], excluding fit for purpose [FFP] Tests, assuming that each of these wafers has a potential sales value of approximately £1600 [ASP-1997]. Had the company been in a position to sell this additional capacity it would have generated additional sales of approximately £4m? The simple message from the data suggests that:

1 – Without these losses if no further orders had been forthcoming, that the Company could have reduced the manufacturing costs dramatically.

2 – If the Company's capacity were limited by its overall throughput then the losses would have generated direct additional sales for the same manufacturing costs.

3 – If no improvement is made, the Cost of Doing Nothing [CoDN] is £4m.

In the same year, across six MOVPE Reactors approximately 35% of available production time was lost due to differing "Utilisation" inhibitors.

The primary objective of the business risk analysis will be to define subsequent priorities for further analysis or derivation, prior to applying any formal techniques such as *Failure Mode & Effects Analysis* [FMEA] or *Downtime and Product Failure Analysis* to derive the actions and priorities.

Most formal techniques including FMEA suggest that the priorities should be selected as a standard function of the output based upon statistical derivations such as Pareto. The standard statistical outputs define that the failure mode with the highest ranking should be first to be addressed and so on.

One major practical implication of the standard interpretation for IQEE is that the largest failure mode, as suggested the higher priority, however the potential start, to project completion may have a prolonged objective timescale with a large budgetary implication. The intention in the analysis is to offer a unique interpretation of FMEA principles by including additional variables as operators within the evaluation. These variables are a function of predicted project simplicity, anticipated improvement, timescale and budgetary requirements, thus enabling a full objective derivation for improving, utilising a function of *FMEA, Business Risk and Return.*

This FMEA exercise will enable priorities to be determined by deriving "weights" for the known problem severity, the frequency of the failure mode occurring and the detect ability of the failure mode. A Risk Priority Number [RPN] can be determined from the defined weighting.

5.2.2 – Business Risk Analysis

Every run undertaken loaded with Substrates loaded within the company is undertaken for one of three reasons:

Product - Sales
Engineering - Process Calibration
Test - Source, Material or Process Fit for Purpose

Every grown and characterised structure [wafer] is allocated a status either pass or fail [procedurally known as determination, a decision based upon specification compliance of the wafer characteristics - manual], including test and calibration runs. The run status is logged on a database with allocated failure codes. The coding categories are as follows:

Wafer Yield -
Hardware Failure
Morphological Failure
Doping Failure
PL Failure
Composition Failure
Thickness Failure
Errors
Sources Failure

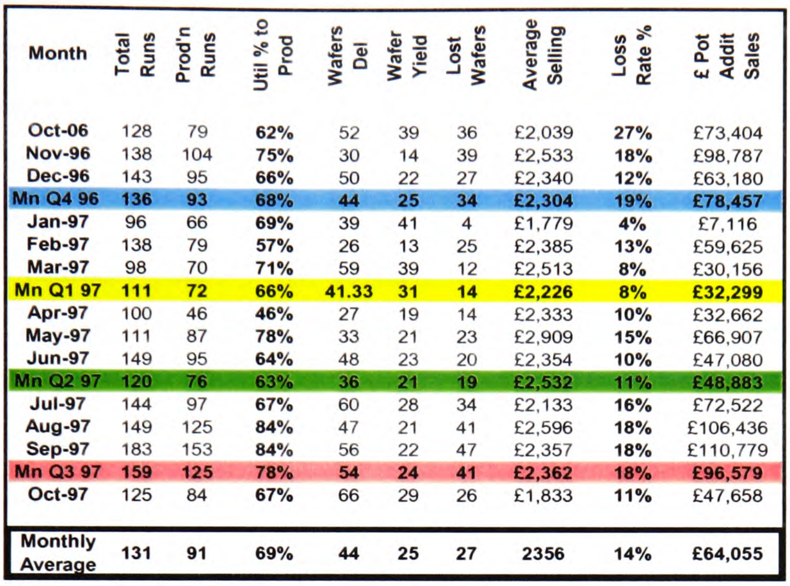
Hardware -
Aborted Run
Bath Temperature
Computer Failure
Diffuser Failure
Flow Control Failure
General Failure
Heating Source Failure
Rotation Failure
General Services Failure
Vacuum System/Leak Integrity Failure

The operational performance or utilisation of the process equipment is analysed, but is not currently failure classified. For this exercise, any reason for delay shall be classified as an "Utilisation" failure. The codes currently in use for "Time" allocation are as follows:

Utilisation -
Load/Unload
Leak Checking
Routine maintenance
Non-Routine maintenance
Problem Solving
Waiting

5.2.2.1 - Wafer Yield

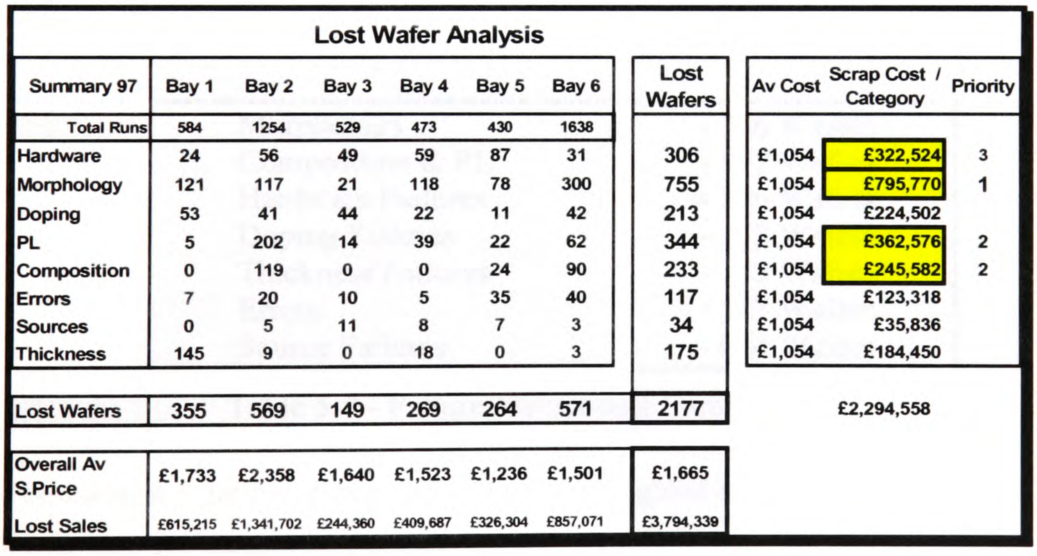
By collating the yield per category for the year 1997 (Table 5-6) across the six production units and allocate the company average wafer production cost to each machine [cross platform allocation], a "Scrap Value" per category can be derived. This "Scrap Value" can be used as an operator in future analysis. The following information is derived from runs/wafers that are categorised as "production". Each of the manufacturing units is treated as individual business unit; the typical monthly reporting metric for 1997 is detailed in Table 5-5.



Month	Total Runs	Prod'n Runs	Util % to Prod	Wafers Del	Wafer Yield	Lost Wafers	Average Selling	Loss Rate %	£ Pot Addit Sales
Oct-06	128	79	62%	52	39	36	£2,039	27%	£73,404
Nov-96	138	104	75%	30	14	39	£2,533	18%	£98,787
Dec-96	143	95	66%	50	22	27	£2,340	12%	£63,180
Mn Q4 96	**136**	**93**	**68%**	**44**	**25**	**34**	**£2,304**	**19%**	**£78,457**
Jan-97	96	66	69%	39	41	4	£1,779	4%	£7,116
Feb-97	138	79	57%	26	13	25	£2,385	13%	£59,625
Mar-97	98	70	71%	59	39	12	£2,513	8%	£30,156
Mn Q1 97	**111**	**72**	**66%**	**41.33**	**31**	**14**	**£2,226**	**8%**	**£32,299**
Apr-97	100	46	46%	27	19	14	£2,333	10%	£32,662
May-97	111	87	78%	33	21	23	£2,909	15%	£66,907
Jun-97	149	95	64%	48	23	20	£2,354	10%	£47,080
Mn Q2 97	**120**	**76**	**63%**	**36**	**21**	**19**	**£2,532**	**11%**	**£48,883**
Jul-97	144	97	67%	60	28	34	£2,133	16%	£72,522
Aug-97	149	125	84%	47	21	41	£2,596	18%	£106,436
Sep-97	183	153	84%	56	22	47	£2,357	18%	£110,779
Mn Q3 97	**159**	**125**	**78%**	**54**	**24**	**41**	**£2,362**	**18%**	**£96,579**
Oct-97	125	84	67%	66	29	26	£1,833	11%	£47,658
Monthly Average	**131**	**91**	**69%**	**44**	**25**	**27**	**2356**	**14%**	**£64,055**

Table 5-5 - Sample Business Unit Metric

The data to support the activity detailed in Table 5-6 is available from the standard monthly report sheet per machine.



Lost Wafer Analysis

Summary 97	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	Lost Wafers	Av Cost	Scrap Cost / Category	Priority
Total Runs	584	1254	529	473	430	1638				
Hardware	24	56	49	59	87	31	306	£1,054	£322,524	3
Morphology	121	117	21	118	78	300	755	£1,054	£795,770	1
Doping	53	41	44	22	11	42	213	£1,054	£224,502	
PL	5	202	14	39	22	62	344	£1,054	£362,576	2
Composition	0	119	0	0	24	90	233	£1,054	£245,582	2
Errors	7	20	10	5	35	40	117	£1,054	£123,318	
Sources	0	5	11	8	7	3	34	£1,054	£35,836	
Thickness	145	9	0	18	0	3	175	£1,054	£184,450	
Lost Wafers	355	569	149	269	264	571	2177		£2,294,558	
Overall Av S.Price	£1,733	£2,358	£1,640	£1,523	£1,236	£1,501	£1,665			
Lost Sales	£615,215	£1,341,702	£244,360	£409,687	£326,304	£857,071	£3,794,339			

Table 5-6 - Lost Wafer Analysis 1997

For every wafer produced by IQE a record is maintained of initially its deliverable or fail category, this is a judgement based upon its compliance to specification. If the wafer fails to comply with specification a record of the primary cause [variable furthest from specification limits] is recorded. For example, a wafer may fail on morphology [fail category - effect], however the wafer may have a scratched surface, which would signify handling procedure non compliance, therefore "error" would be listed as the sub category [cause]. The constructed [databased] record of its failure would indicate a morphology failure caused by error. The numbers from these databases are reconciled monthly and contribute to the generation of the business unit data [see Table 5-5] and subsequently used to formulate Table 5-6.

Concluding from the data in Table 5-6, priorities may be allocated to the failure modes. In relative wafer terms, the PL and compositional failures should be grouped together; the justification for this will be discussed later in the Chapter. Table 5-7 summarises the failure mechanisms and ranks the failures from high to low.

Morphology	- 756 Wafers
Composition & PL	- 577 Wafers
Hardware Failures	- 306 Wafers
Doping Failures	- 213 Wafers
Thickness Failures	- 175 Wafers
Errors	- 117 Wafers
Source Failures	- 034 Wafers

Table 5-7 - Failure Mechanism Summary

The Largest 3 failure groups have been highlighted in yellow [masked] in Table 5-6. By simply re-working the data in the above chart, reciprocating the capability percentages, the process manufacturing blockages can be readily identified per process unit. A "manufacturing blockage" is a descriptor for a resistance or obstruction to the optimum performance of the process. Any failure rate greater than 5% will be considered significant for the analysis.

The decision on significance will use a reasoning mechanism based upon a mixture of standard deviation for each failure mechanism and the Pareto-80/20 rule.

The SD of the "Blockage" data in Table 5-8 is identified in Table 5-9. The SD is used as a "measure of volatility" of the process failures. For example: some of the failure mechanisms may be common to the current technological capability of the process and or may be specific to particular product types or material systems, if so these particular failure mechanisms may be attributed to the infancy of the "State of the Art" rather than a specific mechanism of the particular process. The SD is used in this application thus: the higher the SD, then the more volatile the specific process, thus offering an overview machine [bay] comparator.

The SD offers a ranking of the capability blockages, however the options are to work on all of the blockages, sequentially work on the derived priority or use a basic reasoning mechanism to identify a group to be analysed. To optimise the potential benefit and maintain control and focus it is essential to simplistically operate on the SD using a form of reasoning mechanism. A typical such mechanism that can be interpreted as existing in both quality and management folk law today is the Pareto rule. The Pareto-80/20 rule offers some rationale to the choice of blockage operation.

Manufacturing Capability Blockages							
Summary 97	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	% Lost Runs
Total Runs	584	1254	529	473	430	1638	
Deliverable	30%	46%	63%	34%	30%	56%	
Monitor Wafers	9%	9%	9%	9%	9%	9%	
Hardware	4%	4%	9%	12%	20%	2%	18%
Morphology	21%	9%	4%	25%	18%	18%	33%
Doping	9%	3%	8%	5%	3%	3%	11%
PL	1%	16%	3%	8%	5%	4%	13%
Composition	0%	9%	0%	0%	6%	5%	7%
Errors	1%	2%	2%	1%	8%	2%	6%
Sources	0%	0%	2%	2%	2%	0%	2%
Thickness	25%	1%	0%	4%	0%	0%	10%
Lost Wafers	355	569	149	269	264	571	

Table 5-8 - Manufacturing Blockages 1997

Table 5-9 reviews the data in Table 5-8 is compared across machines for common failure comparison. For example if a large difference exists between average and range then the failure mechanism is localised, which is confirmed by the SD of the range of numbers.

Failure Mechanism	Std Dev	Max	Min	Range	Average
Thickness	**9.86%**	24.8%	0.0%	**24.83%**	**4.92%**
Morphology	**7.76%**	24.9%	4.0%	**20.98%**	**15.90%**
Hardware	**6.82%**	20.2%	1.9%	**18.34%**	**8.74%**
PL	**5.49%**	16.1%	0.9%	**15.25%**	**6.13%**
Composition	**4.02%**	9.5%	0.0%	**9.49%**	**3.43%**
Doping	**2.92%**	9.1%	2.6%	**6.52%**	**5.07%**
Errors	**2.70%**	8.1%	1.1%	**7.08%**	**2.72%**
Sources	**0.90%**	2.1%	0.0%	**2.08%**	**1.00%**

Table 5-9 - Data, Std Dev Analysis

Equation 4: $(\text{Sum SD\%} > x\%) / SD_c = \text{Pareto Operator } SD_p$

Using Equation 4, with each SD%:

$SD_{10} > 10\%$ - $SD_p = 0\%$
$SD_9 > 9\%$ - $SD_p = 25\%$

$SD_8 > 8\%$ - $SD_p=25\%$
$SD_7 > 7\%$ - $SD_p=45\%$
$SD_6 > 6\%$ - $SD_p=60\%$
$SD_5 > 5\%$ - $SD_p=75\%$
$SD_4 > 4\%$ - $SD_p=84\%$
$SD_3 > 3\%$ - $SD_p=84\%$
$SD_2 > 2\%$ - $SD_p=99\%$
$SD_1 > 1\%$ - $SD_p=100\%$

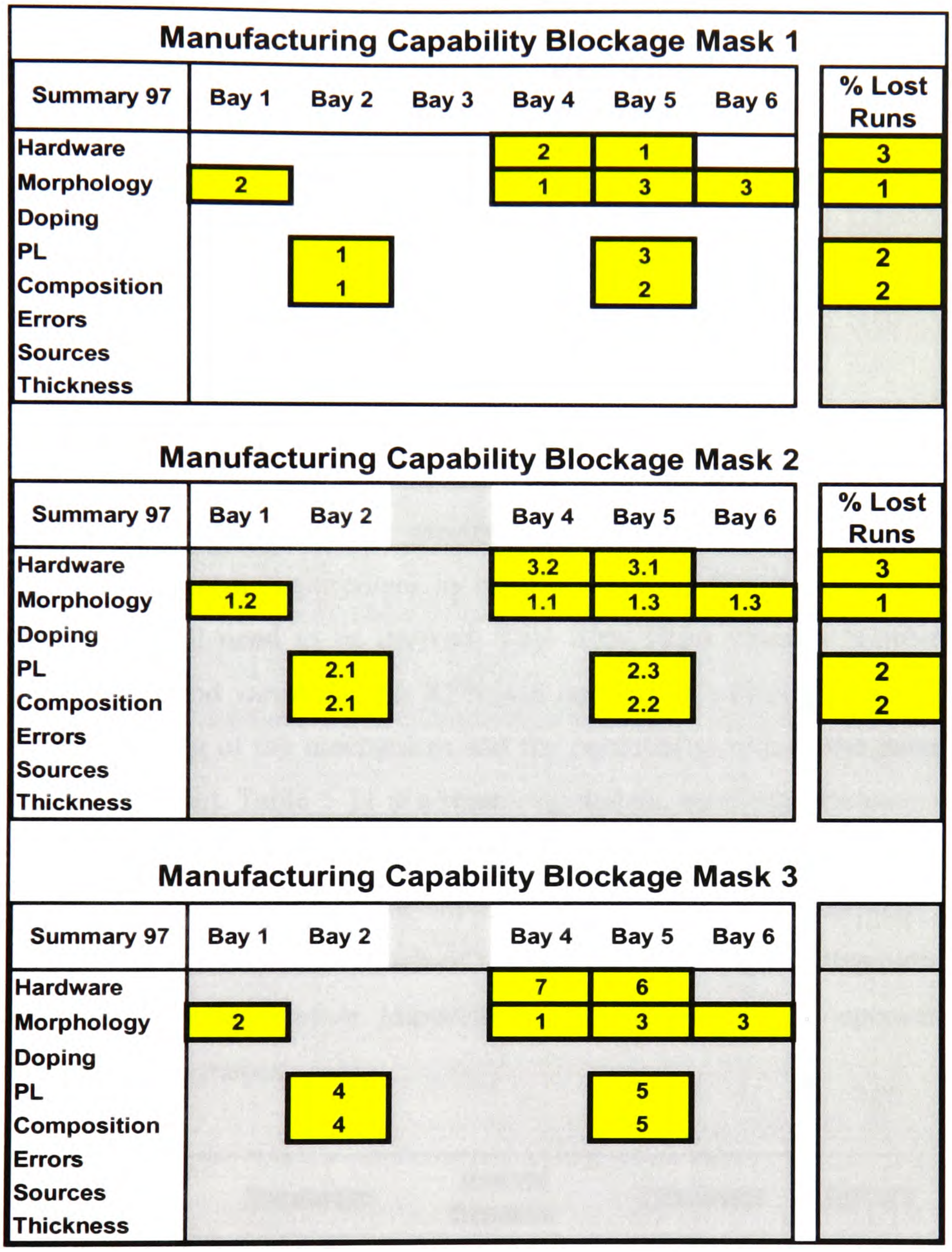
Using the Pareto rule the selected operating SD is >5, as this offers the nearest Pareto operator up to 80%.

Therefore if a cumulative Failure Rate has a SD of greater than 5% it will then be operated on per bay, Table 5-9 summarises the overall standard deviation.

As for Table 5-6, in Table 5-8 both x-ray/composition and PL failures are grouped, although the effect of the failure may differ in characterisation of the material, the cause is identical [both measure the intrinsic material quality but used for potentially different material systems]. By identifying the major deviants in each failure category per machine, a mask can once again be identified (Figure 5-2).

The identified "masks" can be used to define the characteristic priorities. This technique derives directly the priority action plan as a function of the largest failure mechanism attributed to its source in descending order.

From the masking exercise, the ranking of the priorities can be derived. This, however is a simple prioritisation tool and should be used as "Part" of the priority screening process. The priority information offered from the "masking exercise" (Table 5-10) will be one of the operating variables.



Manufacturing Capability Blockage Mask 1

Summary 97	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	% Lost Runs
Hardware				2	1		3
Morphology	2			1	3	3	1
Doping							
PL		1			3		2
Composition		1			2		2
Errors							
Sources							
Thickness							

Manufacturing Capability Blockage Mask 2

Summary 97	Bay 1	Bay 2		Bay 4	Bay 5	Bay 6	% Lost Runs
Hardware				3.2	3.1		3
Morphology	1.2			1.1	1.3	1.3	1
Doping							
PL		2.1			2.3		2
Composition		2.1			2.2		2
Errors							
Sources							
Thickness							

Manufacturing Capability Blockage Mask 3

Summary 97	Bay 1	Bay 2		Bay 4	Bay 5	Bay 6	
Hardware				7	6		
Morphology	2			1	3	3	
Doping							
PL		4			5		
Composition		4			5		
Errors							
Sources							
Thickness							

Figure 5-2 - Blockage Masking Exercise 1997 Data

Priority	Bay	Failure Mechanism
1	4	Morphology
2	1	Morphology
3	5	Morphology
3	6	Morphology
4	2	Composition
5	5	Composition
6	5	Hardware
7	4	Hardware

Table 5-10 - Masking Exercise Results

There are three differing failure mechanisms with each having a different impact and different requirement to offer a practical fix. A "Fail RPN" (Table 5-11) will need to be derived. This RPN [Risk Priority Number] will offer a second variable. This RPN will need to be a direct function of the understanding of the mechanism and the potential to reduce the failure mechanism impact. Table 5-11 is a reasoning matrix, enabling extension of the prioritisation process to include a summary evaluation on the knowledge, control potential and an estimate the required investment to solve the failure mechanism. Each of the operators is weighted depending upon their discrete relative importance. This results in an operating algorithm for the matrix.

Failure Mechanism	Knowledge	Control Potential	Investment	Fail RPN
Morphology	2	9	8	3
Composition	8	6	6	11
Hardware	7	8	6	12
Scaling	!0 - Total	10 - Total	10 - High	
Weight	2	1	1.5	
Algorithm	((K x KW) x (CP x CPW)) / (I x IW) = RPN			

Table 5-11 - Mechanism RPN

An additional critical variable in the decision-making is the product priority that runs on each of the reactors [bays]. This will be incorporated with fail and mechanism RPN's in a final Decision Matrix (Table 5-12).

Priority	Bay	Failure Mechanism	Bay Product Weight	Fail RPN	Action RPN
1	4	Morphology	50	3	150
2	1	Morphology	70	3	105
3	5	Morphology	75	3	75
3	6	Morphology	40	3	40
4	2	Composition	30	11	80
5	5	Composition	75	11	160
6	5	Hardware	75	12	156
7	4	Hardware	50	12	89
Algorithm		(BPW x FRPN) / Pr = Action RPN			

Table 5-12 - Action RPN Table

The previously determined priorities will need re-defining following the outcome of Table 5-12, concluding on the "Risk Priority Number" for the action plan. Table 5-13 conclude on the overall rating.

Priority	Bay	Failure Mechanism	Bay Product Weight	Fail RPN	Action RPN	% of Max
5	5	Composition	75	11	160	100%
6	5	Hardware	75	12	156	97%
1	4	Morphology	50	3	150	94%
2	1	Morphology	70	3	105	66%
7	4	Hardware	50	12	89	56%
4	2	Composition	30	11	80	50%
3	5	Morphology	75	3	75	47%
3	6	Morphology	40	3	40	25%

Table 5-13 - Action Priorities

The action RPN's are ranked in descending order (Table 5-13), and all are calculated as a percentage of the highest RPN number. Each action RPN defines each risk relative to each other, the higher the number the higher the risk. The cumulative RPN may also be used, for example to evaluate 80% [Pareto] of the cumulative RPN, how many mechanisms are included.

Almost 40% of the total cumulative RPN [(160+156)/855] is within the top, two listed failures. Further investigations will concentrate on these failure categories:

Composition & Hardware.

Although morphology has proved within the preceding techniques to be a major failure mechanism, it is the least understood of all of the mechanisms to date. Cumulatively both composition & hardware rank slightly higher and will take investigative authority.

The analyses of the categories need defining in a structured hierarchy enabling organised analysis.

The structured hierarchy is defined as:

Step 1 - Define Failure Categories
Step 2 - Define Failure Category Instrumental Mechanisms
Step 3 - Define & Evaluate Actual Mechanisms
Step 4 - Derive Mechanism Causes

5.2.3 – Failure Mechanism Analysis

5.2.3.1 – **Step 1** - *Define Failure Categories*

This initial step is fully dependant upon the contribution from the preceding section 5.1.2, which has justified both "Composition and Hardware" for further analysis. These are identified as the priority one blockages to the overall manufacturing performance following the action derivation.

5.2.3.2 – **Step 2** - *Define Failure Category Mechanisms*

<u>Composition</u>

A deviation from specification of the fundamental “Material Mixture”, there are several “Failure Mechanisms” that have an adverse effect on the mixture proportions. The generic groups are:

1 - Incorrect Material Prescription - Human Failure
  Process Definition Incorrect
  Process Program Incorrect
  Machine “Set Up” Incorrect

2 - Incorrect Material Prescription – Hardware Failure
  Flow Controllers Delivering Out of Control Flow
  Material Vapour Conditions Out of Control Temp & Press
  Process Timing Control Out of Control
  Material Isolation or Diversion Out of Control
  Compositional Uniformity Out of Specification
  Inter-Source Conduit Integrity Compromise
  Growth Temperature Out of Specification

3 - Incorrect Material Prescription – Source Failure
  Contaminated Source Material
  Oxidisation of Source – Leak to Air

Hardware - *Typical*

This is the fundamental “Material Mixture”; there are several failure mechanisms that have an adverse effect on the mixture proportions. The generic groups are:

1 – Flow Control Source
  Flow Controllers Injection Failure
  Flow Controllers Source or Dilution Failure
  Material Vapour Conditions Out of Control Temp & Press
  Process Timing Control Out of Control
  Material Isolation or Diversion Failure

2 – Flow Control Carrier
  Flow Controllers M.Organic, Dopant, Hydride Failure
  Flow Controllers Source or Dilution Failure
  Cell Injection System Alignment Out of Specification
  Inter-Source Conduit Integrity Compromise

3 –Pressure Control
  Pressure Controllers M.Organic, Dopant, Hydride Failure
  Cell Growth Pressure Out of Specification
  Blockage or Resistance in Any Gas Flow Path

4 –Temperature Control
    Temp Controlled Storage Vessels for Sources Out of Spec
    Cell Temperature Control System Out of Specification
    Blockage or Resistance in Any Gas Flow Path
    Ambient Temperature Control Low-Source Condensation
    Ambient Temperature Control High-Source Pre-Deposition

5 –Process Timing
    Process Control Timing Failure
    Slow Reacting Flow Controllers
    Slow Reacting Flow Diversion Valves
    Blockage or Resistance in Any Gas Flow Path
    Wafer Rotation Control

6 – System Leak Integrity
    Hydrogen Diffuser Membrane Integrity
    Leak Integrity to Air
    Internal Valve Leak integrity
    Internal Seal Leak Integrity

This is a list of "typical" failures to cause the described effect as seen in the grown material.

5.2.3.3 – **Step 3** - *Define & Evaluate Actual Mechanisms*

Definition of human errors and the chemistry requirement for source failure Analysis identifies the ideal starting point as the hardware mechanism. Supporting the hardware failures both reactively and proactively have an impact on the process, downtime.

Hardware

Records are maintained on every wafer in every run, these records are available for analysis. Every growth run undertaken that fails due to a discreet hardware failure is very easily identified. Identifying the actual cause of failure with the resulting effect of a compositional shift cannot be directly identified.

The Hardware failure code allocated to all runs, production, engineering and test, can be produced as a chart of failure types against each production unit (see Table 5-14). It is not necessary to allocate lost costs against the differing failure codes.

Hardware Failure Codes		Wafer Failures Total/Active Month x 12							
Code	**Description**	**Bay 1**	**Bay 2**	**Bay 3**	**Bay 4**	**Bay 5**	**Bay 6**	**Total / Code**	**Perf %**
Ha	Aborted Run	72	17	81	40	60	7	**277**	**41%**
Hb	Bath Temperature	0	16	0	0	0	0	**16**	**2%**
Hc	Computer/Software Fail	0	13	0	22	0	2	**37**	**6%**
Hd	Diffuser failure	0	0	0	0	0	0	**0**	**0%**
Hf	Flow Control	0	32	0	6	23	17	**78**	**12%**
Hg	General	0	7	0	7	32	5	**51**	**8%**
Hh	Heat Source RF/IR	0	8	0	0	5	1	**15**	**2%**
Hr	Rotation	18	0	21	44	70	0	**153**	**23%**
Hs	Services (Water/Power etc)	14	1	0	0	10	4	**29**	**4%**
Hv	Vacuum Leak Integrity	0	1	0	11	2	2	**16**	**2%**
	Total/Bay est 12 months	**104**	**96**	**102**	**130**	**202**	**38**	**672**	
	Active Months	6	10	8	12	11	12		
	Performance % of Total	**15%**	**14%**	**15%**	**19%**	**30%**	**6%**		

Table 5-14 - Hardware Failure Analysis: 1

Concluding from the Table 5-14:

The total Wafer Failures allocated to Hardware Failures in Table 5-8 were 306, and yet from Table 5-14, the site summary identifies 672 failures being generated and yet discreetly coded. Suggesting that the data available is unreliable, additional data sources or comparisons require investigating. An MTBF (de Bruijin, 2000) analysis (Table 5-15) for the data summary above will offer an indication.

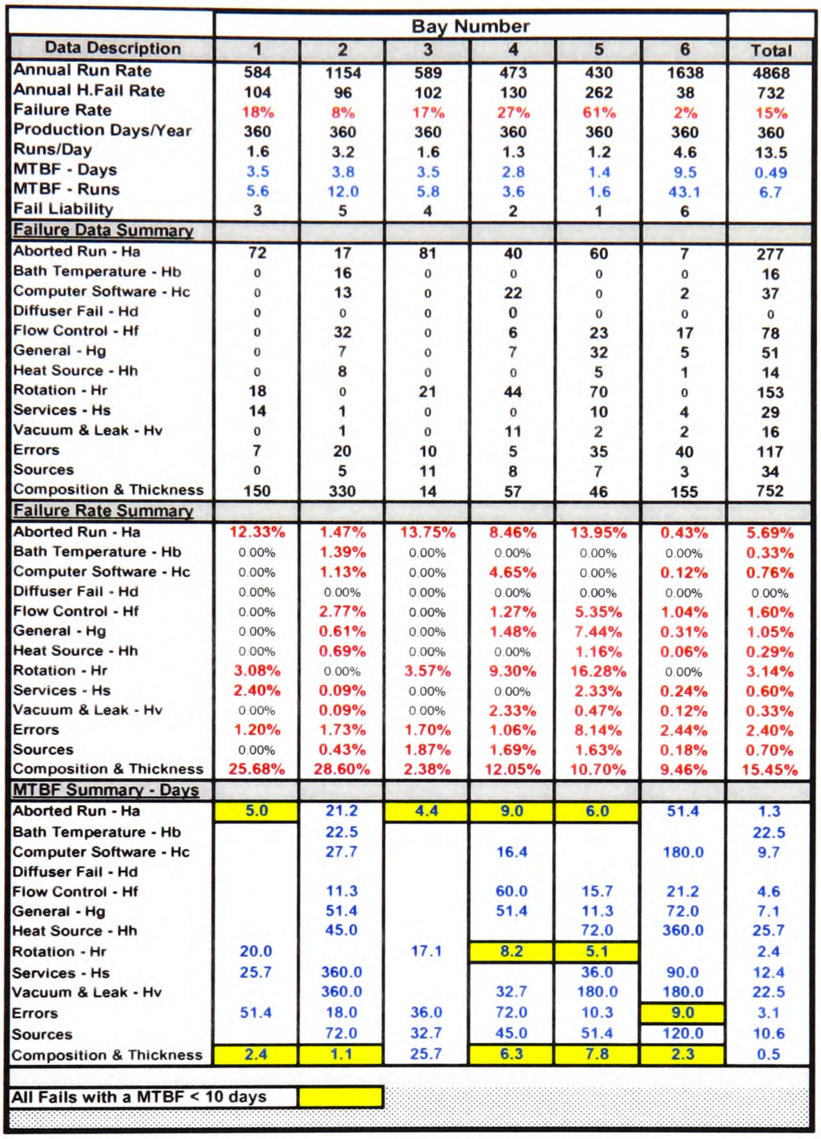
	Bay Number							
Data Description	**1**	**2**	**3**	**4**	**5**	**6**	**Average**	**Total**
Annual Run Rate	**584**	**1154**	**589**	**473**	**430**	**1638**	**811**	**4868**
Annual H.Fail Rate	**104**	**96**	**102**	**130**	**262**	**38**	**122**	**732**
Failure Rate	**18%**	**8%**	**17%**	**27%**	**61%**	**2%**	**22%**	**15%**
Production Days/Year	**360**	**360**	**360**	**360**	**360**	**360**	**360**	**360**
Runs/Day	**1.6**	**3.2**	**1.6**	**1.3**	**1.2**	**4.6**	**2.3**	**13.5**
MTBF - Days	**3.5**	**3.8**	**3.5**	**2.8**	**1.4**	**9.5**	**4.1**	**0.49**
MTBF - Runs	**5.6**	**12.0**	**5.8**	**3.6**	**1.6**	**43.1**	**12.0**	**6.7**
Fail Liability	3	5	4	2	1	6		

Table 5-15 - Hardware MTBF Analysis

The "worst case" identified in Table 5-15 suggests that the most unreliable bay suffers a failure every 1.4 days or 1.6 runs. Although not previously derived this appears a high MTBF, when encompassing all of the "Failure Codes".

To expand on the derived principal further, an MTBF (Table 5-16) relationship can be derived for each of the specific hardware failure modes. This will need supporting with the general data from the original business risk analysis. There will be no overlap of data, as only primary failure codes will be used. Error data will also be included as the rate can be defined within a MTBF analysis.

MTBF [Mean Time Between Failures] is a technique that enables evaluation of each specific failure rate and how often they occur, included within each calculated time is the MTTR [Mean Time To Repair]. Specific details and interpretations for MTBF and MTTR are widely distributed; Feigenbaum (1991) discusses such examples.



	Bay Number						
Data Description	1	2	3	4	5	6	Total
Annual Run Rate	584	1154	589	473	430	1638	4868
Annual H.Fail Rate	104	96	102	130	262	38	732
Failure Rate	18%	8%	17%	27%	61%	2%	15%
Production Days/Year	360	360	360	360	360	360	360
Runs/Day	1.6	3.2	1.6	1.3	1.2	4.6	13.5
MTBF - Days	3.5	3.8	3.5	2.8	1.4	9.5	0.49
MTBF - Runs	5.6	12.0	5.8	3.6	1.6	43.1	6.7
Fail Liability	3	5	4	2	1	6	
Failure Data Summary							
Aborted Run - Ha	72	17	81	40	60	7	277
Bath Temperature - Hb	0	16	0	0	0	0	16
Computer Software - Hc	0	13	0	22	0	2	37
Diffuser Fail - Hd	0	0	0	0	0	0	0
Flow Control - Hf	0	32	0	6	23	17	78
General - Hg	0	7	0	7	32	5	51
Heat Source - Hh	0	8	0	0	5	1	14
Rotation - Hr	18	0	21	44	70	0	153
Services - Hs	14	1	0	0	10	4	29
Vacuum & Leak - Hv	0	1	0	11	2	2	16
Errors	7	20	10	5	35	40	117
Sources	0	5	11	8	7	3	34
Composition & Thickness	150	330	14	57	46	155	752
Failure Rate Summary							
Aborted Run - Ha	12.33%	1.47%	13.75%	8.46%	13.95%	0.43%	5.69%
Bath Temperature - Hb	0.00%	1.39%	0.00%	0.00%	0.00%	0.00%	0.33%
Computer Software - Hc	0.00%	1.13%	0.00%	4.65%	0.00%	0.12%	0.76%
Diffuser Fail - Hd	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Flow Control - Hf	0.00%	2.77%	0.00%	1.27%	5.35%	1.04%	1.60%
General - Hg	0.00%	0.61%	0.00%	1.48%	7.44%	0.31%	1.05%
Heat Source - Hh	0.00%	0.69%	0.00%	0.00%	1.16%	0.06%	0.29%
Rotation - Hr	3.08%	0.00%	3.57%	9.30%	16.28%	0.00%	3.14%
Services - Hs	2.40%	0.09%	0.00%	0.00%	2.33%	0.24%	0.60%
Vacuum & Leak - Hv	0.00%	0.09%	0.00%	2.33%	0.47%	0.12%	0.33%
Errors	1.20%	1.73%	1.70%	1.06%	8.14%	2.44%	2.40%
Sources	0.00%	0.43%	1.87%	1.69%	1.63%	0.18%	0.70%
Composition & Thickness	25.68%	28.60%	2.38%	12.05%	10.70%	9.46%	15.45%
MTBF Summary - Days							
Aborted Run - Ha	5.0	21.2	4.4	9.0	6.0	51.4	1.3
Bath Temperature - Hb		22.5					22.5
Computer Software - Hc		27.7		16.4		180.0	9.7
Diffuser Fail - Hd							
Flow Control - Hf		11.3		60.0	15.7	21.2	4.6
General - Hg		51.4		51.4	11.3	72.0	7.1
Heat Source - Hh		45.0			72.0	360.0	25.7
Rotation - Hr	20.0		17.1	8.2	5.1		2.4
Services - Hs	25.7	360.0			36.0	90.0	12.4
Vacuum & Leak - Hv		360.0		32.7	180.0	180.0	22.5
Errors	51.4	18.0	36.0	72.0	10.3	9.0	3.1
Sources		72.0	32.7	45.0	51.4	120.0	10.6
Composition & Thickness	2.4	1.1	25.7	6.3	7.8	2.3	0.5

All Fails with a MTBF < 10 days 🟨

Table 5-16 - MTBF Analysis

The top four, bay specific mechanisms from Table 5-16 that hold a MTBF of less than 10 days where the data average is 9.4 days are:

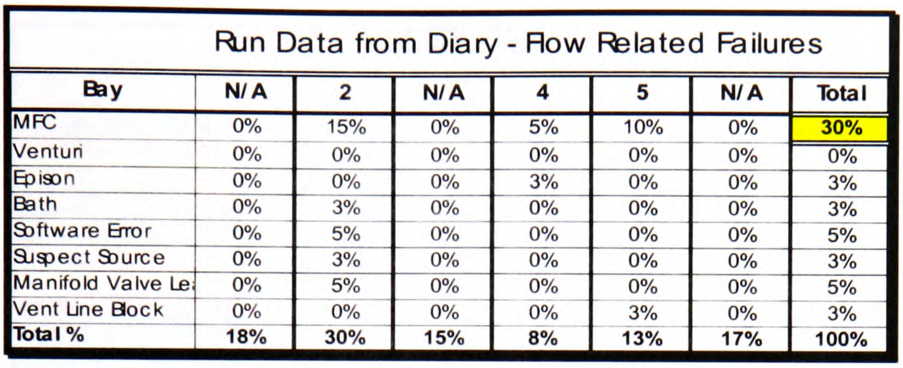
Mechanism	**MTBF**
Composition & Thickness Control	0.5 days
Aborted Runs	1.3 days
Wafer Rotation	2.4 days
Errors	3.1 days

This data will allow prioritising and construction of a process FMEA, however prior to full acceptance a "sanity check" on the data is therefore required, as a suspicion on data accuracy has previously been raised.

Each bay operator records tasks on a daily basis, which can be representative of the failure activity of each reactor (Figure 5-3, Figure 5-4, Figure 5-5).

