Application of Commercial Best Practices for New Technology Development within the Constraints of Defense Contract Funded R&D

By

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ABSTRACT

This thesis explores the application of commercial best practices for new technology development within the constraints of the defense contract funded research and development (R&D) environment. Key elements of successful new product development (NPD) are identified from the literature, including strategic fit, organizational structure, financial considerations, and use of Stage-Gate™ type processes. Constraints, conflicts, and issues which arise in the defense contract funded R&D world but not in the commercial world are explored, including a multiplicity of funding sources, short funding cycles, and ambiguous ownership of go/kill decisions and gating criteria. Existing defense industry Technology Readiness Level (TRL) and new Engineering and Manufacturing Readiness Level (EMRL) and Manufacturing Readiness Level (MRL) metrics are evaluated as potential gating mechanisms relevant to the defense industry. We determine that the EMRL and MRL metrics meet many of the criteria necessary for good NPD gates, but they must still be supplemented by commercial best practices such as ensuring strategic fit, good organizational structure, financial attractiveness and competitive evaluation. A resulting combined framework of "soft" and "hard" criteria is applied to a case study of an optical component currently under development with contract R&D dollars. The output of this study helped to shape strategic decisions regarding this component and to identify next steps in the technology maturation roadmap. Application of these frameworks in defense should ensure that future successful technical performance is also supported by an appropriate business strategy and by a process maturation plan for manufacturing consistent with the upcoming Department of Defense (DOD) MRL requirements.

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Table of Contents

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List of Figures

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List of Tables

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Chapter 1: Introduction

The defense industry today is looking for ways to improve new product development processes in order to deliver new technologies on schedule and within budget. Recent studies have shown that use of commercial industry best practices for new product development, especially addressing manufacturing concerns early in the technology development timeline, correlates well with meeting cost and schedule targets [1]. This has driven some changes in defense policy to build a knowledge-based process for product development decisions into the defense acquisitions structure. On the positive side, it is recognized that the policy itself has been updated to reflect the recommendations of the Government Accountability Office (GAO) to incorporate more commercial best practices into technology development requirements [2]. On the down side, it is also recognized that "acquisition officials are not effectively implementing the revised acquisition policy's knowledge-based process," so the desired improvements in outcome are not yet being realized [2].

On the whole, the approach taken to date has been primarily a top-down approach: it operates on the premise that to achieve use of commercial best practices in technology development for the defense industry, mandates must flow from the Department of Defense (DoD) through program offices to contractors performing the work. This has resulted in "roughly 11 revisions to DoD's acquisition policy between 1971 and 2005" [2]. However, "despite these efforts, defense acquisition programs in the past three decades continued to routinely experience cost overruns, schedule slips, and performance shortfalls" [2].

This observation prompts one to question whether a top-down approach is the most effective means towards implementing commercial best practices into new product development for defense. Put another way, what could be the effect of independently applying commercial best practices for new product development from the very early stages of technology creation, on the part of the contractor, in a bottom up approach? What steps can government contractors take on their own to emulate commercial best practices to ensure optimal performance on the contracts they win? How should they adapt commercial best practices to meet constraints of the contract-funded research and development environment? Finally, as DoD policies are slowly changed to mandate more use of commercial best practices from top down, how can contractors best ready themselves for upcoming changes?

In this thesis, we will explore these questions as they apply to early stage technology development using defense contract research and development (R&D) dollars. We will first outline in Chapter 2 key elements of successful commercial new product development as studied in the literature. In Chapter 3 we will identify constraints or conflicts which arise in the defense contract funded R&D world but not in the commercial world, and their implications. We will also identify practices which are directly addressed by some of the top-down changes being made in the defense world. While commercial best practices recommend using technology gating mechanisms such as Stage-Gate™ processes [3], [4], in Chapter 4 we will consider several approximately parallel mechanisms developed by various government funding agencies: existing Technology Readiness Level (TRL, [5]) and new Engineering and Manufacturing Readiness Level (EMRL, [6]) and Manufacturing Readiness Level (MRL, [7], [8]) frameworks will be compared in order to provide a recommendation of the most suitable metric for a given program.

Finally, we will examine how the resulting best practices might be applied, using a case study of a technology currently in early stage R&D. On the business side, in Chapter 5 we will explore issues such as strategic fit, organizational leadership, and financial attractiveness, and how these may shape future development paths. On the technology development side in Chapter 6, we will evaluate elements of the technology against MRL metrics to identify potential critical issues such as sole/foreign sourcing, design maturity precedence requirements, and process control capabilities. It is recognized that "up to 85% of costs are committed during design and development" [8] so this is truly an opportunity to explore how early in the process recommendations could be made to impact success at later stages.

Through this bottom up approach, we will seek to identify key issues which can impact long term success of a technology development project. We will also try to evaluate the longer term implications of the top-down approach being proposed through the GAO and DoD. Specifically, if a product development team uses the manufacturing readiness framework, will the contractor be better positioned in the long run? Is this framework sufficient? If not, what other types of concerns should be addressed during technology development? Learnings both specific to our case study and applicable to the defense industry in general will be summarized in Chapter 7. We hope through this work to provide a case for taking a pro-active approach to technology development and manufacturing readiness in defense contract work, independent of the pace of official DoD policy changes.

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Chapter 2: Commercial Best Practices for New Product Development

Commercial new product development (NPD) and how to do it well has been the subject of extensive research for several decades, especially as globalization has increased the number of competitors in the market and as the speed of technological change has increased. Although the products developed within the defense industry may not have as extensive a customer base or as broad a market appeal as products in the commercial sector, it is quite reasonable to expect that using practices which lead to successful commercial products will also lead to successful defense products (and firms). Indeed, GAO studies have shown that DoD programs which most closely followed commercial best practices "had better outcomes" in terms of schedule and cost [1]. Thus it is well worthwhile to consider how a defense contractor might incorporate commercial best practices into new technology development efforts in order to reap benefits both for the contractor and for the DoD. What are the key elements to NPD success? What modifications may be needed to adapt these to the defense environment? How do commercial best practices compare to the best practices being recommended by the GAO?

