PLANNING FOR SUCCESS IN TRANSITIONING NEW TECHNOLOGIES INTO ECONOMICAL FULL-SCALE PRODUCTION

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A number of technology-driven industries, including semiconductor manufacturing in its early development as well as other related industries more recently, have been characterized by the failure of many R&D initiatives to reach the goal of affordable products that can be manufactured on a large scale. There is hardly a shortage of brilliant concepts which have been readily proven on a laboratory scale. Likewise, there is not a lack of market research into the potential commercial application of many of these concepts, and at what price range a given product can make a successful entry into an available market. What *is* absent is a life-cycle template to serve as a methodology for smooth transition from R&D to volume manufacturing. In many of these cases, the failure is due in large measure to the inability of corporate management, using a specific set of attributes, to technically assess the economics of transition from the laboratory to large-scale production.

For the purpose of this discussion, the focus will be a rather broad range of process-based technologies with most, if not all, of the following characteristics:

- Multi-step processing in which various layers or films are applied onto a substrate
- A requirement for cleanroom manufacturing conditions for all steps or certain critical steps
- One or more patterning steps by photolithography and/or laser ablation
- Fabrication of an optical or optoelectronic device or component
- The requirement to ramp from development to production on substrates which are much larger (4X or more) than the "proof" size and or require a volume increase of greater than 100X from product prototyping to full production.

Virtually all technology-driven process, product, and factory maturation will progress through a natural life cycle from R&D to pilot operations to full-scale manufacturing, as indicated by Figure 1.

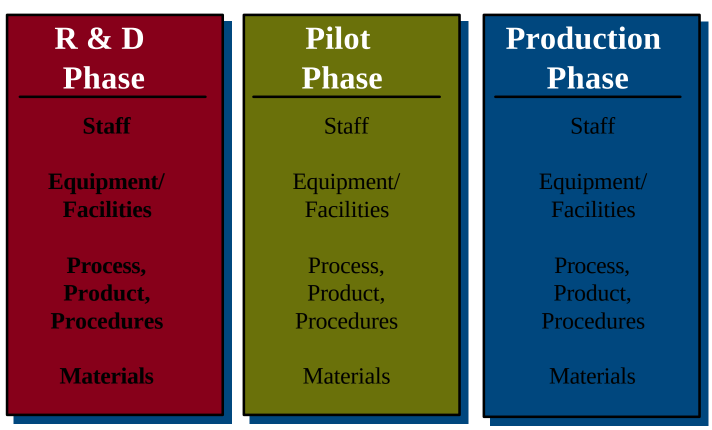

***Figure 1** - Typical phases of industrial R&D process*

These different phases may be thought of as a series of “gates,” each of which has it own distinct set of characteristics. These phases can be characterized with respect to the following:

- Staff
- Equipment and Facilities
- Process, Product, and Procedures
- Materials

It must be emphasized that although life cycle phase duration, transition management, and characteristic specifics must be modified and optimally managed on a technology to technology basis to allow for competitive success, failing to follow the basic natural sequence will almost always insure failure characterized by extended production schedules, inflated operation costs, and a sub-optimal final product feature set.

Life Cycle Template

Research and Development

Figure 2 represents the typical support components and tasks associated with the R&D Phase of an industrial research and development process. These characteristics are by no means comprehensive, and will naturally vary depending upon the structure, philosophy, and collective experience of each organization. It is intended as a template, or guideline, by which technology managers can assess progress and plan accordingly. Although there are often different objectives for both research and development, they are combined here to reflect the actual organization usually found in most technology-driven companies. This environment ideally focuses on individual achievement by a technical staff driven by discrete events. *Demonstration* of concepts is far more important that *repetition* of results during this phase.

R & D Phase

Staff	•Define and demonstrate theoretical concepts in a lab-scale industrial environment. •Technical staff hard science- and research-oriented (80% technologists, 20% engineers). •High degree of individual contribution. •Primary compensation based 90% individual, 10% team. •Focused on discrete events and intradiscipline interactions.
Equipment/ Facilities	•Provide a lab-scale industrial environment for development and prototyping activities. •Uncharacterized tools utilized with non-optimized equipment recipes. •Tool set flexible, portable, and multifunctional. •Work areas decentralized with layout optimized for intradiscipline research and development.
Process, Product, Procedures	•Define individual process steps and confirm initial sequence of operations. •Process variables understood through modeling/simulation and individual step sensitivity studies. •Chemical reactions and scaling parameters understood. •Produce a fully featured and functional prototype. •Initial prototype produced and characterized with respect to key performance variables. •Provide a flexible framework for the coordination of diverse development activities.
Materials	•Provide a basic set of materials specifications including initial sensitivity analysis with respect to intramaterial variation. •Initial experiments done with lab purity materials to obtain highest theoretical properties. •Material alternatives and substitutions freely examined with “decision to use” based on first-order impacts.