Run Data From Diary - Aborted Runs							
Recording Perf %	**86%**	**57%**	**100%**	**67%**	**69%**	**0%**	
Abort Reason	**Bay 1**	**Bay 2**	**Bay 3**	**Bay 4**	**Bay 5**	**Bay 6**	**Total**
Pump	0%	0%	2%	2%	2%	0%	6%
253 Valve	0%	2%	2%	0%	0%	0%	4%
T/C wire U/S	2%	0%	0%	0%	0%	0%	2%
Power cut	4%	0%	0%	0%	0%	0%	4%
Scrubber errors	0%	0%	2%	0%	0%	0%	2%
Water leak	0%	0%	2%	0%	0%	0%	2%
RF trip	0%	2%	0%	0%	0%	0%	2%
Lamp failure	4%	0%	4%	2%	6%	0%	**17%**
Software	2%	4%	2%	0%	0%	0%	8%
Source run out	0%	8%	0%	6%	0%	0%	**15%**
MFC	0%	0%	0%	0%	2%	0%	2%
Filters blockage	0%	0%	4%	6%	6%	0%	**17%**
Elbows blockage	0%	0%	4%	2%	2%	0%	**8%**
Thimble blockage	0%	0%	4%	0%	0%	0%	**4%**
Fire in extract line	0%	0%	0%	2%	2%	0%	4%
DOR failure	0%	0%	0%	0%	2%	0%	2%
Bay Totals.Site %	13%	17%	27%	21%	23%	0%	100%
Total Diary	6	8	13	10	11	0	48
Total D.Base	7	14	13	15	16	7	72

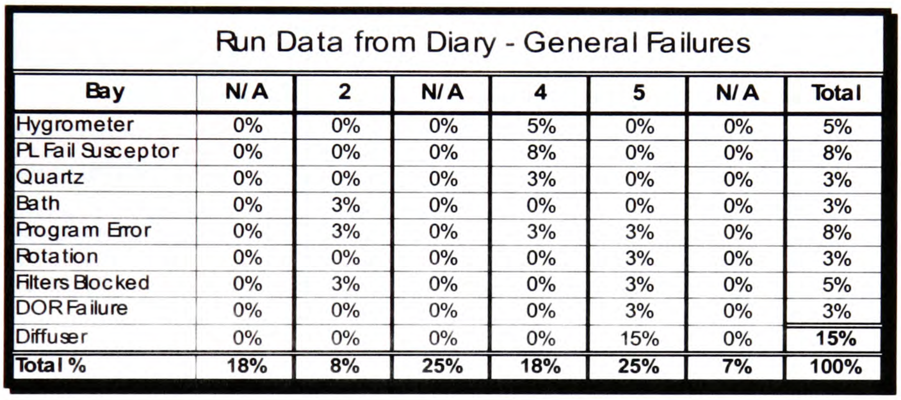
Figure 5-3 - Aborted Run Data



Run Data from Diary - Flow Related Failures

Bay	N/A	2	N/A	4	5	N/A	Total
MFC	0%	15%	0%	5%	10%	0%	**30%**
Venturi	0%	0%	0%	0%	0%	0%	0%
Epison	0%	0%	0%	3%	0%	0%	3%
Bath	0%	3%	0%	0%	0%	0%	3%
Software Error	0%	5%	0%	0%	0%	0%	5%
Suspect Source	0%	3%	0%	0%	0%	0%	3%
Manifold Valve Le	0%	5%	0%	0%	0%	0%	5%
Vent Line Block	0%	0%	0%	0%	3%	0%	3%
Total %	**18%**	**30%**	**15%**	**8%**	**13%**	**17%**	**100%**

Figure 5-4 - Flow Related Failures

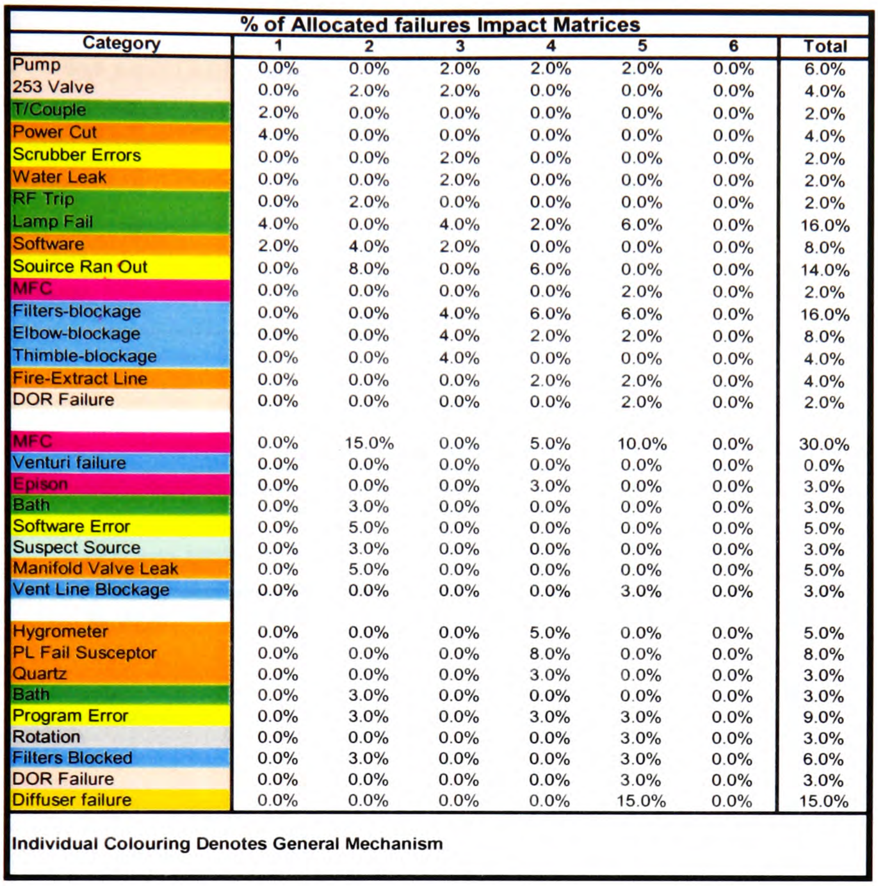


Run Data from Diary - General Failures

Bay	N/A	2	N/A	4	5	N/A	Total
Hygrometer	0%	0%	0%	5%	0%	0%	5%
PL Fail Susceptor	0%	0%	0%	8%	0%	0%	8%
Quartz	0%	0%	0%	3%	0%	0%	3%
Bath	0%	3%	0%	0%	0%	0%	3%
Program Error	0%	3%	0%	3%	3%	0%	8%
Rotation	0%	0%	0%	0%	3%	0%	3%
Filters Blocked	0%	3%	0%	0%	3%	0%	5%
DOR Failure	0%	0%	0%	0%	3%	0%	3%
Diffuser	0%	0%	0%	0%	15%	0%	**15%**
Total %	**18%**	**8%**	**25%**	**18%**	**25%**	**7%**	**100%**

Figure 5-5 - General Failures

The previous MTBF data has been generated from the "Lost Wafer Analysis", to compare this directly with the practically based experience of each operator. A summary (Figure 5-6) of Figure 5-3, Figure 5-4 and Figure 5-5 offers additional data to compare.

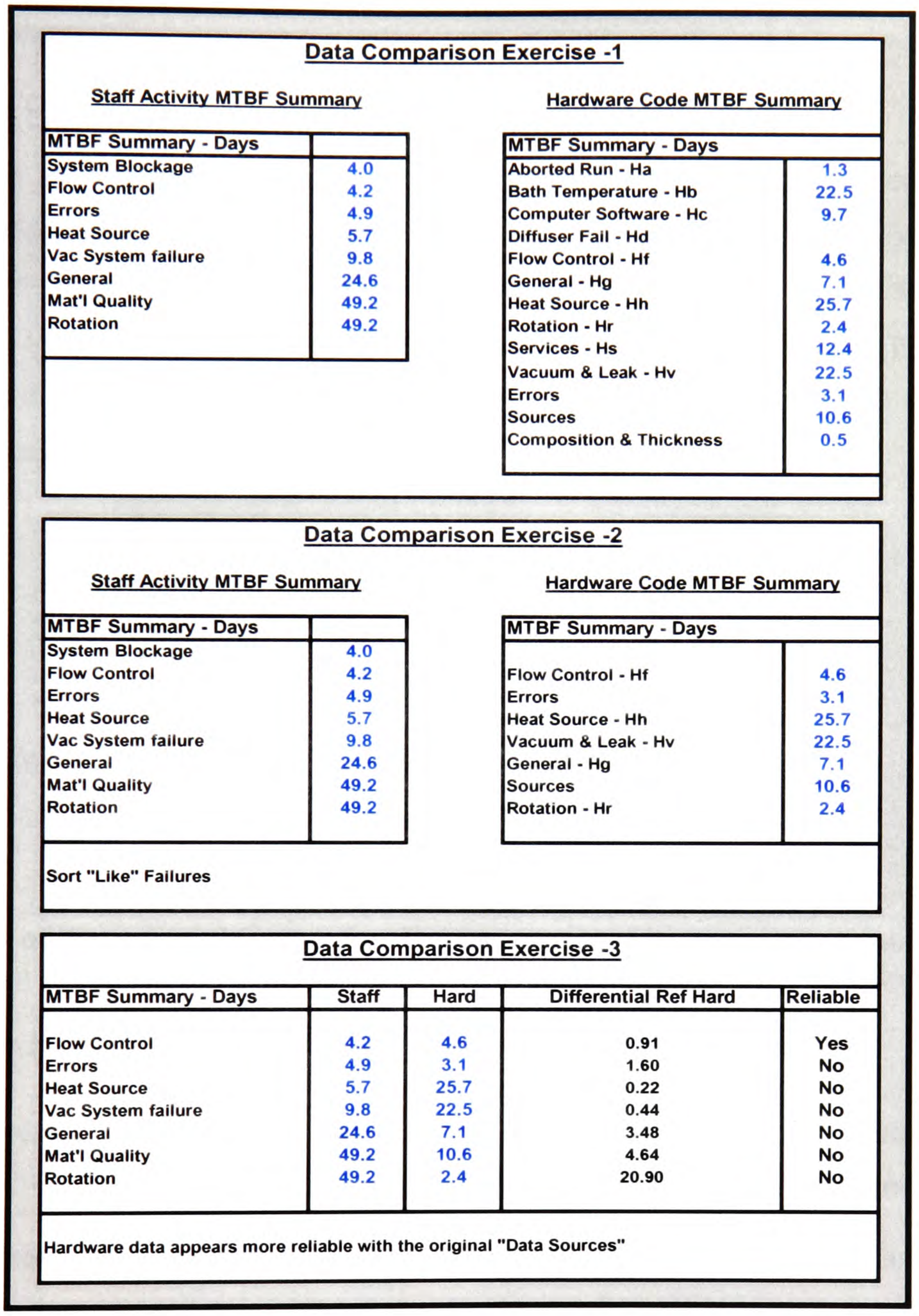


% of Allocated failures Impact Matrices							
Category	1	2	3	4	5	6	Total
Pump	0.0%	0.0%	2.0%	2.0%	2.0%	0.0%	6.0%
253 Valve	0.0%	2.0%	2.0%	0.0%	0.0%	0.0%	4.0%
T/Couple	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%
Power Cut	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.0%
Scrubber Errors	0.0%	0.0%	2.0%	0.0%	0.0%	0.0%	2.0%
Water Leak	0.0%	0.0%	2.0%	0.0%	0.0%	0.0%	2.0%
RF Trip	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%	2.0%
Lamp Fail	4.0%	0.0%	4.0%	2.0%	6.0%	0.0%	16.0%
Software	2.0%	4.0%	2.0%	0.0%	0.0%	0.0%	8.0%
Souirce Ran Out	0.0%	8.0%	0.0%	6.0%	0.0%	0.0%	14.0%
MFC	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	2.0%
Filters-blockage	0.0%	0.0%	4.0%	6.0%	6.0%	0.0%	16.0%
Elbow-blockage	0.0%	0.0%	4.0%	2.0%	2.0%	0.0%	8.0%
Thimble-blockage	0.0%	0.0%	4.0%	0.0%	0.0%	0.0%	4.0%
Fire-Extract Line	0.0%	0.0%	0.0%	2.0%	2.0%	0.0%	4.0%
DOR Failure	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	2.0%
MFC	0.0%	15.0%	0.0%	5.0%	10.0%	0.0%	30.0%
Venturi failure	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Epison	0.0%	0.0%	0.0%	3.0%	0.0%	0.0%	3.0%
Bath	0.0%	3.0%	0.0%	0.0%	0.0%	0.0%	3.0%
Software Error	0.0%	5.0%	0.0%	0.0%	0.0%	0.0%	5.0%
Suspect Source	0.0%	3.0%	0.0%	0.0%	0.0%	0.0%	3.0%
Manifold Valve Leak	0.0%	5.0%	0.0%	0.0%	0.0%	0.0%	5.0%
Vent Line Blockage	0.0%	0.0%	0.0%	0.0%	3.0%	0.0%	3.0%
Hygrometer	0.0%	0.0%	0.0%	5.0%	0.0%	0.0%	5.0%
PL Fail Susceptor	0.0%	0.0%	0.0%	8.0%	0.0%	0.0%	8.0%
Quartz	0.0%	0.0%	0.0%	3.0%	0.0%	0.0%	3.0%
Bath	0.0%	3.0%	0.0%	0.0%	0.0%	0.0%	3.0%
Program Error	0.0%	3.0%	0.0%	3.0%	3.0%	0.0%	9.0%
Rotation	0.0%	0.0%	0.0%	0.0%	3.0%	0.0%	3.0%
Filters Blocked	0.0%	3.0%	0.0%	0.0%	3.0%	0.0%	6.0%
DOR Failure	0.0%	0.0%	0.0%	0.0%	3.0%	0.0%	3.0%
Diffuser failure	0.0%	0.0%	0.0%	0.0%	15.0%	0.0%	15.0%

Individual Colouring Denotes General Mechanism

Figure 5-6 - Impact Matrix

Figure 5-6 can be summarised into groups (Table 5-17), this will enable a comparison against previously summarised MTBF data.



Data Comparison Exercise -1

Staff Activity MTBF Summary

MTBF Summary - Days	
System Blockage	4.0
Flow Control	4.2
Errors	4.9
Heat Source	5.7
Vac System failure	9.8
General	24.6
Mat'l Quality	49.2
Rotation	49.2

Hardware Code MTBF Summary

MTBF Summary - Days	
Aborted Run - Ha	1.3
Bath Temperature - Hb	22.5
Computer Software - Hc	9.7
Diffuser Fail - Hd	
Flow Control - Hf	4.6
General - Hg	7.1
Heat Source - Hh	25.7
Rotation - Hr	2.4
Services - Hs	12.4
Vacuum & Leak - Hv	22.5
Errors	3.1
Sources	10.6
Composition & Thickness	0.5

Data Comparison Exercise -2

Staff Activity MTBF Summary

MTBF Summary - Days	
System Blockage	4.0
Flow Control	4.2
Errors	4.9
Heat Source	5.7
Vac System failure	9.8
General	24.6
Mat'l Quality	49.2
Rotation	49.2

Hardware Code MTBF Summary

MTBF Summary - Days	
Flow Control - Hf	4.6
Errors	3.1
Heat Source - Hh	25.7
Vacuum & Leak - Hv	22.5
General - Hg	7.1
Sources	10.6
Rotation - Hr	2.4

Sort "Like" Failures

Data Comparison Exercise -3

MTBF Summary - Days	Staff	Hard	Differential Ref Hard	Reliable
Flow Control	4.2	4.6	0.91	Yes
Errors	4.9	3.1	1.60	No
Heat Source	5.7	25.7	0.22	No
Vac System failure	9.8	22.5	0.44	No
General	24.6	7.1	3.48	No
Mat'l Quality	49.2	10.6	4.64	No
Rotation	49.2	2.4	20.90	No

Hardware data appears more reliable with the original "Data Sources"

Table 5-17 - MTBF Summary

Minor differences are evident between the "Hardware" listed failures and the yield; the data submitted from the "Operator" logs may not be a realistic representation of "Process failures". The data recorded would probably include but not differentiate activities carried out for routine or following routine maintenance tasking, resulting in "lost time" and not lost product.

5.2.3.4 – **Step 4** - *Derive Mechanism Causes*

The Effects of the Failures has been analysed in the previous step, the priorities have also been derived using the MTBF analysis. The next step therefore is to somehow define the Causes of such effects. A very simple and yet powerful technique to use in such an exercise is FMEA. An FMEA for the generic causes of the following effects as defined in Step 3 of the procedure.

Mechanism	**MTBF**
Composition & Thickness Control	0.5 days
Aborted Runs	1.3 days
Wafer Rotation	2.4 days
Errors	3.1 days

Only two of the listed Causes are directly hardware related:

Composition & Thickness Control
Wafer Rotation

All of the potential Causes for the two generic effects can only be sourced from either the "Gas Handling" or "Cell" areas of the Growth Machines.

The FMEA technique that will be typical using operators such as:

Severity – An evaluation of the Process Impact that a Failure Mode can "Inflict" upon the potential product, 10 is devastating, 1 is minimal impact.

Occurrence – An evaluation on "How often" this failure Mode has the potential of occurring, 10 is all the time, 1 is infrequent.

Detectability – An evaluation of the Ease of identifying a problem and that the specific mode is the cause, 1 is very easy, 10 is very difficult.

The simplest way to establish the ranking for these numbers is to use full scale with best and worst situations, and then rank all other mechanism operators relatively. All of these are taken into account when deriving the **RPN** [Risk Priority Number]. Differing authors classify RPN independently, for example: Stamatis (1995) describes it as a "Risk Priority Number". In real terms it is a pure operator and may as FMEA, be operated flexibly, as APN [Accident Priority Number] as defined in AMEA (Accident Mode Effect Analysis – Williams and John, 1998) The RPN is some function of all three, Severity, Occurrence and Detectability. The function can take any form, each of the three operators may be weighted, multipliers, divisors etc. to realistically replicate the analysis to be undertaken.

For the Purpose of this exercise equal weights of 1 will be issued to each operator, the resulting RPN will therefore equate to:

Equation 5: $RPN = (1xS) \times (1xO) \times (1xD)$

The resulting RPN's can then be used as a secondary operator to derive overall "Cause Probability Profile". This will be discussed in section 6.3.3.

Table 5-18 & Table 5-19 briefly summarise the process problems that are currently experienced on a regular basis that have occurred due to a problem within the gas handling and cell or growth chamber section of the MOVPE process machine, all of these problems cause specification degradation of the grown product. Also included in the determined high priority areas is a functional action. In Table 5-18 [incomplete analysis] a column identified as "Likely Cause" is used as a "sub-cause" identifier behind the generic cause. This is a potential issue with complex system evaluation.

Gas Handling Process FMEA

Failure Mode	Effect of Failure	Severity	Cause of Failure	Occurrence	Current Controls	Detectable	Product Char	Likely Cause	RPN	Action
Injection MFC Stability	Compositional, PL Variability, Banding	8	Control System Transients	7	Product Characteristic Feedback	5	Multiple or Broad DXRD, PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	280	Review system operating back pressures in differing Run Conditions
Dilution MFC Stability	Compositional, PL Variability, Banding	5	Control System Transients	2	Composition Analyzer Stability	2	DXRD & Wavelength Trending Away from Expectation	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	20	
Pick Up MFC Stability	Compositional, PL Variability, Banding	5	Control System Transients	2	Composition Analyzer Stability	2	Broad DXRD or PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC or line	20	
Source Press Control Stability	Compositional, PL Variability, Banding	9	Control System Transients	7	Composition Analyzer Stability only in certain cases	8	Broad DXRD or PL Peaks	Too Low a pressure balancing Flow or Debris affecting Control valve Operation	504	Investigate Dp on pressure balancing systems
Non-Linear Material Pick Up	Compositional & PL Variability	4	Materials Handling Design	9	Composition Analyzer Monitoring - Manual	2	DXRD & Wavelength Trending Away from Expectation	Source Running Out, Pressure Control System Performance or blockage in Line	72	Analysis of System, and Design Pro-Active Control System
Gas Path Streaming	Unpredictable System Performance	8	Exhaust/Moly Ring Condition	7	Monitoring Exhaust Temperatures - Manual	9	DXRD & Wavelength Trending Away from Expectation	Restricted Moly Ring or Exhaust Port	504	Gas Mixing System design
Temp Control Bath Stability	Compositional & PL Variability	4	Changes in Vapour Temperature conditions of source	4	Composition Analyzer Stability	2	Multiple or Broad DXRD, PL Peaks, Normally Producing Satellite Peaks	Anti-freeze mixture not suitable	32	Re-Design Bath Use and Control
Non Linear Gas Mixing	Unpredictable System Performance	4	Differing Gas Flow, resulting in variable H2 and source mixing	3	Run Injector MFC's at low flows rather than risking pick up flow change	7	PL, DXRD, Doping non linear with respect to given flow	Pipework design problems	84	Gas Mixing System design
Valve Switching Perf	Poor Quality Material Interfaces	8	Slow to operate or leak across valves	2	Electro / Pneumatic operators on Switching valve and large volume air lines	9	Additional peaks in structures or poor interfaces	Low Pneumatic pressure, sticking valve actuator or Debris in valve	144	
Particles in Lines	Morphology deterioration-Features on wafer	9	Oxide or exhaust system debris in the Gas system, potential Cracking of grp iii material	9	Product Characteristic Feedback	9	Small "Grown In" defects, possibly in a streaming pattern over wafer	Line Heater out of control, leak to air or Exhaust system/Cell Pressure transients	729	Identify Sources of Contamination / Oxidation
Line Heater Control	Compositional & PL Variability	3	Incorrect Installation of Control Equipment	3	On/Off Thermostats with daily manual checks	1	Multiple peaks normally satellites	Thermocouple or heaters incorrectly installed	9	Re-Design System without need for Line heaters
Pressure Balancing Control	Poor Quality Material Interfaces	9	Unstable Vent/Run Lines during flow switching and subsequent transient Response	7	None	9	DXRD Fringing, PL Peak shoulders	Line restrictions via oxide build up or system resistance's / pipe sizes	567	Full Design Review of Systems and Performance "ON Line" is required
System Leak Integrity	Undoped Background and PL Intensity	9	System leaking in Air at low pressure, the O2 content affecting PL and background Doping Level	4	Daily He Leak Checks	8	High Intrinsic Doping Levels and Low Intensity Pl Peaks	Normally following poor quality machine integrity interruptions	288	Investigate & Derive easy regular means of checking M/C Integrity
Dew Point Stability	Undoped Background and PL Intensity	9	If the Source/Carrier dewpoint raise above -110 degC the O2 content is higher than expected	1	Manual Checking	10	High Intrinsic Doping Levels and Low Intensity Pl Peaks	Palladium Diffuser Membrane Rupture	90	

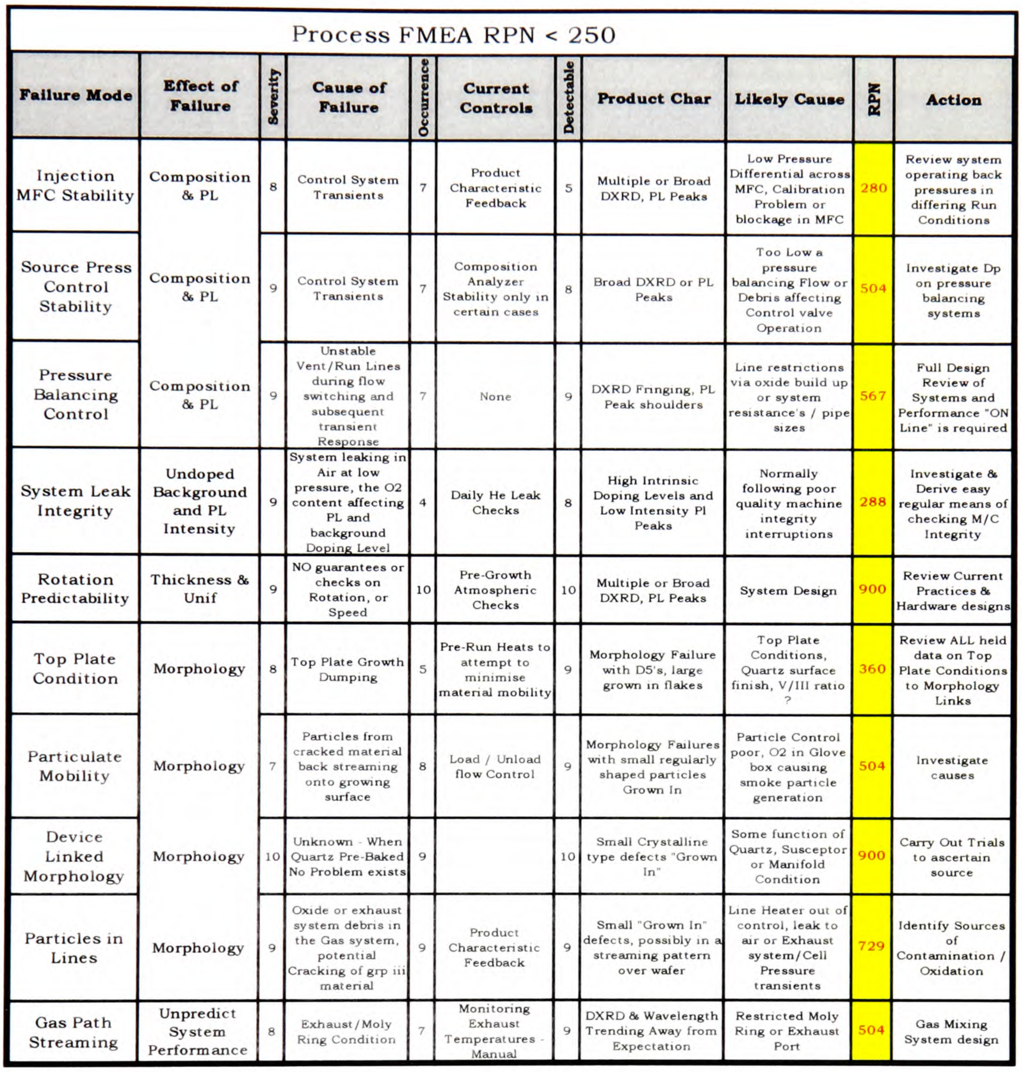
Table 5-18 - Gas Handling FMEA

Cell Process FMEA

Failure Mode	Effect of Failure	Severity	Cause of Failure	Occurrence	Current Controls	Detectable	Product Char	Likely Cause	RPN	Action
Rotation Predictability	Characteristic Uniformity - Scrap Product	9	NO guarantees or checks on Rotation, or Speed	10	Pre-Growth Atmospheric Checks	10	Multiple or Broad DXRD, PL Peaks	System Design	900	Review Current Practices & Hardware designs
Rotation Stability	Characteristic Homogeneity	3	Inability to Ensure rotation exceeds 1 Rev/s	1	None	10		System Design	30	
Susceptor Thermal Uniformity	Growth Rate/Doping	2	Inability to Check Temperature Profile of the Susceptor	1	Thyristor Current	4		System Design	8	
Rotation Gas Flow	Characteristic Uniformity	2	MFC Stability, Quartz to Graphite Interface Reliability	1	None	9		System Design	18	
Injection Nozzle Condition	Characteristic Uniformity	6	Excessive Growth on Nozzle, Incorrect fitting or Nozzle	7	Change Nozzle regularly	5			210	
Gas Path Streaming	Growth Rate & Growth Profile	7	Poor Interfaces & Banding	3	Manual temperature checks	8			168	
Exhaust Ring Condition	Growth Rate & Compositional Variability	4	Gas Flow Path Over Ring and Back Pressure On Cell Increasing Growth Pressure, Increasing Residence Time	4		6	Multiple or Broad DXRD, PL Peaks, Normally Producing Satellite Peaks	Cell Back Pressure, Carrier MFC	96	
Exhaust System Condition	Morphology degradation	8	Pressure Transients	5		3			120	
Radial Depletion Effects	Non uniform Thickness Profile even with Rotation	2	Nutrient Material Fully depleted early in cell	1		2	High % Growth rate drop towards edges of rotated wafer	Blocked Molybdenum Ring	4	
Heater Control System	Potential Banding of material	1	Control system Transients	2		3			6	
Top Plate Condition	Morphology Deterioration	8	Top Plate Growth Dumping	5	Pre-Run Heats to attempt to minimise material mobility	9	Morphology Failure with D5's, large grown in flakes	Top Plate Conditions, Quartz surface finish, V/III ratio ?	360	Review ALL held data on Top Plate Conditions to Morphology Links
Particulate Mobility	Grown In Morphology Deterioration	7	Particles from cracked material back streaming onto growing surface	8	Load / Unload flow Control	9	Morphology Failures with small regularly shaped particles Grown In	Particle Control poor, O2 in Glove box causing smoke particle generation	504	Investigate causes
Exhaust Line "Flipping"		4		2		6			48	
Device Linked Morphology	Grown In Particles	10	Unknown - When Quartz Pre-Baked No Problem exists	9		10	Small Crystalline type defects "Grown In"	Some function of Quartz, Susceptor or Manifold Condition	900	Carry Out Trials to ascertain source

Table 5-19 - Cell FMEA

Summarising the two preceding Table 5-18 and Table 5-19 using the RPN operator as a prioritising tool an operating chart can be produced (see Table 5-20). Operating on all modes with a selected RPN of greater than 250 [close to SD] and producing a single list combining both gas handling and cell, grouping effects.



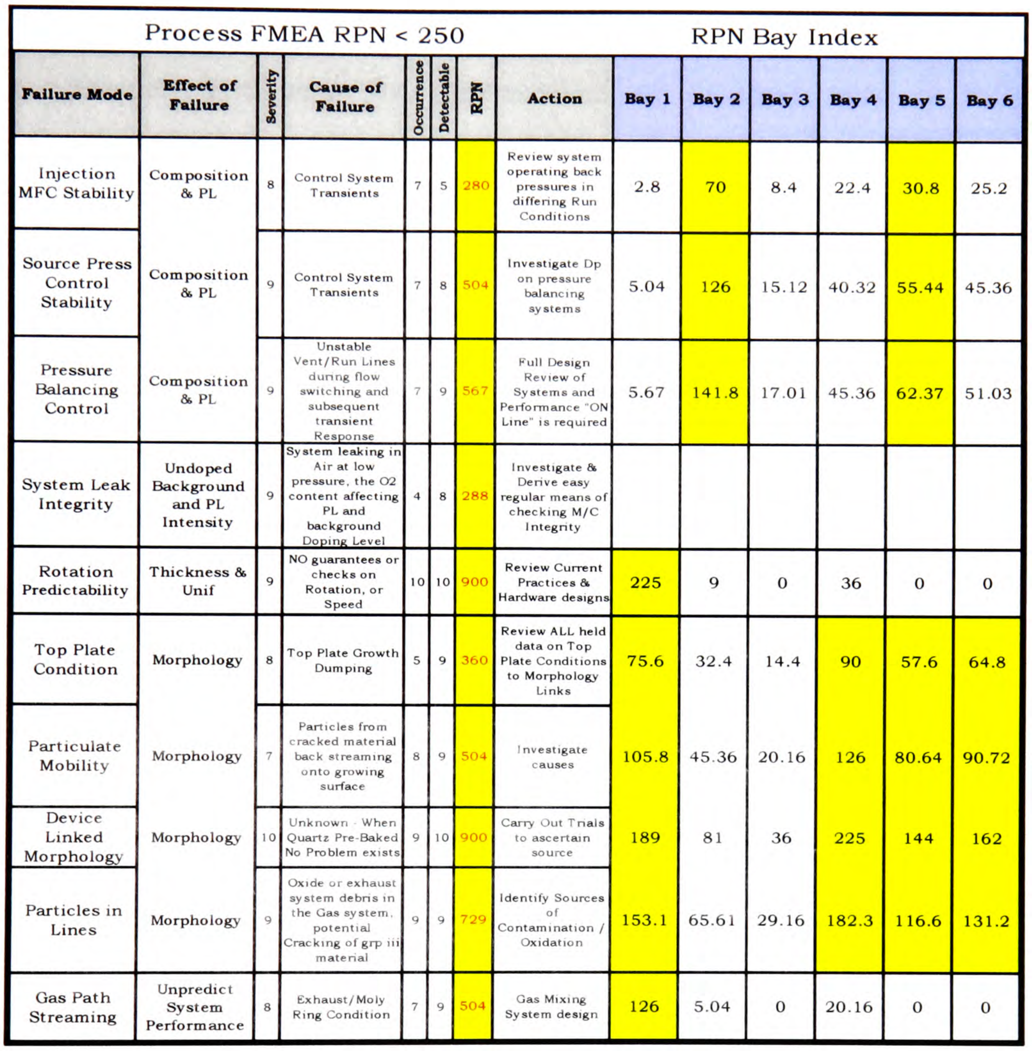
Process FMEA RPN < 250

Failure Mode	Effect of Failure	Severity	Cause of Failure	Occurrence	Current Controls	Detectable	Product Char	Likely Cause	RPN	Action
Injection MFC Stability	Composition & PL	8	Control System Transients	7	Product Characteristic Feedback	5	Multiple or Broad DXRD, PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	280	Review system operating back pressures in differing Run Conditions
Source Press Control Stability	Composition & PL	9	Control System Transients	7	Composition Analyzer Stability only in certain cases	8	Broad DXRD or PL Peaks	Too Low a pressure balancing Flow or Debris affecting Control valve Operation	504	Investigate Dp on pressure balancing systems
Pressure Balancing Control	Composition & PL	9	Unstable Vent/Run Lines during flow switching and subsequent transient Response	7	None	9	DXRD Fringing, PL Peak shoulders	Line restrictions via oxide build up or system resistance's / pipe sizes	567	Full Design Review of Systems and Performance "ON Line" is required
System Leak Integrity	Undoped Background and PL Intensity	9	System leaking in Air at low pressure, the O2 content affecting PL and background Doping Level	4	Daily He Leak Checks	8	High Intrinsic Doping Levels and Low Intensity Pl Peaks	Normally following poor quality machine integrity interruptions	288	Investigate & Derive easy regular means of checking M/C Integrity
Rotation Predictability	Thickness & Unif	9	NO guarantees or checks on Rotation, or Speed	10	Pre-Growth Atmospheric Checks	10	Multiple or Broad DXRD, PL Peaks	System Design	900	Review Current Practices & Hardware designs
Top Plate Condition	Morphology	8	Top Plate Growth Dumping	5	Pre-Run Heats to attempt to minimise material mobility	9	Morphology Failure with D5's, large grown in flakes	Top Plate Conditions, Quartz surface finish, V/III ratio ?	360	Review ALL held data on Top Plate Conditions to Morphology Links
Particulate Mobility	Morphology	7	Particles from cracked material back streaming onto growing surface	8	Load / Unload flow Control	9	Morphology Failures with small regularly shaped particles Grown In	Particle Control poor, O2 in Glove box causing smoke particle generation	504	Investigate causes
Device Linked Morphology	Morphology	10	Unknown - When Quartz Pre-Baked No Problem exists	9		10	Small Crystalline type defects "Grown In"	Some function of Quartz, Susceptor or Manifold Condition	900	Carry Out Trials to ascertain source
Particles in Lines	Morphology	9	Oxide or exhaust system debris in the Gas system, potential Cracking of grp iii material	9	Product Characteristic Feedback	9	Small "Grown In" defects, possibly in a streaming pattern over wafer	Line Heater out of control, leak to air or Exhaust system/Cell Pressure transients	729	Identify Sources of Contamination / Oxidation
Gas Path Streaming	Unpredict System Performance	8	Exhaust/Moly Ring Condition	7	Monitoring Exhaust Temperatures - Manual	9	DXRD & Wavelength Trending Away from Expectation	Restricted Moly Ring or Exhaust Port	504	Gas Mixing System design

Table 5-20 - Summary FMEA

This offers a profile of causes for the process failures, when planning to improve the process on non-like equipment it is necessary to re-evaluate the data against each machine type.

To enable evaluation, two previously identified and used techniques require combination to derive the action path/plan. Using the FMEA RPN priority 1 list [>250], linking with the manufacturing blockages per machine for each effect, would enable Failure evaluation per machine type. This essentially offers a double reporting FMEA (Table 5-21) for multi platform evaluation [DrFMEA].



Process FMEA RPN < 250								RPN Bay Index					
Failure Mode	**Effect of Failure**	**Severity**	**Cause of Failure**	**Occurrence**	**Detectable**	**RPN**	**Action**	**Bay 1**	**Bay 2**	**Bay 3**	**Bay 4**	**Bay 5**	**Bay 6**
Injection MFC Stability	Composition & PL	8	Control System Transients	7	5	280	Review system operating back pressures in differing Run Conditions	2.8	70	8.4	22.4	30.8	25.2
Source Press Control Stability	Composition & PL	9	Control System Transients	7	8	504	Investigate Dp on pressure balancing systems	5.04	126	15.12	40.32	55.44	45.36
Pressure Balancing Control	Composition & PL	9	Unstable Vent/Run Lines during flow switching and subsequent transient Response	7	9	567	Full Design Review of Systems and Performance "ON Line" is required	5.67	141.8	17.01	45.36	62.37	51.03
System Leak Integrity	Undoped Background and PL Intensity	9	System leaking in Air at low pressure, the O2 content affecting PL and background Doping Level	4	8	288	Investigate & Derive easy regular means of checking M/C Integrity						
Rotation Predictability	Thickness & Unif	9	NO guarantees or checks on Rotation, or Speed	10	10	900	Review Current Practices & Hardware designs	225	9	0	36	0	0
Top Plate Condition	Morphology	8	Top Plate Growth Dumping	5	9	360	Review ALL held data on Top Plate Conditions to Morphology Links	75.6	32.4	14.4	90	57.6	64.8
Particulate Mobility	Morphology	7	Particles from cracked material back streaming onto growing surface	8	9	504	Investigate causes	105.8	45.36	20.16	126	80.64	90.72
Device Linked Morphology	Morphology	10	Unknown - When Quartz Pre-Baked No Problem exists	9	10	900	Carry Out Trials to ascertain source	189	81	36	225	144	162
Particles in Lines	Morphology	9	Oxide or exhaust system debris in the Gas system, potential Cracking of grp iii material	9	9	729	Identify Sources of Contamination / Oxidation	153.1	65.61	29.16	182.3	116.6	131.2
Gas Path Streaming	Unpredict System Performance	8	Exhaust/Moly Ring Condition	7	9	504	Gas Mixing System design	126	5.04	0	20.16	0	0

Table 5-21 - Summary DrFMEA

The results from the novel DrFMEA exercise (Table 5-21) identify the predominant cause on each bay for each major failure type. Each bay RPN is derived by multiplying the FMEA RPN with each individual Bays Blockage percentage as detailed in Table 5-8. This results in a specific

RPN [URPN – Unit RPN] for each manufacturing unit. Thus enabling more precise derivation and analysis of the failure modes.

5.3 – Chapter Summary

This Chapter is key to the overall success of the improvement programme. The need for improvement or business need is fully identified, £4m lost sales potential, 2500 wafers rejected or 50% wafer yield. To the organisation the CoDN is £4m, it is therefore critical to understand these losses and define the areas for improvement. The preceding Chapters contribute techniques and knowledge on the process and materials.

Using the basic data initially issued within the companies profit and loss statements and re-worked to offer a business risk analysis, from which a set of priorities are defined from within the process failure mechanisms. Utilising additional information from hardware, utilisation and operator logs MTBF, MTTR and sectional FMEA exercises have been completed. The FMEA exercise is generic to the equipment in use, and not a function of the process being run, as the demands are increased by the product complexity. The original business analysis identifies that differing platforms [MOVPE machines] have differing performance versus identical criterion; this is some function of machine similarity or the product expectation. This is assimilated using a standard deviation operator on the data, identifying machine variability or product weakness.

This results in a failure impact matrix that enables an original FMEA interpretation, allowing multi-platform comparison against generic causes and effects [DrFMEA]. The original contribution from this DrFMEA technique allows differing processes potentially running on like plant failure modes, causes and effects to be simultaneously plotted with individual RPN outcomes, identifying the equipment threat to the business performance. Further derivation is possible with standard deviation operation on the linked RPN's, however in this case it is not necessary.

The subsequent Chapter offers further derivation of the business threats and interpretation on the process flow.

Chapter 6 - Process Evaluation

6.1 - Introduction

The preceding Chapter identifies the business need for improvement and the business/process threats using raw failure data, an FMEA exercise and the business risk analysis. The generic process flow also requires derivation to identify the critical path and any further risks or threats from the flow of activity. The results from this and the preceding Chapter may be handled jointly to further the investigation, to produce a hierarchy of threats or risk.

6.2 – Overall Evaluation

6.2.1 - Process Performance Analysis

Definitions:

Product - *The Grown Material*
Product Feedback - *The Measurement Detail of the Grown Material*

Process Equipment - *The Equipment used in the production of the product*
Equipment F.back - *Data available detailing machine performance*

Process - *The Activity of Producing the Grown Material*
Process Feedback - *Info available during & from Equip & Product*

Process Engineering- *Definition of the Process Recipe & Char Analysis*
Engineering F.back - *Characterisation, Program & Equipment Data*

Device - *The final use of the grown mat'l in Component Form*
Device Feedback - *Information regarding Device Performance*

A major anomaly exists between the definitions above. It would appear reasonable that, if the grown material meets all of the specified characteristics then the material when transformed into a device will perform. This is not necessarily the case. Many instances exist where materials are acceptable but the devices fail, where the causes of such material failures are unknown.

This would suggest that either:

1- Not ALL of the appropriate Material Characteristics have been specified.
2- That some activity post MOVPE and Characterisation is impacting upon the desired performance.
3- Some change in Characteristics takes place with some function of [Time or Environment].
4- Not all of the Material Characteristics can be accurately measured or are as yet defined.

It is not currently understood which of the four has an impact if any, but is assumed that all contribute to some extent.

The overall process system can be described as fully interdependent, even though information is available at each step, for example:

Raw Materials – Upon receipt a certificate is issued detailing the impurities within each source. For example: O_2 at less than 5 ppm is contained within an Aluminium source. Unfortunately this is far too inaccurate; 1ppm of O_2 will result in product “write off’. For most of the raw materials there is no known means today of analysing the material constituents/contaminants to the levels required.

Most of the raw materials and equipment can be characterised as fit for purpose following processing into a grown structure and characterising the material i.e. Oxygen affects the “Photo Luminescence” and “Intrinsic Doping” [measurement of impurity atoms]. All differing materials will have some effect, again some function of the contained amount.

Therefore raw materials are considered acceptable, only after fitting to the process, undergoing a growth and full characterisation of the grown material. Once cleared as fit for purpose each source may be considered eligible for all like process.

The Growth Process - None of the product characteristics can be accurately and reliably monitored from within the growth process, the only evidence available during process is the variation in set point from requested set point for:

Source Pressures & Temperatures
Source Flows
Dilution Flows
Growth Pressure
Growth Temperature

Trials are underway today [as of 07/11/01] to operate an optical analysis of "in process" growth to identify the thickness of the grown material. This however is still very much in an R&D style operation. Once proven this will allow the growth to be controlled by a closed loop controlling layer thickness rather than the current implied growth rate and recipe times technique.

These are the physical characteristics of the growth process; these are all on their independent control systems with set points centrally set from the process program. It is possible for all of the above to be within the specified operating component tolerances and the final product being out of specification.

Therefore the growth equipment also is only considered acceptable, after undergoing a growth and full characterisation of the grown material. Differing types of structure are grown to prove differing fit for purpose standards, for example Photo Luminescence, Uniformity, Growth rate, Doping etc. Once declared fit for purpose the process may vary before or during each process run.

Once material has been "Grown" full characterisation of the material can take in excess of 24 hrs, depending upon measurement complexity and availability, typically the first simple measurement details are available after 4 hours post growth end. The optimum situation here would be to have In-Situ monitoring within the "Growth Zone", detailing all of the physical characteristics of the grown material.