In this chapter we will review commercial best practices for new product development. These can be separated into critical success factors from process and product standpoints. On the process side, we will also review characteristics leading to high quality execution of Stage-Gate™ processes. Finally, we will review recommended must-meet criteria for early phase milestone reviews. We will use our learning here as a foundation for the next chapter, in which we will identify constraints which are likely to affect implementation in the defense industry.

2.1 Critical success factors

To first order, success in new product development can be simplified to "doing projects right" and "doing the right projects," according to Robert Cooper, author of Winning at new products: Accelerating the process from idea to launch [3] and Product leadership: Creating and launching superior new products [4], from which books the bulk of this chapter is drawn. In these works, Cooper has synthesized extensive research identifying how successful firms do new product development and how other companies fail at similar efforts. "Doing the right projects" means selecting products for development which meet key strategic and market criteria and which demonstrate technical and financial feasibility. "Doing projects right" focuses on elements of execution: these include issues such as organizational structure, leadership, and the use of frameworks such as the widely adopted Stage-Gate™ process for new product development. Cooper uses these two broad groupings to separate critical NPD success factors into elements of process and elements of product. Although it is tempting to focus on elements of product first, a key learning is that firms which do well have an appropriate NPD process in place, which allows them to identify which projects or products are in fact the right ones to pursue.

2.1.1 Commercial NPD process success factors

Studies of successful firms have shown that their NPD processes share six primary characteristics, summarized in Table 2-1. First, good NPD processes emphasize early and ongoing evaluation of products and projects, both before work begins and as the project proceeds. The main two causes of new product failure are "inadequate market analysis" and "product problems or defects" [3]. Both of these causes can be mitigated by making sure that the process includes detailed analysis of market and technical issues before a project is given a green light and significant resources are spent. For this reason, up-front market and technical homework, integration of the voice of the customer, and clear product definition are the top three criteria for a good NPD process (see Table 2-1, adapted from [4]). Markets can change, unforeseen technical hurdles may arise, and uncertainties at project inception may be resolved either positively or negatively as time goes on, though, so it is also important to have an ongoing evaluation of the firm's project portfolio. Good NPD processes thus include specific decision points at which projects are reviewed and at which projects are terminated: having and using "go/kill" decision points is the fourth critical success factor. Studies show that for each successful new product, there are 1.3 to 1.5 product launches, three to four products in development, and seven to eleven new product ideas [3], so it is clear that there must be an appropriate culling method to narrow the number of projects in the NPD funnel (see Figure 2-1). Costs and resource requirements typically increase at each development stage, and down-selection between projects allows firms to concentrate their resources on projects with the best probability of success [9].

1	*"Management emphasizes doing up-front [market and technical] homework...before projects enter the Development phase"*
2	*NPD process "emphasizes a strong market orientation" and "the voice of the customer"*
3	*Product definition occurs "before Development work begins"*
4	*The process has clear go/kill decision points and projects are actually killed.*
5	*"Quality of execution" is emphasized*
6	*The NPD process is "complete or thorough ... but ... also flexible."*

Table 2-1. Critical NPD process success factors, from [4].

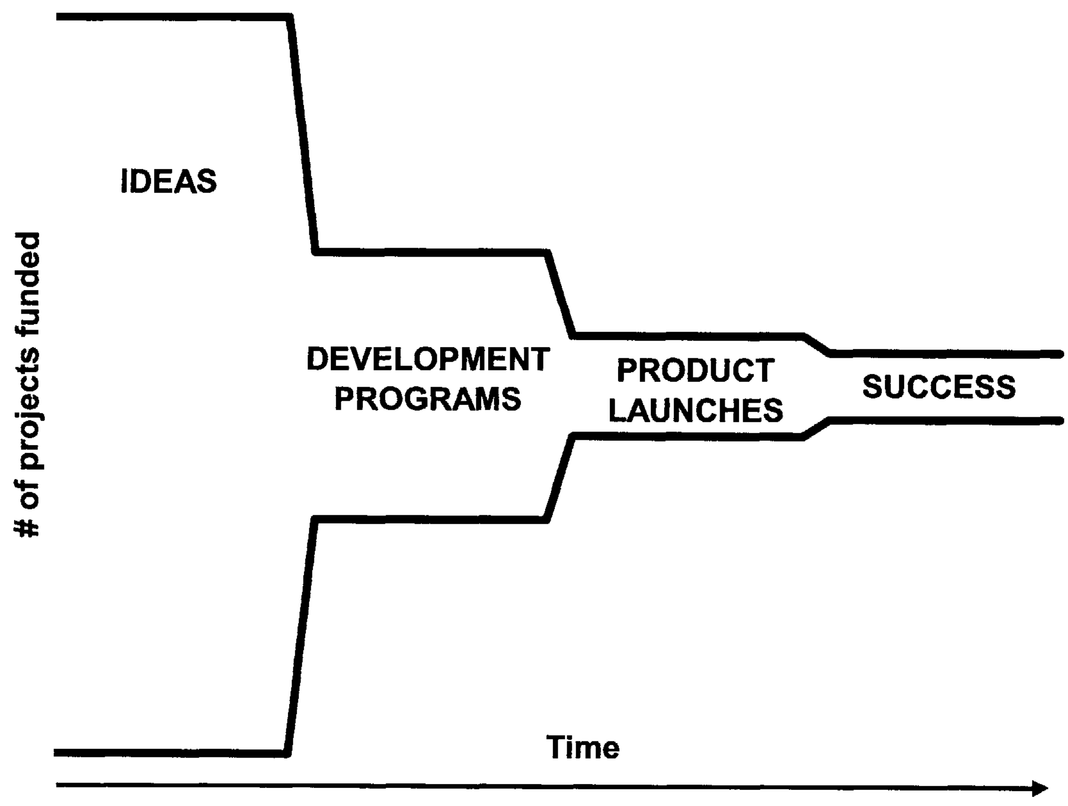

Figure 2-1. Schematic project down-selection funnel in top commercial firms.