Figure 2 - *Composition of the R&D Phase*

In the R&D Phase, scientists typically have work and laboratory spaces that foster creativity, and they are unencumbered by the demands of daily production. In many cases, the R&D Phase is unfortunately marked by a lack of documentation, possibly attributable to the fact that the necessary support systems and infrastructure are not in place. There is also a natural tendency to disregard “failures,” although the experiential knowledge gained from these failures is vital to future developments. Thus, our experience has shown that meticulous documentation is most important during this phase, preventing expensive and time-consuming redundant engineering, although documentation's importance cannot be overstated at any point in the life-cycle.

Pilot

Figure 3 shows the organizational elements needed for a typical transition into a product's Pilot Phase. (The term pilot is often misleading, and has no universal standard. In this usage, "pilot" is equivalent to "prototype," and refers to an environment providing full-scale manufacturing, although a “one-of” tool set is common.) One aspect of this phase that is often overlooked is the makeup of the technical staff. The key during piloting operations is the staff transition from hard scientists to inter-functional teams, composed primarily of manufacturing engineering disciplines. The technical staff during piloting is ideally balanced evenly between hard science and engineering disciplines, with the scientists naturally predominating early in this phase. Early in the initial transition from R&D, it is important to supplement the predominantly research-oriented staff with engineers who will become the core engineering staff for the future full-scale operations.

Pilot Phase

Staff	•Integration of developed concepts in a prototype manufacturing environment. •Technical staff balanced (50% hard science- and research-oriented and 50% engineering). •High degree of intrafunctional teams. •Focused on system-level events with balance between intra- and interdiscipline interaction.
Equipment/ Facilities	•Provide a manufacturing-scale environment for initial production equipment burn-in and pilot production. •One-of-each fully sized tools with optimized equipment recipes. •Tool set user-friendly, repeatable, and functionally optimized. •Layout optimized for efficient manufacturing flow and support area centralization. •Involve vendors in partnership relationships.
Process, Product, Procedures	•Integrate process steps and define manufacturing flow. •Process integration variables understood through sensitivity analysis. •Manufacturing process model defined and characterized. •Produce a fully featured and functional production-worthy product in limited volumes. •Final production product defined framework supporting manufacturing requirements. •Provide a flexible but defined framework supporting manufacturing requirements. •Production support infrastructure defined and implemented.
Materials	•Freeze production bill-of-materials and provide initial intermodule/intermaterial sensitivity analysis. •Define final material purity and compositional requirements. •Determine proper cost vs. performance material trade-offs with ‘decision to use’ based on first-order. •Develop qualification requirements for vendors and materials. •Involve vendors in partnership relationships.

Figure 3 *- Composition of the Pilot Phase*

Process transfer is a useful metric that occurs near the conclusion of the Pilot Phase. Process transfer, usually implemented incrementally by process steps, is generally accompanied by a definition of the process parameters by which a product of a certain quality (not always optimal) may be produced. It marks the end of formal development and provides a baseline against which other processes may be measured.

Production

The defining characteristics of the Production Phase are generally well understood and almost universally accepted across a wide range of industries. As shown in Figure 4, staffing requirements, equipment and facilities, process, product and procedures markedly differ from the R&D Phase and the Pilot Phase. Typically in technology-driven companies, the overwhelming focus during this phase is on *procedure*, often at the expense of other equally important life-cycle elements. Throughout the production phase, the operation should be driven by statistical process control, and procedural issues such as rigorous documentation and process change control should be weighted heavily. At this point, process decisions are made on the basis of data, not the intuition of researchers.