It is therefore appropriate to assume that the growth process is a part of the overall "Product" control system and that the "feedback loop" has five parallel activities:

Equipment Data logging
Raw Material Qualification
Equipment Qualification
Measurement Equipment Calibration
The Critical: Process Confirmation - Material Characterisation

The parallel activities suggest that the process feedback loop may be described in a simple diagram (see Figure 6-1):

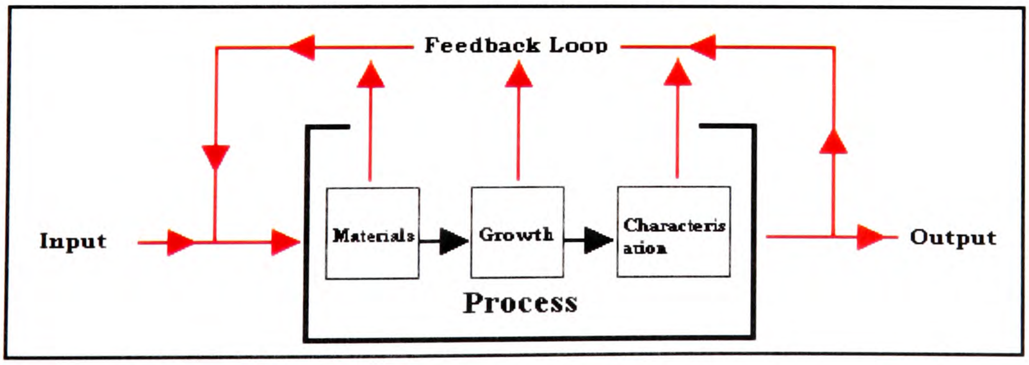


Figure 6-1 - Process Flow

This is the practical evaluation, however "the sum" of the individual inputs does not prove process fit for purpose or product in specification. The full summation of the material characterisation is the only step that can evaluate whether the produced material emanating from the process is acceptable, deciding whether the process is "Fit for Purpose".

This therefore defines the process closed loop, and that the links, influences between all of the process steps are not fully understood and that re-work is not an available option, a typical "Black Box" theorem (see Figure 6-2) therefore predominates.

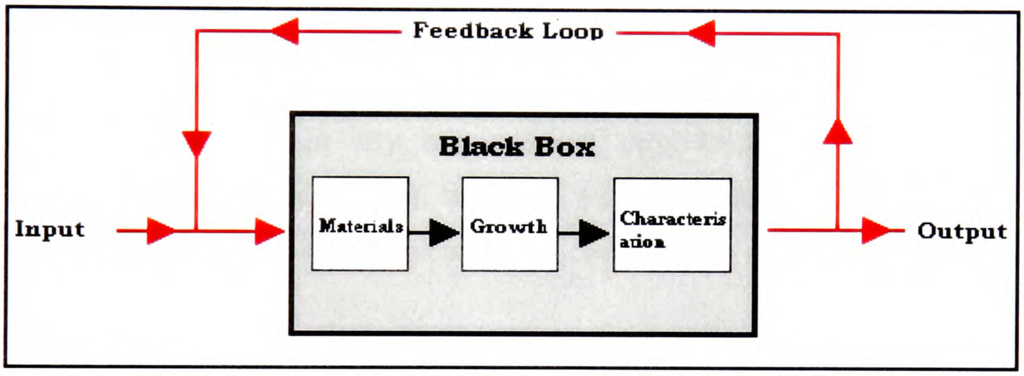


Figure 6-2 - Process "Black Box"

From each internal step, there is no defined control loop for product; the only feedback is post full cycle. Accreditation of failure or variability can only be carried out following full characterisation of each growth.

The following are the known general characteristics of the system:

1 - Failure Mechanisms Exist in the Product

2 - Failure Mechanisms Exist in the Process

3 - Variation Exists in like Product

4 - Variation Exists in the Measurement of Product

5 - Not All links between Failures in Process to Product links are known and understood.

6 - Raw Material quality in most cases cannot be defined as fit for purpose before process activity.

7 - Variation exists in the interpretation of the grown material Characterisation.

8 - Variation Exists in repeatable process. (Inter Process)

9 - Wafer Variation Exists in each run. (Inner Process)

10- Customer Product performance lags by up to 6 months.

11- In some cases "Measurement Gauge" alone, is greater than Customer-required specification

The preceding series of statements describe the overall process starting point for improvement, suggesting that all areas of process and peripheral activity require improvement. This requires a differing evaluation technique from the typical and therefore a technique needs to be derived, enabling the definition of the overall performance datum.

The initial activity in any improvement programme is to "gain" an understanding of where, what, how and why the process is and the same questions for process variations and their causes.

Any sub process or activity [PA] acts as an amplifier to the variability of each output in the activity series.

For Example: for a "Bearing on Shaft" – the components shown in Figure 6-3. Each of the components are manufactured to given tolerances, the tolerances are selected so that the assembly should still work with a given lifetime. This may be seriously influenced by the end users tolerance on the shaft assembly, and therefore the end users input may be required at tolerance setting stage, it is not so the bearing manufacturer issues a tolerance to the OEM assuming compliance, identification of the series influences could be critical to a robust process. The following example describes the issue.

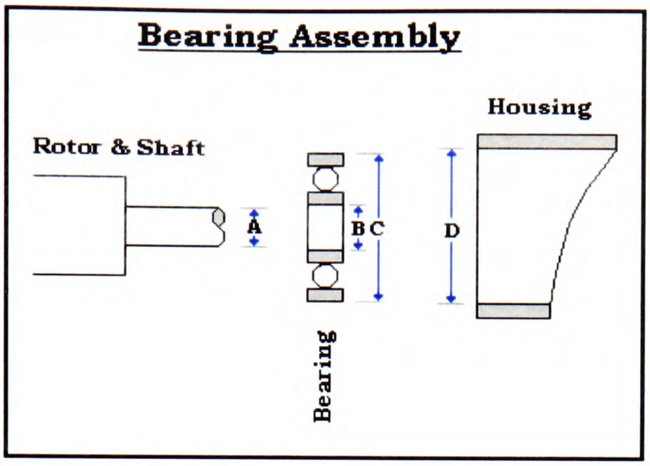


Figure 6-3 - Bearing Assembly - 1

Each of the above components (see Figure 6-3) is machined to a "Target" dimension [i.e. Inner Diameter] with an allocated tolerance, for example +/- 0.05 mm. The bearing will be pressed onto the shaft as Figure 6-4 (interference fit), as the interference increases the compression on the balls will increase; this will effect lifetime and efficiency. If the housing dimension is at the low end of its diametric tolerance then the forces will increase further, thus amplifying or compounding the variation, [Heat, Vibration, Noise, - Lifetime].

Bearing on Shaft – Completed Assembly

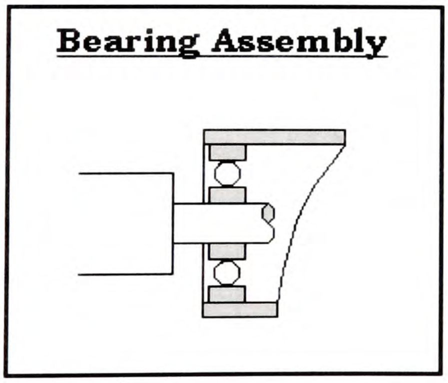


Figure 6-4 - Bearing Assembly - 2

Today's machining technologies enable Engineers to select tolerances so that the effect of the issued tolerances are minimising the "Quality Compromise" on the product.

6.2.2 - Process Analysis Techniques

Any "Global or Process Overall" analysis technique needs to initially focus on the overall manufacturing activities, by applying a typical "P diagram" technique, as described by Phadke (1989) shown in Figure 6-5, any product/process can be analysed in it's most simplistic form.

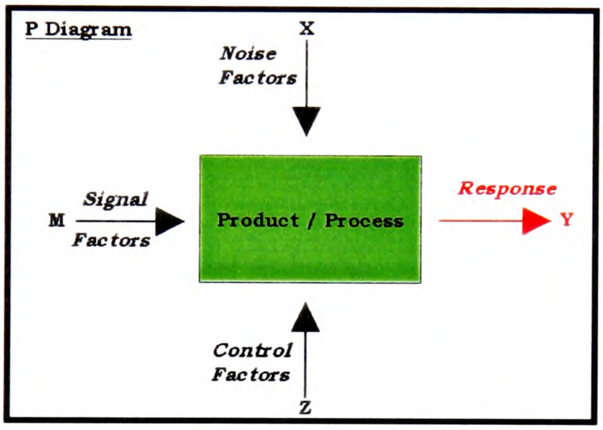


Figure 6-5 - Typical "P" Diagram

Phadke has definitions for the parameters used in the diagram in Figure 6-5. These parameters in summary form are:

A number of parameters can influence the quality characteristic or response of the product. These parameters can be classified into the following three classes [note that the word parameter is equivalent to the word factor in most of Robust Design literature]

Signal factors (M)	*These are the parameters set by the user of operator of the product to express the intended value for the response of the product*

Noise factors (X)	*Certain parameters cannot be controlled by the designer and are called noise factors*
Control factors (Z)	*These are parameters that can be specified freely by the designer - the manufacturing cost.*

The block diagram of Figure 6-5 can be used to represent a manufacturing process or even a business system. Identifying important responses, signal factors, noise factors, and control factors in a specific project are critical tasks

Utilising this basic principle, the intention is to modify this technique with novel interpretation to evaluate the process relationships of each series/parallel activity within the "Process Chain".

Examples

<u>1 - Series</u> - Printed Circuit Board Assembly

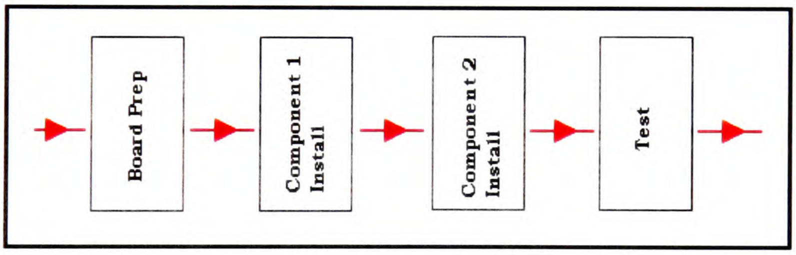


Figure 6-6 - Series Manufacturing

<u>2 - Series/Parallel</u> - Motor Vehicle Assembly

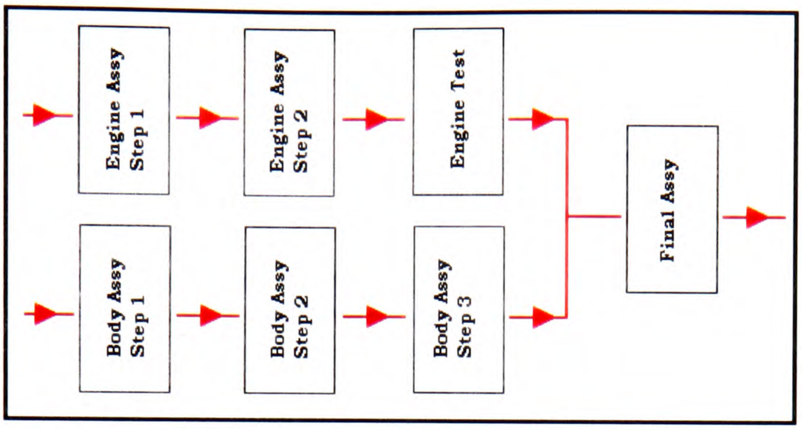


Figure 6-7 - Series/Parallel Manufacturing

3 - Complex Series - III/V Semiconductor Manufacture

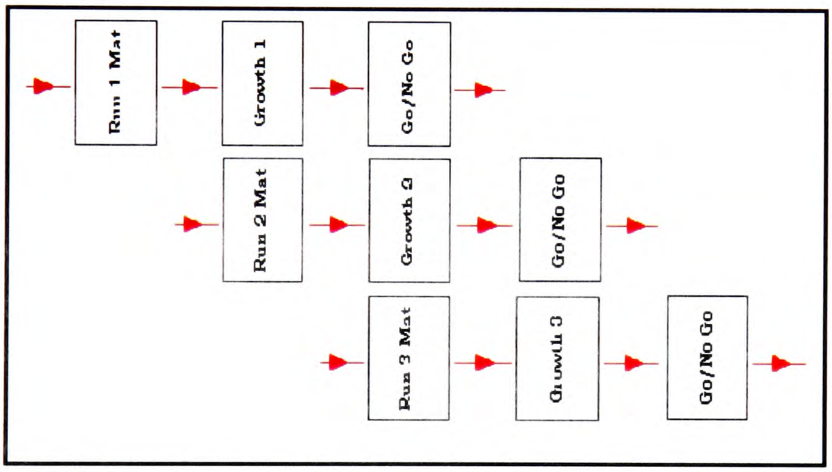


Figure 6-8 - Complex Series Manufacturing

Considering the three activity examples, Figure 6-6, Figure 6-7 & Figure 6-8, 1 & 3 are direct series activities, with both 1 & 2 any test failures will be "Hospitalised" for repair or adjustment, with 3 the only process re-work is in the measurement all other activities cause product "write off".

The "P" diagram as described by Phadke (1989) appears to be the perfect tool to use with modification. The standard diagram however cannot be used for a complex series manufacturing process (see Figure 6-8).

For a basic interpretation of the principle, for consideration with a complex series process (see Figure 6-9).

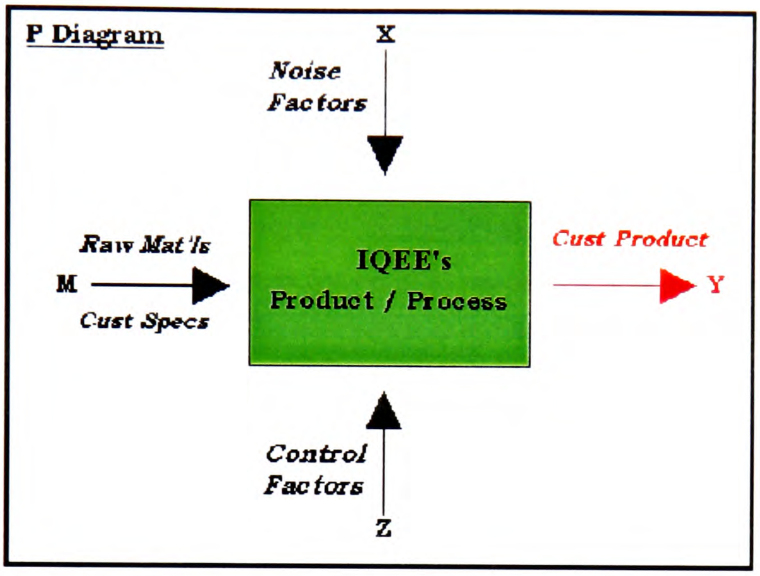


Figure 6-9 - Modified "P" Diagram - Stage 1

In it's current modified form, to evaluate "an Overall Parallel Process" the technique will need further modification or extension to enable a more broad based approach, using the above (Figure 6-9) technique modified as a secondary operator.

A "Schematic Process Path" (1-SPP) must be drawn up to derive the critical steps and their relationships i.e. series, parallel and series/parallel.

Even though the "Time Frame" from 1st activity in each critical path to the tested product may be extended in each case (i.e. 1 cycle) the overall consequential losses / risks vary.

Any process that has "Batch ZERO Re-work" has a higher business dependency.

Typical Series Overlap Process' Include:

Pharmaceutical
Food
Brewing
Electronic Component (LEDs, Transistors etc.)

Concluding thus far it is essential that the critical process path is understood and whether series and or parallel activities exist.

For Series activity the technique is "Single Pass", for parallel the technique is "Multi Pass". The multi pass for parallel processes will take the form of:

1 - Single pass for each discernible parallel activity
2 - On completion of 1, a single pass for any downstream series activity

6.2.2.1 - Global - Stage 1 - MAS

The formal "Process Path" as previously defined requires derivation; this can be achieved by defining each step in the manufacturing process, A manufacturing activity sequence [MAS] may be produced for the overall process, see Table 6-1. This sequence analysis is similar to the complexity tables as commonly used in General Systems Theory (Begley, 1999).

Manufacturing Activity Sequence	
Activity No	Activity
1	Issue of Customer Required Specification
2	Check Specified Requirements against Capability / Material Stocks / Work Schedules
3	Define any Calibration requirements of Customer Specification
4	Batch "Like" Material groups and Schedule manufacture
5	Draw off Specific Raw Materials
6	Produce Process Program
7	Configure Growth Machine for Specification i.e. 2", 3" or 4", Fit sources etc.
8	Carry out any Calibration Growths, Wavelength, Composition, Thickness, Doping
9	Request Appropriate Measurements on Grown Calibration Structure
10	Interpret Measurement Characteristics
11	Determine Specification Go/No Go
12	Input any Changes into Production Process Program
13	Carry Out Production Growths
14	Request Appropriate Measurements on Grown Production Structure
15	Carry Out requested Product Measurements
16	Interpret Measurement Characteristics
17	Determine Product v Specification Go/No Go
18	If Go "Sign Off" for Report Writing and dispatch, If No Go evaluate failure issues, define any required changes and re-run
19	Write Report or Certificate of Conformance and Dispatch

Table 6-1 - Manufacturing Activity Sequence - MAS

Table 6-1 the MAS require additional derivation into the “Critical Generic Activities” and “Grouped” accordingly (Figure 6-10):

Manufacturing Activity Sequence		
Activity No	Activity	Group ID
1	Issue of Customer Required Specification	
2	Check Specified Requirements against Capability / Material Stocks / Work Schedules	
3	Define any Calibration requirements of Customer Specification	
4	Batch "Like" Material groups and Schedule manufacture	
5	Draw off Specific Raw Materials	A
6	Produce Process Program	
7	Configure Growth Machine for Specification i.e. 2", 3" or 4", Fit sources etc.	
8	Carry out any Calibration Growths, Wavelength, Composition, Thickness, Doping	
9	Request Appropriate Measurements on Grown Calibration Structure	
10	Interpret Measurement Characteristics	
11	Determine Specification Go/No Go	
12	Input any Changes into Production Process Program	
13	Carry Out Production Growths	B
14	Request Appropriate Measurements on Grown Production Structure	
15	Carry Out requested Product Measurements	C
16	Interpret Measurement Characteristics	D
17	Determine Product v Specification Go/No Go	D
18	If Go "Sign Off" for Report Writing and dispatch, If No Go evaluate failure issues, define any required changes and re-run	
19	Write Report or Certificate of Conformance and Dispatch	E

Table 6-2 - Manufacturing Activity Summary

Five groups of generic activity exist - A, B, C, D, E

A - Raw Materials

B - Growth Process

C - Product Measurement

D - Interpret Measurement & Determination v Spec

E - Dispatch

The two activities listed in D can be summarised as “Engineer Screening”.

A Series Activity chart (Figure 6-10) may be derived.

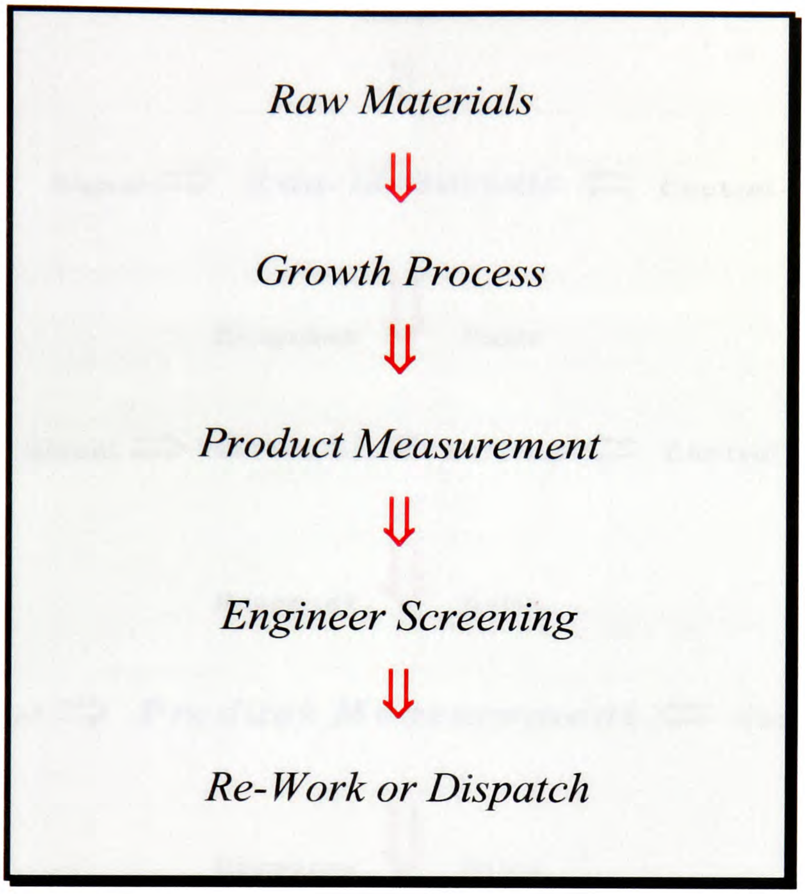


Figure 6-10 - Series Activity Chart - 1

This derived "Global" technique has defined the "Series" activities, for further analysis, application of a modified P-diagram technique to the SAC (Figure 6-10) resulting in Figure 6-11 the combination of P and series techniques.

6.2.2.2 - Global - Stage 2 - SPP

This stage defines the overall framework for investigation / understanding for the "overall manufacturing process - Global".

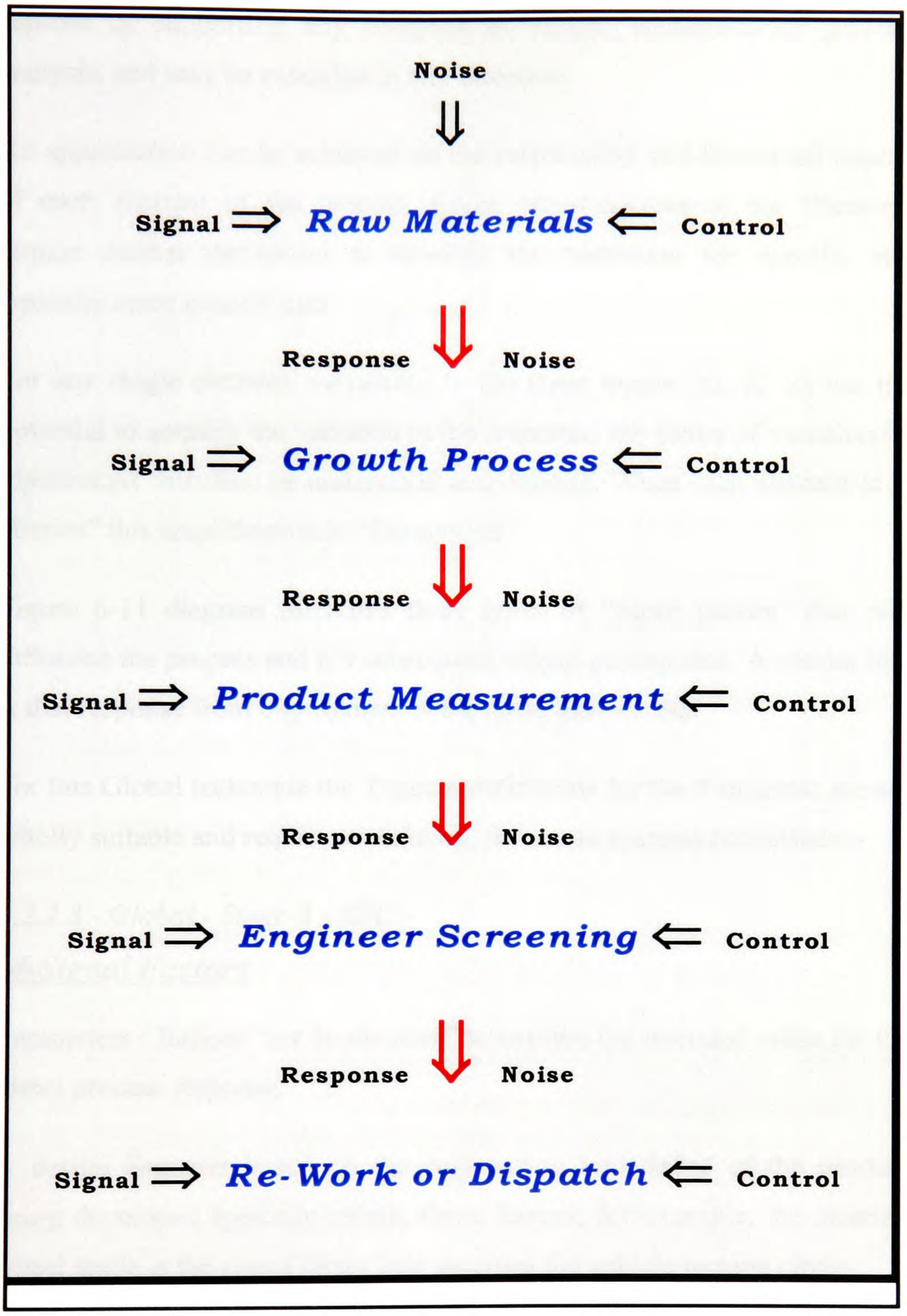


Figure 6-11 - Series Activity Chart - 2

Figure 6-11 fundamentally defines the modifications from the original "P" diagram technique as defined by Phadke (1989); the technique is now capable of supporting any complex or simple manufacturing process analysis, and may be extended in any direction.

An appreciation can be achieved on the relationship and functional impact of each element of the process. Local interpretations of the “Factors” require further derivation to develop the technique for specific and typically more generic use.

For any single element, variability in the three inputs [M, X, Z] has the potential to amplify the variation in the response; the forms of variation on inputs must therefore be understood and defined. When each element is in ”Series” this amplification is “Compound”.

Figure 6-11 diagram identifies three types of “Input factors” that will influence the process and it’s subsequent output or response. A crucial link is that response from one element is the noise into another.

For this Global technique the Taguchi definitions for the P-diagram are not wholly suitable and require re-defining, for use as systems definitions: -

6.2.2.3 - Global - Stage 3 - SNC

M-Signal Factors

Parameters / Indices “*set by the user*” to express the intended value for the direct process response.

A design engineer based on the engineering knowledge of the product being developed typically selects these factors; for example, the steering wheel angle is the signal factor that specifies the vehicle turning circle.

Definition

“The factor or multi factors that will define the process output as a function of the user set, input”.

For example:

Single Factor - [Single Input - Single Output]
90° clockwise on the steering wheel define a right hand turning circle of 40m +/- 3%.

Multi Factor - (Multiple Input - Multiple Output)
3000-rpm engine speed will approximately offer 15 mph-1st gear, 25mph-2nd gear, 40 mph-3rd gear, 60 mph-4th gear and 80 mph-5th gear.

The previous definition for most processes can be used as direct, once proven, the "Signal" to output ratio is understood for the design of a system and the only variance is the defined tolerance excluding failure mechanisms.

With the current state of the MOVPE equipment and art this is not the case, a particular successful set up today will not offer the same successful product tomorrow within acceptance tolerances.

The classical definition assumes that the Input/Output responses are understood from a design and operational viewpoint. With this overall evaluation technique, situations where Input/Output relationships are not fully understood or in control and require defining may be addressed.

It seems most appropriate therefore to re-interpret the classical definition of "Signal Factors" for this exercise, enabling the use of this global technique to define the intrinsic process [or system] signal factors.

Evaluating the MOVPE process, its characteristic calibration data and variables, it is most appropriate to re-define the signal factors to:

Re-Definition

"The variability that can be introduced into the process by the user following interpretation or feedback on the process position."

Typically for the process in use:

Process - Time
Temperature
Gas / Nutrient Flow
Pressures
Process Equipment Calibration
Measurement Equipment Calibration
Machine Set Up
Feedback Quality
Characteristic Decision Quality
Fit for Purpose Evaluation

X-Noise Factors - (Causes of Variation)

These factors are typically a function of the performance of a product, as measured by the quality characteristics varying in the field [Fab, process and product reproducibility – systems], due to a variety of causes.

External - Environmental - Temperature
Humidity
Vibration
Dust
Supply Voltage
Unit-to-Unit - Process Variation from Target
Deterioration - Operating Lifetime

Definition:

"With the exception of the Unit to Unit factors all of the noise factors are a feedback function on the performance of the Product in Use".

As the derived links between product use and wafer manufacture are not fully understood and customer feedback lagging manufacture averaging 6 months, it is impractical to again use the classical definition.

There are many factors in the process, environment, raw material quality and operation that are not fully understood and that the user is not in control of today, even though they influence the users overall output, these are the factors that will be interpreted as Noise factors.

The "Noise Factors" shall in definition be specific to those activities and influences directly attributable to the operation of a MOVPE reactor in a clean room [Fab] environment, derived specifically for this project, thus:

"The factors that influence the output of the process that are out of control today with unknown impact but are potentially feasible to gain control over".

External -	Environmental – Temperature
	Humidity
	Vibration
	Raw Materials
	Operator Training
	Procedural Suitability
Unit to Unit -	Variation from Target
	Process Reliability
	Process Repeatability
	Process Uniformity
	Measurement Variation
Deterioration -	Machine Calibration

Raw Material Shelf Life
Operating Conditions
Handling

These differ from the generic Taguchi definition of Noise, which may be quoted as "the interference that degrades what the product is trying to deliver. The process tolerances are defined from the process "Noise" which must be identified and are within the acceptable specification range demanded by the customer.

Z-Control Factors

The factors, which can be freely specified by the designer. The designer holds the responsibility to determine the optimum parameter consideration given the manufacturing cost.

The classical definition of a control factor, *"the performance, specification and tolerance of the components in use"*.

The specification of a component i.e. bearing 25mm ID, 55mm OD, 15mm depth, ball race, will have a direct cost. Using a 30mm ID bearing will not affect the overall cost, however any change to the standard manufacturing tolerances will. From 25mm +/- 0.05mm to +/- 0.005mm as a specified tolerance will incur a major cost to manufacture. These factors are a function of a measurable product performance versus business decision.

As much of the variation in input for a process can be a function of the quality of the signal input of the user, for this technique the "Control" factors will be re-defined as:

Those factors that have influence on the Quality, Tolerance or Noise of the "Signal" factors and will enhance the overall Process Control (i.e. Formal Manufacturing Rules).

Formal - Controlled Manufacturing Process

Controlled Measurement
Controlled Equipment Evaluation
Controlled Calibration
Controlled Operator Evaluation
Formal Process Evaluation

6.3 - Process Analysis

General Summary

One of the major objectives and challenges in any improvement plan is to ensure that planned improvement activity is prioritised and controlled.

Once identified, the SNC factors influencing the process, the technique will require extension to include input variability. This variability extension requires to be quantified and prioritised enabling a "controlled and effective" improvement plans to be defined.

The next stage, therefore, must demand that the above factors be derived and weighted for "Overall Process Effect" or "Impact Weighting". Thus enabling a prioritisation plan to be defined using the overall process impact of each variable.

6.3.1.1 - Global Stage 4 - Derivation

Expanding on the Series activity path defining the input factors enable derivation of the input and the subsequently the output variables (Table 6-3).

Highlighted are the "Noise" variables that are the "Output" from the previous series element:

Raw Materials		
Signal	***Control***	***Noise***
Q.Control	Specification	Supp Quality
Mat'l FFP	Supp Relat'p	Environment
	FFP Specif'n	Shelf Life
	Test Spec	

⇓

Growth Process		
Signal	***Control***	***Noise***
Time	Conditions	Raw Materials
Temperature	Structure	Training
Gas Flows	Materials Sel	M/C FFP
Pressures	Procedures	Environment
M/C Set Up	Calib Algori'm	M/C Stability
Program	SPC	
Errors	FFP Specif'n	
Interp'n Fback		
Staff Capab'ty		
M/C Integrity		
M/C Prepar'n		
M/C Maint		

⇓

Product Measurement		
Signal	***Control***	***Noise***
M/C Set Up	**Procedures**	**Product**
M/C Maint	**M/C Calib**	**Meas Gauge**
Chem Prep'n	**FFP Specif'n**	**Chem Qual**

⇓

Engineer Screening		
Signal	***Control***	***Noise***
Interpretation	Cont'l Process	Measurements
SPC Capab'ty	SPC	Process SPC
SPC Interp'n	Education	Meas Quality
Proc Know'ge	Procedures	Meas Time
Pers Capab'ty	Proc Capab'ty	
Proc Confid'ce		

⇓

Re-Work or Dispatch		
Signal	***Control***	***Noise***
		Decision Qual

Table 6-3 - Summary SNC Table

For the “Global” approach this can be defined thus:

1 - Elements
2 - Elemental - Signal/Control/Noise
3 - Elemental Series

This then completes the “Primary” objective of the technique, which is to understand the “Events” that when linked complete the manufacturing process cycle.

As previously mentioned, each element’s input variability will amplify the “Output Gauge” for each element and in series manufacturing each elements output gauge variability will multiply together to give an overall amplification of the “Manufacturing Output Gauge”.

The second objective of the technique therefore must be to derive a principle to evaluate the output gauge for each element, thus enabling identification of the “Series Priority”, based on “Manufacturing Output Gauge” impact. This can be achieved by analysing the various FFP [Fit for Purpose] data that exists or can be generated for each element (see Table 6-4). Using Raw Materials as an example:

Raw Materials		
Source	*Not FFP*	*Priority*
TMA	0%	
TMG	0%	
TMI	33%	2
AsH3	10%	4
PH3	20%	3
Dopants	0%	
Substrate	2%	
Test Fails	70%	1

Table 6-4 - Materials FFP

Of all runs undertaken 30% are to "Qualify" the process following an "Event", the events are broken down:

25 % to Qualify a New Source

5 % to Qualify Process subsequent to Maintenance

The data above suggests that 70 % of the qualification 25% fail; this is a major blockage to business performance and risk to customer quality. Each of the above requires further evaluation to derive a variable that can be evaluated against all other elements.

6.3.1.2 - Global Stage 5 - Evaluation

Table 6-5 describes the first stage, a series path that must be generated for all elements:

Raw Materials		
Source	*Not FFP*	*Priority*
TMA	0%	
TMG	0%	
TMI	33%	2
AsH3	10%	4
PH3	20%	3
Dopants	0%	
Substrate	2%	
Test Fails	70%	1

⇓

Growth Process		
Activity	*Not FFP*	*Priority*
Leak Integ	20%	5
PL AlGaAs	38%	3
PL AlInGaP	43%	2
Q Calib	33%	4
Mnt Event	13%	7
Source Act'y	67%	1
Prod Proc	20%	5

Growth Process		
Char	*Not FFP*	*Priority*
Hardware	6%	3
Morph	15%	1
Doping	4%	5
PL	7%	2
XRD	5%	2
Errors	2%	6
Thickness	4%	4

⇓

Product Measurement		
Meas	*Gauge*	*Priority*
POP	40%	1
B & Stain	20%	2
Alphastep	12%	3
Surfscan	2%	4
PL	2%	4
XRD	2%	4

⇓

Engineer Screening		
Activity	*Error Rate*	*Priority*
Prog Error	30%	1
Interpret ?	10%	3
Prem Chng	20%	2

⇓

Re-Work or Dispatch		
Activity	*Failure Rate*	*Priority*
Breakage	0.02	4
Fail Spec	0.55	2
Re-Meas	0.75	1
Re-Grow	0.55	2
Sign Off	0.05	3

Table 6-5 - Series Activity Failure Rate

Several differing techniques may utilised to evaluate series elemental performance:

FFP - Fit for Purpose
Gauge
Error Rate
Failure Rate

It is not appropriate to compare the differences in these; it is essential that these be primarily treated as performance evaluation techniques. Each of the elements in the above series has been evaluated relative to performance indices; from these a priority or ranking can be easily determined as a function of element "Impact". This technique has defined which functions require prioritisation within each element.

The next step in Global technique development has to be to "Weight" the elements so that the elemental series priorities can be "Globally Prioritised".

Failures can be "Grouped" into four categories, linking all of the above elements into each of these categories will take justification, but can then the justifiably weighted.

- *Sub Standard Raw Materials*
- *Process Equipment Reliability*
- *Measurement Accuracy*
- *Human Error*

The evaluations for the weighting will be derived from the direct yield loss category (see Table 5-6), for measurement accuracy the gauge of the measurement must be utilised to fraction the total category losses for more generic failures.

Overall Error Rate - Ca 3%
Sub Standard Raw Materials - Ca 15% (This includes activity)
Overall Process Reliability -? - OPR
Measurement Accuracy -? - MA
Overall Wafer Yield 1997/8 - Ca 42%
Yield Loss due to Test Wafers 1997/8 - 11%

Therefore: -

Equation 6: Total Yield Loss = 100% - (42% + 11%) = 47%

Total Yield Loss - Known Generic Losses = Unknown (MA + OPR)

Equation 7: 47%- (3% + 15%) = 29% (MA + OPR)

With current data the two variable MA, OPR are indistinguishable, they a bound in the overall process yield. However the differing measurements that make up MA and a corresponding factor for OPR can be derived from within the overall process yield (Table 6-6).

For example:

Product Doping Failure is: -

f (Doping Measurement, Process Instability-flow)

A practical approach to this dilemma is to identify certain global critical variables and interpolate a realistic function.

1 - Overall loss per characteristic i.e. Doping Failure
2 - Identify Number of measurements taken and the measurement "Gauge", as a function of deliverable specification.
3 - Identify the Required Specification.
4 - Calculate the potential Yield Loss % attributable to each measurement.
5 - Re-distribute the overall loss characteristic as a function of potential

measurement yield loss %.

6 - Summate to identify MA.

7 - Calculate for OPR and identify “Weights”.

Overall Losses Measurement Accuracy - MA

Measurement	Meas Gauge	Typical Spec	Char Range	No Of Meas	Failure Prob / Meas	Meas Yield	Overall Yield Loss		Yield Losses - Meas
PL	1.00	10	11	1	9%	9%	7%		0.64%
Doping	40%	60%	100%	2	40%	20%	4%		0.87%
Composition	10	1000	1010	1	1%	1%	5%		0.05%
Thickness	10%	20%	30%	4	33%	8%	4%		0.30%
								Total	1.85%
Total Loss - Measurement Accuracy						Total	2%		

Table 6-6 - Measurement Accuracy

The resulting data from Table 6-6 enables continuation with the overall derivation, as MA [measurement accuracy] is defined as 2%:

Re-iterating from page 6-137

Overall Error Rate - Ca 3%
Sub Standard Raw Materials - Ca 15% (This includes activity)
Overall Process Reliability -? - OPR
Measurement Accuracy -? - MA
Overall Wafer Yield 1997/8 - Ca 42%
Yield Loss due to Test Wafers 1997/8 - 11%

Equation 8: 47%- (3% + 15%) = 29% (MA + OPR)

Equation 9: 47%- (3% + 15% + 2 %) = 27% (OPR)

Concluding:

Overall Error Rate - Ca 3% [Pg 6-137]

Sub Standard Raw Materials - Ca 15% [This includes activity] [Pg 6-137]

Overall Process Reliability - Ca 27% [Eq 8]

Measurement Accuracy - Ca 2% [Eq 9]

Using each factor as a multiplier of the overall the weighting numbers may be established (Table 6-7).

Loss Evaluation for Weighting				Weight
· **Sub Standard Raw Materials**	-		15%	1.32
· Process Equipment Reliability	-		27%	1.57
· Measurement Accuracy	-		2%	1.04
· Human Error	-		3%	1.06
	Total		**47%**	

Table 6-7 - Loss Evaluation

The weight is derived as a function of the % per loss as a function of the cumulative, offering a means of prioritisation for further derivation. This established weight as defined in Table 6-7 can additionally act as the functional priority for the "Improvement Path Plan" as defined in Figure 6-12.

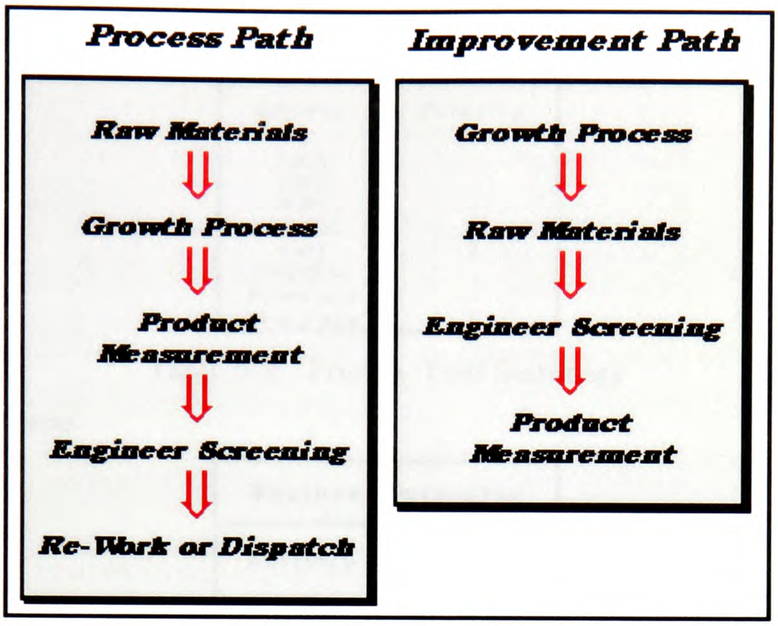


Figure 6-12 - Improvement Path

Using the data from the Improvement Path Figure 6-12 in the evaluation stage, prioritisation of improvement areas can be undertaken (see Table 6-8, Table 6-9, Table 6-10, Table 6-11). This summary prioritisation is as follows:

Priority One

Growth	
Activity	*Priority*
Leak Integ	5
PL AlGaAs	3
PL AlInGaP	2
Q Calib	4
Mnt Event	7
Source Act'y	1
Prod Proc	5

Process	
Char	*Priority*
Hardware	3
Morph	1
Doping	5
PL	2
XRD	2
Errors	6
Thickness	4

Table 6-8 - Priority One Summary

Priority Two

Raw Materials

Source	*Priority*
TMA	
TMG	
TMI	2
AsH3	4
PH3	3
Dopants	
Substrate	
Test Fails	1

Table 6-9 - Priority Two Summary

Priority Three

Engineer Screening

Activity	*Priority*
Prog Error	1
Interpret ?	3
Prem Chng	2

Table 6-10 - Priority Three Summary

Priority Four

Product Measurement

Meas	*Priority*
POP	1
B & Stain	2
Alphastep	3
Surfscan	4
PL	4
XRD	4

Table 6-11 - Priority Four Summary

Each of the identified priority steps requires further derivation, to commence derivation of the overall plan the priority one section will be developed in Table 6-12.