All of the above point to the need to have a process and to stay with it, which leads to the fifth and sixth critical success factors for good NPD processes: executing projects and process well, while at the same time incorporating enough flexibility into the NPD process so that the process itself does not become a barrier to success. These two success factors go hand in hand. First, a focus on quality of execution, making sure that corners are not cut even when time and resource pressures make cuts tempting, helps to avoid the pitfall of accidentally skipping over key elements such as the up-front market and technical investigation. Second, the emphasis on flexibility recognizes that there is competition for time and resources and the NPD process should not consume these in a non-value added manner or in an exclusive manner. Where resource competition does require compromise, flexibility in the process may be allowed, for example in the timing of a specific step, but decisions must be made consciously with recognition of the associated risks, and a plan for subsequent recovery or accommodation. This last element is in fact the natural evolution [4] after a firm has successfully met the first five criteria, not a justification for skipping them as some might hope. Formal new product development processes started as fairly rigid "checklist" type first-generation processes in the 1960s which focused on ensuring task execution and completion within functional domains. These evolved into second generation Stage-Gate™ processes emphasizing cross functionality and integration across the organization (e.g., marketing, engineering, and manufacturing), up-front work, and best practices. Companies which have successfully implemented second-generation processes have been able to learn from these to make conscious decisions for streamlining or parallel processing in their current programs, leading to what are now called third-generation processes. These firms' proficiency comes, though, from the years of practice with the more formal approach, just as the skill and proficiency of a performer or an athlete may come from hours of drilling and practice. As cautioned in [4], companies should "strive first for a basic and effective new product process" before advancing to a more flexible process. They must learn to "walk before [they] run."

2.1.2 Commercial NPD project success factors

Once a firm has a good process in place to facilitate execution of NPD projects, individual firms and individual projects may still succeed or fail. Across firms, there is competition in the new product marketplace, while within firms the NPD process itself will involve culling of projects. Studies have shown that successful technology development efforts also share several critical success factors, both internally with firms, and externally facing the market. Cooper has synthesized these to seven critical success factors of successful firms, reproduced in Table 2-2. Of the seven factors, four seem to be primarily inwardly (*I*) focused or controlled: resource commitment, organizational structure, design and climate, product synergies with firm core competencies, and speed of execution. Three factors focus on the product relative to external (*E*) competition: having a superior product, having a broad international focus, and being sold into an attractive market.

1	*Resource commitment to the NPD project from senior management*	*I*
2	*Having a superior differentiated product that delivers unique benefits and better value to the customer*	*E*
3	*The right organizational structure, design, and climate*	*I*
4	*Look to the world product: an international orientation*	*E*
5	*Leverage core competencies: Synergy with the base business and its strengths (vs. "step-out" projects)*	*I*
6	*Use market attractiveness for project selection and prioritization*	*E*
7	*Speed, without sacrificing quality of execution*	*I*

Table 2-2. Critical NPD project success factors, adapted from [4].

2.1.2.1 Inwardly controllable elements of success

The most important internal factor is having resource commitment from senior management. Adequate staffing and budget must be provided for critical new product projects. This means not only providing resources, but also ensuring that those resources are available to support the project. On the people side, personnel must not be assigned to too many projects such that they become overwhelmed and cannot support any of them well. On the financing side, sufficient resources must be committed at each phase in the NPD process to enable the team to reach the objectives of that phase.

The resources committed by senior management must then be fed into the appropriate organizational structure, design, and climate. Here, key elements of success include "having an assigned team of players" who form a "cross-functional team" with a "dedicated," "defined," "empowered" and "accountable" team leader. Better success comes from having a leader who is "responsible for the project from beginning to end," not just during one project phase. Similarly, better success is correlated with this project leader being "dedicated to [only] one project at a time." The team, however, must bring together views from across the organization, including "multifunction (and outsider) representation on development projects from the start" [10]. As an example, a team might include representatives from R&D, engineering, marketing, finance, and operations. The team can be organized in many different ways. These include (1) functionally, or (2) in a functional matrix, in both of which cases authority remains with a functional head, (3) in a balanced matrix (e.g., with authority shared between a project manager and functional heads), or (4) in a project matrix or (5) a project team, in which latter cases authority primarily rests with the project manager and functional managers only provide personnel. Success rates are much higher for the three latter forms, while the functional approaches tend to underperform in terms of schedule, cost, and technical performance [3]. Finally, projects which are structured to have frequent communications, formal and informal, do better. Formally, team members meet for project updates and progress reviews and are kept apprised of the state of the project as it goes through the NPD process. Informal communications are facilitated by co-location, preferably setting up team members to work within 100 m of one another [4].

Successful firms also develop products that are synergistic with their core competencies and strengths, and which support their base business. Synergy can come from both technological and marketing arenas [4]. Technologically, the product should build on existing skills, technology, and resources, including any existing manufacturing or operations base. Market-wise, the product does better if it fits well into the existing sales and distribution channels of the firm, and can utilize existing market resources. Conversely, products which are "step-out" or new-to-the-firm products tend to do quite poorly. Cooper reports failure rates as high as 77% when both marketing and technological fit are poor, and failure rates of 67% and 59% when one of technology fit and marketing fit are poor, respectively [4]. The highest success rates accompany projects with at least moderate marketing fit and moderate to good technology fit.

Finally, the last internal factor correlated with product success is speed, provided that quality of execution does not suffer. Here, speed is translated into an ability to be one of the first movers in the market, ideally with the notion of capturing more value. Research shows this to be true, but also shows that second and third movers in the market may still retain high success rates and positive profitability [4]. Rather than emphasize speed for its own sake, Cooper prefers to emphasize quality of execution which will translate into faster speed to market. By doing things right the first time, building in up-front homework, voice-of-the-customer, and cross-functional inputs, a team can avoid having to repeat poorly executed steps later in the process. Speed is thus a *result* of a well executed process, not a goal in and of itself.

2.1.2.2 Externally related elements of success

We have focused to this point on success elements which are at least in theory somewhat controllable by the firm itself. We turn now to the external factors which correlate with new product success. Here, the firm still has an internal choice to make, in terms of whether or not to pursue a particular project or product, but external factors can determine whether or not the product under consideration is likely to be successful.