Production Phase

Staff	•Sustain and continually improve the ongoing production operations. •Technical staff 90% engineering and 10% hard science- and research-oriented. •High degree of interfunctional teams. •Primary compensation based 40% individual, 60% team. •Focused on system-level events and interdiscipline interaction.
Equipment/ Facilities	•Provide a fully operational manufacturing environment for high-volume production. •Multiplexed, fully characterized production tool set running stable, frozen equipment recipes. •Tool set fully instrumented, in-situ monitored, and optimally automated. •Layout optimized for maximum output, minimal cycle time, and lowest manufacturing cost.
Process, Product, Procedures	•Running a frozen manufacturing process flow. •Process driven by statistical controls. •Manufacturing process model only changed through continued characterization in incremental steps and market-driven demand changes. •Fully characterized products running in high volumes. •Final production product specifications frozen. •Provide a stable, defined framework preventing variation. •Production support infrastructure optimized.
Materials	•Bill-of-materials components optimized for cost reduction and supply consistency. •Low cost materials substitutes investigated and qualified. •Cost vs. performance trade-offs controlled tightly. •Vendors become full partners and part of the manufacturing flow.

Figure 4 *- Composition of the Production Phase*

If the process and product are to be frozen at this point in the life-cycle, it follows that the technical staff, including support functions such as information technology and procurement, must be adjusted accordingly as well. This does not mean, of course, that the process engineers who have supplanted the research-oriented staff of earlier phases should lack creativity. On the contrary, their creativity should now be focused on troubleshooting and *fixing* the existing process, not changing the process. In a similar manner, the flexibility demanded of a purchasing manager during R&D is no longer an asset, and that person's ability to implement an active program to include raw material vendors as full partners now becomes critical.

Key Success Drivers

A careful analysis of those technologies, facilities, and products whose transition from R&D to manufacturing *has* been successful reveals a number of remarkable similarities. It is useful to review these similarities with respect to the underlying supporting factors which drive maturation and phase transition utilizing them to develop a “roadmap” for future successes. It is critical that corporate managers be given the tools and the insight to make accurate assessments as progress is made through the natural life-cycle so that optimal orchestration of the four areas listed above can then be shaped accordingly. This discussion offers a detailed review of the key drivers, which enable promising new concepts destined for high-technology manufacturing, to economically evolve into large-scale production.

As a technology, facility, or product progresses through its maturation life-cycle, it is important to understand how the critical success factors constantly change. For example, during the R&D Phase, optimizing cycle-time on specific process experiments needed to verify the baseline process is the primary WIP (Work in Progress) movement goal. During the Pilot Phase, however, this focus needs to shift toward manufacturing priorities enabling process integration, process flow qualification, and equipment certification. Finally, during the manufacturing ramp into the Production Phase, sheer product output, factory overall product cycle-time, and operating costs become the primary drivers. There is risk in misreading the priority success factors that dominate at any given time in the life-cycle.

Manufacturing Drivers

A successful factory understands and balances critical “Manufacturing Success Drivers.” These include Product Output, Product Performance, Constraint Equipment Uptime (Reliability), Constraint Equipment Cycle-Time (Run-Rate), Constraint Equipment Utilization (Effectiveness), and Production Yield. These drivers are in turn influenced by several factors, all of which evolve throughout the life-cycle.

Equipment Capabilities

Equipment capability requirements vary throughout a factory’s life-cycle. During the R&D phase, flexibility and multi-functionality are at a premium, whereas during the Prototype (Ramp) Phase, user-friendliness and reliability become the critical considerations. During the Production Phase, controls instrumentation, optimal automation, and in-situ process monitoring become the key attributes.

Equipment Maintenance

Leveraging tool performance and enhancing operability and serviceable life are critical. This is necessary due to the complexity and cost for large scale, high-volume production equipment such as 300mm production tools, which must be specified, constructed, and maintained for successful operation. Today's manufacturers must be prepared to plan and fund for the staffing, training, and management of high-performance equipment maintenance teams.

Equipment Characterization/Monitoring Methodologies

The most fail-safe method to insure equipment suitability for manufacturing is to establish a thorough equipment specification for the tool vendor. In addition, setting a clear set of acceptance criteria, which include both performance and equipment metrics, is vital. Once equipment characterization/initial process parameters are established, a repeatable method for equipment and process monitoring must be determined. The instrumentation for these process controls (equipment and process metrology) must be designed into the tools and systems from the outset, and not added belatedly as an afterthought.