Priority One

List One

List Two

Growth

Activity	Priority
Leak Integ	5
PL AlGaAs	3
PL AlInGaP	2
Q Calib	4
Mnt Event	7
Source Act'y	1
Prod Proc	5

Process

Char	Priority
Hardware	3
Morph	1
Doping	5
PL	2
XRD	2
Errors	6
Thickness	4

Table 6-12 - Priority One Stage 2

List 1 is predominately material fit for purpose related to growth, with the single exception of the “Q” calibration [“Q”uaternary]. This shall be discussed with the “List 2” considerations. The “Q” calibration run is purely used as a fit for purpose test on the hardware, which should link into list 2, and be incorporated into the hardware category.

List 2 which should include the Q calibration data from list 1 should also loose the error data to priority 4 [Human Errors]. Errors are to be considered a function of measurement and accuracy.

1 - Hardware Failures
2 - Morphological Failures
3 - Doping Level Failures
4 - PL Failures
5 - XRD Failures
6 - Layer Thickness Failures

In list 2 above, failure types 3 to 6, with the measurement accuracy removed are predominately a function of gas flow imbalance, mixing, absolute flow rate, flow instability etc., this can be singly identified as “Flow Control”.

Each of the above needs further sub-division to derive a new priority listing for the following failure groups:

- Flow Control
- Hardware Failures
- Morphology Failures

Further definition of theses “Failure Groups” will enable an overall impact summary to be produced (Table 6-13).

Flow Control

Within the hardware failure category there is an accounted for 2% of flow control failures, these will be transferred to this section.

The total overall process equipment failures equate to 27% of “Yield Loss”.

A reasonable check can be made of this data from a cross check of 1997 performance failure summary:

% of Failures	Failure Code	Runs	Wafers	% of Total Run Activity
33%	Morph	478.94	957.88	9.76%
41%	Flow Control	593.15	1186.3	12.09%
18%	Hardware	261.24	522.48	5.32%
	Total	1333.3	2666.7	27.17%

Table 6-13 - Global, Failure Summary

The overall total is similar, offering enough confidence to use the data for full prioritisation of the Improvement plan.

6.4 – Chapter Summary

This Chapter in conjunction with Chapter 5 are key to the overall success of the improvement programme. The overall company process is defined, it is typical in such circumstances to use a standard process flow diagram, however the intrinsic weakness with this technique is that the "Influence or Impact" [System - Signal to Noise] on each output is not defined until a late stage in process flow evaluation [discussed in Chapter 2]. The analysis in this chapter using an original composite function of P-diagram and flow diagram is successful, in deriving a set of ranked failure causes utilising an original numerical analysis technique with the potential for weighting impact of each activity. Thus contributing an early stage a sort on the impact for the process flow evaluation. These causes make up a total of 92% [cumulative % of failures, from Table 6-13] of the overall failure mechanisms, CoDN £3.68m.

It is therefore essential that solutions be identified to these process problems. The process discussed in this Chapter is the entire "Process" within the engineering function, raw materials through to product despatch.

The subsequent Chapter offers interpretations and techniques to both define problem solving and define a technique to progress in a controlled manner.

Chapter 7 - Process Evaluation

7.1 – Introduction

The techniques in the preceding Chapter contribute a prioritised list of effects that are responsible for 92% of all process scrap. Identifying the effect however does not solve the problem. The precise cause/s of the effects has to be defined. A precise interpretation of what must be achieved is crucial; to enable this interpretation a concise understanding of "Process Problem Solving" must be available.

Once this process problem solving is defined a technique is applied to control activities, characterise the problems and link effects to causes. The resulting causes can then be analysed to offer a problem to be solved, or the highest failure mode – cause.

7.2 – Process Problem Solving

It is essential that clear interpretations exist for the prescribed activity. General interpretation of "Problem" and "Solving" will culminate in a precise interpretation.

7.2.1 - Problem?

General interpretations and or definitions:

7.2.1.1 - References "Problem"

1st Reference - [alternatives]

The alternative as detailed by *Microsoft Office 2000 (2000),* English U.K. Thesaurus:

"Problem"– difficulty, trouble, crisis, dilemma, predicament, quandary

2nd Reference

The definition as detailed by *The Infoplease Dictionary (2000)*:

"prob•lem" - *Pronunciation:* (prob'lum), [key]
—n.
1. any question or matter involving doubt, uncertainty, or difficulty.
2. a question proposed for solution or discussion.
3. *Math.* a statement requiring a solution, usually by means of a mathematical operation or geometric construction.

—adj.
1. difficult to train or guide; unruly: *a problem child.*
2. *Literature.* dealing with choices of action difficult either for an individual or for society at large: *a problem play.*

3rd Reference

Newnes Family Reference Dictionary 1st Edition
Problem – abridged interpretation

Prob'lem
1. A matter difficult of settlement or solution

2. A source of perplexity

4th Reference

`ref : Harris,R.(1999)`

Regardless of what they do for a living or where they live, most people spend most of their waking hours, at work or at home, solving problems. Most problems we face are small, some are large and complex, but they all need to be solved in a satisfactory way. Before we look at the area of problem analysis and solution, though, let's take a few moments to think about just what we mean by a problem.

What is a Problem?
One of the creative thinker's fundamental insights is that most questions have more than one right answer and most problems have more than one solution. In keeping with this insight, we will offer more than one definition of a problem, in hopes of filling out it's meaning as fully as possible. Different definitions yield different attitudes and approaches and prevent us from becoming fixed in the rut of "Oh No! A Problem!"

1. A problem is an opportunity for improvement. A problem can be a real break, the stroke of luck, opportunity knocking, a chance to get out of the rut of the everyday and make yourself or some situation better. Note that problems need not arrive because of external factors or bad events. Any new awareness you have that allows you to see possibilities for improvement brings a "problem" for you to solve. This is why the most creative people are "problem seekers" rather than "problem avoiders."

Developing a positive attitude toward problems can transform you into a happier, saner, more confident person who feels (and is) much more in control of life.

Train yourself to respond to problems with enthusiasm and eagerness, rising to the opportunity to show your stuff, and you will be amazed at the result.

2. A problem is the difference between your current state and your goal state. A problem can result from new knowledge or thinking. When you know where you are and where you want to be, you have a problem to solve in getting to your destination. The solution can and should be fun and exciting as you think over the various possible solution paths you might choose. When you can identify the difference between what you have and what you want, you have defined your problem and can aim toward your goal.

3. A problem results from the recognition of a present imperfect and the belief in the possibility of a better future. Isn't it interesting here that hope produces problems? The belief that your hopes can be achieved will give you the will to aim toward the better future. Your hopes **challenge** you, and challenge is another definition of a problem.

Using the preceding references (ref 1,2,3,4, section *7.2.1.1*) a summary definition/interpretation may be made that is related to “Process Problem Solving” specific to this project. Figure 7-2 offers that contribution on page 155.

7.2.1.2 – Process Problem Definition

A specific derivation or definition of “Process Problem” requires definition for use within the techniques within the project. It is essential to understand what a problem is and what solving entails. From the above definitions an interpretation unique to this project and its derived techniques can be offered. A definition for “Process Problem” will be contributed specific to this process using the preceding interpretations and definitions as a reference and is described in Figure 7-1: -

> *“Any Issue” experienced within a process that causes unpredicted deviation from expectation, causing difficulty, uncertainty, dilemma or quandary in implementing corrective action.*
>
> In this circumstance the Process can be declared enigmatic and therefore there is an Intrinsic or Latent “Problem” within the Process.

Figure 7-1 - Process Problem Definition

Now that a definition exists for a problem, the activity of finding a solution or solving needs understanding and derivation.

7.2.2 - Problem Solving?

General interpretations and/or definitions for derivation of "solving":

7.2.2.1 - References "Solve & Solution"

1st Reference

The definition as detailed by ***Microsoft Office 2000 (2000),*** English U.K. Thesaurus:

"Solve"– resolve: crack: answer: explain: work out

"Solution"– answer: explanation: resolution

2nd Reference

The definition as detailed by *The Infoplease Dictionary (2000)*:

Solve - *Pronunciation:* (solv), [key] — *v.t., solved, solv•ing.*
1. to find the answer or explanation for; clear up; explain: *to solve the mystery of the missing books.*
2. to work out the answer or solution to (a mathematical problem).

So•lu•tion - *Pronunciation:* (s*u*-lOO'sh*u*n), [key] —*n.*
1. the act of solving a problem, question, etc.: *The situation is approaching solution.*
2. the state of being solved: *a problem capable of solution.*
3. a particular instance or method of solving; an explanation or answer: *The solution is as good as any other.*
4. *Math.*
a. the process of determining the answer to a problem.
b. the answer itself.
5. *Chem.*
a. the process by which a gas, liquid, or solid is dispersed homogeneously in a gas, liquid, or solid without chemical change.
b. such a substance, as dissolved sugar or salt in solution.
c. a homogeneous, molecular mixture of two or more substances.
6. *Pharm.*Also called liquor. a liquid, usually water, in which a medication is dissolved.
7. *Med.*
a. the termination of a disease.
b. a breach or break in anything, esp. one in parts of the body normally continuous, as from fracture or laceration: *solution of continuity.*

3rd Reference

Newnes Family Reference Dictionary 1st Edition
Problem – abridged interpretation

Solve

To unbind: to dissolve: to settle to clear up or explain

To find an answer to or way out of

Solution

The act of solving or dissolving: the resulting theorem: explanation: removal of doubt; the state, condition, or fact of being solved

The solving of a problem

4th Reference

Harris, Robert. 1998

What is a Solution?

In our ordinary discourse, we often think of "solving a problem" in the sense of making it go away, so that the problem no longer exists. This indeed is one kind of solution, but it is not the only kind. Some problems cannot be eliminated entirely: we are never likely to eliminate trash, or the wear on automobile tires, or the occurrence of illness. We can, however, create solutions or treatments that will make each of these problems less harmful.

For our purposes, then, we will define a solution as *the management of a problem in a way that successfully meets the goals established for treating it.* Sometimes the goal will be to eliminate the problem entirely; sometimes the goal will be only to treat the effects of the problem. The possibilities inherent in the problem, together with the ambitiousness, resources, and values of the problem solver, will help shape the goals.

7.2.2.2 – Process Problem Solving Definition

A specific derivation or definition of "Process Problem Solving" requires definition for use within the techniques within the project. It is essential to understand what a problem is, this is defined in section 6.2.1.6. From the above definitions an interpretation unique to this project and its derived techniques can be offered, for process problem solving.

Process Problem Solving will be defined as Figure 7-2: -

> *The activity, of deriving a corrective action programme of work or study, to define the problem boundary conditions, cause and/or solution.*

Figure 7-2 - Process Problem Solving Definition

To enable the derivation of any process "issue" a very simple "Physical Scientific Rule" must be honoured and understood, for example:

Newton's Third Law of Motion:

III. For every action there is an equal and opposite reaction.

Figure 7-3 - Newton's 3rd Law

Interpreting "Newton's" 3rd Law, as detailed in Figure 7-3 into a problem solving scenario, as described in Figure 7-4:

For every process change, there will be a response either positive or negative that can be either blatant or latent, of varying magnitude.

Figure 7-4 - Process Problem Law

Thus for a "Complex Process" the act of problem solving is typically controlled using escalation culminating in a "Process Expert". Problem solving techniques and analysis have been historically evaluated predominately by Psychologists and Economists. Mathematicians view a problem solved when it is "reduced" (Pollak, 1997). Statisticians however have a major role in the development or understanding of a problem; to quote Kumar (2000) "applied statistics is a part of the information gathering and learning process, which is undertaken to inform decisions and actions".

A list of the "key issues" regarding decision-making and problem solving follows, as derived by Simon and Associates (© 1986):

- Problem Solving has been scientifically studied historically by principally psychologists, and more recently by researchers in "Artificial Intelligence".
- The laboratory study of "Problem Solving" has been supplemented by field studies of professionals solving real-world problems.
- Empirical definition of "Problem Solving": Problem Solving usually proceeds by selective searches through sets of possibilities, using rules of thumb to guide this research.
- Search Guiding Techniques, such as "Hill Climbing" or "Means-Ends Analysis" are identified.
- The contemporary theory of "Problem Solving" has been able to provide an explanation for the phenomena of intuition and judgement frequently seen in experts' behaviour.

Simon's article's discussion revolves around the expert having a full understanding of the activity or process, chess for example. It is generally understood that as understanding and experience increase the expectation on the "Expert" or the specification of "World Class" within any given field of activity will change with time.

7.2.3 - Problem Solving Generic Operators

In compound semiconductors it is generally accepted that "not all of the handles that operate the bells and whistles" are fully understood and that "rule of thumb" is very limited in the "Product Chain" (Figure 7-5).

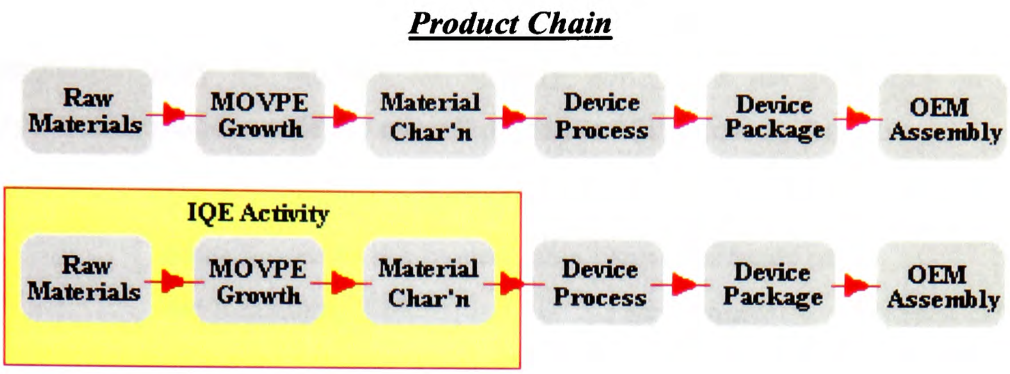


Figure 7-5 - Product Chain

The current experts therefore have still "a lot to learn". Heuristics play a large part in prioritisation during problem solving, however this is totally functional upon the gained experience and knowledge. In many cases of problem solving within compound semiconductors the problem appears unrelated to prior art and appears novel.

Many of the techniques (as discussed by: Simon and Associates, © 1986) in use today base themselves on the fact that "work has to be done" to gain a full determination of the problem, and that the problem must be well understood.

The major problem areas for process improvement were defined previously in Chapter 7, see Table 7-1.

% of Failures	Failure Code	Runs	Wafers	% of Total Run Activity
33%	Morph	478.94	957.88	9.76%
41%	Flow Control	593.15	1186.3	12.09%
18%	Hardware	261.24	522.48	5.32%
	Total	1333.3	2666.7	27.17%

Table 7-1 - Global Failure Summary

Two discreet activities need to be completed, so that an appropriate technique may be derived, to identify and solve the problems in a systematic manner with the overall objective of improving the process.

1 - A technique enabling derivation of the major contributors to the overall, this forms the basis of the Reasoning Mechanism for the technique.

2 - A specific problem solving technique based upon the derived reasoning mechanism identifying the performance inhibitors and derivation of potential solutions, [Process Improvement Problem Solving – PIPS].

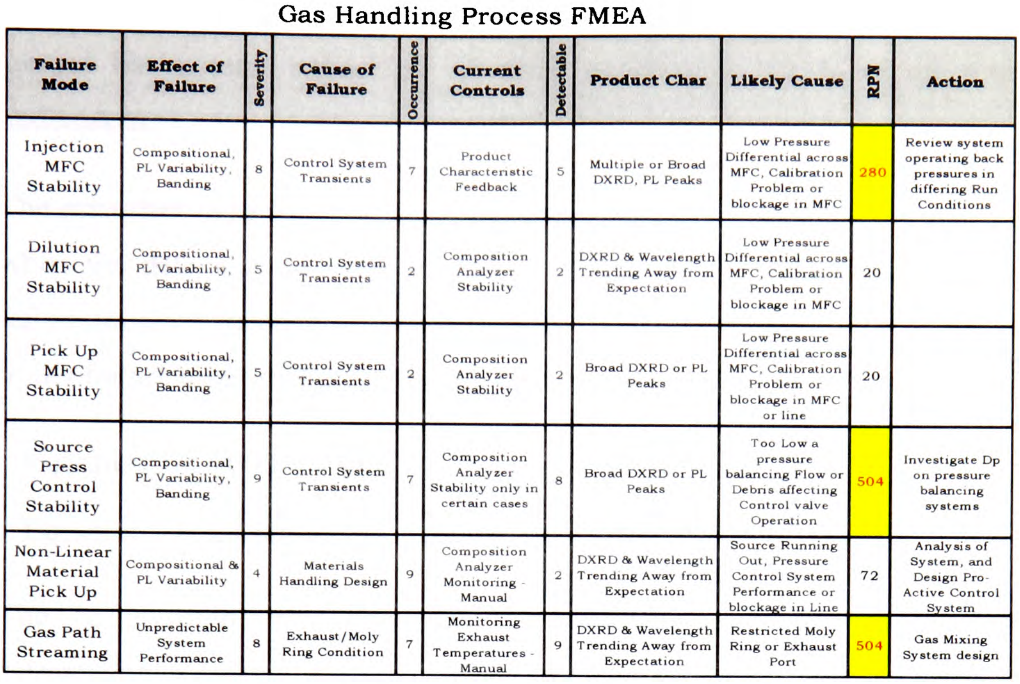
7.2.3.1 – Reasoning Mechanism

For many years a basic technique in engineering has been used for evaluation of plant failure analysis and the actual causes of failure, Failure Mode Effect Analysis [FMEA].

To derive priorities using a typical FMEA again a standard technique may be used, one of deriving a risk priority number [RPN] following selection of appropriate operating indices i.e.

Severity
Occurrence
Detectability

This standard technique can be used as the foundation of prioritisation and sorting multiple effect causes.



Gas Handling Process FMEA

Failure Mode	Effect of Failure	Severity	Cause of Failure	Occurrence	Current Controls	Detectable	Product Char	Likely Cause	RPN	Action
Injection MFC Stability	Compositional, PL Variability, Banding	8	Control System Transients	7	Product Characteristic Feedback	5	Multiple or Broad DXRD, PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	280	Review system operating back pressures in differing Run Conditions
Dilution MFC Stability	Compositional, PL Variability, Banding	5	Control System Transients	2	Composition Analyzer Stability	2	DXRD & Wavelength Trending Away from Expectation	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	20	
Pick Up MFC Stability	Compositional, PL Variability, Banding	5	Control System Transients	2	Composition Analyzer Stability	2	Broad DXRD or PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC or line	20	
Source Press Control Stability	Compositional, PL Variability, Banding	9	Control System Transients	7	Composition Analyzer Stability only in certain cases	8	Broad DXRD or PL Peaks	Too Low a pressure balancing Flow or Debris affecting Control valve Operation	504	Investigate Dp on pressure balancing systems
Non-Linear Material Pick Up	Compositional & PL Variability	4	Materials Handling Design	9	Composition Analyzer Monitoring - Manual	2	DXRD & Wavelength Trending Away from Expectation	Source Running Out, Pressure Control System Performance or blockage in Line	72	Analysis of System, and Design Pro-Active Control System
Gas Path Streaming	Unpredictable System Performance	8	Exhaust/Moly Ring Condition	7	Monitoring Exhaust Temperatures - Manual	9	DXRD & Wavelength Trending Away from Expectation	Restricted Moly Ring or Exhaust Port	504	Gas Mixing System design

Figure 7-6 - Typical FMEA - Example

By utilising these indices and then a suitable mathematical operator a suitable prioritising medium can be used. The "Prod Char" column [Product Characterisation] is an additional identifier for the noted effect. In Figure 7-6, for example scales of 0 to 10 have been selected for all of the indices and a direct multiplier. The resulting number can then be used in ascending order for priority. The resulting RPN may be used in a discreet or functioned form as the appropriate mechanism.

7.2.3.2 – Process Improvement Problem Solving - Technique

The novel discrete technique will use a form of the previously discussed reasoning mechanism in a generic form that can be modified as a function of the objective.

To reiterate the process major performance blockages, as listed in Table 7-1.

The first problem identified in Chapter 6 is that some function of flow control has a total impact on all runs, equating to 12 % of all runs undertaken.

The manufacturing function averaged approximately 5000 runs per annum when the data was collated. Equation 10 derives the impact of a single failure mode or mechanism [Flow Control], and Equation 11 offers a value of the failure mechanism in capacity terminology.

Equation 10: $5000 \times 0.121 = 605$ runs/yr f(Flow Control)

Equation 11: £3.8m x 0.41 = £1.6m lost Sales/yr f(Flow Control)

The justification for improvement can be directly identified, also determining a datum for monitoring the "overall objective" and "payback".

One major objective is to offer a "simple" technique that may be used by an individual, group or business that believes that some of its problems are ill defined and yet needs to make progress.

7.3 - Process Improvement Problem Solving: "PIPS"

The technique used to identify the topical process improvement is critical to the success of any improvement programme. It is essential that individual preferences and "rule of thumb" be minimised. It has been proven thus far that the RPN or some derived function, as an operator is very successful.

This section derives and describes the use of such a novel technique.

The "PIPS" Technique

The fundamental activity list for the PIPS technique is a six-stage action programme, see Figure 7-7. The basic operating system of this technique is a derivate function of the chosen reasoning mechanism FMEA:

1 - Acknowledge

2 - Characterise Effects

3 - Tabulate Causes

4 - Investigate Cause & Effect

5 - Offer Solutions

6 - Necessary Response

Figure 7-7 - PIPS Action Summary

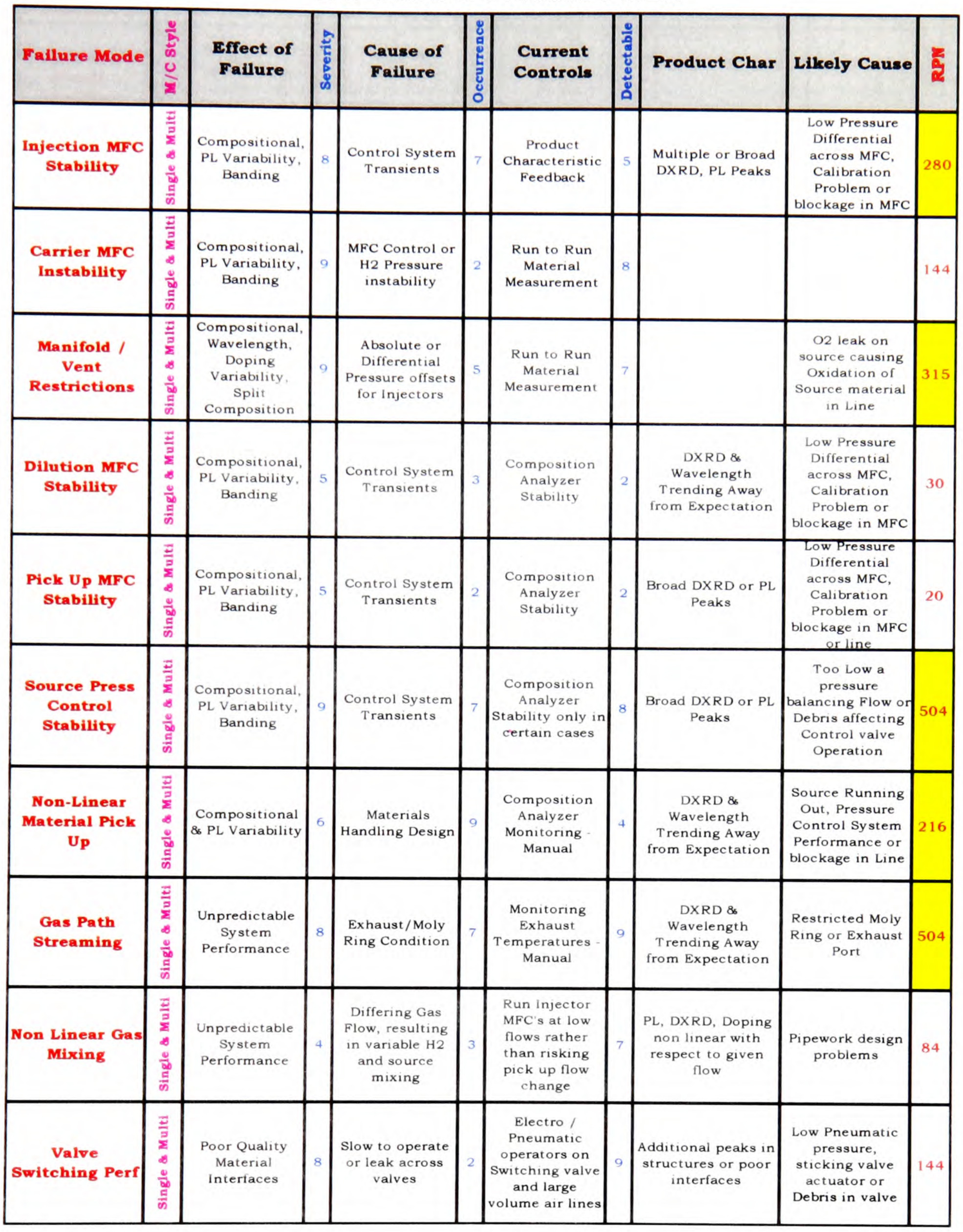
7.3.1 - Acknowledge > Identify Problem

The problem is acknowledged; the data above defines the problem:

$$f(\text{Flow Control})$$

An FMEA may be derived for the flow control problems, Figure 7-8:

Flow Control Process FMEA



Failure Mode	M/C Style	Effect of Failure	Severity	Cause of Failure	Occurrence	Current Controls	Detectable	Product Char	Likely Cause	RPN
Injection MFC Stability	Single & Multi	Compositional, PL Variability, Banding	8	Control System Transients	7	Product Characteristic Feedback	5	Multiple or Broad DXRD, PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	280
Carrier MFC Instability	Single & Multi	Compositional, PL Variability, Banding	9	MFC Control or H2 Pressure instability	2	Run to Run Material Measurement	8			144
Manifold / Vent Restrictions	Single & Multi	Compositional, Wavelength, Doping Variability, Split Composition	9	Absolute or Differential Pressure offsets for Injectors	5	Run to Run Material Measurement	7		O2 leak on source causing Oxidation of Source material in Line	315
Dilution MFC Stability	Single & Multi	Compositional, PL Variability, Banding	5	Control System Transients	3	Composition Analyzer Stability	2	DXRD & Wavelength Trending Away from Expectation	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	30
Pick Up MFC Stability	Single & Multi	Compositional, PL Variability, Banding	5	Control System Transients	2	Composition Analyzer Stability	2	Broad DXRD or PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC or line	20
Source Press Control Stability	Single & Multi	Compositional, PL Variability, Banding	9	Control System Transients	7	Composition Analyzer Stability only in certain cases	8	Broad DXRD or PL Peaks	Too Low a pressure balancing Flow or Debris affecting Control valve Operation	504
Non-Linear Material Pick Up	Single & Multi	Compositional & PL Variability	6	Materials Handling Design	9	Composition Analyzer Monitoring - Manual	4	DXRD & Wavelength Trending Away from Expectation	Source Running Out, Pressure Control System Performance or blockage in Line	216
Gas Path Streaming	Single & Multi	Unpredictable System Performance	8	Exhaust/Moly Ring Condition	7	Monitoring Exhaust Temperatures - Manual	9	DXRD & Wavelength Trending Away from Expectation	Restricted Moly Ring or Exhaust Port	504
Non Linear Gas Mixing	Single & Multi	Unpredictable System Performance	4	Differing Gas Flow, resulting in variable H2 and source mixing	3	Run Injector MFC's at low flows rather than risking pick up flow change	7	PL, DXRD, Doping non linear with respect to given flow	Pipework design problems	84
Valve Switching Perf	Single & Multi	Poor Quality Material Interfaces	8	Slow to operate or leak across valves	2	Electro / Pneumatic operators on Switching valve and large volume air lines	9	Additional peaks in structures or poor interfaces	Low Pneumatic pressure, sticking valve actuator or Debris in valve	144

Figure continued overleaf

Injection Nozzle Position	Multi	Compositional & PL Variability	8	Mal-Adjusted or Incorrectly Fitted	7	Operator Checks	6			336
Injection Nozzle Condition	Multi	Characteristic Uniformity	6	Excessive Growth on Nozzle, Incorrect fitting or Nozzle	5	Change Nozzle regularly	5			150
Gas Path Streaming	Single & Multi	Growth Rate & Growth Profile	7	Poor Interfaces & Banding	3	Manual temperature checks	8			168
Exhaust Ring Condition	Multi	Growth Rate & Compositional Variability	4	Gas Flow Path Over Ring and Back Pressure On Cell Increasing Growth Pressure, Increasing Residence Time	4		6	Multiple or Broad DXRD, PL Peaks, Normally Producing Satellite Peaks	Cell Back Pressure, Carrier MFC	96
Exhaust System Condition	Single & Multi	Morphology degradation	8	Pressure Transients	5		3			120
Radial Depletion Effects	Multi	Non uniform Thickness Profile even with Rotation	2	Nutrient Material Fully depleted early in cell	1		2	High % Growth rate drop towards edges of rotated wafer	Blocked Molybdenum Ring	4
H2 Pressure Stability	Single & Multi	Growth Rate & Compositional Variability	7	Diffuser or Line Pressure Control	1	Manual Pressure Checks	2			14
Particulate Mobility	Single & Multi	Grown In Morphology Deterioration	7	Particles from cracked material back streaming onto growing surface	8	Load / Unload flow Control	9	Morphology Failures with small regularly shaped particles Grown In	Particle Control poor, O2 in Glove box causing smoke particle generation	504
Exhaust Line "Flipping"	Multi	Growth Rate & Compositional Variability	6		8		6			288
Flow Component Direct Failure	Single & Multi		10		4		8			320
Pressure Component Direct Failure	Single & Multi		10		2		8			160

Figure 7-8 - Flow Control Specific FMEA

7.3.2 - Characterise Effects

The above Figure 7-8 - FMEA can be rearranged and summarised and presented in Figure 7-9, the inclusion of a failure number allows for future referencing:

Flow Control Process FMEA

Failure Mode	Failure No	M/C Style	Effect of Failure	Effect Category	Severity	Occurrence	Detectable	RPN
Injection MFC Stability	**1**	Single & Multi	Compositional, PL Variability, Banding	1	8	7	5	280
Carrier MFC Instability	**2**	Single & Multi	Compositional, PL Variability, Banding	1	9	2	8	144
Manifold / Vent Restrictions	**3**	Single & Multi	Compositional, Wavelength, Doping Variability, Split Composition	1	9	5	7	315
Dilution MFC Stability	**4**	Single & Multi	Compositional, PL Variability, Banding	1	5	3	2	30
Pick Up MFC Stability	**5**	Single & Multi	Compositional, PL Variability, Banding	1	5	2	2	20
Source Press Control Stability	**6**	Single & Multi	Compositional, PL Variability, Banding	1	9	7	8	504
Non-Linear Material Pick Up	**7**	Single & Multi	Compositional & PL Variability	1	6	9	4	216
Gas Path Streaming	**8**	Single & Multi	Compositional & PL Variability	1	8	7	9	504
Non Linear Gas Mixing	**9**	Single & Multi	Compositional & PL Variability	1	4	3	7	84
Valve Switching Perf	**10**	Single & Multi	Poor Quality Material Interfaces	1	8	2	9	144

Figure continued overleaf

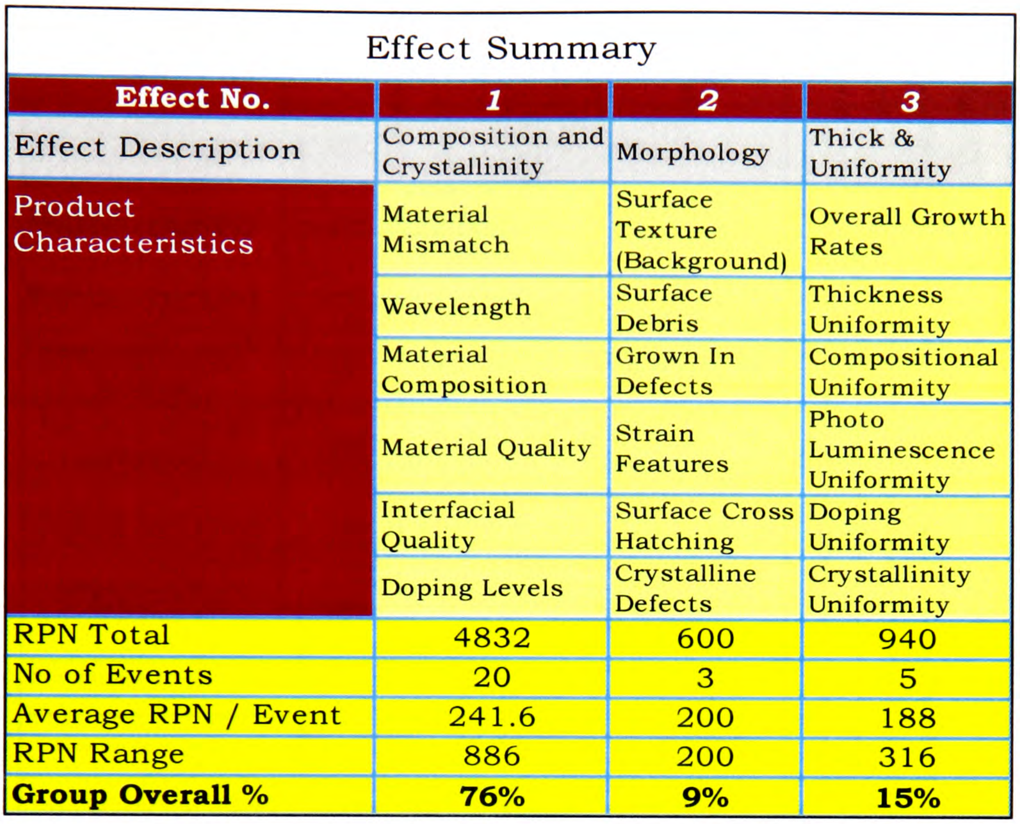
Pressure Balancing Control	**11**	**Single & Multi**	Poor Quality Material Interfaces	1	9	7	9	567
Rotation Predictability	**12**	**Multi**	Characteristic Uniformity - Scrap Product	1	9	10	10	900
Rotation Stability	**13**	**Multi**	Characteristic Homogeneity	1	3	1	10	30
Rotation Gas Flow	**14**	**Multi**	Characteristic Uniformity	1	2	1	9	18
Injection Nozzle Position	**15**	**Multi**	Compositional & PL Variability	1	8	7	6	336
Injection Nozzle Condition	**16**	**Multi**	Characteristic Uniformity	1	6	5	5	150
Gas Path Streaming	**17**	**Single & Multi**	Growth Rate & Growth Profile	3	7	3	8	168
Exhaust Ring Condition	**18**	**Multi**	Growth Rate & Compositional Variability	1	4	4	6	96
Exhaust System Condition	**19**	**Single & Multi**	Morphology degradation	2	8	5	3	120
Radial Depletion Effects	**20**	**Multi**	Non uniform Thickness Profile even with Rotation	3	2	1	2	4
H2 Pressure Stability	**21**	**Single & Multi**	Growth Rate & Compositional Variability	1	7	1	2	14
Exhaust Line "Flipping"	**22**	**Multi**	Growth Rate & Compositional Variability	3	6	8	6	288
Flow Component Direct Failure	**23**	**Single & Multi**	Any	1,2,3	10	4	8	320
Pressure Component Direct Failure	**24**	**Single & Multi**	Any	1,2,3	10	2	8	160

Figure 7-9 - Characterised Flow Control FMEA

The Effects listed above, fall into three fundamental categories:

1 - Composition and Crystallinity
2 - Morphology
3 - Thickness & Uniformity's

Table 7-2 identifies the "Product Characteristics" (as defined in Figure 7-9) that are grouped in each effect group number.



Effect Summary

Effect No.	**1**	**2**	**3**
Effect Description	Composition and Crystallinity	Morphology	Thick & Uniformity
Product Characteristics	Material Mismatch	Surface Texture (Background)	Overall Growth Rates
	Wavelength	Surface Debris	Thickness Uniformity
	Material Composition	Grown In Defects	Compositional Uniformity
	Material Quality	Strain Features	Photo Luminescence Uniformity
	Interfacial Quality	Surface Cross Hatching	Doping Uniformity
	Doping Levels	Crystalline Defects	Crystallinity Uniformity
RPN Total	4832	600	940
No of Events	20	3	5
Average RPN / Event	241.6	200	188
RPN Range	886	200	316
Group Overall %	**76%**	**9%**	**15%**

Table 7-2 - Effect Summary

The RPN total as detailed in Table 7-2, for each group represents the “Total Impact” that each group has on the overall failure rate. The event average, “RPN/Event” indicates the impact/event for each failure in the group. An “average RPN/Event” offers a generic scaling for the impact of each effect group. The RPN range indicates the overall scale of the effect.

It can be concluded from Table 7-2 that “Group 1 Effects” have the major contribution to the overall failure rate, 76 % of RPN total. This is confirmed by the highest effect event count.

7.3.3 - Tabulate Causes

Using the previous FMEA data as listed in Figure 7-9 and grouping the causes for each failure mode, enables a cause tabulation to be produced. (see Table 7-3)

Failure Mode	Cause	Category	Severity	Occurrence	Detectable	RPN
Injection MFC Stability	**Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, Calibration Slippage**	1	8	7	5	280
Carrier MFC Instability	**Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage**	1	9	2	8	144
Manifold / Vent Restrictions	**Δ Pressure too Low, Dust Contaminated causing Blockage, Press Balancing Control System faulty, Leak to Air**	1	9	5	7	315
Dilution MFC Stability	**Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage**	1	5	3	2	30
Pick Up MFC Stability	**Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage, Bubbler Blockage / Restriction**	1	5	2	2	20
Source Press Control Stability	**Δ Pressure too Low, Supply MFC Reading Low, Injector MFC Reading High, Press Control Valve unable to shut off flow, Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage, Bubbler Blockage / Restriction**	1	9	7	8	504
Non-Linear Material Pick Up	**Source Pressure changing with total flow, Bubbler material channeling, Source level low, Contaminated source, leak to air**	1	6	9	4	216
Gas Path Streaming	**Exhaust System, Port, Molybdenum Ring restrictions, Carrier Flows too High, Absolute Growth Pressure Low**	1	8	7	9	504
Non Linear Gas Mixing	**Flexibility of flow , gas dilution and Nutrient flows not adequately mixed, Bubbler material contaminated / oxidised, Bubbler pressure High**	1	4	3	7	84
Valve Switching Perf	**Material leaking from Run to Vent through valve or V.Versa, Low Air Pressure, Electro Pneu Circuit failure**	1	8	2	9	144
Pressure Balancing Control	**Δ Pressure must be maintained +/- 0.002 b if not then - diff transducer calibration or diaphragm rupture, control system settings, line resistance's have changed**	1	9	7	9	567
Rotation Predictability	**Susceptor bearing surfaces must be kept particle free, particles must not be ground in, rotation speed is a function of coating / bearing condition / alignment**	1	9	10	10	900
Rotation Stability	**Susceptor Condition, Growth Debris, Face scoring, gas transfer rod condition, alignment**	1	3	1	10	30
Rotation Gas Flow	**Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, Calibration Slippage**	1	2	1	9	18
Injection Nozzle Position	**Incorrect Alignment at Installation, Incorrect fitting allowing movement / time, broken nozzle vanes**	1	8	7	6	336
Injection Nozzle Condition	**Growth on Nozzle Inner face**	1	6	5	5	150
Exhaust Ring Condition	**Moly exhaust ring not changed during regular maintenance**	1	4	4	6	96
H2 Pressure Stability	**Pressure Control - either Low pressure regulator to Reactor or High Pressure Regulator to diffuser, Diffuser cold, Diffuser fully contaminated**	1	7	1	2	14
Flow Component Failure	**Component Failure**	1	10	4	8	320

Table 7-3 - Cause Tabulation

The "Cause Inclusion" within Table 7-3 is an accumulation of the many causes identified within the incomplete FMEA exercise (of which Figure

7-8 is typical) and intrinsic process knowledge that is currently unproven within empirical trials.