The most critical external factor is, of course, having a product which is truly superior and unique *in the eyes of the customer.* This means the product or technology "meets customers' needs better than competing products," provides them with better quality, gives them access to "unique benefits and features," and "solves problems with competitive products." The product should "reduce the customer's total in-use costs" and have at least some "highly visible benefits." Innovation and novelty do enter into criteria for unique, superior products, but their importance falls behind the six factors listed above. Note also that the relevant perspective in all evaluations is that of the customer. Using a "technology push" approach, in which a firm invents a technology or a device, deciding internally what it is the customer wants, is in fact one of the two most-common causes of failure [4]. Convincing firms that technology push is a poor strategy, however, is clearly a challenge: despite the fact that it delivers only "mediocre performance," about one-fourth of businesses choose to pursue a technology push approach [3]. Although payoffs in some cases can be high, neglecting market orientation leads to targeting unattractive markets, with "little fit, synergy, or focus in the types of products and markets exploited" [3].

Market importance is also emphasized in the other two critical external factors: having an international "look-to-the-world" product, and selecting products based on market attractiveness. Although designing for a global market may be less relevant for a defense contractor who typically designs only for one customer (the U. S. Government, and perhaps sales to approved allies), it is worth noting at least one reason why having an international focus is important: products which are designed for the world market "do better abroad" *and* "also do better in the home market" [3]. Awareness of potential international competition raises the "standard of excellence" and the project team develops a product which is superior to those developed by firms with only a local focus. Finally, actual market attractiveness is important in order to target products which will yield returns for the firm. Growing markets with customer pull for the product are most attractive, especially when the product life cycle is still in growth stages. However, even products targeted at highly competitive markets are only marginally less successful than products targeted at highly attractive markets: All of the other factors, especially product superiority, quality of execution, and synergies with the business, are far more important in determining product success.

2.1.3 Quality of execution

High quality of execution is called out explicitly in critical success factors for a good NPD process and implicitly in the four internally focused critical success factors for projects or products themselves. It is consequently important to spend a bit more time to identify how firms can ensure high quality of execution in the projects they undertake. Cooper suggests that high quality of execution can be obtained by making sure that six criteria are met. First and foremost, quality is ensured by having quality control checkpoints in a gated NPD process. Checkpoints are only as good as those controlling them, however, so we must know who the gatekeepers are. The intent of gate reviews is to give a green light to projects which meet the firm's criteria for moving forwards, while making sure that projects which should not proceed are killed. Thus gatekeepers must have the authority to approve resources for the next phase of a project and must be able to understand the impact of project approval across the firm. For this reason, gatekeepers are usually members of the leadership team (criterion #2), preferably from multiple functions in the organization. This leadership team should use clear and objective metrics (criterion #3) at each gate against which all projects may be independently assessed. The criteria should be defined such that they are universal to all projects, eliminating a tendency to adapt criteria for individual projects. Likewise, specific activities and tasks are built into the process at each stage, again independent of project or product (criterion #4), to ensure that key deliverables are met for each stage (criterion #5). If the above criteria are met, the firm should be able to exit the gate review with a clear understanding of what was accomplished in the last phase, and a clear understanding of what is needed in the next phase. This in turn should help the firm to predict what resources are needed for the next phase and how these resources should be allocated. The final criterion (#6) to ensure high quality of execution is that the resulting resource allocation method at gate reviews must be effective, so that project teams may continue on to the next phase as soon as approval is given. These criteria are summarized in Table 2-3, reproduced from [4].

1	*Implement quality control checkpoints (gates)*
2	*Designate leadership team as gatekeepers*
3	*Use clear and consistent metrics at the gates (objective & proficient)*
4	*Define activities, tasks, methods, and best practices built into the stages of the process*
5	*Specify visible deliverables to the gates*
6	*Have effective resource allocation method at gates*

Table 2-3. Stage-Gate™ process elements for high quality of execution, from [4].

2.1.4 Making quality go/kill decisions

Use of go/kill decision points is frequently the weakest element of firms' NPD processes [3]. Poor evaluation criteria and prioritization processes and the momentum of a project once it has been started all lead to firms having too many projects in the pipeline, with inadequate resources to properly execute them all [9]. Ideally, using a well-defined NPD process and ensuring that projects and products are closely aligned with the success factors outlined above will produce good decisions at gate checkpoints.

However, since we have not yet discussed what specific evaluation criteria at checkpoints might be, it is worthwhile here to briefly look at some "clear and consistent metrics" which can be used to evaluate projects.

Many firms use scoring methods on a portfolio of projects, in order to determine which projects will pass to the next phase. Cooper suggests that the gatekeeping team independently score projects against both "must-meet" and "should-meet" criteria. Must-meet criteria are a series of "yes/no" criteria to which the gatekeepers must be able to answer "yes" in order for the project to proceed to the next phase. Should-meet criteria are criteria for which an answer may be given on a sliding evaluation scale, where certain characteristics are desirable, but where the absence of a feature or characteristic will not result in project failure. Thus should-meet criteria are useful for prioritization among a list of projects, as they can help gatekeepers determine which projects may have the best probability of future success, while must-meet criteria control whether a project even makes it into the prioritization phase. As we will see later, prioritizing among projects at the defense contractor firm level may appear less critical when the firm's own resources are not being put into play (although prioritization should probably still be incorporated into initial decisions on which contracts to pursue), but we do believe that using must-meet criteria is still critical for the defense contractor.

Must-meet criteria are developed by each individual firm as part of their NPD process, and are likely to be tailored to an individual firm or an industry. Still, it is possible to identify a few key criteria which will be common to all firms. Cooper suggests the seven must-meet criteria in Table 2-4 as a starting point for gate reviews in the first three stages of the Stage-Gate™ process. These parallel the success factors discussed above, in the inclusion of criteria such as strategic alignment, market need, product advantage, and positive return versus risk. They also add criteria such as an assessment of technical feasibility and the absence of show-stopper variables. These criteria become more important as the project moves to later stages, as work done in each stage eliminates more and more of the uncertainty inherent in a project at inception. According to one study, the top three criteria used at stage one are market potential, strategic fit, and technical feasibility, while at stage two they are technical feasibility, sales objectives, and product performance [9].