Constraining Tool Utilization Improvements

Identification and elimination of key production capacity bottlenecks is mandatory in managing an aggressive manufacturing ramp. Throughout a manufacturing ramp, the constraining tools will shift and process/production simulation can be utilized to preview the constraint sequencing. A balance between equipment characterization, equipment upgrade/modification, engineering process development/optimization, and production material needed for baseline establishment must be actively directed.

Run-Rate Prototyping Strategies

We have found it most valuable to implement specific programs designed to "shake-out" portions of a manufacturing line prior to their required full-capacity utilization. Many problems which occur during a production ramp are not detected until the equipment and process are exercised at capacity level rates. Areas specifically vulnerable to this phenomenon are mechanical repeatability during maximum cycling, process control, and optimized preventative maintenance requirements.

Factory Ramp Up/Capacity Planning

A factory moving from the R&D Phase and initial start-up into the Prototype/Ramp Phase is at its most critical juncture. Many yet unseen hurdles pertaining to staffing, materials, equipment, and process emerge during this stage. Setbacks at this stage can most immediately manifest themselves as failures to attain the technical milestones required for continued project viability.

Simulation/Factory Layout

Full factory floor layout and production simulations are imperative to prevent unforeseen factory floor design flaws. It is difficult to overstate the importance of these tools in the planning phase. Without these tools there is a significant risk of improperly matched operating capabilities, poorly designed manufacturing flows, and restricted options for future expansions and process changes.

Production/Operating Plan Generation and Risk Analysis

It is vital to understand the pertinent variables required to build a self-consistent, multi-year operating plan including the materials, labor, and equipment input components as well as the product output and associated costs. All of these factors must be incorporated into the development of an operating template. In addition, realistically understanding the associated risks and developing early contingency plans is critical to reducing the overall time-to-independence viability for the business.

Manufacturing Benchmarking

It is advantageous that a project management team has functional, practical experience with manufacturing companies from a low-volume, custom product emphasis as well as a mass production, lowest-cost focus. That enables a team to reliably compare performance actuals with realistic milestone goals, and to effectively judge a reasonable rate of progress leading to successful full capacity manufacturing.

Business/Enterprise Success Drivers

There are three fundamental parameters that dictate the cost effectiveness model for many emerging high-technology production operations:

- Product performance
- Manufacturing yield.
- Product durability, *i.e.* reliability.

Any comprehensive program must focus on these parameters, and map out a plan to achieve economic viability milestones in each parameter. Underlying these parameters also exists a set of factors which must be closely managed throughout the life-cycle.

Technology Maturity

A technology survey early in a product development program is exceptionally important to expeditiously scale up processes whose technologies and performance are already proven. As a result, the manufacturer gains insight into which processes have a high probability of success through direct scale-up, and which processes must be piloted so that more process knowledge can be gathered.

Processing Step Interaction

High-technology manufacturing involves multi-step processing in which each unit operation may be quite dependent on the preceding step. Accordingly, process experiments must be designed to take into account both dependent and independent variables, and how those variables will interact during production scale-up. Failure to do this properly would threaten the ultimate optimization of the process parameters.

Process Characterization

In order to communicate effectively with potential equipment and materials vendors, a process specification for each process step must be developed. The only way to establish an effective definition for both materials suitability and equipment performance is to characterize the process sensitivity ranges for individual process steps as well as for the integrated process flow. By focusing early on process characterization, significant time and costs can be saved during the subsequent production ramp, where both customer dissatisfaction and a growing expense base are significant negatives.

Process Monitoring

It is important to attend to instrumentation and monitoring considerations during the early Prototype Phase, since that is when many critical variables are identified. Many of the successful products appear to be overly instrumented and controlled at the Pilot Phase, but this is often necessary to adequately define the critical variables at each step as well as *interdependent variables* between the process steps. This is also an appropriate time to develop a strategy to properly monitor and eventually control the various process steps in the Production Phase. The focus needs to be on reducing variability first, and then optimizing the parameter targets.

Task Force/Technical Program Management

In many cases, a "Tiger Team" approach to program management must be taken. One case history of this approach enabled a cross-functional team of engineers, scientists, process technicians, and maintenance technicians to successfully increase equipment uptime by 50% and increase the effective run-rate by 150%.