Failure Mode	Cause	Diffuser or Control	D Pressure too Low	MFC Dust Contaminated	Control System faulty	Leak to Air	Supply MFC Reading Low	Injector MFC Reading High	Press Control Valve unable to shut	Bubbler Blockage / Restriction	Source Pressure change with flow	Susceptor bearing surfaces	Gas transfer rod condition	Susceptor [coating / bearing / alignment]	Nozzle Fitting/Alignment	Growth on Nozzle Inner face	Moly exhaust ring	Electro Pneu Circuit failure	Low Air Pressure	Material leak from Run to Vent or V.Versa	Contaminated source	Bubbler material channeling	Source level low	H2 Pressure low	Dust Contaminated causing Blockage	Press Balancing Control System faulty	Calibration Slippage	RPN	Causes	RPN/Cause
Injection MFC Stability	Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, Calibration Slippage		■	■	■	■																					■	280	5	56
Carrier MFC Instability	Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage		■	■	■	■																		■			■	144	6	24
Manifold / Vent Restrictions	Δ Pressure too Low, Dust Contaminated causing Blockage, Press Balancing Control System faulty, Leak to Air		■			■																			■	■		315	4	79
Dilution MFC Stability	Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage		■	■	■	■																		■			■	30	6	5
Pick Up MFC Stability	Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage, Bubbler Blockage / Restriction		■	■	■	■				■														■			■	20	7	3
Source Press Control Stability	Δ Pressure too Low, Supply MFC Reading Low, Injector MFC Reading High, Press Control Valve unable to shut off flow, Dust Contaminated, Control System faulty, Leak to Air, H2 Pressure low, Calibration Slippage, Bubbler Blockage / Restriction		■	■	■	■	■	■	■	■															■		■	504	10	50
Non-Linear Material Pick Up	Source Pressure changing with total flow, Bubbler material channeling, Source level low, Contaminated source, leak to air					■					■										■	■	■					216	5	43
Gas Path Streaming	Exhaust System, Port, Molybdenum Ring restrictions, Carrier Flows too High, Absolute Growth Pressure Low		■	■													■								■			504	4	126
Non Linear Gas Mixing	Flexibility of flow , gas dilution and Nutrient flows not adequately mixed, Bubbler material contaminated / oxidised, Bubbler pressure High									■											■	■						84	3	28
Valve Switching Perf	Material leaking from Run to Vent through valve or V.Versa, Low Air Pressure, Electro Pneu Circuit failure																	■	■	■								144	3	48
Pressure Balancing Control	Δ Pressure must be maintained +/- 0.002 b if not then - diff transducer calibration or diaphragm rupture, control system settings, line resistance's have changed		■		■	■																			■	■		567	5	113
Rotation Predictability	Susceptor bearing surfaces must be kept particle free, particles must not be ground in, rotation speed is a function of coating / bearing condition / alignment											■		■														900	2	450
Rotation Stability	Susceptor Condition, Growth Debris, Face scoring, gas transfer rod condition, alignment											■	■															30	2	15
Rotation Gas Flow	Δ Pressure too Low, MFC Dust Contaminated, Control System faulty, Leak to Air, Calibration Slippage		■	■	■	■																					■	18	5	4
Injection Nozzle Position	Incorrect Alignment at Installation, Incorrect fitting allowing movement / time, broken nozzle vanes														■													336	1	336
Injection Nozzle Condition	Growth on Nozzle Inner face															■												150	1	150
Exhaust Ring Condition	Moly exhaust ring not changed during regular maintenance																■											96	1	96
H2 Pressure Stability	Pressure Control - either Low pressure regulator to Reactor or High Pressure Regulator to diffuser, Diffuser cold, Diffuser fully contaminated	■																										14	1	14
Press Component Failure	Component Failure	■	■		■		■	■	■		■		■					■	■	■				■		■	■	###	14	11
		2	9	7	7	9	1	1	1	3	1	2	1	1	1	1	2	1	1	1	2	2	1	3	4	2	6	66		

Table 7-4 - DoFMEA Matrix

7.3.4 - Investigate Cause & Effect

Using the "Effect data" summarised in Table 7-2, it is possible to summarise and quantify the "Cause data", using a similar mechanism. This mechanism is DoFMEA, and is formulated in Table 7-4.

This unique handling of causes in this DoFMEA in Table 7-4 enables pure derivation of the process problems ranking.

Each of the failure modes or mechanisms has multiple causes; the multiple failure modes may and will have some "Overlap" effect in this cause derivation. This is impossible to handle in a standard FMEA activity.

The FMEA used to investigate the causes will be "Double Operating" the cause against each failure mechanism. The resulting cause "Hit Rate" and RPN will be allow full definition of the process improvement activity definitions.

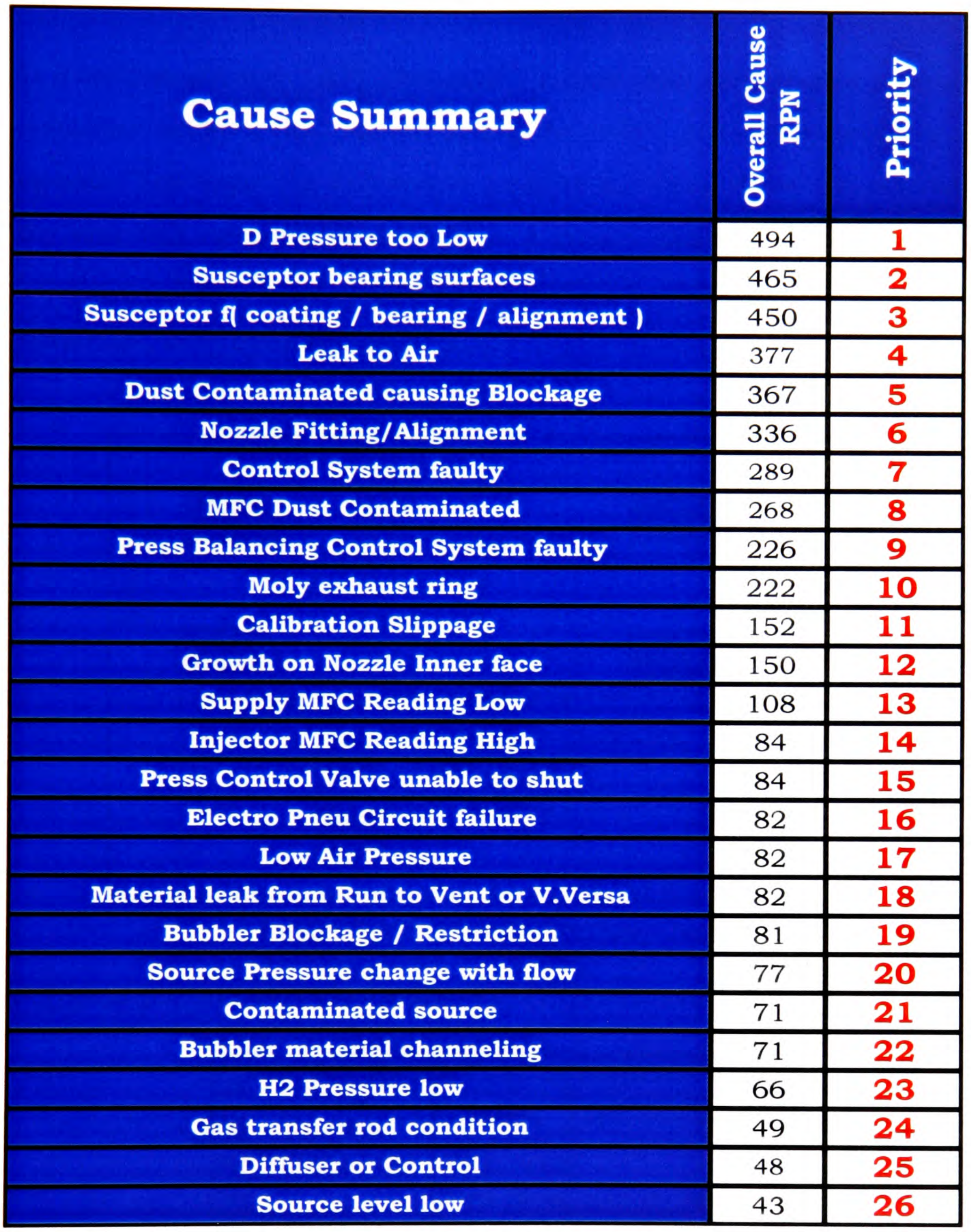
To summarise the DoFMEA exercise results from Table 7-4, the RPN result tabulation requires undertaking. This will then allow construction of a simple "Problem Prioritisation Chart" see Table 7-5. The data presented in Table 7-5 needs presenting in a manageable format so that local problem solving may take place on the prioritised causes. Table 7-6 summarises the data.

For the DoFMEA the "Causes or Effects" are two-dimensionally plotted and the potential mix of causes plotted.

Summarised RPN/Cause

	1194	174	652	180	117	500	667	616	206	518	Total	Priority
	14									34	48	
D Pressure too Low	56	24	79	5	3	50	113	126	4	34	494	1
MFC Dust Contaminated	56	24		5	3	50		126	4		268	8
Control System faulty	56	24		5	3	50	113		4	34	289	7
Leak to Air	56	24	79	5	3	50	43	113	4		377	4
		24				50				34	108	
						50				34	84	
						50				34	84	
					3	50			28		81	
							43			34	77	
Susceptor bearing surfaces	450	15									465	2
		15								34	49	
Susceptor I(coating / bearing / alignment)	450										450	3
Nozzle Fitting/Alignment			336								336	6
				150							150	
Moly exhaust ring					96			126			222	10
									34	48	82	
									34	48	82	
									34	48	82	
							43		28		71	
							43		28		71	
							43				43	
		24		5	3					34	66	
Dust Contaminated causing Blockage			79			50	113	125			367	5
Press Balancing Control System faulty			79				113			34	226	9
	56			5	3	50			4	34	152	

Table 7-5 - Summarised "Cause" RPN



Cause Summary	Overall Cause RPN	Priority
D Pressure too Low	494	1
Susceptor bearing surfaces	465	2
Susceptor f(coating / bearing / alignment)	450	3
Leak to Air	377	4
Dust Contaminated causing Blockage	367	5
Nozzle Fitting/Alignment	336	6
Control System faulty	289	7
MFC Dust Contaminated	268	8
Press Balancing Control System faulty	226	9
Moly exhaust ring	222	10
Calibration Slippage	152	11
Growth on Nozzle Inner face	150	12
Supply MFC Reading Low	108	13
Injector MFC Reading High	84	14
Press Control Valve unable to shut	84	15
Electro Pneu Circuit failure	82	16
Low Air Pressure	82	17
Material leak from Run to Vent or V.Versa	82	18
Bubbler Blockage / Restriction	81	19
Source Pressure change with flow	77	20
Contaminated source	71	21
Bubbler material channeling	71	22
H2 Pressure low	66	23
Gas transfer rod condition	49	24
Diffuser or Control	48	25
Source level low	43	26

Table 7-6 - Cause Prioritisation

7.3.5 - Offer Solutions

Each of the listed priorities in Table 7-6 can be detailed as individual improvement projects.

*For Example (*from Table 7-6*):*

Priority No 1 – D. Pressure too Low

D is the abbreviation for "Differential", a mass flow controller or pressure controller within a flow control system requires a differential pressure to operate. The larger the differential pressure the more stable and accurate the unit will operate. Figure 7-10 is a typical example of this type of handling system. Each component within this operating system has a minimum ΔP of approximately 350mb.

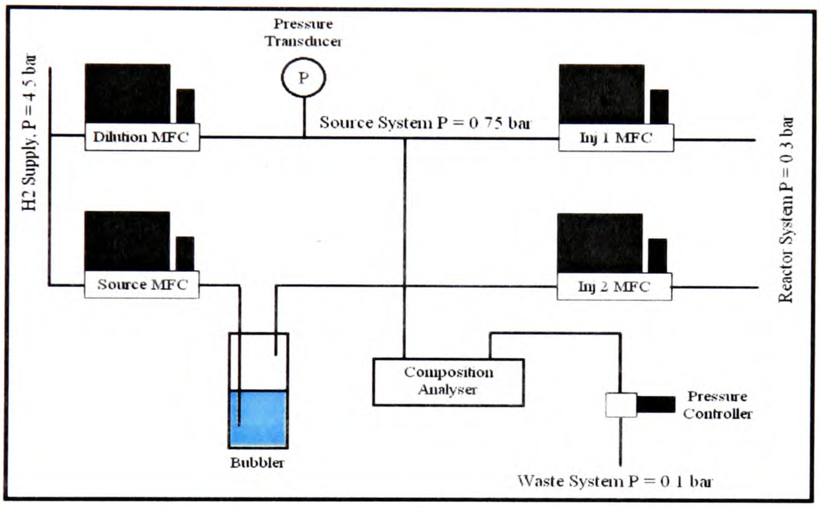
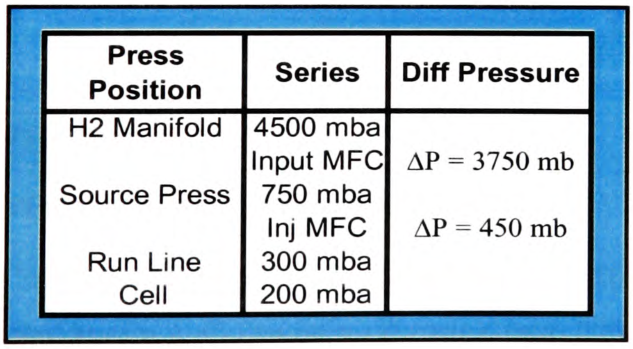


Figure 7-10 - Bubbler System - Nest

A typical pressure cascade for this type of system is as Table 7-7:



Press Position	Series	Diff Pressure
H2 Manifold	4500 mba	
	Input MFC	ΔP = 3750 mb
Source Press	750 mba	
	Inj MFC	ΔP = 450 mb
Run Line	300 mba	
Cell	200 mba	

Table 7-7 - System Pressure Summary

The data is suggesting that ΔP is an issue, evaluating the series list as defined in Table 7-7 there are five listed pressures involved.

1 – Manifold Gas (H_2) Pressure	4500 mba
2 – Source Gas Pressure (Pick Up)	750 mba
3 – Run Line Pressure	300 mba
4 – Cell Operating Pressure	200 mba
5 – Minimum MFC Operating Pressure	350 mba

Equation 12: $\Delta P1\ [FoS] = 3750/350 = 10.7$

as $\Delta P1$ is 3750 mb, this equates to 10.7 x Minimum Operating Differential

Equation 13: $\Delta P2\ [FoS] = 450/350 = 1.28$

as $\Delta P2$ is 450 mb, this equates to 1.28 x Minimum Operating Differential

Both Equation 12 and Equation 13 calculate the FoS for the MFC's in the different positions, however on such a dynamic system the **ΔP** will fluctuate with the control system. In conclusion **ΔP2** is very close to minimum operating pressure, a process FoS of 1.28 is too small, thus confirming the finding of Table 7-6. These systems flow into the run line at 300mb, add to this the minimum operating MFC ΔP of 450 mb then the minimum FoS should be:

$$\text{Min } \Delta P2\ [FoS] = (450+300)/350 = 2.1$$

7.3.6 - Necessary Response

The Options are therefore (see Table 7-8):

1 – Increase Source Operating Pressure from 750 mba
2 – Reduce the Cell Operating Pressure from 200 mba
3 – Reduce Run Line Resistance from 100 mb

No	Options	Impact
1	Increase Source Operating Pressure from 750 mba	Increase in Operating Pressure reduces the potential Source "Pick Up". This has potential providing that the pick up is not saturated.
2	Reduce the Cell Operating Pressure from 200 mba	This would entail a change in the Gas Dynamics in the Cell that could potentially intrinsically alter the material shipped to the customer
3	Reduce Run Line Resistance from 100 mb	Dropping the line resistance would require a basic system re-design, any increase in system volume would alter the Source "Time to Cell". All lines would have to be re-designed.

Table 7-8 - Option Impact Summary

The Option decision-making can also use some function of RPN logic. Using:

1-10 Product Risk – 10 being potentially devastating
1-10 Time to Execute – 1 is immediate, 10 is long term [1year +]
1-10 Ease of Change – 1 no investment, 10 is high relative

Options	Impact	Product Risk	Time to Execute	Ease of Change	RPN
Increase Source Operating Pressure from 750 mba	Increase in Operating Pressure reduces the potential Source "Pick Up". This has potential providing that the pick up is not saturated.	2	2	3	24
Reduce the Cell Operating Pressure from 200 mba	This would entail a change in the Gas Dynamics in the Cell that could potentially intrinsically alter the material shipped to the customer	10	2	1	40
Reduce Run Line Resistance from 100 mb	Dropping the line resistance would require a basic system re-design, any increase in system volume would alter the Source "Time to Cell". All lines would have to be re-designed.	1	6	3	36
1 is Low or Easy 1 to 10 Scales	(PRx2) x (ToEx1) x (EoCx1) = PRN				

Table 7-9 - Option Justification

Each of the RPN operators are weighted, the weighting is based upon potential impact on the product. The RPN calculation in Table 7-9 suggests that the 1st option for improving the process stability for the differential pressure problem is:

"Increasing the Source Operating Pressure, ensuring that the pick up is not saturated."

This typical exercise can then be re-worked for all of the secondary priorities identified earlier.

7.4 – Chapter Summary

Chapter 5 offers a series of effects that require cause identification and the cause solutions defined. This Chapter offers an original definition and a technique for process improvement problem solving. The derived technique operates on a typical FMEA reasoning mechanism and derives further original modifications to the FMEA technique contributing a simple two dimensional analysis of a complex multiple cause/cause analysis, namely double operating FMEA [DoFMEA].

The result of this DoFMEA analysis is a prioritised list of process causes or failure mechanisms. Additional derivation of the process primary failure mode offers options on improving the process. This failure mechanism theoretically by statistical projection offers a process improvement

The subsequent chapter evaluates the derived highest priority failure mechanism as identified within this Chapter and review, offers a design change to improve the overall process effect of that specified failure mode.

Chapter 8 - Improvement Pilot Study

8.1 - Introduction

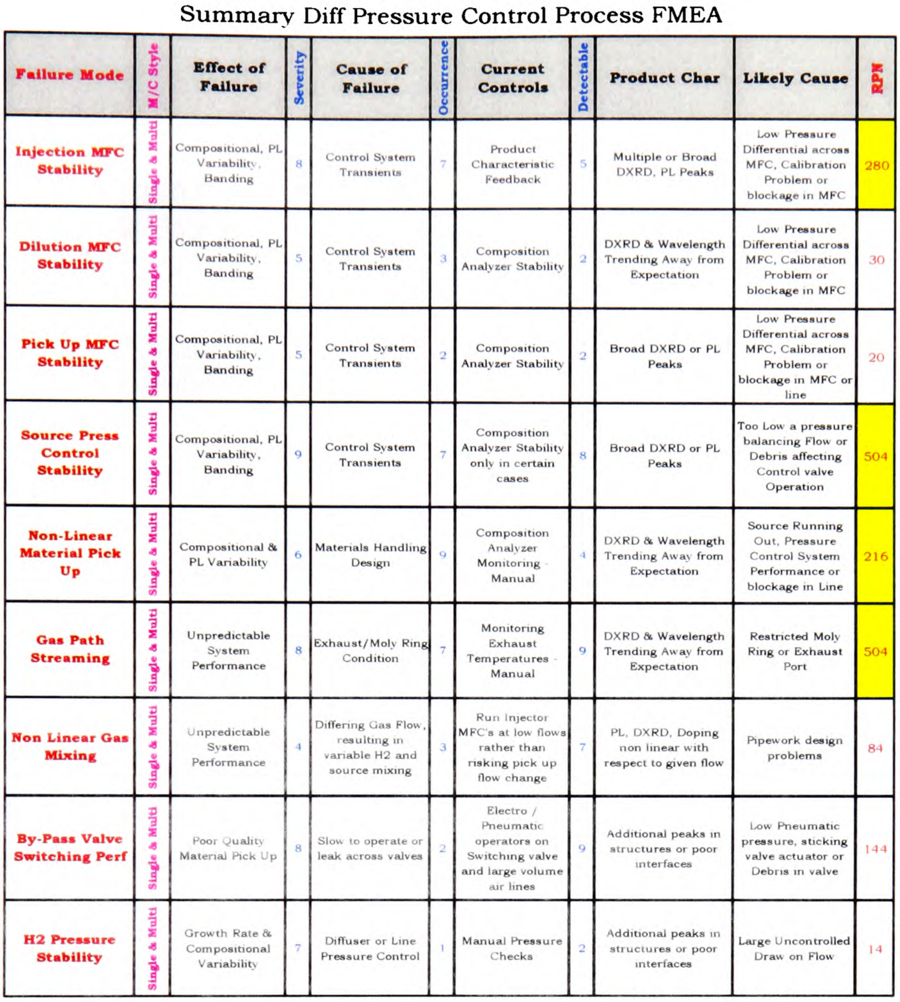
The preceding Chapter identifies a cause [Differential Pressure – Delta Pressure low] as the highest priority failure mechanism to improve, and offers a variety of options to improve this aspect of the process and its performance. The system is re-designed offering an improvement in the control and reproducibility. One of the MOVPE reactors is modified and a series of repeat structures run through the re-design transition stages.

8.2 - Worked Example

The overall top priority concluded within the "Cause Summary" (Table 7-5) defines that the single most critical cause is "Delta Pressure Too Low".

8.2.1 - What is? - "Delta Pressure Too Low"

In pure terms the statement encompasses several potential causes all resulting in a similar effect, a specific FMEA may be derived from the original data Table 5-18 and Table 5-19 detailing FMEA exercises, Table 8-1 is the resulting specific data.



Summary Diff Pressure Control Process FMEA

Failure Mode	M/C Style	Effect of Failure	Severity	Cause of Failure	Occurrence	Current Controls	Detectable	Product Char	Likely Cause	RPN
Injection MFC Stability	Single & Multi	Compositional, PL Variability, Banding	8	Control System Transients	7	Product Characteristic Feedback	5	Multiple or Broad DXRD, PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	280
Dilution MFC Stability	Single & Multi	Compositional, PL Variability, Banding	5	Control System Transients	3	Composition Analyzer Stability	2	DXRD & Wavelength Trending Away from Expectation	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC	30
Pick Up MFC Stability	Single & Multi	Compositional, PL Variability, Banding	5	Control System Transients	2	Composition Analyzer Stability	2	Broad DXRD or PL Peaks	Low Pressure Differential across MFC, Calibration Problem or blockage in MFC or line	20
Source Press Control Stability	Single & Multi	Compositional, PL Variability, Banding	9	Control System Transients	7	Composition Analyzer Stability only in certain cases	8	Broad DXRD or PL Peaks	Too Low a pressure balancing Flow or Debris affecting Control valve Operation	504
Non-Linear Material Pick Up	Single & Multi	Compositional & PL Variability	6	Materials Handling Design	9	Composition Analyzer Monitoring - Manual	4	DXRD & Wavelength Trending Away from Expectation	Source Running Out, Pressure Control System Performance or blockage in Line	216
Gas Path Streaming	Single & Multi	Unpredictable System Performance	8	Exhaust/Moly Ring Condition	7	Monitoring Exhaust Temperatures - Manual	9	DXRD & Wavelength Trending Away from Expectation	Restricted Moly Ring or Exhaust Port	504
Non Linear Gas Mixing	Single & Multi	Unpredictable System Performance	4	Differing Gas Flow, resulting in variable H2 and source mixing	3	Run Injector MFC's at low flows rather than risking pick up flow change	7	PL, DXRD, Doping non linear with respect to given flow	Pipework design problems	84
By-Pass Valve Switching Perf	Single & Multi	Poor Quality Material Pick Up	8	Slow to operate or leak across valves	2	Electro / Pneumatic operators on Switching valve and large volume air lines	9	Additional peaks in structures or poor interfaces	Low Pneumatic pressure, sticking valve actuator or Debris in valve	144
H2 Pressure Stability	Single & Multi	Growth Rate & Compositional Variability	7	Diffuser or Line Pressure Control	1	Manual Pressure Checks	2	Additional peaks in structures or poor interfaces	Large Uncontrolled Draw on Flow	14

Table 8-1 - Delta P FMEA

All of the included “Causes” are based on one generic system on the process equipment of which many are in use, the double dilution flow control nest, as described in Figure 7-10 and replicated for Figure 8-1.

The term “Delta Pressure Too Low” encompasses all of the above failure mode inclusions.

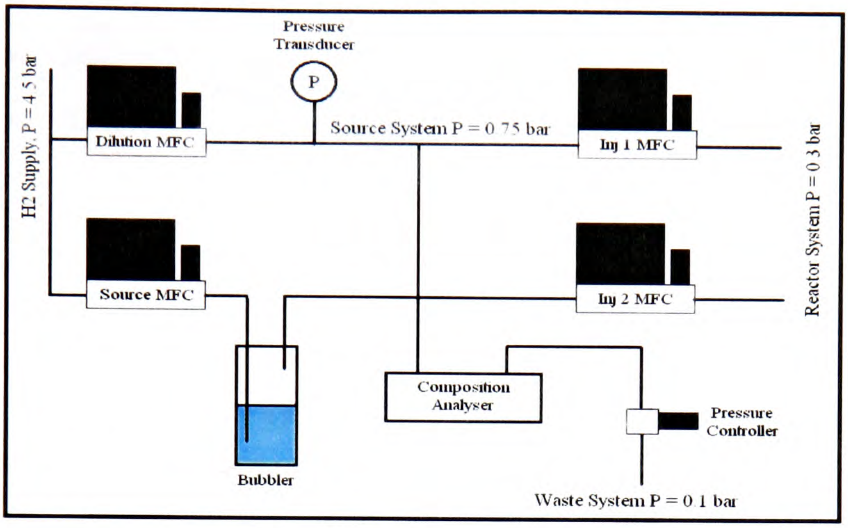


Figure 8-1 - Bubbler System "Nest"

The accuracy of the above system relies upon each component within the system performing at an optimum. Even then it is unlikely for the system to ensure compliance with product specifications.

8.2.2 – Major Weaknesses

There are four major drawbacks with the type of system described in Figure 8-1:

1 – Large Number of Components
2 – That "Mixed Materials" are Spilled
3 – The System Pressure Cascade is CRITICAL
4 – Gas Mixing (Nutrient & Dilution) within Nest

<u>1 – Large Number of Components</u>

The PoS of the system has been identified previously:

Single Source **Probability of** Success = 0.961 for each Injector MFC

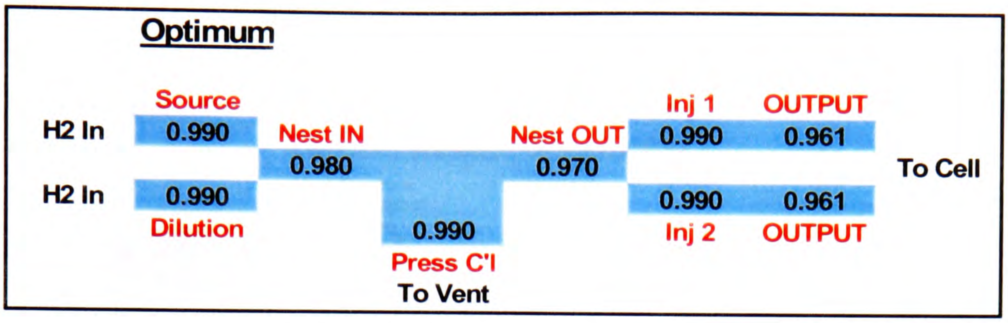


Figure 8-2 - Current Optimum

It is possible with re-design of the system to increase the PoS of the current system, as described in Figure 8-2 and therefore directly impact upon the potential process yield.

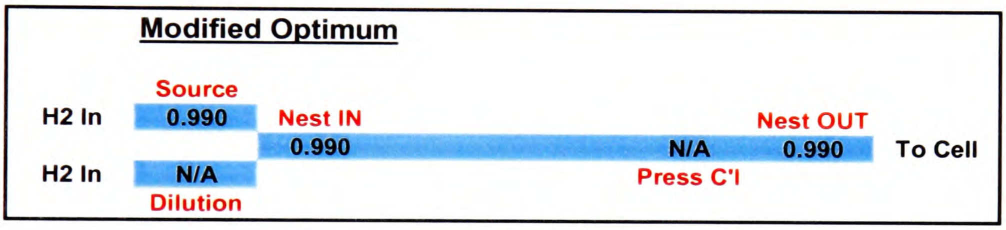


Figure 8-3 - Modified Optimum

The modified optimum design as described in Figure 8-3 reduces dramatically the probability of failure increasing the PoS to 0.99 from 0.961, a calculated increase in PoS of 2.9%, when compared to the system identified in Figure 8-2. The compound improvement effect with up to 3 lines, each using 2 injectors modified in use at any one time has the potential of improving the Compound PoS from:

Equation 14: Standard 3x2 – PoS = $0.961^6 = 0.7876$

Equation 15: Modified 3x2 equiv – PoS = $0.990^3 = 0.97$

A re-design could offer a PoS increase of 0.18; this would have the potential of decreasing the Yield Loss attributed to this cause by:

1-0.7867 = Old% = 100% = 0.2133

1-0.97=New% = 0.03

Improvement in Failure Rate equates to 1-(0.03/0.2133) = 86%

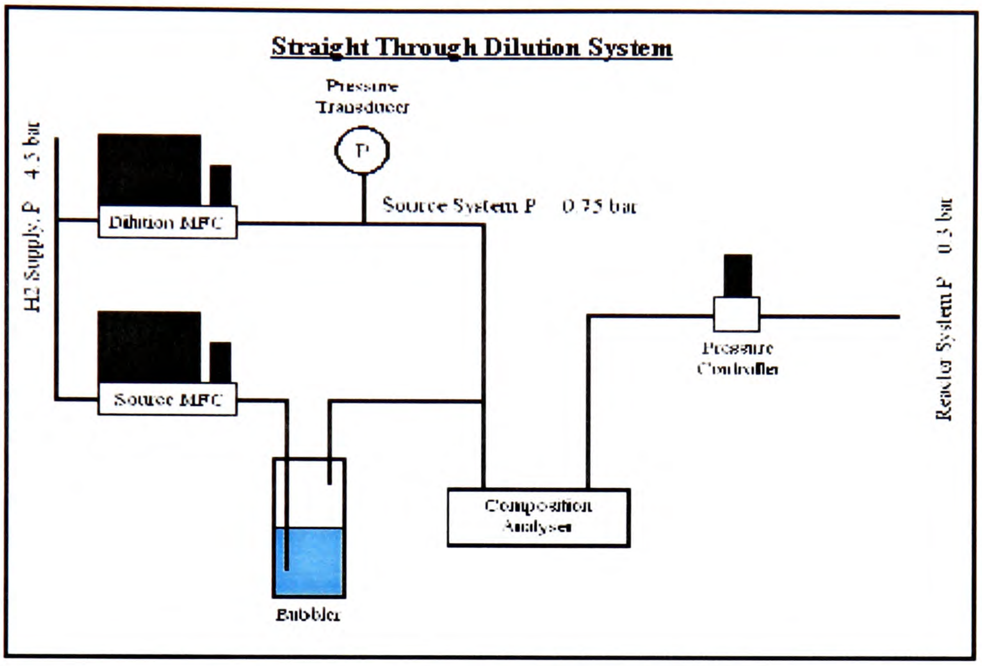


Figure 8-4 - Modified Bubbler System "Nest 2"

One machine has been modified as detailed in Figure 8-4; this is the physical interpretation of the system defined in Figure 8-3. Trials are currently in progress some preliminary data exists, and this will be discussed later in this chapter. The mass flow of nutrient in this system is only impacted by the source MFC. The Volumetric and Pick Up impact is still affected by the Pressure Controller however.

2 – That "Mixed Materials" are Spilled

This problem has been eradicated by the system re-design. In the new system no material is spilled.

3 – The System Pressure Cascade is CRITICAL

This generic problem still exists within the new system; it is however far less critical providing the pressure control flow range is adequately sized.

For the system trials the operating pressure has been raised from 750 to 1000mba [abs].

4 – Gas Mixing (Nutrient & Dilution) within Nest

For this system the need for gas mixing under variable flow conditions has been eradicated, as a no spill system now exists.

In those applications where the standard double dilution nest must be used a "Zero Pressure Drop" mixing head has been designed and fitted to systems. A description of this mixing head is included in the appendices.

8.3 - Worked Example Feedback

A Specific Reactor has been chosen as the "Proof of Concept" machine. This machine has been chosen because it has close to a single product being run and many "Double Dilution" nests are in use at any one time. The performance data for the machine on this product line for the year 2000 is as follows:

Total Runs:	1200
Total Wafers Delivered:	3294
Total Wafers Used:	5400
Yield excluding Test Pieces less +14%:	75%
Yield loss to PL, XRD:	18%
Lost Wafer – Flow Control/Diff P	972
Average Selling Price	£600
Lost Wafer Sales	£583,200

The preceding section quotes from the POS data that the flow control failure rate can be improved by 86% (failure rate improvement p 8-180). Now assuming that this were achievable and that all of the failures can be attributed to this failure mechanism then the predicted numbers should be:

Yield loss to PL, XRD:	2.52%

Lost Wafer – Flow Control/Diff P	136
Average Selling Price	£600
Lost Wafer Sales	**£81,648**

An improved Sales output for this machine without any utilisation improvement of £501,552.

This is a purely hypothetical number calculated using the previous PoS data. The real data for the machine requires analysing across the modification and any improvement defined and extrapolated for the same period.

8.3.1 - The Data

A data collation exercise for "Average Centre Point Mismatch" (averaged across all wafers within that run) from July to September 2000. During this period 2 lines were modified as discussed in 12.1. The 1st modification took place the end of August 2000 and the 2nd line modified the end of September.

The centre point mismatch is measured in ppm for this exercise; the product has a general compositional specification of range +400 to –600ppm, it however also has a photo luminescence Intensity and uniformity specification. The PL intensity and uniformity have a direct link to the composition, a typical range of +200 to –500 [see upper and lower Control Limits, Figure 8-5] offers the optimum photo luminescence performance. Thus reducing the compositional specification offered and agreed by the customer. The process generally drifts negatively.

The "Centre Point Mean Mismatch" data for the period is as summarised in Figure 8-5 (data sample in Appendix 7 – Data Analysis). The mismatch mean is an average of the seven wafers grown during each run. Each data point on the on the plot is the averaged result for the "Centre Point average" for each run undertaken within the quoted period. The data in this format is very difficult to discern, however there are four distinct stages of development during the period.

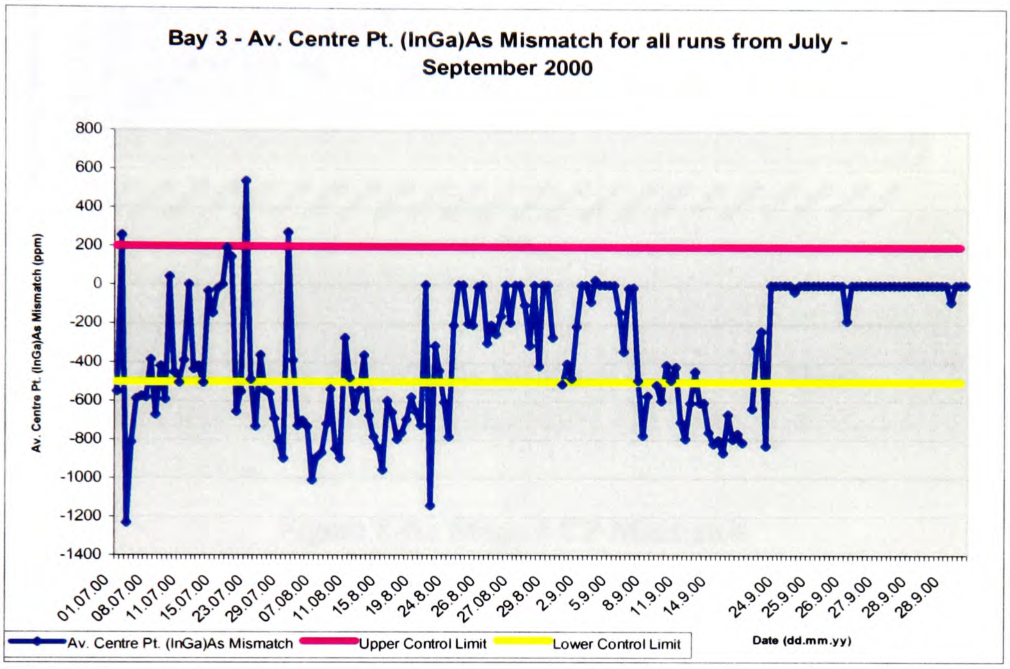


Figure 8-5 - CP Mismatch Chart

- Stage 1 - Pre Modifications
- Stage 2 - 1st Line Modified
- Stage 3 - Adjust 1st Mod & Centre Point Offset
- Stage 4 - 2nd Line Modified

The four stages mentioned are in series within chronological order in the data series of Figure 8-5.

8.3.2 - Staged Data

Figure 8-7 has a single data point missing; the CP mismatch for this run was not discernable.

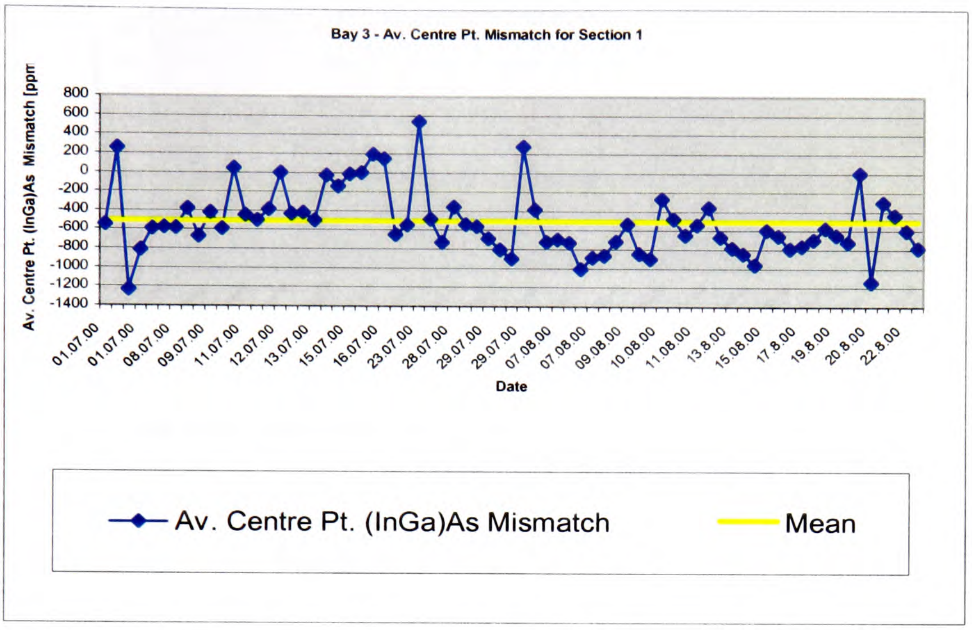


Figure 8-6 - Stage 1 CP Mismatch

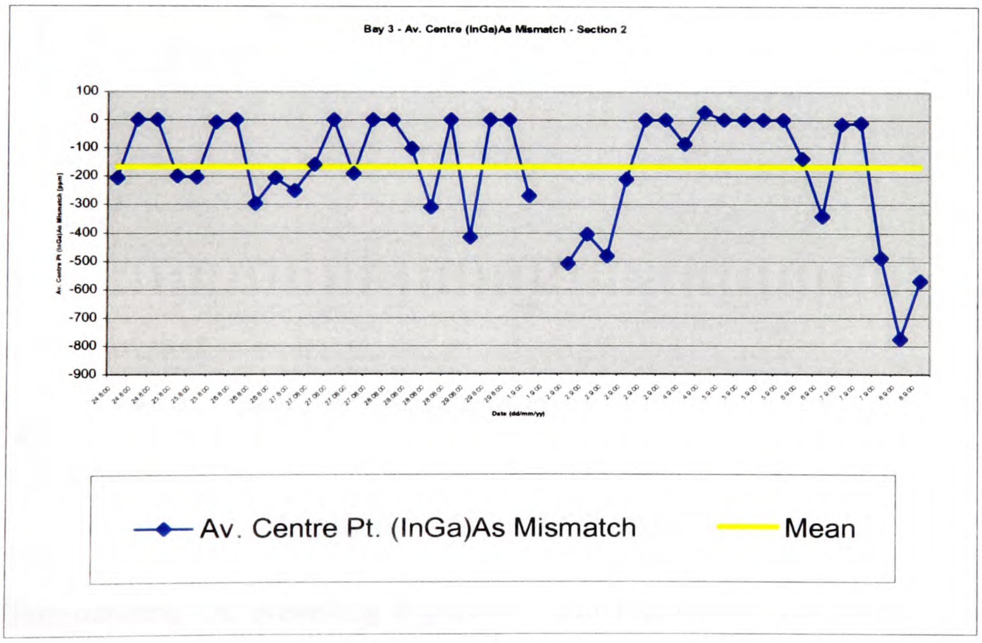


Figure 8-7 - Stage 2 CP Mismatch

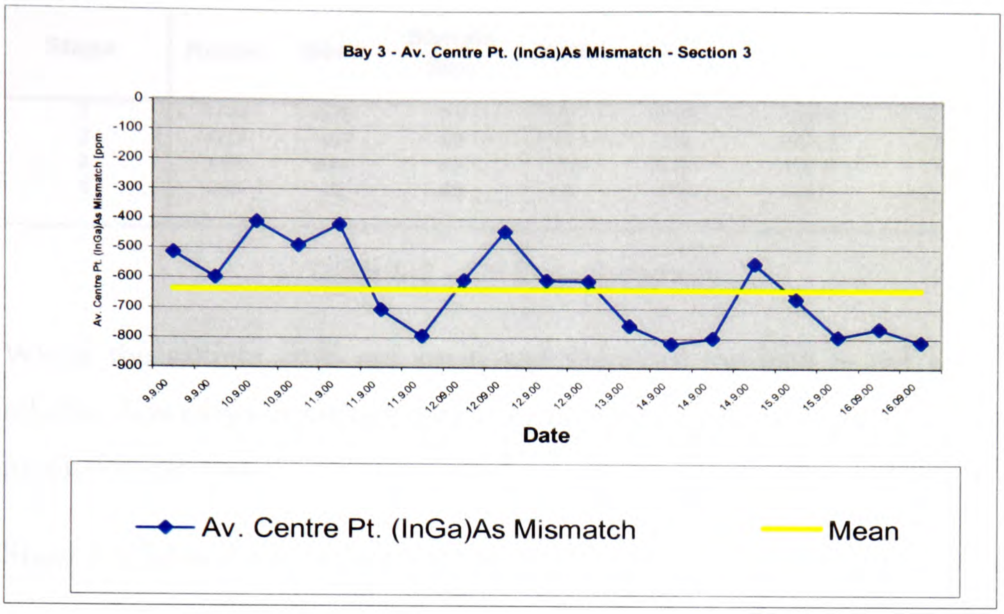


Figure 8-8 - Stage 3 CP Mismatch

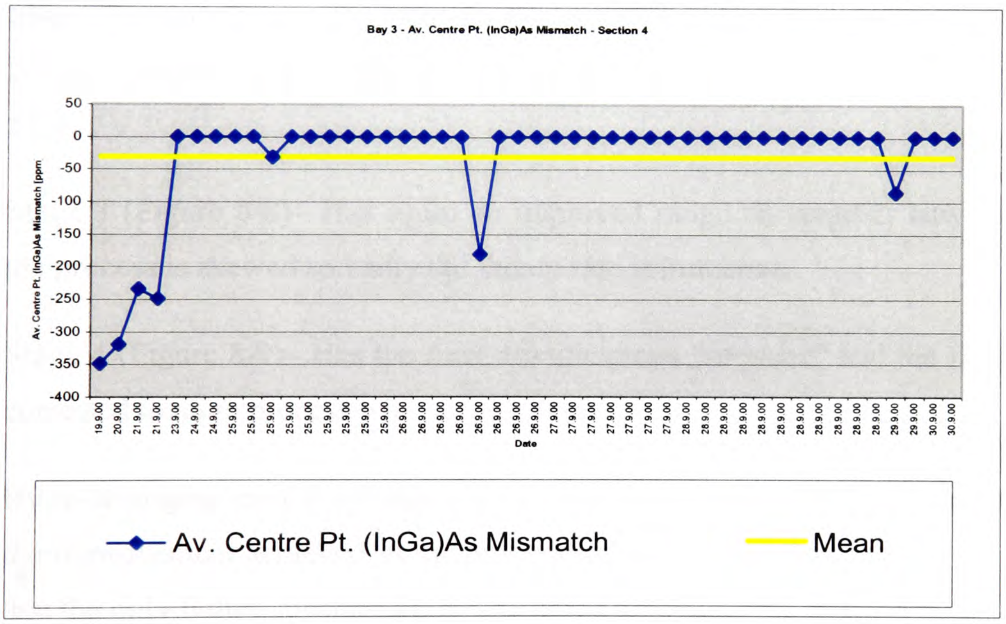


Figure 8-9 - Stage 4 CP Mismatch

Summarising the preceding Figure 8-8 and Figure 8-9, produces a centre point [CP] data summary Table 8-2:

Stage	Range	Mean	Sample Size	Fails	Fail %	Op Limit -ve	Op Limit +ve
1	1770	-518	71	31	44%	-1403	367
2	803	-167	42	1	2%	-568.5	234.5
3	457	641	19	12	63%	412.5	869.5
4	350	-32	46	0	0%	-207	143

Table 8-2 - CP Data Summary

Whilst the sample sizes are small and therefore the data is not wholly reliable, however a summary conclusion can be derived and a performance prediction derived.