1	*Strategic alignment (fits the business strategy)*
2	*Existence of market need (minimum size)*
3	*Reasonable likelihood of technical feasibility*
4	*Product advantage (unique customer benefits)*
5	*Meets safety, health, environment, and legal policies*
6	*Positive return vs. risk*
7	*No show-stoppers (killer variables)*

Table 2-4. Example must-meet gate decision criteria for down-selection, reproduced from [4].

2.2 Summary

We have seen that critical success factors for successful new product development can, in fact, be defined broadly such that they are applicable to the wide range of commercial products developed by firms today. First and foremost, it is important to have an actual process through which product development is managed and funded. Projects must then be selected according to objective, measurable criteria, and their progress through the different stages of development must be monitored. At each stage, project teams should undertake specific activities using best practices. The outcome of these tasks should be specific deliverables to the next gate review, at which resources may then be approved and allocated only for projects which should truly move on to the next stage.

So far, we have seen very few elements which appear directly in conflict with models of defense funded programs, other than perhaps the idea of a "look-to-the-world" product. Thus, we are led to believe that implementation of these types of practices in the defense world should lead to improved new technology development outcomes. However, implementation of some of these best practices is constrained by the specific structure of defense contract funded development world. In the next chapter, we will explore these constraints. We will then suggest adaptations of the commercial best practices presented here, appropriate to the defense world, in order to come up with a set of comprehensive defense-relevant best practices which we may use to benchmark technology development in our case study.

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Chapter 3: Constraints on Use of Commercial Best Practices in a Defense Contract Environment

Several constraints specific to the contract funded R&D world make implementation of the commercial best practices reviewed in Chapter 2 challenging or at least complicated. In this chapter we explore how issues such as disparate funding sources, short funding cycles, financial incentives, and go/kill decision ambiguity can constrain implementation of commercial best practices in the defense world.

3.1 Management responsibility for NPD process and product

Best practices identified in Chapter 2 emphasize significant responsibilities on the part of management in the NPD process. Management is expected to support up front market and technical work, provide committed resources, implement quality control checkpoints, and designate members of the leadership team as gatekeepers. In the world of defense contract funded R&D, this leads to the question of "who is management?" In other words, who owns the responsibility for the NPD process and the product? Is it the contract funding agency? Or is it the contractor? How is the defense world different from the commercial world in this respect?

In the commercial world, Stage-Gate™ type processes help commercial companies to allocate scarce resources appropriately to the product development efforts with the best probability for commercial success, and to exit from lower performing opportunities when necessary. A key driver of this model is the fact that the entity funding new product development is also the entity which will produce the product, and which will ultimately sell (and profit from) the product. It is thus in the commercial company's best interest to incorporate manufacturability, reliability, cost, and market attractiveness assessments early into the new product development process. A firm which spends time and money up front on investments in process improvements, and thus in capability, will reap the benefits of these investments in the future [11]. As a single entity, the commercial firm has a clear incentive to develop and follow a good NPD process.

In contrast, in the defense contract funded R&D sector, the funding source changes as a program develops. Funding sources for Basic Research (6.1), Applied

Research (6.2) and Advanced Technology Development (6.3) may not be the same, and the final procurement customer is usually different. For example, initial exploration may be funded through an agency such as Defense Advanced Research Projects Agency (DARPA), a later system demonstration may be funded through the Air Force Research Laboratory (AFRL) and a final system might be procured by the Air Force. In the current procurement structure, funding for manufacturing risk assessment, mitigation and capability development are also explicitly left to the later stages of product development and early stages of production. Cost and manufacturing technology are in general not recognized to be part of the core program of the Science and Technology (S&T) community [12].

Short funding cycles add to the challenges of funding source diversity. Funding is allocated for periods on the order of one to a few years, so that each R&D phase must be authorized individually. While this provides necessary oversight and gating capability in one respect, it is also recognized by the GAO that "the acquisition environment emphasizes delaying knowledge capture and problem identification since these events can have a negative influence on obtaining annual program funding" [1]. A contractor who identifies at an early stage an issue that might only surface later during environmental testing is believed to be at a disadvantage relative to a contractor who has not uncovered a future issue, and who thus may have a rosier outlook. This is in contrast to the commercial world in which early identification of potential problems is more likely to be rewarded than punished.

Overall, diversity in funding sources has the effect of breaking the end-to-end connection between a positive final deployed system outcome and upfront work in the early R&D stages. Each funding entity "owns" its own position in the development chain, but does not tend to focus on deliverables to the next phase. Although external organizations such as the GAO continue to call for an integrated end-to-end NPD approach, in practice today all work is driven solely by the contract in hand. With limited budget resources, each funding entity has an incentive to only focus on its area of responsibility, and the defense contractor is legally bound by contract to do only the work specified in the contract. This pushes firms to work hard to deliver short term results, but means fewer resources are usually spent on developing capability necessary for long term success [11]. External "management" has effectively come to be temporary, associated with the specific contract in hand. This also splits gates into two parts. Exiting a current contract or phase successfully does not guarantee entry into the next phase, since a new proposal must be submitted, often to a new agency.

In this challenging environment, it is even more critical that management internal to the contracting firm still carry out the best practices of Chapter 2, emphasizing early market and technical work, providing resources and instituting a quality NPD process. This is because the contractor will (if successful) be involved in the product from early R&D stages all the way through to production phases, unlike the funding agencies. Improvements in performance in the early stages should yield more competitive bids in the later stages of development, which should help these firms to win the later contracts. The firm enters a positive reinforcing loop [11]. Conversely, skipping steps at the beginning will result in overruns and schedule slips which ultimately will degrade the contractor's reputation, rate structure, and ability to win new contracts. To a large extent, at least until the defense industry mandates an integrated end-to-end NPD process through the DoD 5000 series acquisition guidelines, there is an advantage to the individual defense contracting firm that takes responsibility for making sure a good NPD process is followed even in the absence of customer pull.