Related Technology Understanding

There is much technology and manufacturing methodology that is common to the production of such varied products as semiconductors, flat panel displays, fine chemicals, photovoltaics and architectural glass coating technologies. It is valuable to draw upon the knowledge and experience that "cross pollinates" among those industries. This broad awareness helps identify the "best of the best" technologies and strategies from these different industries related to manufacturing practices and methods, overall factory productivity optimization, instrumentation and controls, and familiarity with equipment manufacturers.

Expense, Capital, and Cost Management

The ability to construct a logical, realistic operating budget, with a clear understanding of the risk management which must be utilized to successfully guide the applications of resources, is critical not only during the implementation portion of a manufacturing start-up business but also during operating plan development. Without real knowledge of the potential resource hurdles a production start-up will encounter, a realistic, executable business strategy is extremely difficult to construct and implement.

Materials Procurement/Vendor Sourcing/Partnering Strategies

In some cases, vendor sourcing may take the form of a partnership between a manufacturer and its suppliers. This is particularly important in developmental processes to which the equipment manufacturer brings a depth of process experience. Vendors, like the clients they serve, want to be associated with success. The qualification procedure works in both directions, and equipment manufacturers and material suppliers generally want to be an interactive part of the team. Also, much of the equipment required for high-technology manufacturing is long lead and requires significant time for start-up and debugging. The procurement process must be integrated into the overall plan early in the process.

Organizational Alignment-Design/Institutional Skill Identification

The identification and management of the specific technical/operational talent required is critical for factory success. Part of this process includes the ability to map the current institutional skill-set with the strategic organizational goals and objectives identifying core competency gaps. This process requires an understanding of in-depth organizational dynamics as well as practical, high-level operational management experience.

Change Management

The phase transitions experienced in a manufacturing ramp are dramatic and varied. Consequently, the methodology by which one manages, leads, and directs an organization through these phases becomes imperative to success. The economics of capital costs and time required to re-tool an organization throughout this maturation process would be prohibitive. For that reason, it is important to apply an optimal deployment of resources at the outset. Achieving this requires transition of process control from research scientists to an emerging plant engineering organization; and the transfer of equipment sustaining and maintenance responsibilities from the engineering organization to a focused equipment maintenance group.

Life Cycle Schedule

The attached Technology Product Industrial Life Cycle (Figure 6) provides a hypothetical time-line for the three discrete phases in the life cycle of a technology-driven product. While the durations shown are of course dependent upon the complexity of the technology involved, the actual linkages among the individual phases provides a historically accurate model. In some cases, there have been specific products which have been accelerated quickly through one or more of the phases. Even though it may appear that the phase has been "skipped," the transition in staff, materials, procedures, etc. is still necessary to establish the groundwork for future success. These transition phases may be apparently short in duration, but they are a necessary "stepping-stone" for future generations of product(s) that will ensure successful continuity.

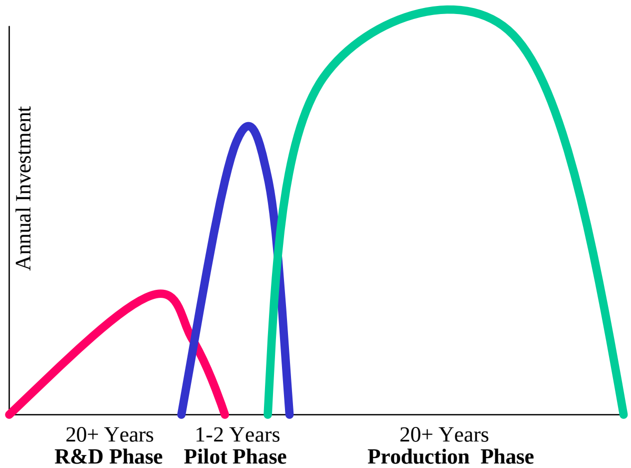

Figure 6 *- Technology Product Industrial Life Cycle*

The Authors - Mr. Causey is a member of the Advanced Technology Group for IDC, a leading provider of design and construction services for industrial clients worldwide. His areas of expertise include microelectronics manufacturing, flat panel display technology, fiber optic manufacturing, specialty fibers and composites, photovoltaic processing, vacuum coating operations, and continuous and batch high temperature processing. Mr. Causey has been a central figure in the development of conceptual processes and equipment engineering strategies for new high-technology manufacturing enterprises. His involvement in such efforts encompasses development of specifications, data sheets, functional requirements for a range of process and process support equipment, cleanroom layouts, process utility matrices, and overall process flow concepts.

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