Stage 1 (Figure 8-6)– Is an out of control process, skewed too far negative relative to specification. This skew is manually controlled by the flow set point of one of the constituent elements.

Stage 2 (Figure 8-7)– The changes made to the system have had a major positive impact to the control of the mismatch; the range is reduced by 55%.

Stage 3 (Figure 8-8)– Has again an improved range on stage 2, however the process is skewed so badly the failure rate is immense.

Stage 4 (Figure 8-9)– Has the final modifications "in place" and the flows corrected to align process with specification.

By re-arranging the CP mismatch data (Table 8-2) it is possible to identify the improvement achieved in the process assuming (detailed in Table 8-3) that the only failure mechanism on the failed product is the mismatch.

Performance Analysis per Process

		Above Spec 400+	Above Opt 200 to 400	In Opt -500 to 200	Below Opt -500 to -600	Below Spec
Population		**1**	**2**	**108**	**19**	**47**
Stage 1	**Proc 1**	**1.43%**	**1.43%**	**31.43%**	**21.43%**	**44.29%**
Stage 2		0.00%	4.65%	88.37%	4.65%	2.33%
Stage 3		0.00%	0.00%	21.05%	10.53%	68.42%
Stage 4	**Proc 2**	**0.00%**	**0.00%**	**95.65%**	**0.00%**	**4.35%**

Table 8-3 - Stage Performance Analysis

The listed process 1 has a failure rate of 45.7%; the predicted failure rate improvement was 86%. Process 2 (Stage 4) has a failure rate of 4.35%; this results in an improved process probability of success.

The achieved failure rate Improvement is – 76%

This is 10 % less than the optimum prediction; it will however result in a potential, by re-working the 2000 numbers previously detailed on page 8-180:

Improved Sales output for this machine without any
utilisation improvement of £443,232.

8.4 – Chapter Summary

This chapter contributes an evaluation on the highest priority failure mechanism as determined in Chapter 6. An FMEA is derived for the delta pressure mechanism. There are several very high-ranking RPN outputs from the FMEA exercise; the re-design has impact upon all of these failure modes.

The system is modified in three stages from the original configuration, each of which alters the response of the system. From statistical prediction the estimated impact upon the selected failure mode is a proposed rate reduction of 86%, in practice however this is proved to return a reduction of 76%. The modification in this instance has a single machine potential of

£443k increase in sales output. This result is a dramatic improvement upon the previous situation.

The subsequent chapter concludes on the output of the project and offers an insight into the actual impact that the project has had on the company longer term.

Chapter 9 - Conclusion & Future Developments

9.1 - Introduction

The previous Chapter considers a singular improvement on one of the process machines. This Chapter reviews the contribution of the content of the project, concludes on the progress and comments on the linking work within the company, and the potential transportation of the novel techniques.

9.2 - Conclusion

The generic objective of this thesis is to offer a controlled process improvement plan for the process of MOVPE, based upon the operations within IQEE. Chapter 2 discusses the potential of controlled "Total Quality" cultures and identifies a set of common singular assumption expectations are that the process influences may not necessarily be in control however there is a reasonable understanding of these influences, enabling controlled analysis and experimental development to take place.

With a dynamic and flexible process model and many influences not identified it is essential that the produced material is 100% inspected to ensure compliance. This typically equates to many more standard industries and their situation during the 1950's (Feigenbaum, 1983), where this was more the norm. If the product range were reduced to a single product per machine or like machine types thus enabling the rationalisation of the machine configuration specifically for each product. Therefore reducing the need for flexibility resulting in a potentially less complex system to control (discussed in Chapter 3).

The techniques used and developed within the ongoing project have enabled sensitivity analysis of the "Business Metrics" and typically long-term improvement techniques to be "short circuited" for a dynamic situation with a large number of influences.

The metrics do not identify the causes for 100% process evaluation, however by maintaining this evaluation what the customer receives does not change, what is achieved is maintaining the identical service to the customer at a much cheaper cost to IQEE. Thus allowing either a reduction in operating charges, an increase in gross margin or the potential to re-utilise the now excess capacity.

These metrics have been supported by additional information from hardware, utilisation and operator logs MTBF, MTTR, DrFMEA and sectional FMEA exercises. The assimilation of this data is concluded using a standard deviation operator on the data, and identifies the machine variability or product weakness, as a volatility measure. The double function of this "Volatility Number" and the failure scale offers a very simple method of evaluating whether the failure mechanisms are platform, product and/or generic growth philosophy related, this has and is used as a preliminary sort for evaluating potential improvement path potentials.

The overall company process is simply defined identifying the influence and impact of each activity, The system "Signal/Noise" definitions in conjunction with a composite function of P-diagram and flow diagram is successful, in deriving a set of ranked failure causes utilising an original numerical analysis technique with the potential for weighting impact of each activity. Thus contributing an early stage a sort on the impact for the process flow evaluation.

Following the subsequent derivation through the DoFMEA a singular improvement path has been identified. One of the MOVPE systems is modified in three stages from its original configuration, each of which alters the response of the system. From statistical prediction the estimated impact upon the selected failure mode is a proposed rate reduction of 86%, in practice however this is proved to return a reduction of 76%. The modification in this instance has a single machine potential of £443k increase in sales output. This result is a dramatic improvement upon the previous situation.

The practical evaluation of the process offers a much-enhanced understanding of the link between product effects and process/equipment failure mechanisms offering the potential to "design out" such effects. With the resulting knowledge from this project and all of the current parallel activities, the understanding of the process is such that the foundation for a more typical culture may be developed within the organisation. The culture that appears most suitable and is most common within the "Electronics" industry is "Six Sigma". The general implementation within an organisation should be controlled and could follow the implementation guidelines for "six sigma" as summarised by Bendell (2000).

9.3 - Contributions

The project objective as detailed in the opening summary of the project is detailed as follows:

- ☐ To determine and evaluate the key variables in controlling the MOVPE process equipment
- ☐ To evaluate available analysis techniques
- ☐ To develop novel analysis techniques to identify and offer solutions to the process failure mechanisms

- Implement effective solutions to improve process capability and stability
- To derive a “Full Process Map”
- To evaluate proposed process changes

The defined objectives have been satisfied, where a greater understanding now exists on the limitations of the process and how it must be manipulated to improve the “Probability of Success”. Many techniques have been evaluated and some original interpretations derived to contribute to the evaluation of the differing components of a complex process system, deriving qualitative outputs for the process improvement programme.

These original techniques [contributions] are listed as follows in the order of use:

9.3.1 - BRA – Business Risk Analysis

This novel technique is used as the primary sort routine for identifying the “Business Strengths and Weaknesses” of each manufacturing unit in the analysis in Chapter 5, utilising data readily available via the company’s profit and loss reporting structure. This data is re-worked to offer a business risk analysis, and deriving a set of priorities from within the process failure mechanisms. The overall original scope of this work involves the use of standard deviation as a means of defining process volatility, manufacturing blockage analysis and simple rule setting and masking of insignificant [to this exercise] variables. Utilising additional information from hardware, utilisation and operator logs MTBF, MTTR and sectional FMEA exercises have been completed.

The contribution of this analysis is to offer a very accurate, simplistic prioritisation tool to identify the major failure mechanisms or process weaknesses, readily for further derivation. The general justification for this technique is discussed in Chapter 2 and the contribution discussed in Chapter 5. This generic technique may be used in any multi business unit or platform operation, ranking risks; the key operators with the identified risks are the SD operators. If the SD is high the process used is volatile, normally suggesting that somewhere the activity is completed better than others, if low the activity is generically performing the same. The key issue here is if all platforms etc. were performing the same what impact would this have on the overall losses. This technique is now in use in other Companies within the IQE group, not utilising the same process as IQEE.

9.3.2 - DrFMEA - Double reporting FMEA

This novel technique is used in conjunction with the output data from the business risk analysis, in Chapter 5, resulting in a failure impact matrix that enables an FMEA interpretation; typical FMEA however is designed for simple single process evaluation. A novel derivation of the FMEA technique has been developed allowing multi-platform comparison against generic causes and effects [DrFMEA]. The contribution from this DrFMEA technique allows differing processes potentially running on like plant failure modes, causes and effects to be simultaneously plotted with individual RPN outcomes.

The contribution of this novel DrFMEA is to identify the hierarchy of causes using a modified RPN, URPN [Unit Risk priority number] in a complex system. The output from this analysis offers specific rather than factory wide justification for further cause and effect evaluation. The general justification for this technique is discussed in Chapter 2 and the contribution discussed in Chapter 5.

The key with this technique is that an overall improvement hierarchy may be determined; this process may be carried out in any multi Unit/Platform operation.

9.3.3 - Global - "P" Diagram & SNC definitions

This novel technique is used to define the overall company process flow. It is typical in such circumstances to use a standard process flow diagram, however the intrinsic weakness with this technique is that the "Influence or Impact" [Signal, Noise and Control] on each output is not defined, at the outset, and requires additional derivation. The analysis in Chapter 6 uses an original composite function of P-diagram and process flow diagram and is successful in deriving a set of "Ranked Failure Causes" utilising an original numerical analysis technique with the potential for weighting impact of SNC on each series or parallel activity, thus contributing at an early stage a sort on the impact for the process flow evaluation. The definitions for the control factors are unique to this project.

The contribution of this technique is to identify and rank the activities in the process flow. The general justification for this technique is discussed in Chapter 2 and the contribution discussed in Chapter 5. A typical process flow evaluation requires full derivation of all steps and activities; this technique offers a quick identification/evaluation method of the overall process identifying the activity that has the greatest impact or variability of the overall output.

9.3.4 - Process Problem & Solving Definitions

An interpretation derived in Chapter 7 to enable the scope of process problem solving to be concise. This links the overall scope of the project to the used and derived techniques.

> The activity, of deriving a corrective action programme of work or study, to define the problem boundary conditions, cause and/or solution.

The resulting output from the project satisfies the statement. This original interpretation contributes a mission statement for the activity of process problem solving.

9.3.5 - PIPS - Process Improvement Problem Solving plan

An original six-stage action plan that reflects the precise activity plan that supports a controlled technique utilising FMEA as a reasoning mechanism. This general technique utilises an additional original interpretation of an FMEA Technique DoFMEA. The Six Stages are defined thus:

1 - Acknowledge
2 - Characterise Effects
3 - Tabulate Causes
4 - Investigate Cause & Effect
5 - Offer Solutions
6 - Necessary Response

This technique contributes a controlled evaluation of the cause and effect relationship with offered solution options for a complex process system. The general justification for this technique is discussed in Chapter 2 and the contribution discussed in Chapter 6. Using the FMEA operator as a reasoning mechanism reduces the “personal interpretation” or expert intervention.

9.3.6 - DoFMEA - Double operating FMEA

This novel technique is used as a prioritisation tool as part of the PIPS activities in Chapter 7. The derived technique operates on a typical FMEA reasoning mechanism and derives further original modifications to the FMEA technique contributing a simple two dimensional analysis of a complex multiple cause/cause analysis, namely double operating FMEA [DoFMEA].

The result of this DoFMEA analysis is a prioritised list of process causes or failure mechanisms. Additional derivation of the process primary failure mode offers options on improving the process. This failure mechanism, theoretically by statistical projection, offers a process improvement hierarchy plan.

This technique contributes a potential sorting technique for multiple cause, multiple effect systems where the standard FMEA technique is difficult to enact for a complex process system. The general justification for this technique is discussed in Chapter 2 and the contribution discussed in Chapter 6.

The generic techniques that have been used and / or manipulated as operators, reasoning mechanisms or analysis techniques, have proved invaluable and extremely flexible. These techniques with further derivation could be used for any other process improvement programme, offering a key advantage where the reverse working of FMEA [Effect⇨Cause⇨F.Mode - HistoFMEA], may result in many interrelated or influencing operators.

9.4 – Implementation Results

The starting point for the Company as described in Chapter 5 was: *during 1997, approximately 2500 wafers were scrapped due to one or more failure mechanism [approx 50% of all wafers grown], excluding fit for purpose tests, assuming that each of these wafers has a potential Sales value of approximately £1600 [ASP-1997]. Had the company been in a* *position to sell this additional capacity it could have generated additional sales of approximately £4m.*

These results "set the scene" and identify the need to improve the overall process performance. The quoted results are following some years of "Chaotic" process improvement projects; in 1995 for example the overall wafer yield was 38%. An essential conclusion from the discussions in Chapter 2 is that the improvement programme must be controlled. This enables a progressive action plan to be derived.

Table 2-1 details the financial losses incurred across all of the recognised failure mechanisms.

Sitewide Financial Losses 1997

Fail Category	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	Lost Wafers
Total Runs	584	1254	529	473	430	1638	
Hardware	£25,296	£59,024	£51,646	£62,186	£91,698	£32,674	£322,524
Morphology	£127,534	£123,318	£22,134	£124,372	£82,212	£316,200	£795,770
Doping	£55,862	£43,214	£46,376	£23,188	£11,594	£44,268	£224,502
PL & XRD	£5,270	£338,334	£14,756	£41,106	£48,484	£160,208	£608,158
Errors	£7,378	£21,080	£10,540	£5,270	£36,890	£42,160	£123,318
Sources	£0	£5,270	£11,594	£8,432	£7,378	£3,162	£35,836
Thickness	£152,830	£9,486	£0	£18,972	£0	£3,162	£184,450
Lost Wafers	£374,170	£599,726	£157,046	£283,526	£278,256	£601,834	£2,294,558

Table 9-1 - Table 2:1 Copy - Losses

Since 1997 the ASP for varying products, and the product types have changed as a function of "market forces". To fully evaluate "in context", the financial contribution [worth] of this single cycle of improvement the benefit can be imposed upon the 1997 incurred losses as detailed in Table 9-1. Two resulting evaluations are produced, initially detailing the improvement on the machine that the improvement evaluation was completed on (Table 9-2), and secondly carrying those modifications through to all of the original six machines assuming the same performance contribution is achievable (Table 9-3).

Projected Sitewide Financial Losses

Summary 97	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	Lost Wafers
Total Runs	584	1254	529	473	430	1638	
Hardware	£25,296	£59,024	£51,646	£62,186	£91,698	£32,674	£322,524
Morphology	£127,534	£123,318	£22,134	£124,372	£82,212	£316,200	£795,770
Doping	£55,862	£43,214	£46,376	£23,188	£11,594	£44,268	£224,502
Flow Control	£5,270	£338,334	£3,541	£41,106	£48,484	£160,208	£596,943
Errors	£7,378	£21,080	£10,540	£5,270	£36,890	£42,160	£123,318
Sources	£0	£5,270	£11,594	£8,432	£7,378	£3,162	£35,836
Thickness	£152,830	£9,486	£0	£18,972	£0	£3,162	£184,450
Lost Wafers	£374,170	£599,726	£145,831	£283,526	£278,256	£601,834	£2,283,343
Single M/c Projection	£0	£0	£11,215	£0	£0	£0	£11,215

Table 9-2 - Projected Losses, Single M/c

Projected Sitewide Financial Losses - 2

Summary 97	Bay 1	Bay 2	Bay 3	Bay 4	Bay 5	Bay 6	Lost Wafers
Total Runs	564	1,254	529	473	430	1,638	
Hardware	£25,296	£59,024	£51,646	£62,186	£91,698	£32,674	£322,524
Morphology	£127,534	£123,318	£22,134	£124,372	£82,212	£316,200	£795,770
Doping	£55,862	£43,214	£46,376	£23,188	£11,594	£44,268	£224,502
Flow Control	£1,265	£1,265	£3,541	£9,865	£11,636	£38,450	£66,023
Errors	£7,378	£21,080	£10,540	£5,270	£36,890	£42,160	£123,318
Sources	£0	£5,270	£11,594	£8,432	£7,378	£3,162	£35,836
Thickness	£152,830	£9,486	£0	£18,972	£0	£3,162	£184,450
Lost Wafers	£370,749	£263,911	£146,360	£252,758	£241,838	£481,714	£1,757,331
Single M/c Projection	£3,421	£335,815	£11,215	£30,768	£36,418	£120,120	£537,756

Table 9-3 - Projected Losses - Site wide

Table 9-2 indicates a projected loss re-contribution for the 1997 cost analysis for the machine modified [bay 3], resulting in a reduction in manufacturing charge of £11k. If the same percentage improvement were achievable across all other platforms following the same modification then using again the 1997 data the estimated saving could equate to £538k. The company now operates 16 machines [IQEE] most of which today have either been specified with this system or have been modified to accommodate the proposed changes.

Although the outcome or direct deliverable for this project is a singular process improvement offering a single payback [sales potential £443k - 2000], the key intrinsic deliverables are:

1. That the Business Risk Analysis has prioritised the Product Failure Mechanisms (see Chapter 5, Table 5-11).

2. That the DrFMEA has offered a map identifying machine exposure to critical failure mechanisms (see Chapter 5, Table 5-21).
3. That the DoFMEA has offered a summary and prioritised improvement plan for the identified Product Failure Mechanism, in the form of Cause Prioritisation (see Chapter 7, Table 7-6).
4. That a solution utilising FMEA has a positive contribution to the Process Improvement programme.
5. That the Improvement process undertaken is transportable to other forms of Business Management Strategy.
6. Reduction in per unit financial cost to manufacture.
7. Reduction in process variability related to "Flow Control"
8. A sound understanding of the process enabling further organisational progression and development for more classical cultural Quality development. [e.g. Six Sigma]

Listed items 1 to 4 are tools that enable short-term analysis in a business where the need for process change is required. These offer the potential to long-term plan, the improvement process. A secondary offering from the included work herein is the generic contribution for use of the developed techniques in other process industries whether like or not. With little to no adaptation only interpretation to specific processes the techniques could be used as a generic process improvement tool.

A series of process causes and effects have been identified, and prioritised, the highest identified priority has undergone a design review and identified the key weakness. This weakness has been addressed and offers a business improvement in the overall performance of the process and a considerable reduction in the run-to-run process variation.

The influences in certain areas having a large impact have now been identified, the developments and resulting knowledge allow the prior blockage of process understanding to be removed and allow progression in an established culture more typical to the Semi Conductor industry, enabling a structured process development.

9.5 - Developments

In practice many physical improvements to the process have been initiated and implemented as a product of the work undertaken within this project. The potential benefits from the exercises are many-fold and will continue within and beyond the extent of this project.

This project in it's initial stages spawned a double associate Teaching Company scheme in collaboration with UWCN, to develop an "Expert" and "Data Mining" system for the use of problem solving from a practical day to day viewpoint. Thus consolidating "problem solving" as a skill as discussed by Simon and Associates (1986), with AI [artificial intelligence] for this application, Michael (1999) and Richards (2000). Thus replacing the demand upon the system experts, and with the eventual application of "Neural Networks" enhances the expert capability.

A functional department [Technology Group] is now in operation within IQEE with an operating brief including:

9.5.1 - "On Line" SPC

Each of the Reactor systems have data logging systems that log up to 200 control systems per second, in runs lasting up to eight hours, data is collected across 16 reactors. The Group concerned have now centralised this data logging information and are able to offer SD, Mean, Range for all of the control systems, across all of the machines for any layer. This satisfies the need to fully understand variables such as "Flow Control Issues" as defined within this project. The system has a capability of E-mailing the process engineering function any of the key functions exceeding specification limits. This SPC project has now been progressing for 2 years. Although the produced product in the event of a delinquent variable will be out of specification, the cause is already identified. In-situ systems are being considered at present to "On Line" adjustment for such variable compensation.

9.5.2 - Expert System

An issue discussed in Chapter 2 is the need for experts to manage the problem solving and process strategy. This relies upon the knowledge, experience and memory of each of the involved experts. The weaknesses with this system are consistency across several people and a 24-hour day, 7 days per week. An expert system however for this process is potentially the only way qualitative process problem solving on a 24hr 7-day basis may be achieved. In 1998 IQEE set an objective of developing an "Intelligent Expert System" specific to the III/V compound semiconductor process of MOVPE. This work was initiated as a part of the evaluation work of this project, and is still in progress.

9.5.3 - Full SOP Operation

IQEE has a full set of operating procedures for practical tasks, loading machines, machine maintenance etc. Defining the philosophy of machine set up, maintenance regularity, process change authority and limits are typically the responsibility of again a process expert. Standard operating procedures are currently being written considering each product line. This should ensure that each time a product batch is run the same preparation is operated.

9.5.4 - Process Equipment Development

Chapter 7 of this project presents a development for the improvement of the process. Whilst carrying out preliminary investigation it was found that nutrient gas mixing was varying as a function of the cumulative flow through a "Double Dilution Nest". A novel mixing head has been designed and installed, the detail of which is available in Appendix 4.

At present all of the constituent flows per layer are controlled as a function of time, temperature, flow and pressure. With in-situ monitoring devices [currently under evaluation] IQEE will be in a position to dial up a composition and thickness. This will negate the issue of flow, time and pressure dependency.

9.5.5 - 3 Stage Problem Solving Escalation

Following the derivation of the process FMEA within this project it has made possible the compilation of "Out of Control Action Plans" [OCAP's] supported by the Expert system with time. This therefore enables the process problem solving to be delegated through the organisation.

Stage 1 – Operator/ Process Engineer – OCAP

Stage 2 – Senior Process Engineer

Stage 3 – Process Expert

9.5.6 - Process Metric and Evaluation Software

Since the identification of the precise implication of each failure mechanism in Chapter 5, it is essential that such variables are identified and communicated through the organisation on a regular basis. "On Line" standards for uptime, downtime MTTR, Wait time etc, are now readily available from a "Group" generated system named Bay Watch.

IQEE has invested immensely over the past few years in a Resource Planning system, within the next 3 months the Company will have wafer yield details as discussed in Chapter 5 on a real time basis.

9.5.7 - "Query" Engine development for Problem Solving

A key issue with any problem solving system whether OCAP or Expert system, they are only as good as the information on problem solving as presented on the day of construction. The Expert system is being built to accept feedback from the Users. As this database of feedback enlarges the system will automatically run a "Data Mining" program that will offer the current most likely cause. This will take into account failure mechanisms changing as systems are modified and product changes.

All of the discussed objectives have been defined and in operation following evaluation and justification of certain "key" Company objectives that have followed derivation and justification within this project.

Any project such as this must have a "formal ending". The project compilation and activity will continue for a considerable timescale following the formal academic submission, as previously mentioned in the preceding sections.

It is key that IQEE is able to practically offer both formalisation and consolidation of it's process and enhancing it's capability to work with companies such as Motorola on key projects (Altium Capital, 2001).

9.5.8 – A "Portable" Evaluation Toolbox

It is essential that all Companies/Operations be evaluated using consistent metrics and improvement indices/tools. The tools developed within this project have proven to be transportable across differing process types and businesses, within the IQE group of Companies, offering a consistent controlled approach and evaluation mechanism.

9.5.9 – Equipment Improvement Programmes

IQE staff and Equipment vendors now work in partnership, operating DFMEA and PFMEA exercises for the improvement of performance, stability, longevity and reliability.

9.5.10 – Staff Development Programmes

Several key IQE staff have been nominated and are currently undergoing external Six-Sigma "Black Belt" development for the Cardiff based IQEE plant. Thus enabling the more global company and process development.

9.6 – Project Summary

This project, whilst limited to a singular analysis of a "Compound Semiconductor" application and resulting in again a singular improvement cycle, has offered and successfully developed a set of multi purpose tools and mapping technique. These have been successful in this application and are currently in use in additional applications that differ to the process discussed within this project,

The generic gains following this activity for IQEE are manyfold, and the contributions have the potential of being transported to other applications and industries.

9.7 – Chapter Summary

This Chapter concludes on the techniques developed, discusses the original contribution contained within the project, describes the direct IQEE benefit and the potential developments that have been generated as a result of the project or linked sub activity.

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Spengler, C.S. (1999) "Equivalence Relations Within the Failure Mode and Effects Analysis", 1999 Proceedings Annual Reliability and Maintainability Symposium, 352-357

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Appendices

Appendix 1 – Related & Participative Papers

Michael, C., Rowlands, H., Stanton, M., Meadows, C. and Williams, H. (1999) "Expert Systems in Semiconductor Manufacturing", 2nd Workshop on European Scientific and Industrial Collaboration, (WESIC99), Newport UK, 301-308

Michael, C., Rowlands, H., Stanton, M., Meadows, C. and Williams, H. (2001) "A model based system for a semiconductor company", 19th IASTED (International Association for Science Technological Development), (AI2001), Innsbruck, Austria, 171-176

Griffiths, E., Williams, H. and Pearce, A. (2001) "Networking Systems to Facilitate Statistical Process Optimisation in a Foundry Operation", 1st CS-Max Conference, Boston, USA July 9th to 11th, 2001

Richards, C., Williams, H., Meadows, C., Rowlands, H. and Stanton, M. (2001) " Data Modelling & Acquisition in Compound Semiconductor Manufacturing", 3rd Workshop on European Scientific and Industrial Collaboration, (WESIC 2001), Enschede, The Netherlands, 227-235

Williams, H and Rowlands H. (1999) "Back to Basics – The Improvement Process", 2nd Workshop on European Scientific and Industrial Collaboration, (WESIC99), Newport UK, 197-204

Appendix 2 – Material Measurement

A2.1 – Material Structure

Material Composition and Crystallinity (Quality) are measured using a technique called High Resolution X-Ray Diffraction. Using the growth technique of MOVPE it is possible to achieve near perfect crystals, made up of a mixture of elements from Groups III and V of the periodic table.

A crystal may be grown containing a mixture of binary compounds GaAs and InAs, and subsequently produces a ternary compound InGaAs. Identifying the binary compounds GaAs and InAs on a lattice constant diagram (See Figure A-0-1), it is apparent that these two compounds have differing lattice constants. By adjusting the proportions of In and Ga in the ternary compound, any lattice constant in the intermediate range may be achieved.

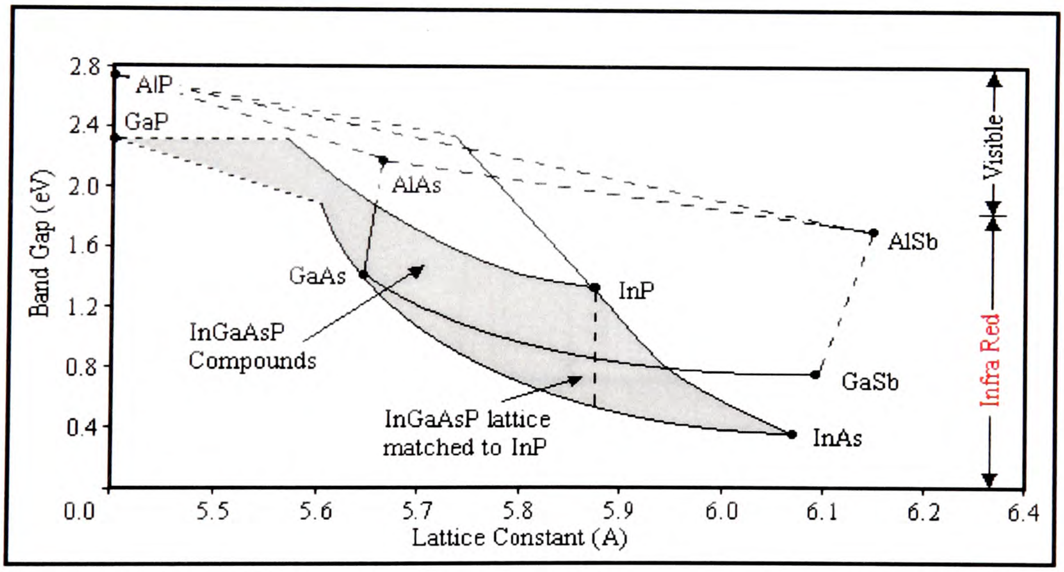


Figure A-0-1 - Compound Lattice Constant Diagram

When measuring a compound on a DXRD machine the lattice constant of the two independent compounds and their differing Bragg diffractions are measured. These measurements are relative to the substrate constant, giving an X-ray diffraction rocking curve. If the lattices constant are matched then the materials composition is considered “perfect”.

An additional critical material property that is gained from a diffraction measurement is the direct purity of the material or crystallinity, to a depth of up to 5 microns. An X-ray peak of a material is a direct function of the amount of material grown and its position in the structure. A narrow peak is indicative of a very pure compound, and conversely the broader the peak the poorer the crystallinity. The area underneath the X-ray rocking curve is directly proportional to the amount of material grown. The crystallinity of a material is measured by a criterion “**F**ull **W**idth **H**alf **M**aximum”, and is measured in arc-seconds. (Figure A-0-2).

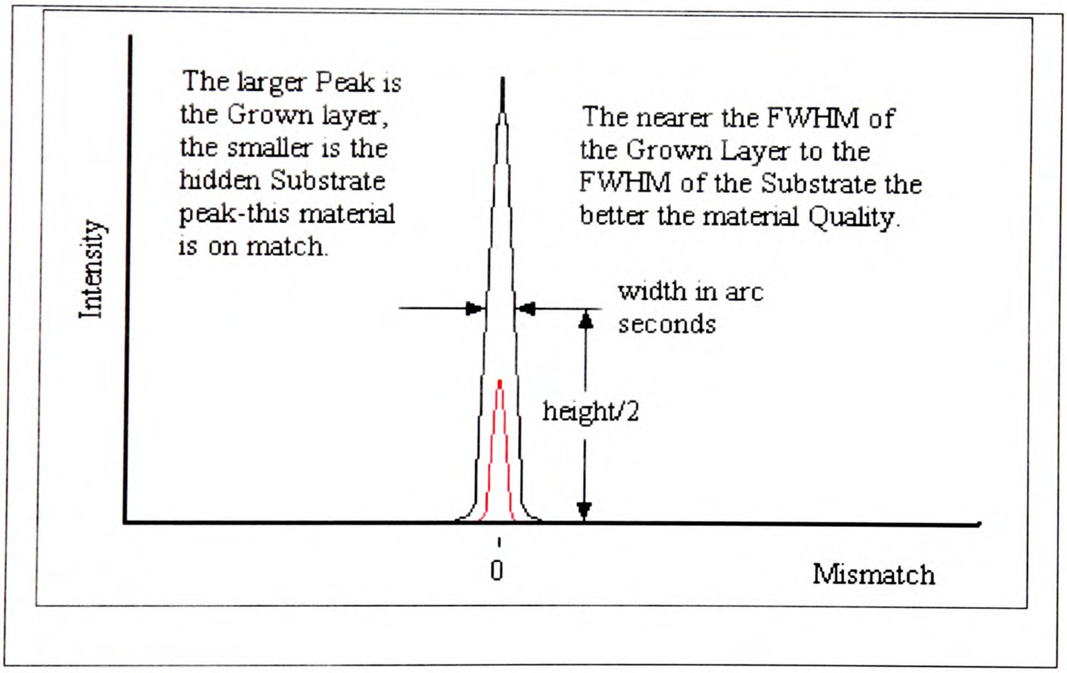


Figure A-0-2 - DXRD Rocking Curve "On Match"

X-Ray Diffraction - the Technique

The vast majority of all structures consist of more than one layer, in a perfect world the inter-atomic spacing of all atoms in all of the layers should all be the same. However, in practise differing materials have different atomic spacing at different temperatures (differential expansion).

The spacing between the atoms is measured using a stream of X-rays whose wavelength is approximately of the same order as the atomic spacing. As the waves hit the various atomic layers, they are diffracted. Figure A-0-3 shows this diagrammatically.

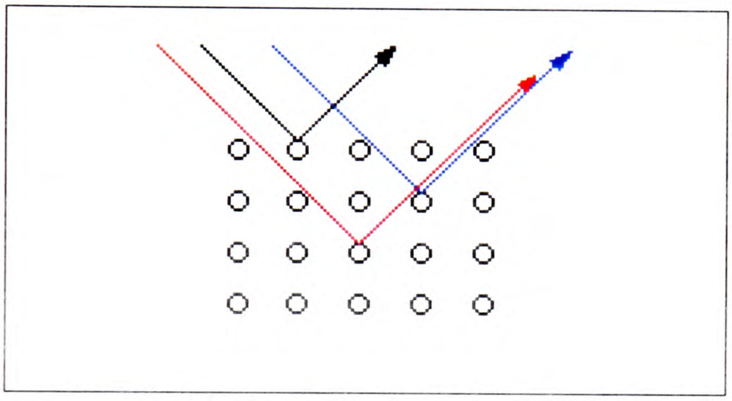


Figure A-0-3 - X-Ray Diffraction

If the X-ray diffraction's emit from equally spaced atoms within a structure, they will tend to be "in phase" with each other. If the spacing is random however, the resulting wave will be small. An additional effect will be the distance between the layers of atoms relative to the X-ray wave. A perfect match can be achieved between wavelength and distance by rocking the sample. The resultant plot is called a Rocking Curve.

A typical rocking curve for a ternary material, InGaAs grown on an InP buffer, InP Substrate with an InP cap (structure Figure A-0-4), where the two peaks are split by 200 ppm, the practical lattice mismatch of the grown materials.

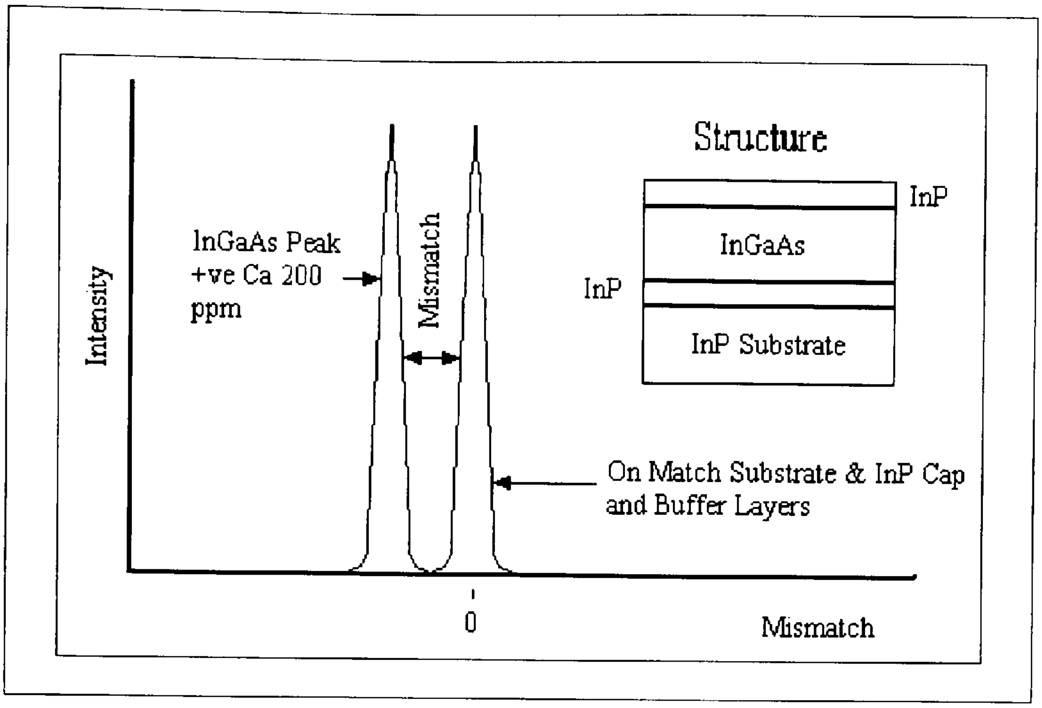


Figure A-0-4 - Typical InGaAs "Rocking Curve"

A2.2 – Photoluminescence Measurement

If a specified structure has a composition such that a specified wavelength of light will be emitted, it is essential that the emitted wavelength be identified. When the material is excited, the electrons are forced to jump to a higher energy level. When these electrons relax to their normal state light energy is emitted. The wavelength of this emitted light is directly related to the band gap of the material. The wavelength is therefore a direct function of the material composition. In bulk material, it is possible to use light energy to excite the electrons.

Quantum theory states, as long as the incoming light is of the same or a greater energy (shorter wavelength), then this energy can be transferred to the electrons in the material. Laser light has the property of being coherent, that is, all the light is concentrated over a very narrow range of wavelengths (see Figure A-0-5). Thus, using a laser as a light source, (with a shorter wavelength than that expected of the material being measured), it is possible to ensure that the incoming light is not confused with the emitted light.

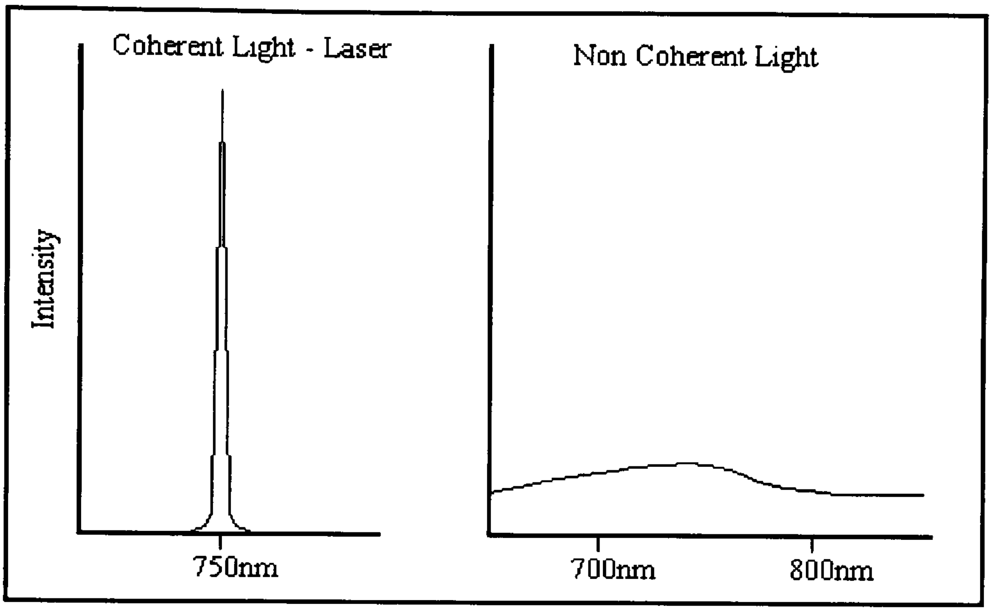


Figure A-0-5 - Coherent Light Diagram

The Photo Luminescence (PL) technique is a non destructive measurement, unfortunately with some structures that incorporate multi emitting layers, it is the nearest to the laser source that absorbs most, sometimes all of the energy making it difficult to measure the wavelength. In these circumstances, the material-emitting wavelength still requires checking. A technique that can be used is that of growing a test piece within the same run, selectively etching off the upper emitting layers and then re-testing.

The visible spectrum of light is usually defined by its wavelength ranging from the smallest visible wavelength for violet - 400 nm to 750 nm for red. The test results can provide a variety of information about the overall purity of the semiconductor.

A2.3 – Thickness Measurement

The achieved thickness and subsequent uniformity of any given layer is critical to the final device performance. Achieving a quality thickness measurement for a specific, group of layers or full structure is of paramount importance as in some circumstances the emitted wavelength of material is directly proportional to the active layer thickness.

Two methods of direct thickness measurement are in practice at present, Alphastep and Ball Lapping, both destructive techniques.

It is convenient that many structures consist of a number of layers of differing materials and compositions, and that some acids etch materials preferentially.

Alphastep

The Alphastep measuring system relies upon, as its name suggests measuring a step. Selective etching the grown material produces this step or shoulder.

Using selective etches; individual layer thickness' can in turn be exposed relative to the previous and next layer, potentially producing a "stair" effect. This can be achieved by placing a chemically inert substance (wax) on part of the surface of a test piece of wafer, acting as an "etch barrier". An example of selective etching, for a layer of InP, Hydrochloric acid is used as the etching material.