3.2 Organizational structure in the case of program specific development

Having the right organization, structure, and climate for NPD, including an empowered team with an accountable leader focused on delivering a well-defined product, can also be a challenge in the defense environment. In a commercial enterprise, a firm typically develops a product with appeal to a broad range of customers. Marketing identifies attributes critical to the majority of customers and the product is developed according to these criteria by a single development team. After the product is introduced to the market, some customization for specific customers may occur, but the overall form, fit and function of the product line is retained. By using a broad technology development approach, the firm matures a technology platform from which several customer needs may be met. In defense funded R&D, however, the contractor develops a product for a specific program funded by a specific agency. The same technology may be developed in parallel for one or more different government customers, but with different key criteria, usually with a discrete leadership structure, and sometimes with a discrete team structure. This is akin to a commercial firm supporting multiple product development teams each focused on a single customer. While it is still possible to have a designated cross-functional team with a dedicated team leader for each funded program, we can see that multiple simultaneous programs will likely stretch skilled resources thin. It may be difficult to maintain clarity regarding technical leadership across multiple programs and it may be difficult to maintain clear product definitions when different customers emphasize different product attributes. Advancing development of a technology platform within the confines of program-specific funding will clearly be difficult.

3.3 Implicit market attractiveness and positive returns

The financial structure of defense contracts can also work against following some NPD best practices. We saw in Chapter 2 that the NPD process should focus on market orientation and that market attractiveness should be used for project selection and prioritization. In the commercial world, this usually means that the firm verifies that the market for a new product is or will be sufficient in size and in willingness to pay so that the firm can recoup NPD investments and generate profits in the future. For the commercial firm, the larger the difference between the product revenue and the cost of goods sold, the larger the firm's profit, so the firm has an incentive to develop high yielding production processes which efficiently use labor, materials, and capital. Development program costs also directly hit the firm's bottom line: the more efficiently R&D dollars are spent, the higher the firm's overall profits. The actions of the commercial firm affect its profit margin.

In contrast, in the defense realm, profit margins are frequently decoupled from actual activity or performance, especially within early stage R&D programs. These programs are usually run on a cost reimbursement or "cost-plus" basis, not on a fixed-price basis. A "cost-plus" contract reimburses the contractor for program expenses, such as labor and materials, plus a percentage for overhead, plus a fee designated as profit. The fee paid can be (1) fixed, irrespective of the final cost of performance, (2) incentive-based, paying somewhere between predetermined limits, based on actual results as compared to initial contractual targets, or (3) determined by the customer based on performance against pre-established criteria [13]. For all of these, the contractor does have an incentive to develop processes and capabilities which will allow submission of a competitive bid. However, once the contract is won, unless the contract is highly incentivized, the contractor receives little to no benefit from yield improvements or cost reductions and individual employees working on a contract may see no benefit or reward. In fact, improving yields or reducing labor content can have the perverse effect of reducing billable hours and thus reducing the potential value of the contract. Paradoxically, if work is not completed on time and a contract extension is required, the firm can even earn a profit on the extension. An overall result of cost-plus contracting is that many programs are automatically profitable to the contractor, independent of process or product improvements, and the hurdle of market attractiveness is effectively removed.[1]

An exception to this "automatic profitability" can occur, though, when a program requires significant capital investment. In this case, the contractor has two options. In one option, capital equipment required for the program may be rolled into the cost of the program, but the equipment is then dedicated to that specific contract and may be "claimed" by the funding agency at the end of the contract. Alternatively, capital equipment may be purchased by the contractor, who then has the right to use the equipment on any contract(s) it may choose, but the costs of the equipment are depreciated over time by the firm, reducing the firm's net profits. This latter course is followed when the equipment is used to support work on many different contracts. In this case, if required capital expenditures are too high, a market may in fact be unattractive even when operating profits (before depreciation) are guaranteed. Barring an intentional decision to pursue an unprofitable market and then roll losses back into higher rates (which will put the firm at a future competitive disadvantage), the firm may be better off not pursuing the investment.[2]

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[1] It is even argued by some that this is the case for fixed-fee contracts as well, given the regulated nature of the contracting. If the firm incurs losses on a program, these are rolled up into the next rate calculation and are passed back to the customer in the form of higher rates on future contracts. Over the long term, in the words of one defense executive "It's a beautiful business. We can never lose money."

[2] It would seem that this would lead to very limited investment in capital intensive new technologies, especially if payback periods are long, which could ultimately put the country at a disadvantage. To

3.4 Weak ownership of go/kill decisions

An outcome of the disparate funding sources, short funding cycles, and built-in profitability of cost-plus contracts discussed above is that execution of go/kill decisions in the defense sector is also compromised. The industry structure effectively defers responsibility for technology down-selection to the diverse funding agencies, which choose one or more competing bidders at the different stages of development. This deferral gives defense industry suppliers the incentive to develop a technology as long as contract R&D funding is available to support it, sometimes without a strategic assessment against other technologies in their portfolios. Although we would like to believe that there are two independent potential down-selection funnels available in the defense environment, in practice it seems that often only one funnel is imperfectly active.

The primary funnel evident in the defense world is at the government level, as the number of contracts given for a specific program is reduced as the program moves to more advanced development stages. For example, for a specific program, the government may award several contracts in the concept development stage. Some of the contractors participating in this stage will be selected for the next stage, technology development. A small number, perhaps just one or two, will be selected for system development and demonstration, and one may win an award for system production and deployment. This is schematically illustrated in Figure 3-1. Note that in this model, go/kill decisions involve selection between competing firms, not within firms, and there is no filter on the program itself once it has been started. In contrast to the commercial best practices model, DoD does not make "trade-off decisions as to which programs should be pursued, and more importantly, not pursued" [15]. More programs are started than are ultimately affordable, but programs are "rarely [prioritized] for funding purposes" [16]. When budget cuts are required, "senior officials tend to make across-the-board cuts to all programs rather than make the hard decisions as to which ones to keep