Following applications of both wax masking and etch application a step or column of materials results (Figure A-0-6). The wax can then be removed and the measurement takes place. This technique passes a stylus over the surface and the displacement measured.

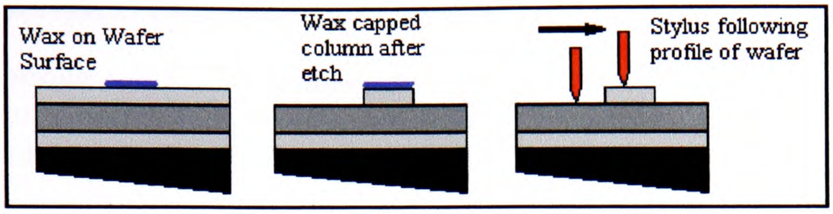


Figure A-0-6 - Alphastep Measurement Technique

This technique is "more" accurate than the second, but can only be used when "selective etching" is possible.

Ball Lapping

Again, with this technique the name describes the basis of the technique. A Ball Bearing of precise dimensions is placed on the surface of the test piece on a thin bed of diamond cutting paste, and then rotated in a controlled manner. The mass of the Ball then grinds a pit into the surface of the test piece (Figure A-0-7). A chemical stain is then placed on the machined surface highlighting the layer interfaces. Layer thickness is then derived by calculation, the size of the ball, depth of the pit and subsequently analysing the differing diameters of the machined material under the microscope.

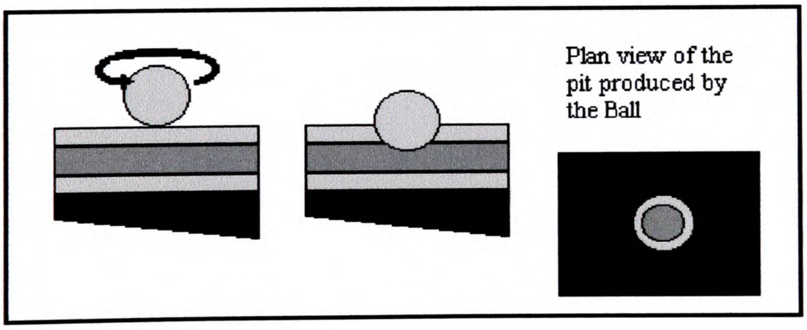


Figure A-0-7 - Ball Lapping Technique

Measurement Capability

Technique	**Tolerance**	**Min Measurement**
Alphastep	+/- 2.5 %	0.10 **μm**
Ball Lap	+/- 10 %	0.25 **μm**

A2.4 – Doping Measurement

Impurity atoms will contribute to both the electrical and optical characteristics of the material. The impact on the product will depend on certain critical parameters, the most important of these being the type, either p or n type. The material compound will always have a background (or *Intrinsic*) impurity level. The additional (mostly deliberate) impurities will either add to or subtract from the existing impurities to produce an overall Carrier Concentration.

The carrier concentration or Doping Level is measured using equipment known as a P.O.P.'s (Post Office Profilers). The technique exposes the test samples to an electrochemical etch, recording certain electrical characteristics as the material profile changes. As the material is etched, the doping level is recorded. (Figure A-0-8)

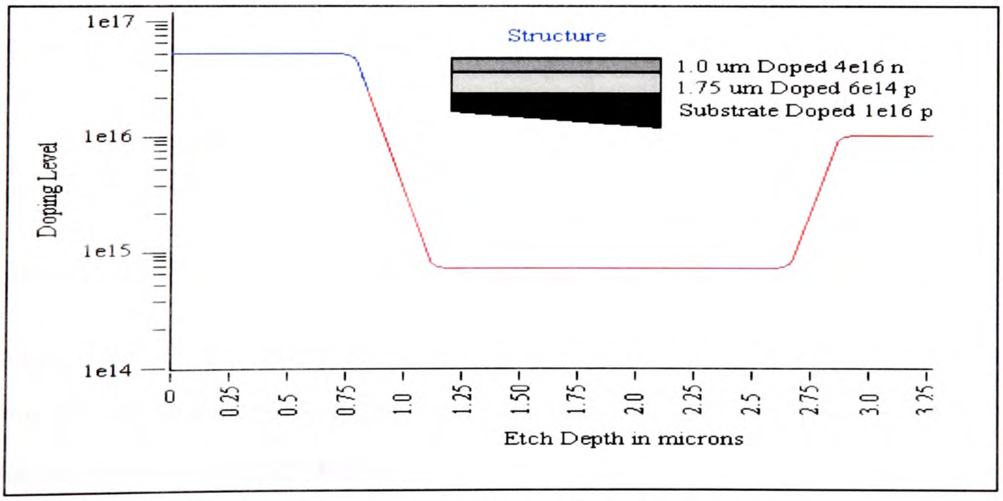


Figure A-0-8 - POP Etch Profile

All electronic components, diodes, detectors etc. will have an electrical performance and response. The same equipment is used for proof of diode performance (a P-N junction). In theory, a typical “forward bias” diode should pass a current when the voltage across it is positive and pass no current when the voltage is reversed. In practice however, it is possible to manufacture diodic material that may have the required “threshold current” (cracking pressure in mechanical devices) but may breakdown or leak earlier than expected. These performance criterions can be evaluated by plotting the I-V (current-voltage) characteristics of the material

A2.5 – Morphology Assessment

A practical interpretation of the word morphology, as used in the semiconductor industry today, would be the study of the form and structure of the surface of grown material.

A single discreet form of morphology assessment encompassing all morphological variables is currently not available, as many criterion, can and do influence the final morphological quality. This is not a generic form of characterisation to III/V semiconductors; it is common throughout the semiconductor industry. Probably the largest single failure mechanism throughout the industry for example:

Up to 75% of all VLSI microelectronics manufacturing, yield loss, is directly attributable to structural defects.

Average of 30% of all failed Wafers are Morphology failures at IQEE.

Note: one of the most common causes of particulate contamination is human intervention. A person can generate up to 100,000 skin particles larger than 0.3 μm per minute.

Generic "Causes" of morphological failures are grouped into two categories, Background and Defect failures. The "Background" is the descriptor offered to the surface texture and finish of the grown material, whereas the Defect descriptor concerning any particulate or crystallographic disruption of the surface. A typical comparative example would be "Stone Chips" and "Orange Peel" on motorcar paintwork. Some classic causes are listed below for the two categories of failure.

Background Failure Causes

Substrate Quality
Substrate Axis (Orientation)
Substrate Doping
Materials and Composition
Structure Thickness

Defect Failure Causes

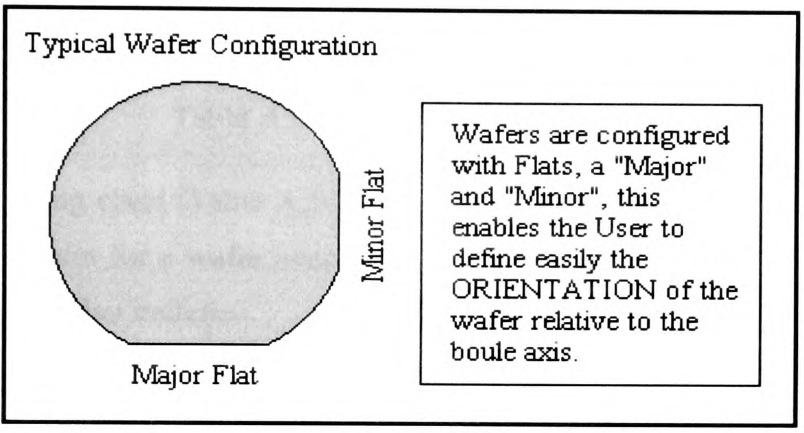
Grown In Defects
Surface Debris
Grown In Debris
Crystalline Defects

Table A:0-1 - Morphological Failure Causes

All of the features as listed in Table A:0-1 will affect the Final Device performance, IQEE's Process Yield and Customer Device Yield.

All of the product manufactured by IQEE will subject to a two-dimensional "Defect Density" specification, the units, a count of the number of defects/cm^2. The specification does not include the entire surface area of a wafer, there is an exclusion zone specified on all wafer sizes. This exclusion zone is normally 5mm off the wafer radius, and is generally accepted as the handling area and the "Flat" wastage (Figure A-0-9).

All of the products manufactured by IQE will subject to a two-dimensional "Defect Density" specification, the units, a count of the number of defects / cm^2. The specification does not include the entire surface area of a wafer, there is an exclusion zone specified on all wafer sizes. This exclusion zone is normally 5mm off the outer wafer radius, and is generally accepted as the handling area and the "Flat" wastage (Figure A-0-9)



Wafers are configured with Flats, a "Major" and "Minor", this enables the User to define easily the ORIENTATION of the wafer relative to the boule axis.

Figure A-0-9 - Substrate Configuration

The issued defect density specification is a direct function of the device design and use, for a PIN diode the defect density specification would be < $10/cm^2$, for a VCSEL the specification would be typically < $50/cm^2$. The measurement technique used for direct evaluation of the defect density is the Surfscan, a laser reflectivity counting technique. The Surfscan technology enables particles/defects to be counted and measured in diameter, $10/cm^2$ may appear a large number, but the size range of particles being measured is 2μm to 25μm and larger, these are categorised into bin sizes as shown in the following chart (Table A:0-2).

Bin No.	Bin Range
1	2 to 4.3
2	4.3 to 6.6
3	6.6 to 8.9
4	8.9 to 11.2
5	11.2 to 13.5
6	13.5 to 15.8
7	15.8 to 18.1
8	18.1 to 20.4
9	20.4 to 22.7
10	22.7 to 25.0
11	25.0 & up

Table A:0-2 - Particle Bin Range

The following chart (Table A:0-3) is an example of the data gained from a Surfscan plot for a wafer near to the particle limit of 10/cm^2; details of bin sizes are also included.

Bin No.	Bin Range	Particles / Bin
1	2 to 4.3	28
2	4.3 to 6.6	31
3	6.6 to 8.9	17
4	8.9 to 11.2	6
5	11.2 to 13.5	4
6	13.5 to 15.8	3
7	15.8 to 18.1	1
8	18.1 to 20.4	1
9	20.4 to 22.7	2
10	22.7 to 25.0	2
11	25.0 & up	20
	Total / Wafer	115
Spec	Total / cm2	9.275
	Mean	10.304
	Std Deviation	80.68%

Table A:0-3 - Surfscan Print Data

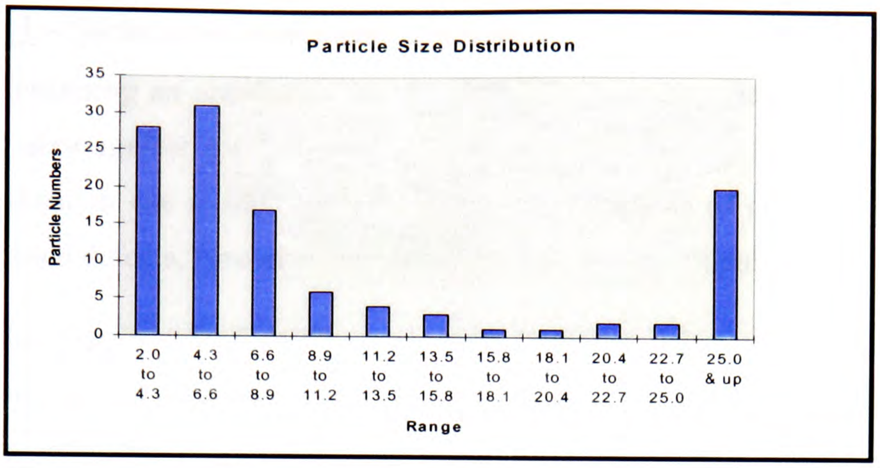
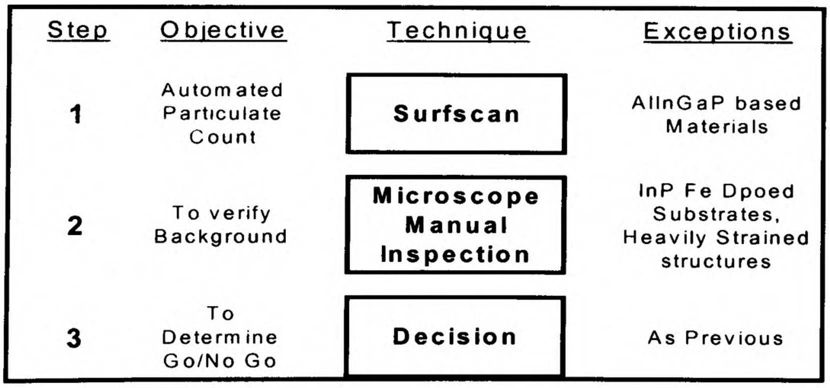


Figure A-0-10 - Particle Distribution Chart

Concluding from the distribution chart (Figure A-0-10), the majority of defects are < 9μm, these may be of zero consequence to the final component, the 25μm plus defects however, will cause "write off" of components in device manufacture.

The Surfscan is currently the first GO/NOGO stage in the assessment of morphology, there are in total three steps (Figure A-0-11) to a qualitative morphology assessment carried out on all potential deliverable wafers, these are:



Step	Objective	Technique	Exceptions
1	Automated Particulate Count	**Surfscan**	AlInGaP based Materials
2	To verify Background	**Microscope Manual Inspection**	InP Fe Dpoed Substrates, Heavily Strained structures
3	To Determine Go/No Go	**Decision**	As Previous

Figure A-0-11 - Activity Schedule

Step 1 - Surfscan measurement, a measurement taken with the objective of determining an absolute value for the defect density within the usable wafer area against a series of specified particle basket or bin sizes. The equipment in use is the "Surfscan"; these are capable of detecting most crystalline defects, "grown in" debris and "grown in" particulates.

The Surfscan is a Surface Contamination Detector, using a high intensity light source and measuring reflection and scatter. One significant weakness of this technique is its inability to differentiate between "Grown In" and "On Surface" features. To gain therefore a precise defect density the wafer must be cleaned before being processed. A general rule may be used, if the wafer fails the defect density specification it is "blown" using a N_2 jet.

Particle Generation

Typical sources of "Grown In" defects are residual Grp III oxide particles, emanating from the gas handling system onto the wafer surface at Growth commencement or structural Interfaces. The entire process system downstream of the Susceptor (Graphite, heated area) is lined with "Cracked" Grp III & V materials in particulate form (typically 0.5 to 3μm), Any *Pressure Transients* during pressure ramps or layer switching may cause the transportation of such particles, potentially deposited on the growing wafer surface. These particulates do not recombine within the process.

Larger particles > 25μm are normally deposited onto the wafer surface by deposition from the Cell Quartz lining dropping onto the wafer surface.

Any measurable amount of oxygen in the gas system prior to the Growth Chamber in any process utilising PH_3 (Phosphine) as the GrpV component, with potentially be affected by a very small particle "grown in" throughout the structure. The O_2 will react with the PH_3 causing smoke to be produced

(PH_3 is pyroforic), the smoke particles once again can be introduced onto the wafer surface via the nutrient gas stream.

It is unlikely that any particle falling onto the surface of the wafer during growth will recombine into the material lattice and will therefore cause a feature. The size of the original particle and the depth in the structure of the particle will both determine the apparent (to Surfscan) feature size. (Figure A-0-12) The principle again may be likened to that of car body paintwork, a particle on the surface acts similar to the effect of moisture or grease on a car body prior to spraying.

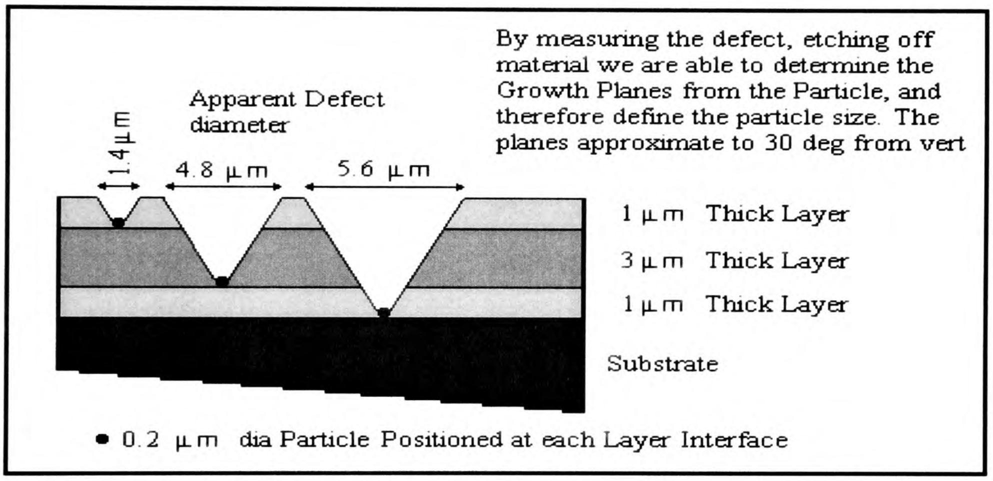

By measuring the defect, etching off material we are able to determine the Growth Planes from the Particle, and therefore define the particle size. The planes approximate to 30 deg from vert

Figure A-0-12 - Feature Development

Step 2 - Microscope Manual Inspection, is the visual examination of the quality of the morphological background. The background morphology for most of the product ranges should be featureless with usually only a slight texture noticed under high Normaski contrast. Again it is only the deliverable area of the wafer must be examined for quality, the exclusion zone however should be analysed as a nick in the edge of the wafer could become a stress concentration area, causing the wafer to cleave/shatter when packaged

Some structures requiring the use of certain specific doping types in the substrate (e.g. Fe) will always produce a coarse, textured surface.

Structure thickness is a crucial variable in the expected surface quality, as a rule the thicker the structure is then the more textured and decorated the morphology is likely to become, perhaps for a similar reason to the previous section. For thin structures such as Lasers, HEMTs the morphology is normally, excellent.

Step 3 - Decision, the wafer is inspected for handling marks, all of the accumulated data is compiled and the wafer declared GO/NOGO, if NOGO, is the morphology a typical failure or a catastrophe?

Appendix 3 – Machine Detail

Two differing classifications of machine are used. These differing types are classified as:

Single Wafer Machines – Longitudinal Cell
Multi-Wafer Machines – Circular Radial Cell

Although both types generically are MOVPE Process machines the Cells are fundamentally different and purposes differ.

The Single Wafer Machines are typically used for:

Small Batch Work

Complex Structures

Research and Development

(See Figure A-0-13)

The Multi-Wafer Machines are typically used for:

Large Volume Repeat Structures

(See Figure A-0-17)

A3.1 - Single/Dual Wafer Machines

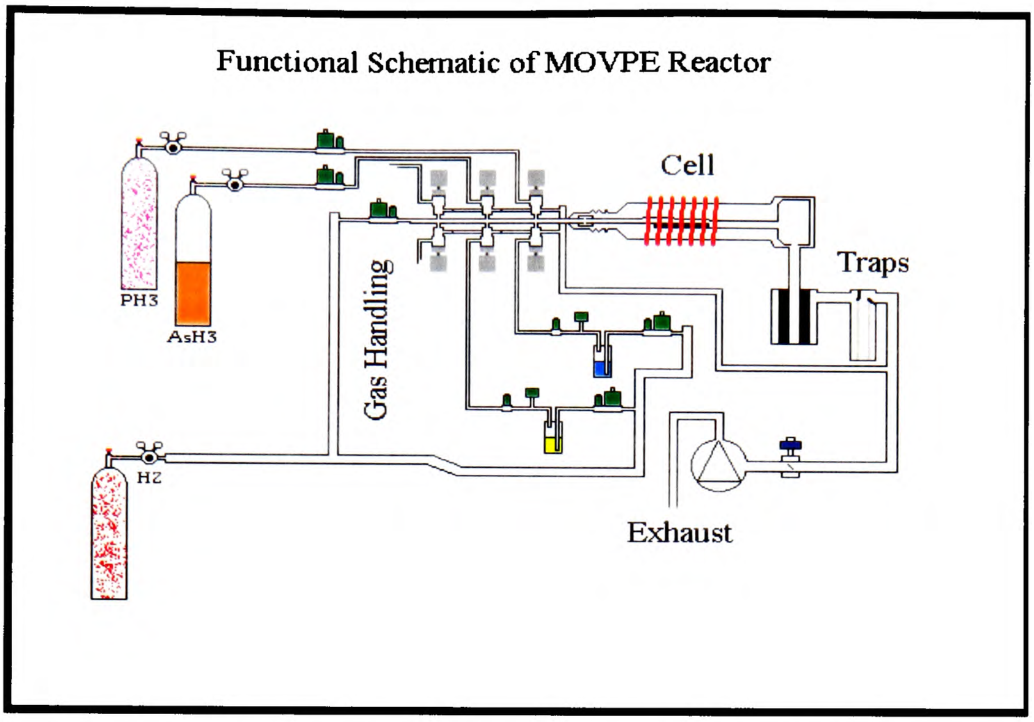
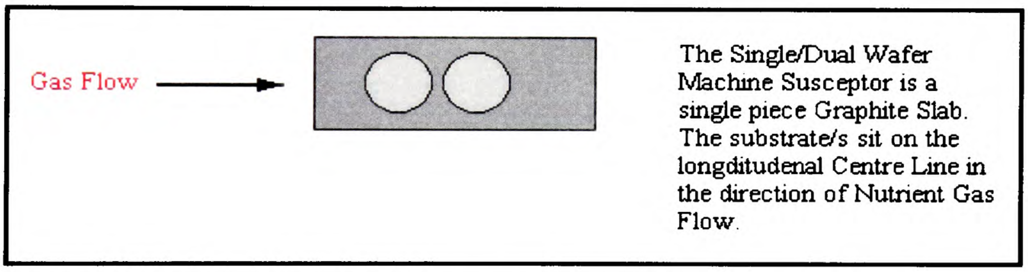


Figure A-0-13 - Basic Process Schematic - Single Wafer



The Single/Dual Wafer Machine Susceptor is a single piece Graphite Slab. The substrate/s sit on the longditudenal Centre Line in the direction of Nutrient Gas Flow.

Figure A-0-14 - Schematic Single Wafer Subs/Susceptor Layout

Substrates of a suitable material are placed on a graphite block (Figure A-0-15) both components are then inserted into the quartz liner tube (Figure A-0-16) of a reactor Liner tube. This liner tube is then inserted into the quartz outer tube so that the susceptor aligns centrally into the heated zone [RF Induction Coil] and moving gas front. The process is typically "run" at pressures of 950, 200 or 100 mbar absolute.

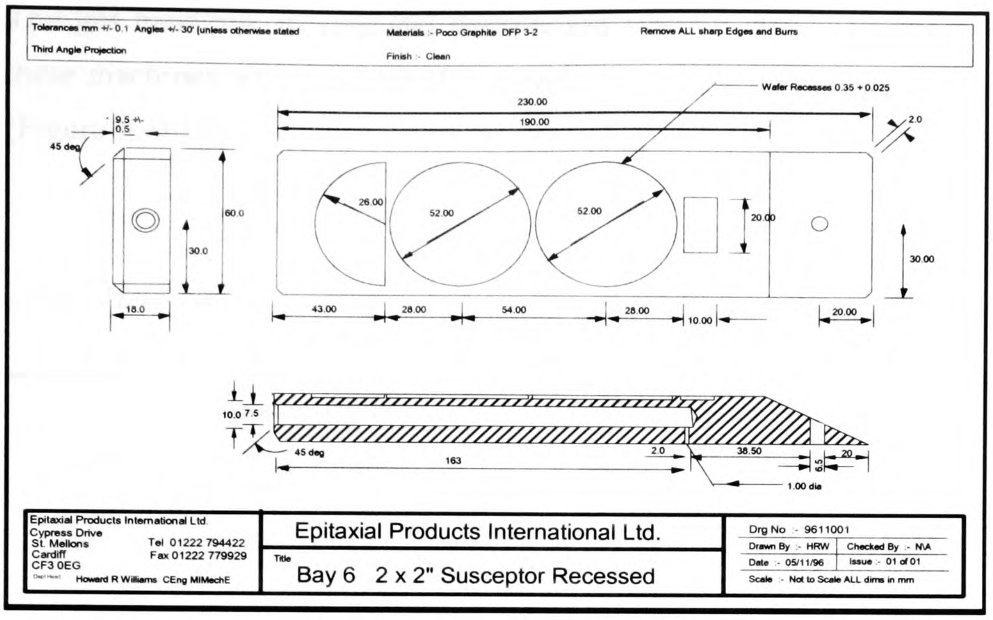


Figure A-0-15 - Single Wafer Susceptor, Specification

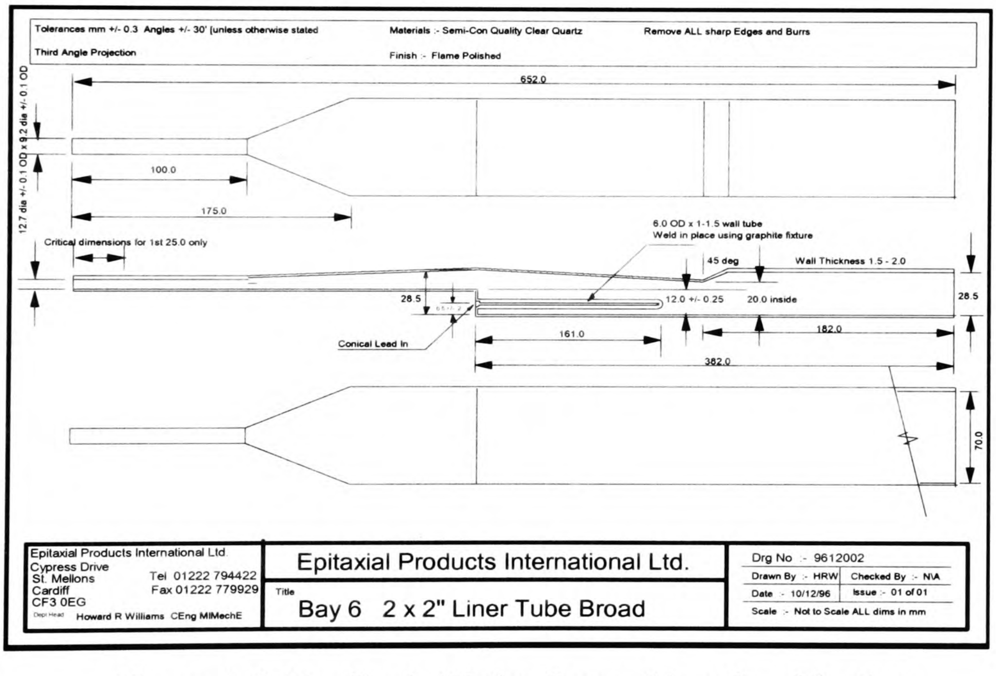


Figure A-0-16 - Single Wafer: Quartz Liner Specification

The gas handling, mixing and distribution systems are very similar for these machines when compared to systems on the Multi-Wafer machines (Figure A-0-17).

A3.2 - Multi - Wafer Machines

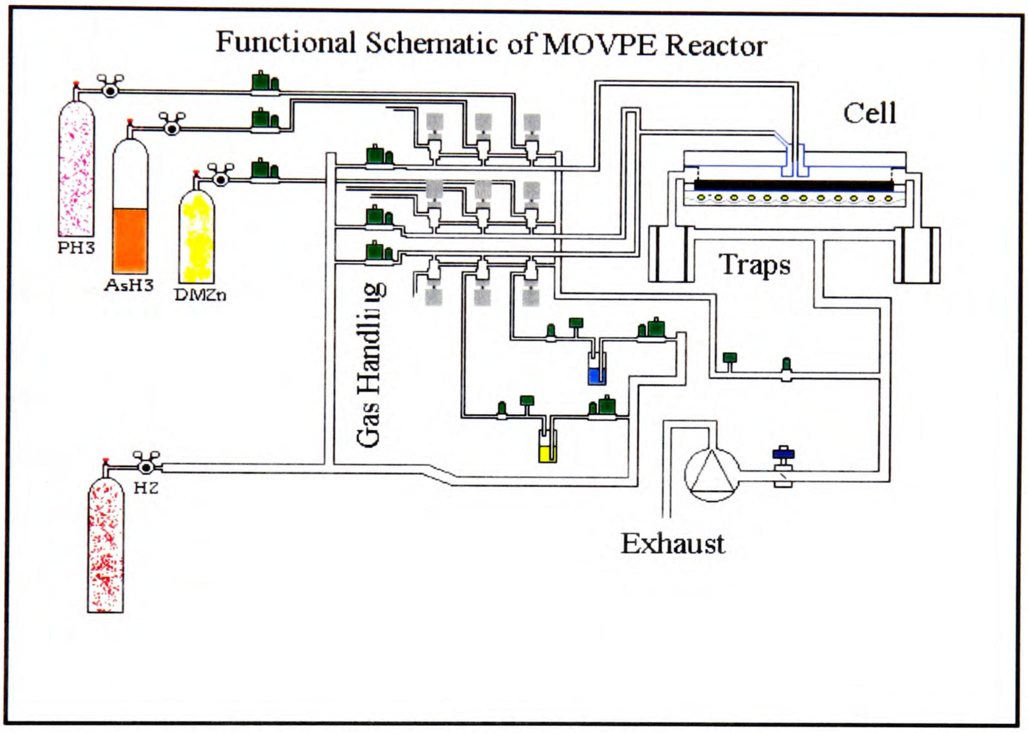
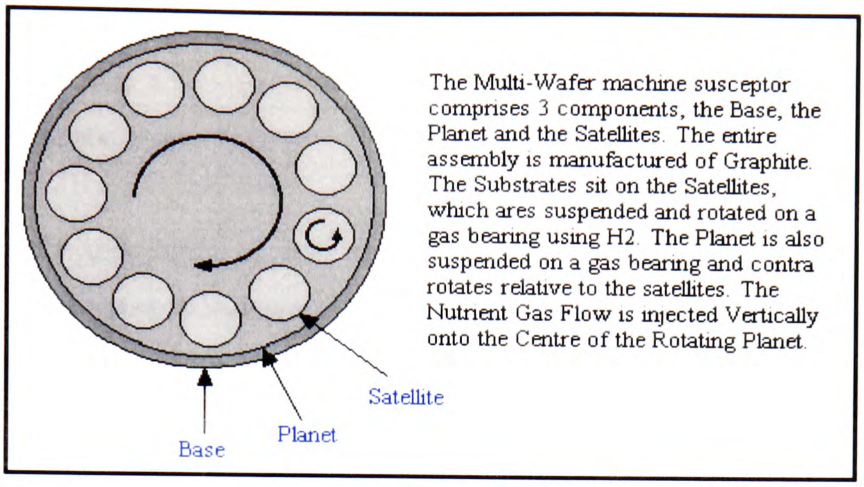


Figure A-0-17 - Basic Process Schematic: Multi Wafer



The Multi-Wafer machine susceptor comprises 3 components, the Base, the Planet and the Satellites. The entire assembly is manufactured of Graphite. The Substrates sit on the Satellites, which ares suspended and rotated on a gas bearing using H2. The Planet is also suspended on a gas bearing and contra rotates relative to the satellites. The Nutrient Gas Flow is injected Vertically onto the Centre of the Rotating Planet.

Figure A-0-18 - Schematic Multi Wafer Subs/Susceptor Layout

Substrates of a suitable material (either InP or GaAs) and size (2”, 3”, 4” or 6”) are placed onto the satellite, a graphite component of the susceptor in the reaction chamber (Figure A-0-18). The base of the susceptor is heated using Infra Red lamps or RF Coils, the satellites are heated via thermal conduction / induction via the planet from the base. The multi wafer process is typically “run”, at either 100 or 200 mbar absolute.

Appendix 4 - Process Practical Improvements

A4.1 - Dilution System Stability

Previously discussed, is the PoS of a double dilution system (Figure A-0-19), this was calculated to be 0.961 for a perfectly run and maintained system.

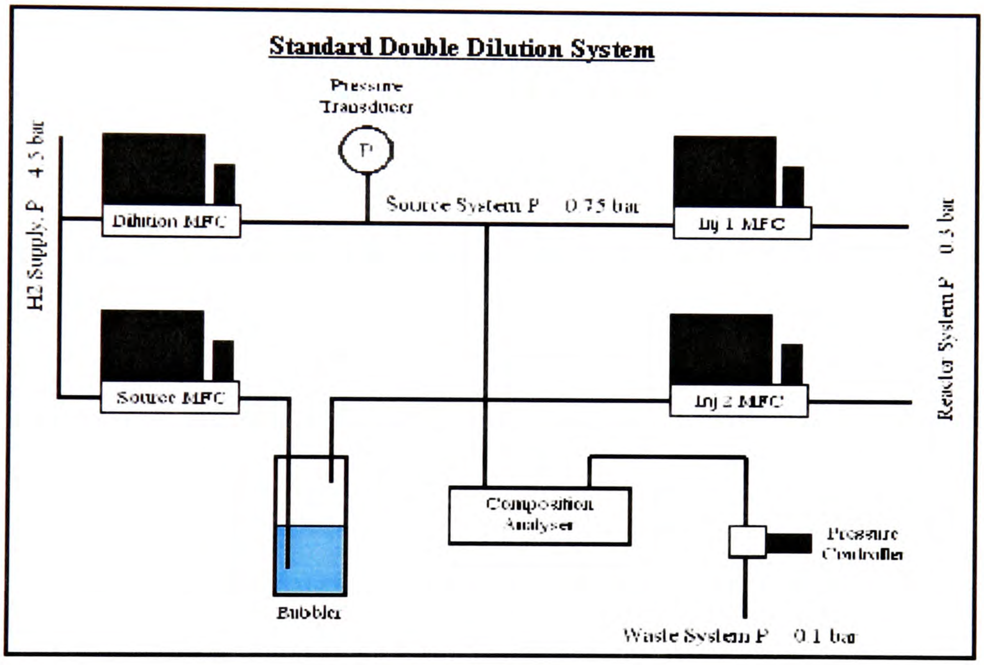


Figure A-0-19 - Bubbler Nest Arrangement

With minor design modifications the system can be re-designed for a more stable/repeatable process, moving the PoS to 0.98.

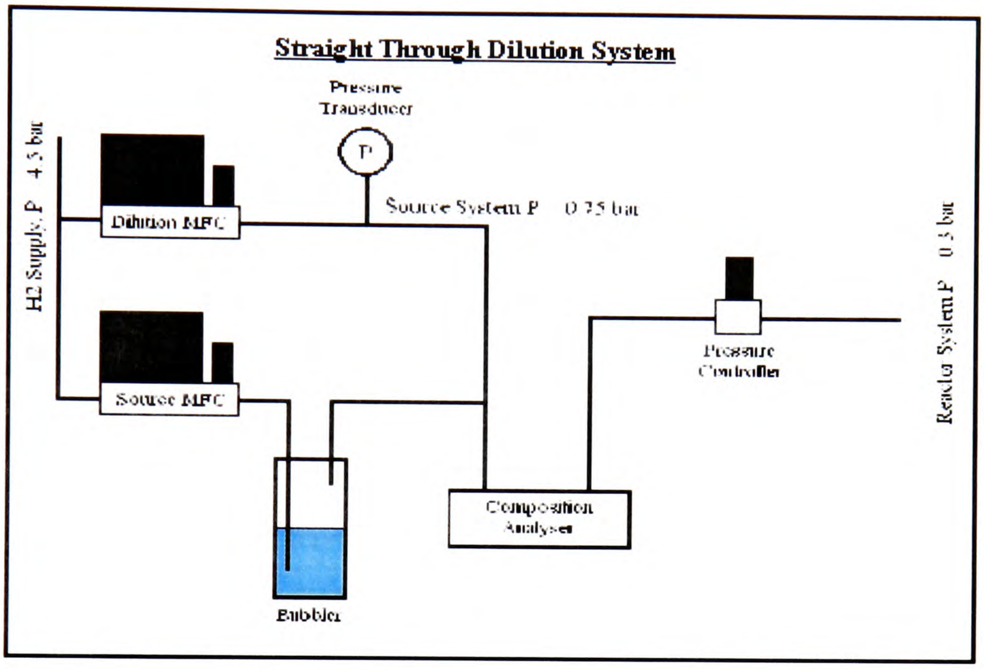


Figure A-0-20 - Modified Bubbler Nest

A4.2 - Bubbler Design

The number of site wide "Source Activity" tests is high, 25% of ALL non-deliverable runs. From a business viewpoint not acceptable, the number of runs is not directly proportional to the number of Source Changes; the Fit for Purpose failure rate is also very high. To review the problem we must understand what is involved.

Average FFP Runs/Grp III Source Change is 1.75 runs
Average FFP Runs/Grp IV Source Change is 1.25 runs
Average FFP Runs/Dopant Source Change is 0.25 runs

For Example:

Each time a source is changed a run is carried out on a machine to qualify the:

- Quality of the Source
- Quality of the Change Procedure Undertaken
- Quality of the Post Event System Preparation

The Source testing evidence suggests that a variable exist in one or multiples of the above. A FFP test following a source change suggests that a FFP run must be carried out at least twice before the Process can be released for production, and that on some occasions the same source transferred across bays passes on the first attempt. For Sources such as TMA and TMG we have data that suggests that ALL sources have passed FFP over the last 2 years, and yet we still carry out the declared number of tests.

This suggests that the FFP failure rate is either a function of Change Procedure or System Conditioning.

Known:

That the change purity must leave less contaminant than 1 in 2 million.
That a Source Container (Bubbler) is charged with N2
That a Source Container has a volume of approximately 1 litre
That approximately 1/3 of the container holds the source material.

The Connecting pipe work is 1/4" OD and is approximately 300mm long on both input and output.

That the process carrier gas is H2 and that ALL of the N2 in the source container must be swept out by the H2 before FFP.

That the "delivered" Source Pressure is 1bar absolute.
That the available vacuum equates to 1x10-2 mb
That the lines are charged with H2 prior to use
That O2 must be kept out of the Pipe work during source change

Essential Steps:

1 - Lines need Inert Gas purging prior to opening
2 - Lines need Inert Gas purge whilst lines are open
3 - Lines need Vacuum and N2 back-fill 5 times prior to H2 conditioning.
4 - To condition lines for H2, drop pressure to leak check Reactor and shut Reactor Source isolation valves.
5 - At Reactor pressure 1000mb absolute, and Reactor on H2 refill lines.
6 - Bubbler Purge Time:
0.66x1=660 cc
Typical Flow rate - 200 sccm
Now using H2 as a purge for N2,
Density H2 =
Density N2 =
Density Ratio H2:N2 - 1:100

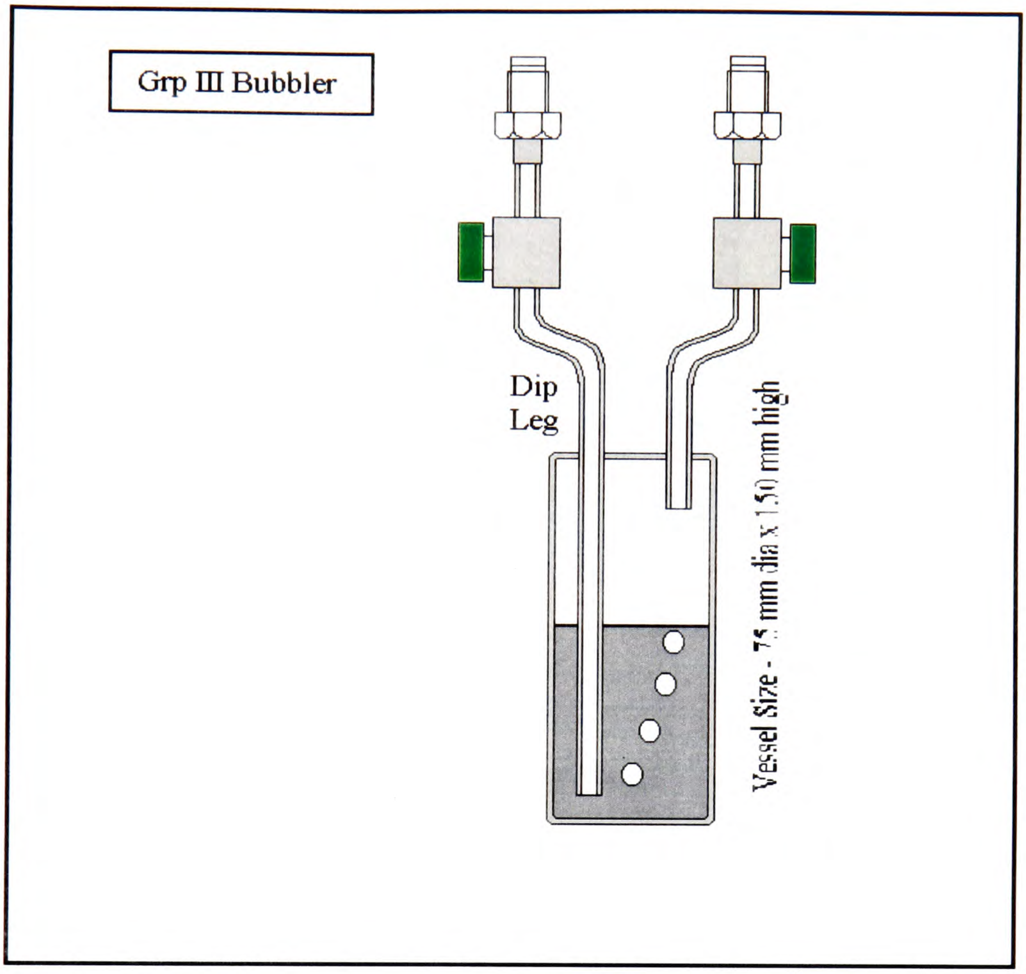


Figure A-0-21 - Grp III - Bubbler

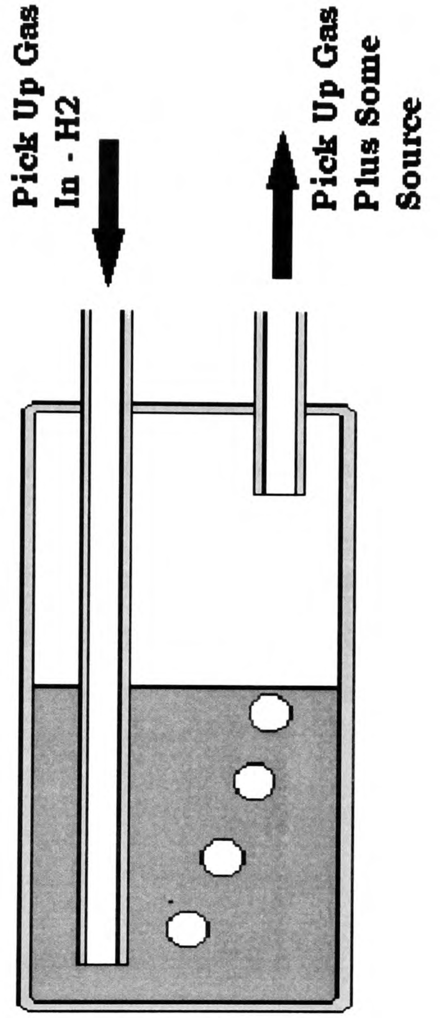


Figure A-0-22 - Bubbler
Operation

The gas flows of H2 used as "Pick Up" for the source a small flows typically 0.4 to 0.8 l/m. Both Inlet and Outlet pipe work are 1/4" OD pipes. The ΔP for the activity will be negligible and the major effect being the viscosity of the source material. If we were to assume that this viscosity was a constant we can assume the system whatever the design has negligible pressure drop.

The practical activity of "Pick Up" is some function of:

- Source Vapour Pressure
- Source State (Solid, Liquid)
- Flow Introduced
- Source Pressure - Flow Correction
- Produced Bubble Surface Area
- Vapour Conditions of Swept Volume

Considering that negligible pressure drop exists between gas injection points to bubbler and that the injector is a cylindrical feature I will assume that the produced "Bubble" equates to Pipe internal diameter.

Example:

Injector ID = 4mm

H_2 Flow is = 200, 400, 600, 800 cc/min (at STP)

				Single Input						
Flow ID Sccm	Press Correction	Flow m3/m	Orifice Dia m	Set Pressure b abs	CSA Injector m2	Bubble Volume m3	Bubbles/Min	Bubbles Surf Area m2	Sheet Area Equiv m2/min	
200	1.35	3E-04	0.004	0.75	12.6E-6	33.5E-9	8060.153	5E-05	0.4052	
300	1.35	4E-04	0.004	0.75	12.6E-6	33.5E-9	12090.23	5E-05	0.6078	
400	1.35	5E-04	0.004	0.75	12.6E-6	33.5E-9	16120.31	5E-05	0.8104	
500	1.35	7E-04	0.004	0.75	12.6E-6	33.5E-9	20150.38	5E-05	1.013	
600	1.35	8E-04	0.004	0.75	12.6E-6	33.5E-9	24180.46	5E-05	1.2156	
700	1.35	9E-04	0.004	0.75	12.6E-6	33.5E-9	28210.53	5E-05	1.4182	
800	1.35	0.001	0.004	0.75	12.6E-6	33.5E-9	32240.61	5E-05	1.6208	
900	1.35	0.001	0.004	0.75	12.6E-6	33.5E-9	36270.69	5E-05	1.8234	
1000	1.35	0.001	0.004	0.75	12.6E-6	33.5E-9	40300.76	5E-05	2.026	

				Multi Input						
		4 Pipes, 4x1mm Injectors Flow/Orifice								
Flow ID Sccm	Flow ID Sccm	Press Correction	Flow m3/m	Orifice Dia m	Set Pressure b abs	CSA Injector m2	Bubble Volume m3	Bubbles/Min	Bubbles Surf Area m2	Sheet Area Equiv m2/min
200	12.5	1.35	1.7E-05	5E-04	0.75	196.4E-9	65.5E-12	257798	7.86E-07	0.2025
					x16					
								4E+06	1.26E-05	3.24
400	25	1.35	3.4E-05	5E-04	0.75	196.4E-9	65.5E-12	515595	7.86E-07	0.405
					x16					
								8E+06	1.26E-05	6.48
600	37.5	1.35	5.1E-05	5E-04	0.75	196.4E-9	65.5E-12	773393	7.86E-07	0.6075
					x16					
								1E+07	1.26E-05	9.72
800	50	1.35	6.8E-05	5E-04	0.75	196.4E-9	65.5E-12	1E+06	7.86E-07	0.81
					x16					
								2E+07	1.26E-05	12.96
1000	62.5	1.35	8.4E-05	5E-04	0.75	196.4E-9	65.5E-12	1E+06	7.86E-07	1.0125
					x16					
								2E+07	1.26E-05	16.2

Table A:0-4 - Bubbler Data

The basic conclusion from the above data is that “ASSUMING” that the available bubbler “Swept Volume” is not a “Saturated Vapour” then by physical re-design of the system we could improve our material pick up and Process Growth Rate by up to a factor of eight.

The assumption in the previous paragraph and the design needs prototyping proof. If the saturated vapour above the source material level in the bubbler is limiting our overall "Pick Up" performance then further modifications to the Bubbler can effect the improvement.

i.e.

Whilst continuing to increase bubbling rate, change the saturated vapour volume as an additional process part.

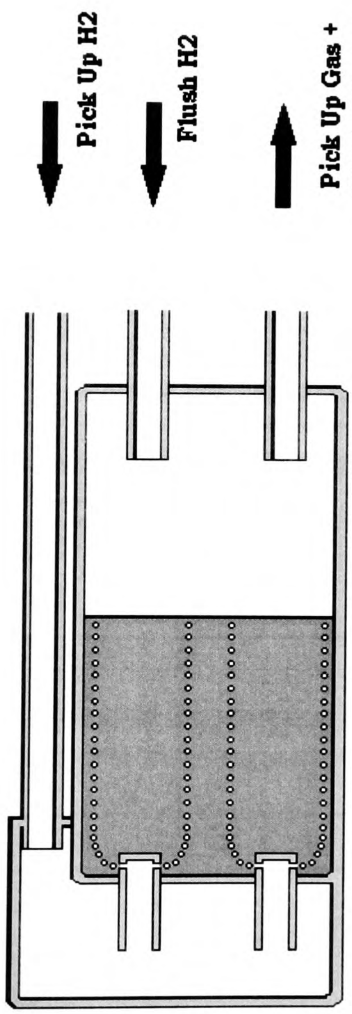


Figure A-0-23 - Modified Bubbler Operation

Outstanding Trials

1-Bubbler N2, H2 purge Time

A4.3 - Source Nest Mixing Stability

With the flexibility requirements of the product mix, many differing conditions have to be prescribed. The dynamic demands on each system therefore change with each recipe. As the H2 flow through the bubbler and the dilution flow changes, the gas mixture will be different with every velocity change; bearing in mind in a Double Dilution system spill takes place.

It is critical therefore that the mixed gases composition is optimised for each flow. A very basic problem that with a system "Back Pressure" is easy to solve. A backpressure on the Bubbler system will cause the material "Pick Up" characteristics to change.

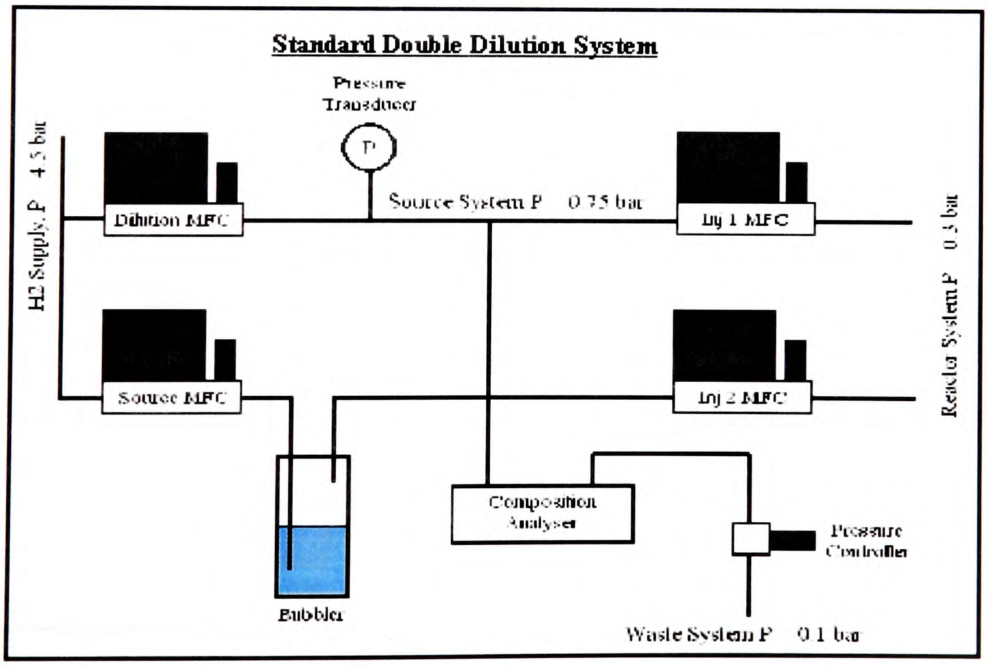


Figure A-0-24 - Bubbler Nest Arrangement

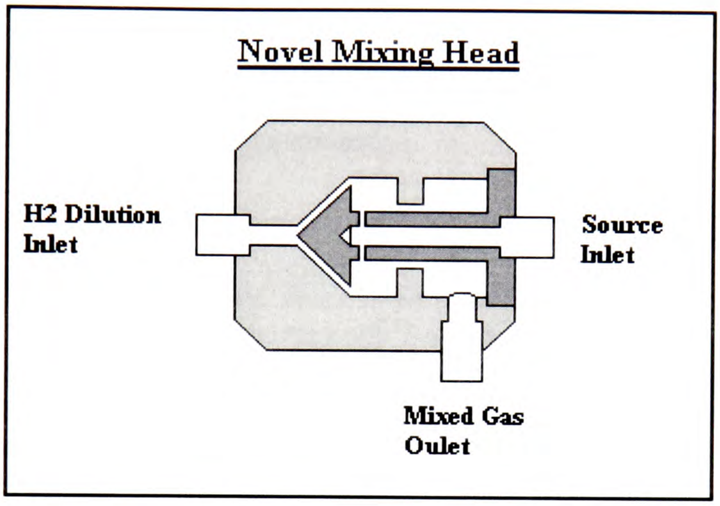


Figure A-0-25 - Mixing Nozzle

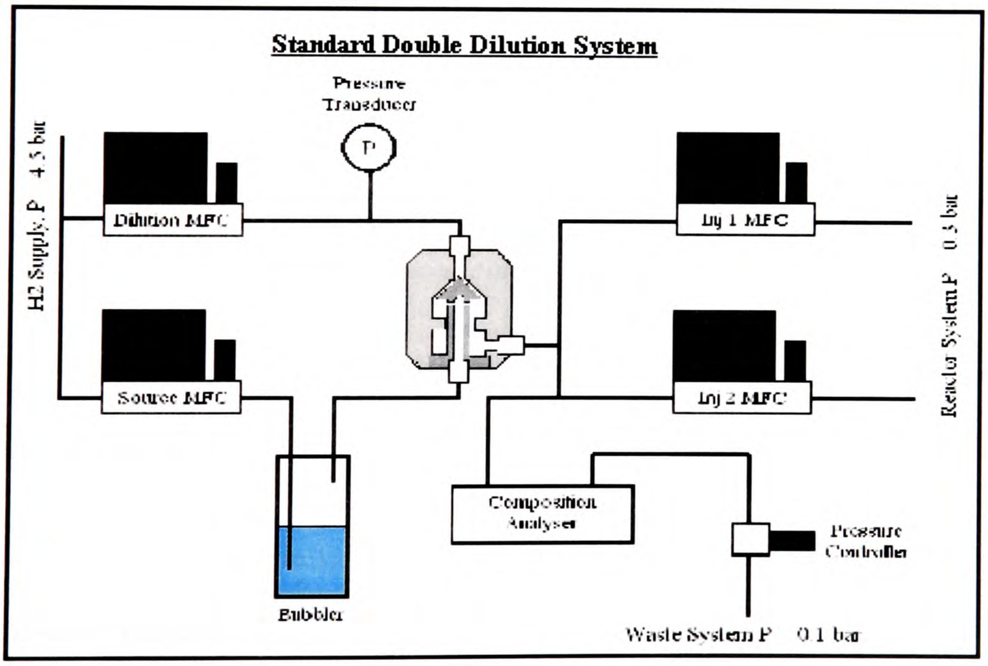


Figure A-0-26 - Nozzle "in Situ"

Appendix 5 - Decision Making & Problem Solving Summary

Exert From:

Decision Making and Problem Solving

by Herbert A. Simon and Associates

A5.1 – Problem Solving

The theory of choice has its roots mainly in economics, statistics, and operations research and only recently has received much attention from psychologists; the theory of problem solving has a very different history. Problem solving was initially studied principally by psychologists, and more recently by researchers in artificial intelligence. It has received rather scant attention from economists.

A5.2 – Contemporary Problem Solving Theory

Human problem solving is usually studied in laboratory settings, using problems that can be solved in relatively short periods of time (seldom more than an hour), and often seeking a maximum density of data about the solution process by asking subjects to think aloud while they work. The thinking-aloud technique, at first viewed with suspicion by behaviourists as subjective and "introspective," has received such careful methodological attention in recent years that it can now be used dependably to obtain data about subjects' behaviours in a wide range of settings.

The laboratory study of problem solving has been supplemented by field studies of professionals solving real-world problems--for example, physicians making diagnoses and chess grandmasters analysing game positions, and, as noted earlier, even business corporations making investment decisions. Currently, historical records, including laboratory notebooks of scientists, are also being used to study problem-solving processes in scientific discovery. Although such records are far less "dense" than laboratory protocols, they sometimes permit the course of discovery to be traced in considerable detail. Laboratory notebooks of scientists as distinguished as Charles Darwin, Michael Faraday, *Antoine-Laurent Lavoisier, and Hans Krebs have been used successfully in such research.*

From empirical studies, a description can now be given of the problem-solving process that holds for a rather wide range of activities. First, problem solving generally proceeds by selective search through large sets of possibilities, using rules of thumb (heuristics) to guide the search. Because the possibilities in realistic problem situations are generally multitudinous, trial-and-error search would simply not work; the search must be highly selective. Chess grandmasters seldom examine more than a hundred of the vast number of possible scenarios that confront them, and similar small numbers of searches are observed in other kinds of problem-solving search.

One of the procedures often used to guide search is "hill climbing," using some measure of approach to the goal to determine where it is most profitable to look next. Another, and more powerful, common procedure is means-ends analysis. In means-ends analysis, the problem solver compares the present situation with the goal, detects a difference between them, and then searches memory for actions that are likely to reduce the difference. Thus, if the difference is a fifty-mile distance from the goal, the problem solver will retrieve from memory knowledge about autos, carts, bicycles, and other means of transport; walking and flying will probably be discarded as inappropriate for that distance.

The third thing that has been learned about problem solving--especially when the solver is an expert--is that it relies on large amounts of information that are stored in memory and that are retrievable whenever the solver recognizes cues signalling its relevance. Thus, the expert knowledge of a diagnostician is evoked by the symptoms presented by the patient; this knowledge leads to the recollection of what additional information is needed to discriminate among alternative diseases and, finally, to the diagnosis.

In a few cases, it has been possible to estimate how many patterns an expert must be able to recognize in order to gain access to the relevant knowledge stored in memory. A chess master must be able to recognize about 50,000 different configurations of chess pieces that occur frequently in the course of chess games. A medical diagnostician must be able to recognize tens of thousands of configurations of symptoms; a botanist or zoologist specializing in taxonomy, tens or hundreds of thousands of features of specimens that define their species. For comparison, college graduates typically have vocabularies in their native languages of 50,000 to 200,000 words. (However, these numbers are very small in comparison with the real-world situations the expert faces: there *are perhaps 10^{120} branches in the game tree of chess, a game played with only six kinds of pieces on an 8 x 8 board.)*

One of the accomplishments of the contemporary theory of problem solving has been to provide an explanation for the phenomena of intuition and judgment frequently seen in experts' behaviour. The store of expert knowledge, "indexed" by the recognition cues that make it accessible and combined with some basic inferential capabilities (perhaps in the form of means-ends analysis), accounts for the ability of experts to find satisfactory solutions for difficult problems, and sometimes to find them almost instantaneously. The expert's "intuition" and "judgment" derive from this capability for rapid recognition linked to a large store of knowledge. When immediate intuition fails to yield a problem solution or when a prospective solution needs to be evaluated, the expert falls back on the slower processes of analysis and inference.

A5.3 – Expert Systems in Artificial Intelligence

Over the past thirty years, there has been close teamwork between research in psychology and research in computer science aimed at developing intelligent programs. Artificial intelligence (AI) research has both borrowed from and contributed to research on human problem solving. Today, artificial intelligence is beginning to produce systems, applied to a variety of tasks that can solve difficult problems at the level of professionally trained humans. These AI programs are usually called expert systems. A description of a typical expert system would resemble closely the description given above of typical human problem solving; the differences between the two would be differences in degree, not in kind. An AI expert system, relying on the speed of computers and their ability to retain large bodies of transient information in memory, will generally use "brute force"--sheer computational speed and power--more freely than a human expert can. A human expert, in compensation, will generally have a richer set of heuristics to guide search and a larger vocabulary of recognizable patterns. To the observer, the computer's process will appear the more systematic and even compulsive, the human's the more intuitive. But these are quantitative, not qualitative, differences.

The number of tasks for which expert systems have been built is increasing rapidly. One is medical diagnosis (two examples are the CADUCEUS and MYCIN programs). Others are automatic design of electric motors, generators, and transformers (which predates by a decade the invention of the term expert systems), the configuration of computer systems from customer specifications, and the automatic generation of reaction paths for the synthesis of organic molecules. All of *these (and others) are either being used currently in professional or industrial practice or at least have reached a level at which they can produce a professionally acceptable product.*

Expert systems are generally constructed in close consultation with the people who are experts in the task domain. Using standard techniques of observation and interrogation, the heuristics that the human expert uses, implicitly and often unconsciously, to perform the task are gradually educed, made explicit, and incorporated in program structures. Although a great deal has been learned about how to do this, improving techniques for designing expert systems is an important current direction of research. It is especially important because expert systems, once built, cannot remain static but must be modifiable to incorporate new knowledge as it becomes available.

Appendix 6 – Key Quotations

A6.1 – Armand V. Feigenbaum, (1991)

12 Key Check Points for Process Control

1. Are understandable product - and process - quality requirements available and thoroughly documented in production operations?
2. Are process capabilities and relationship of inputs to outputs clearly defined?
3. Are causes of process variation explicitly identified and is there an organised procedure for their elimination if needed?
4. Have practical methods been established to control quality of process inputs?
5. Do all production personnel have readily available information about physical, chemical and other standards; quality routines; and decision rules for taking corrective action?
6. Have all equity plans and quality information equipment been thoroughly tried out in the environment and proved effective and practical?
7. Have all control practices and equipment been tested on pilot runs prior to their routine operation?
8. Has study begun of process behaviour and function in the design and development stage of new product information?
9. Have product and process designs and quality plans been balanced with production capabilities/

10. Has provision been made for analysis and immediate corrective follow-through of field complaints in the relevant production operations?
11. Are the data analysed in such a way as to expedite product trace ability and recall?
12. Have sufficient monitoring, auditing and feedback provisions been made to maintain and support control?

A6.2 – Financial Training Partners (1999)

"*Business Risk Analysis – This course is an introduction to analysing Companies. The emphasis is on understanding the key drivers of operating performance and how they affect operating cash flow. It also covers interpreting the links between business events and financial trends.*"

A6.3 – Roger Mills (2001)

"Operational Risk – Risk management has become a hot topic as both shareholders and regulators believe it merits more rigorous attention. Companies are having to find new and more creditable ways of managing and reporting risks of all kinds."

A6.4 – Deming's 14 Point Plan

Deming's 14-point plan, an exceptional concept, breaking traditional Company philosophies and focusing on change and participation.

The 14 points are as follows:

1-Create a constancy of purpose focused on the improvement of products and services. Constantly try to improve product design and performance. Investment in research, development and innovation will have a long-term payback to the organisation.

2-Adopt a new philosophy of rejecting poor workmanship, defective products or bad service. It costs as much to produce a defective unit as it does to produce a good one (and sometimes more). The costs of dealing with scrap, rework and other losses created by defectives are an enormous drain on Company resources.

3-Do not rely on mass inspection to "control" quality. All inspection can do is sort out defectives, and at this point it is too late we have already paid to produce these defectives. Inspection occurs too late in the process, it is expensive, and is often ineffective. Quality results from prevention of defectives through process improvement not inspection.

4-Do not award business to suppliers on the basis of price alone, but also consider quality. Price is a meaningful measure of a Supplier's product only if it is considered in relation to a measure of quality. In other words, the total cost of the item must be considered, not just the purchase price. When quality is considered, the lowest bidder is frequently not the low-cost supplier. Preference should be given to suppliers who use modern methods of quality improvement in their business and who can demonstrate process control and capability.

5-Focus on continual improvement. Constantly try to improve the production and service system. Involve the work force in these activities and make use of statistical methods, particularly SPC problem-solving tools.

6-Practice modern training methods and invest in training for all employees. Everyone should be trained in the technical aspects of their job, and in modern quality and productivity-improvement methods as well. The training should encourage all employees to practice these methods every day.

7-Practice modern supervision methods. Supervision should not consist merely of passive surveillance of workers, but should be focused on helping the employees improve the system in which they work. The numbers one goal of supervision should be to improve the work system and the product.

8-Drive out fear. Many workers are afraid to ask questions, report problems or point out conditions that are barriers to quality and effective production. In many organisations the economic loss associated with fear is large, only management can eliminate fear.

9-Breakdown the barriers between functional areas of the business. Teamwork among different organisational units is essential for effective quality and productivity improvement to take place.

10-Eliminate targets, slogans and numerical goals for the work force. A target such as 'zero defects' is useless without a plan as to how to achieve this objective. In fact, these slogans and 'programs' are usually counterproductive. Work to improve the system and provide information on that.

11-Eliminate numerical quotas and work standards. These have historically been set without regard to quality. Work standards are symptoms of management's inability to understand the work process and to provide and effective management system focused on improving this process.

12-Remove the barriers that discourage employees from doing their jobs. Management must listen to employee suggestions, comments, and complaints. The person who is doing the job is the one who knows the most about it, and usually has valuable ideas about how to make the process work more effectively. The workforce is an important participant in the business, and not just an opponent in collective bargaining.

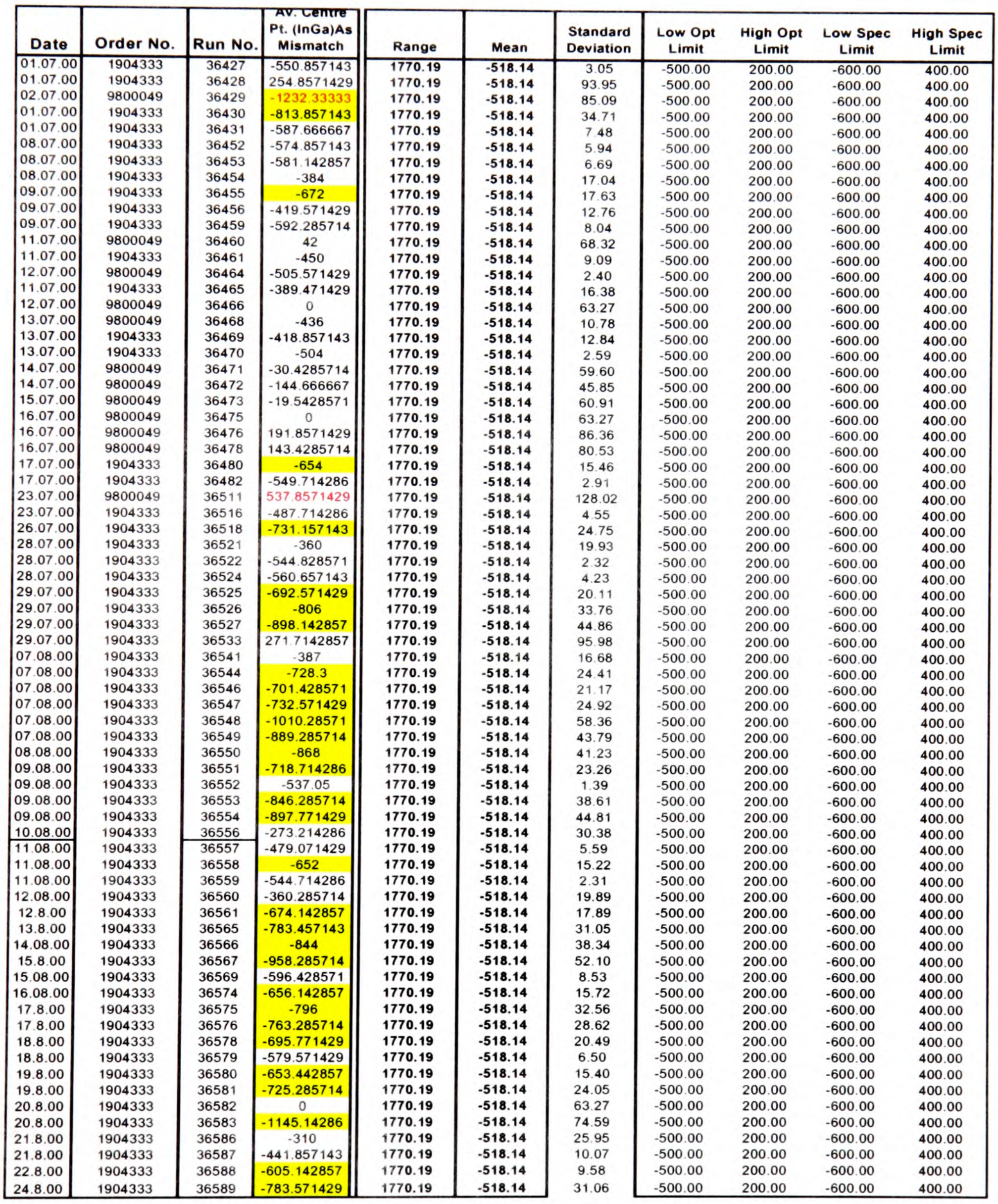
13-Institute an ongoing programme of training and education for all employees. Education in simple, powerful statistical techniques should be mandatory for all employees. Use of the basic SPC problem-solving tools, particularly the control chart, should become widespread in the business. As these charts become widespread, and as employees understand their uses, they will be more likely to look for the causes of poor quality and to identify process improvements. Education is a way of making everyone partners in the quality improvement process.

14-Create a structure in top management that will vigorously advocate the first 13 points.

Appendix 7 – Data Analysis

A7.1 – Bay 3 X-Ray Centre Point Analysis

To enable the production of the data charts used in Chapter 8, pages 8-183 to 8-185, an analysis of growth data has been undertaken. A typical example follows:



Date	Order No.	Run No.	Av. Centre Pt. (InGa)As Mismatch	Range	Mean	Standard Deviation	Low Opt Limit	High Opt Limit	Low Spec Limit	High Spec Limit
01.07.00	1904333	36427	-550.857143	**1770.19**	**-518.14**	3.05	-500.00	200.00	-600.00	400.00
01.07.00	1904333	36428	254.8571429	**1770.19**	**-518.14**	93.95	-500.00	200.00	-600.00	400.00
02.07.00	9800049	36429	-1232.33333	**1770.19**	**-518.14**	85.09	-500.00	200.00	-600.00	400.00
01.07.00	1904333	36430	-813.857143	**1770.19**	**-518.14**	34.71	-500.00	200.00	-600.00	400.00
01.07.00	1904333	36431	-587.666667	**1770.19**	**-518.14**	7.48	-500.00	200.00	-600.00	400.00
08.07.00	1904333	36452	-574.857143	**1770.19**	**-518.14**	5.94	-500.00	200.00	-600.00	400.00
08.07.00	1904333	36453	-581.142857	**1770.19**	**-518.14**	6.69	-500.00	200.00	-600.00	400.00
08.07.00	1904333	36454	-384	**1770.19**	**-518.14**	17.04	-500.00	200.00	-600.00	400.00
09.07.00	1904333	36455	-672	**1770.19**	**-518.14**	17.63	-500.00	200.00	-600.00	400.00
09.07.00	1904333	36456	-419.571429	**1770.19**	**-518.14**	12.76	-500.00	200.00	-600.00	400.00
09.07.00	1904333	36459	-592.285714	**1770.19**	**-518.14**	8.04	-500.00	200.00	-600.00	400.00
11.07.00	9800049	36460	42	**1770.19**	**-518.14**	68.32	-500.00	200.00	-600.00	400.00
11.07.00	1904333	36461	-450	**1770.19**	**-518.14**	9.09	-500.00	200.00	-600.00	400.00
12.07.00	9800049	36464	-505.571429	**1770.19**	**-518.14**	2.40	-500.00	200.00	-600.00	400.00
11.07.00	1904333	36465	-389.471429	**1770.19**	**-518.14**	16.38	-500.00	200.00	-600.00	400.00
12.07.00	9800049	36466	0	**1770.19**	**-518.14**	63.27	-500.00	200.00	-600.00	400.00
13.07.00	9800049	36468	-436	**1770.19**	**-518.14**	10.78	-500.00	200.00	-600.00	400.00
13.07.00	1904333	36469	-418.857143	**1770.19**	**-518.14**	12.84	-500.00	200.00	-600.00	400.00
13.07.00	1904333	36470	-504	**1770.19**	**-518.14**	2.59	-500.00	200.00	-600.00	400.00
14.07.00	9800049	36471	-30.4285714	**1770.19**	**-518.14**	59.60	-500.00	200.00	-600.00	400.00
14.07.00	9800049	36472	-144.666667	**1770.19**	**-518.14**	45.85	-500.00	200.00	-600.00	400.00
15.07.00	9800049	36473	-19.5428571	**1770.19**	**-518.14**	60.91	-500.00	200.00	-600.00	400.00
16.07.00	9800049	36475	0	**1770.19**	**-518.14**	63.27	-500.00	200.00	-600.00	400.00
16.07.00	9800049	36476	191.8571429	**1770.19**	**-518.14**	86.36	-500.00	200.00	-600.00	400.00
16.07.00	9800049	36478	143.4285714	**1770.19**	**-518.14**	80.53	-500.00	200.00	-600.00	400.00
17.07.00	1904333	36480	-654	**1770.19**	**-518.14**	15.46	-500.00	200.00	-600.00	400.00
17.07.00	1904333	36482	-549.714286	**1770.19**	**-518.14**	2.91	-500.00	200.00	-600.00	400.00
23.07.00	9800049	36511	537.8571429	**1770.19**	**-518.14**	128.02	-500.00	200.00	-600.00	400.00
23.07.00	1904333	36516	-487.714286	**1770.19**	**-518.14**	4.55	-500.00	200.00	-600.00	400.00
26.07.00	1904333	36518	-731.157143	**1770.19**	**-518.14**	24.75	-500.00	200.00	-600.00	400.00
28.07.00	1904333	36521	-360	**1770.19**	**-518.14**	19.93	-500.00	200.00	-600.00	400.00
28.07.00	1904333	36522	-544.828571	**1770.19**	**-518.14**	2.32	-500.00	200.00	-600.00	400.00
28.07.00	1904333	36524	-560.657143	**1770.19**	**-518.14**	4.23	-500.00	200.00	-600.00	400.00
29.07.00	1904333	36525	-692.571429	**1770.19**	**-518.14**	20.11	-500.00	200.00	-600.00	400.00
29.07.00	1904333	36526	-806	**1770.19**	**-518.14**	33.76	-500.00	200.00	-600.00	400.00
29.07.00	1904333	36527	-898.142857	**1770.19**	**-518.14**	44.86	-500.00	200.00	-600.00	400.00
29.07.00	1904333	36533	271.7142857	**1770.19**	**-518.14**	95.98	-500.00	200.00	-600.00	400.00
07.08.00	1904333	36541	-387	**1770.19**	**-518.14**	16.68	-500.00	200.00	-600.00	400.00
07.08.00	1904333	36544	-728.3	**1770.19**	**-518.14**	24.41	-500.00	200.00	-600.00	400.00
07.08.00	1904333	36546	-701.428571	**1770.19**	**-518.14**	21.17	-500.00	200.00	-600.00	400.00
07.08.00	1904333	36547	-732.571429	**1770.19**	**-518.14**	24.92	-500.00	200.00	-600.00	400.00
07.08.00	1904333	36548	-1010.28571	**1770.19**	**-518.14**	58.36	-500.00	200.00	-600.00	400.00
07.08.00	1904333	36549	-889.285714	**1770.19**	**-518.14**	43.79	-500.00	200.00	-600.00	400.00
08.08.00	1904333	36550	-868	**1770.19**	**-518.14**	41.23	-500.00	200.00	-600.00	400.00
09.08.00	1904333	36551	-718.714286	**1770.19**	**-518.14**	23.26	-500.00	200.00	-600.00	400.00
09.08.00	1904333	36552	-537.05	**1770.19**	**-518.14**	1.39	-500.00	200.00	-600.00	400.00
09.08.00	1904333	36553	-846.285714	**1770.19**	**-518.14**	38.61	-500.00	200.00	-600.00	400.00
09.08.00	1904333	36554	-897.771429	**1770.19**	**-518.14**	44.81	-500.00	200.00	-600.00	400.00
10.08.00	1904333	36556	-273.214286	**1770.19**	**-518.14**	30.38	-500.00	200.00	-600.00	400.00
11.08.00	1904333	36557	-479.071429	**1770.19**	**-518.14**	5.59	-500.00	200.00	-600.00	400.00
11.08.00	1904333	36558	-652	**1770.19**	**-518.14**	15.22	-500.00	200.00	-600.00	400.00
11.08.00	1904333	36559	-544.714286	**1770.19**	**-518.14**	2.31	-500.00	200.00	-600.00	400.00
12.08.00	1904333	36560	-360.285714	**1770.19**	**-518.14**	19.89	-500.00	200.00	-600.00	400.00
12.8.00	1904333	36561	-674.142857	**1770.19**	**-518.14**	17.89	-500.00	200.00	-600.00	400.00
13.8.00	1904333	36565	-783.457143	**1770.19**	**-518.14**	31.05	-500.00	200.00	-600.00	400.00
14.08.00	1904333	36566	-844	**1770.19**	**-518.14**	38.34	-500.00	200.00	-600.00	400.00
15.8.00	1904333	36567	-958.285714	**1770.19**	**-518.14**	52.10	-500.00	200.00	-600.00	400.00
15.08.00	1904333	36569	-596.428571	**1770.19**	**-518.14**	8.53	-500.00	200.00	-600.00	400.00
16.08.00	1904333	36574	-656.142857	**1770.19**	**-518.14**	15.72	-500.00	200.00	-600.00	400.00
17.8.00	1904333	36575	-796	**1770.19**	**-518.14**	32.56	-500.00	200.00	-600.00	400.00
17.8.00	1904333	36576	-763.285714	**1770.19**	**-518.14**	28.62	-500.00	200.00	-600.00	400.00
18.8.00	1904333	36578	-695.771429	**1770.19**	**-518.14**	20.49	-500.00	200.00	-600.00	400.00
18.8.00	1904333	36579	-579.571429	**1770.19**	**-518.14**	6.50	-500.00	200.00	-600.00	400.00
19.8.00	1904333	36580	-653.442857	**1770.19**	**-518.14**	15.40	-500.00	200.00	-600.00	400.00
19.8.00	1904333	36581	-725.285714	**1770.19**	**-518.14**	24.05	-500.00	200.00	-600.00	400.00
20.8.00	1904333	36582	0	**1770.19**	**-518.14**	63.27	-500.00	200.00	-600.00	400.00
20.8.00	1904333	36583	-1145.14286	**1770.19**	**-518.14**	74.59	-500.00	200.00	-600.00	400.00
21.8.00	1904333	36586	-310	**1770.19**	**-518.14**	25.95	-500.00	200.00	-600.00	400.00
21.8.00	1904333	36587	-441.857143	**1770.19**	**-518.14**	10.07	-500.00	200.00	-600.00	400.00
22.8.00	1904333	36588	-605.142857	**1770.19**	**-518.14**	9.58	-500.00	200.00	-600.00	400.00
24.8.00	1904333	36589	-783.571429	1770.19	**-518.14**	31.06	-500.00	200.00	-600.00	400.00

Table A:0-5 - Bay 3 Statistical Analysis

A7.2 – Bay 6 X-Ray Analysis

For additional analysis of the uniformity profile for the data summarised in Chapter 4, concerning uniformity for a single wafer machine.

Run Sequence	B-X01	B-X02	B-X03	B-X04	B-X05	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Kurtosis	Skew	Range	Minimum	Maximum	Sum	Count	Confidence Level(95%)	Mean + Range/2	Mean - Range/2
1	**440**	**134**	**-149**	**236**	**519**	236	118.39	236	264.7	70084	-0.308	-0.6058	668	-149	519	1180	5	232.044	570.00	-98.00
2	**338**	**134**	**0**	**204**	**511**	237.4	87.505	204	195.7	38286	-0.327	0.38804	511	0	511	1187	5	171.5068	492.90	-18.10
3	**471**	**181**	**0**	**220**	**684**	311.2	119.71	220	267.7	71658	-0.769	0.495	684	0	684	1556	5	234.6356	653.20	-30.80
4	**379**	**141**	**0**	**189**	**566**	255	98.609	189	220.5	48619	-0.593	0.53001	566	0	566	1275	5	193.2695	538.00	-28.00
5	**487**	**149**	**0**	**220**	**644**	300	116.73	220	261	68127	-1.567	0.38175	644	0	644	1500	5	228.7813	622.00	-22.00
6	**306**	**204**	**0**	**291**	**589**	278	94.983	291	212.4	45109	1.4349	0.35725	589	0	589	1390	5	186.1623	572.50	-16.50
7	**409**	**275**	**0**	**330**	**644**	331.6	104.1	330	232.8	54187	1.2216	-0.188	644	0	644	1658	5	204.0381	653.60	9.60
8	**299**	**230**	**0**	**283**	**581**	278.6	92.699	283	207.3	42965	1.7457	0.27709	581	0	581	1393	5	181.686	569.10	-11.90
9	**424**	**259**	**0**	**196**	**676**	311	113.72	259	254.3	64661	0.2064	0.46446	676	0	676	1555	5	222.8864	649.00	-27.00
10	**306**	**204**	**-189**	**299**	**542**	232.4	119.18	299	266.5	71022	2.1036	-0.9793	731	-189	542	1162	5	233.593	597.90	-133.10
11	**432**	**141**	**-141**	**181**	**605**	243.6	128.15	181	286.6	82117	-0.525	-0.0766	746	-141	605	1218	5	251.1762	616.60	-129.40
12	**361**	**134**	**0**	**141**	**589**	245	103.67	141	231.8	53739	-0.184	0.83852	589	0	589	1225	5	203.1913	539.50	-49.50
13	**448**	**157**	**0**	**259**	**448**	262.4	86.275	259	192.9	37217	-1.469	-0.3744	448	0	448	1312	5	169.0966	486.40	38.40
14	**322**	**0**	**0**	**157**	**432**	182.2	86.306	157	193	37243	-2.16	0.35982	432	0	432	911	5	169.1554	398.20	-33.80
15	**387**	**167**	**-34**	**229**	**574**	264.6	102.6	229	229.4	52632	-0.147	0.12755	608	-34.21	573.6	1323	5	201.0889	568.49	-39.29

Table A:0-6 - Bay 6 X-Ray Uniformity Analysis

A7.3 – Failure bay & Group Analysis

An example of initial evaluation for cross comparison between bays and group volatility for failure modes.

Summary 97	Bay 1	δι	Bay 2	δι	Bay 3	δι	Bay 4	δι	Bay 5	δι	Bay 6	δι	Mean loss / Cat	σ / Group
Hardware	24	-27.00	56	5.00	49	-2.00	59	8.00	87	36.00	31	-20.00	51.00	20.49
δι	-20.38		-15.13		30.38		25.38		54.00		-40.38			
Morphology	121	-4.83	117	-8.83	21	-104.83	118	-7.83	78	-47.83	300	174.17	125.83	85.42
δι	76.63		45.88		2.38		84.38		45.00		228.63			
Doping	53	17.50	41	5.50	44	8.50	22	-13.50	11	-24.50	42	6.50	35.50	14.34
δι	8.63		-30.13		25.38		-11.63		-22.00		-29.38			
PL	5	-52.33	202	144.67	14	-43.33	39	-18.33	22	-35.33	62	4.67	57.33	67.27
δι	-39.38		130.88		-4.63		5.38		-11.00		-9.38			
Composition	0	-38.83	119	80.17	0	-38.83	0	-38.83	24	-14.83	90	51.17	38.83	47.94
δι	-44.38		47.88		-18.63		-33.63		-9.00		18.63			
Errors	7	-12.50	20	0.50	10	-9.50	5	-14.50	35	15.50	40	20.50	19.50	13.65
δι	-37.38		-51.13		-8.63		-28.63		2.00		-31.38			
Sources	0	-5.67	5	-0.67	11	5.33	8	2.33	7	1.33	3	-2.67	5.67	3.54
δι	-44.38		-66.13		-7.63		-25.63		-26.00		-68.38			
Thickness	145	115.83	9	-20.17	0	-29.17	18	-11.17	0	-29.17	3	-26.17	29.17	52.18
δι	100.63		-62.13		-18.63		-15.63		-33.00		-68.38			
Mean loss / Bay	44.38		71.13		18.6		33.6		33		71.4			
σ / Bay	54.05		64.72		17.39		36.70		30.41		90.51			

Table A:0-7 - Failure Group & Bay Analysis