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mitigate this, not-for-profit Federally Funded Research and Development Centers (FFRDC) such as MIT Lincoln Laboratory are charged to "ensure that the government has advanced technologies for defense systems." FFRDCs operate under the same cost accounting principles as universities, under which capital expenditures are expensed. The goal of the FFRDC is to "do the most significant work [they] can do" with an equipment base distributed over multiple programs. FFRDCs do not compete with the private sector and do not respond to Broad Area Announcements (BAA), though, so once a program is in the private sector, it remains there [14].

and which ones to cancel or cut back" [17]. Also, the number of firms at the starting point in the funnel has dropped. Consolidation in the defense industry has reduced the number of prime contractors from more than twenty in the mid-1980s to only about six today [15], so the funnel itself is narrower at the top than the ideal commercial funnel. In some cases, there is only one contractor who can produce a component, and who can thus "hold [a program] hostage" [16]. Finally, defense funding is also impacted by the Congressional appropriations process which can add or strike programs outside of the recommendations determined by the services, resulting in projects that "may or may not serve the [DoD]'s interests well" [12]. Overall, these considerations lead to a conclusion that go/kill decisions on the DoD side exist, but operate imperfectly.

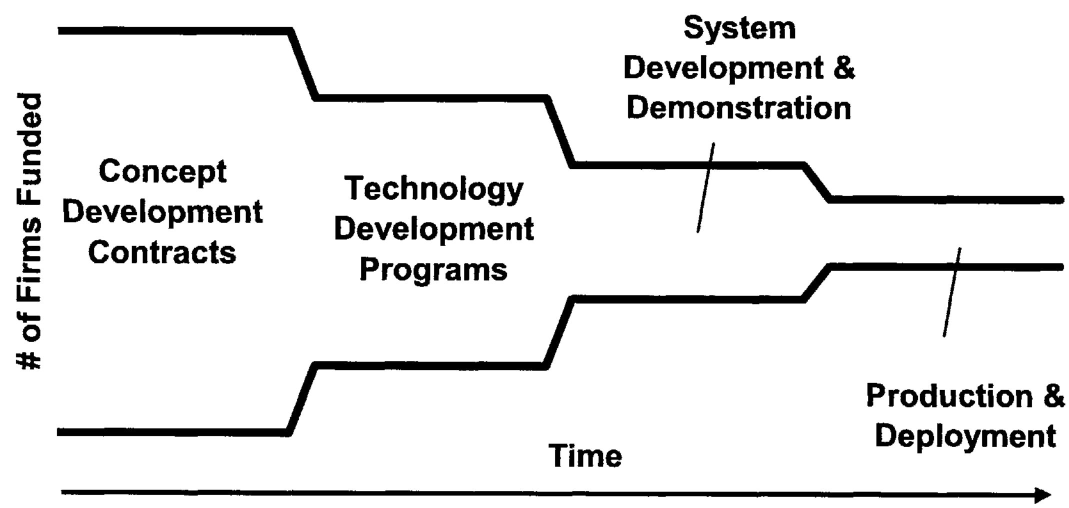

Figure 3-1. Schematic down selection funnel in defense contracting.

The second funnel which could and should be operating in the defense R&D world is the funnel internal to a defense contracting firm. It is the firm's responsibility to decide which programs it should continue to pursue through each stage of development. To a certain extent, by submitting a bid for a successive stage of a program, the defense contractor claims to be able to deliver the project success factors discussed in Chapter 2 (see Table 2-2) to the funding agency. A bid for a program signals that management has committed resources, believes in product superiority, has structured the organization appropriately, and sees the project as consistent with its core competencies. This claim is "certified" in many defense contractors through internal gating processes undertaken to review bid proposals before they are submitted to the customer, so in some respects, these decision points are active. On the other hand, with limited program funds available, there is a strong incentive for defense contractors to submit bids for any successive program stage for which they are eligible, without significant re-evaluation of the product and market at each stage. The contractor also wants to maintain workforce continuity, which again provides an incentive to bid for as many programs as possible, since maintaining the workforce requires funded contracts. Finally, contracts themselves may also include "options" for follow-on work to be completed, provided that performance is demonstrated in early stages. The intent of options is to provide the funding agencies with better visibility into future costs without commitment while technical performance is uncertain. Interviews with defense contractor leaders indicate mixed views on the obligations inherent in options: some claim that options "tie the hands" of the contractor so that they are not free to decide to discontinue work in an area while others maintain that the contractor still has this freedom. Options do seem, however, to break part of the feedback loop which should be present in the NPD process: the intent of a gated process is to use the output from each step to make sure that product feasibility and market attractiveness still hold. If progress to the next step can be triggered by activation of an externally controlled option, this check is inactive.

Overall, the existence of the DoD-side funnel seems to serve to discourage active project down-selection on the part of the contractor. It is well recognized across all industries that it is very difficult to kill projects [9]. If there is another organization outside which may take responsibility, it is tempting for individual firms to promote all projects and allow the funding agencies to make the go/kill decisions between firms instead.

3.5 Metrics and gating criteria

We can tell from the conflicts identified above that there are not in fact clear, objective, and consistent metrics which are used to gate development of new technologies in the defense sector. We can also see that such metrics should probably come from the DoD side, to be consistent with funding ownership and down-selection processes.

To improve performance to cost and schedule milestones, the DoD, the Services, and other government agencies have in fact recently developed and begun to introduce gating metrics designed to provide an objective assessment of new product maturity. These metrics include Technology Readiness Levels (TRL) introduced by the National Aeronautics and Space Administration (NASA) in 1995, and Engineering and Manufacturing Readiness Levels (EMRL) developed by the Missile Defense Agency (MDA) in 2001. Most recently, the DoD and specifically the Manufacturing Technology (ManTech) program developed Manufacturing Readiness Levels (MRL) in 2005 as a uniform metric to use across the Services. Both EMRLs and MRLs are designed to provide objective metrics against which technology maturity and manufacturing readiness may be assessed, in parallel with the technical performance metrics provided by the TRL framework. The simultaneous existence of TRLs, EMRLs, and MRLs complicates the picture for the defense contractor, though. Which metrics should the contractor follow? We will explore the three metrics in detail in Chapter 4 to understand which might be most suitable for a good NPD process and how well they meet the criteria outlined by Cooper.

3.6 Summary of constraints

We have seen above that many factors work against implementation of a quality NPD process in the defense sector. NPD process continuity is disrupted by the presence of multiple funding entities and short funding cycles. Overall technology platform development is diverted to instead develop features specific to individual programs, which can degrade clarity around product features and dilute the effectiveness of development teams and their leaders. Cost-plus financing of early R&D reduces the "market attractiveness" hurdle and increases the temptation to defer go/kill decisions to the funding agencies. Competing maturation frameworks have been proposed which may or may not be sufficient to ensure a quality NPD process. While it is still in the best interest of the defense contractor to follow a good NPD process in order to ensure quality product delivery at the end of the development cycle, this is a challenging task. The defense contractor may be able to align its interests with those of the customer by using some of the new readiness levels under development, which may serve as appropriate gating mechanisms, but we expect from our analysis here that certain best practices will need to be maintained by the defense contractor in addition to the practices which may become mandated by the DoD.

Chapter 4: Government Gating Methods: Readiness Level Metrics

We saw in Chapter 2 that good NPD processes include decision gates through which projects must pass in successive stages of development. Individual commercial firms frequently develop their own gate criteria specific to their industry or product. In other cases, industry groups develop criteria which are used across multiple firms to certify performance criteria to particular levels. Within the defense industry, a need was recognized in recent decades for standardized process improvement approaches in order to address issues of escalating costs and quality issues in several areas; several different programs have been developed to address this. For example, for systems engineering and software development, the DoD sponsored the development of the Capability Maturity Model® Integration (CMMI) framework. For technology hardware development, the National Aeronautics and Space Administration (NASA) formalized the Technology Readiness Level (TRL) framework in 1995 and this was subsequently adopted for DoD programs. Finding that TRLs did not adequately address design for manufacturability, design to cost, yield, supply chain, and other production concerns, though, the DoD revised its own acquisition policy and also gave authority to the Missile Defense Agency (MDA) to develop independent guidance for missile defense systems [18]. The MDA developed Engineering Manufacturing Readiness Levels (EMRL) in 2001. In only the past few years, the DoD and specifically the ManTech program have also developed Manufacturing Readiness Levels (MRL) as a uniform metric to use across the Services.

In this chapter, we examine the three hardware-specific metrics, TRLs, EMRLs, and MRLs to see how well these meet the criteria for good process gates outlined by Cooper. We use this analysis to see whether any given readiness level metric (generally xRL) can be used as a surrogate for a good NPD process gate in the defense industry. Are criteria for the readiness levels clear, consistent, and objective? Do they define activities, tasks, methods and best practices for the various stages of the process? Do they specify visible deliverables at each milestone? Finally, do they incorporate general must-meet requirements common to successful products?

We find from our analysis that EMRL and MRL metrics both incorporate many, albeit not all, of the features of good gating processes in the commercial world. In general, the EMRL and MRL frameworks provide clear objective criteria which can be used to judge technical progress, while the TRL framework is in general insufficient to guarantee good product outcomes, as had been noted by the DoD. Using the EMRL or MRL framework for technology development programs is therefore recommended over simply using TRLs, with the choice of metric based on the end customer until the two metrics are consolidated. We do also find, though, that the xRL metrics are in general incomplete according to the criteria of Cooper. They fit the mold of the checklist-type first generation NPD processes followed by commercial firms in the 1960s but do not yet incorporate many of the "softer" criteria also deemed critical for good NPD processes. Thus for our case-study analysis of hardware component development, we will recommend evaluation based both on the MRL metrics and the inwardly controlled success elements such as organizational structure, strategic fit, and leveraging of core competencies discussed in Chapter 2.

4.1 Technology Readiness Levels (TRLs) – NASA

Technology Readiness Levels were formalized by NASA in 1995 to provide "a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology" [5]. Technology readiness was divided into nine levels, starting with observation of basic principles and ending with "flight proof" of a system in a successful mission operation. A summary of TRL definitions, excerpted from [5], is provided in Table 4-1. Although TRLs were not directly developed for the defense environment, they have in fact been commonly used as a metric to measure technical capability on defense programs. Since 2001, TRLs were the "preferred approach for all new DoD programs" [6]. We will see below, though, that TRLs are focused primarily on performance of a single technology or system, and do not address many issues needed to produce a product in quantities larger than one.

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight proven" through successful mission operations

Table 4-1. Technology Readiness Levels, excerpted from [5].

Overall, TRLs are very generally defined by the level of complexity of the hardware (component, subsystem, or system) and the environment in which it is operated (laboratory, relevant environment, or space). They do not, however, specify clear criteria, tasks, or metrics. For example, TRL 5 is met when a component and/or a breadboard is "validated in a relevant environment" but it is not readily apparent what either validation or relevant environment mean. The more detailed explanation of TRL5 (see Table 4-2) provides a descriptive example of testing, but again does not specify deliverables which could automatically be applied to another product.

TRL 5: *Component and/or breadboard validation in relevant environment*
"At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment. From one to several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array 'blanket' that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability."

Table 4-2. Definition of TRL 5, excerpted from [5].

TRL metrics are also very limited in terms of how far out they look from technical performance of a single device. The metrics do not include any assessment of how the technology compares to competing products (is it superior and differentiated?), whether it can be produced by the supplier (does it leverage core competencies?), or whether it can be produced in a cost-effective manner (what is the cost and is there a positive return?). Thus while TRL metrics may serve to evaluate performance of a technology, they cannot be used to sufficiently evaluate a product based on the technology nor how well such a product can be transitioned into production. Finally, TRL metrics do not identify the gatekeepers, so it is unclear who controls progress through the levels. What entity certifies that a component has reached TRL5?

These and other limitations of TRLs as gating mechanisms for product development were key drivers for the development of both EMRLs and MRLs. The TRL metrics by themselves are insufficient to ensure that contractors follow commercial best practices in developing defense products.

4.2 Engineering and Manufacturing Readiness Levels (EMRLs) – MDA

The MDA supported development of Engineering and Manufacturing Readiness Levels in 2001 to address "Production Readiness" of a technology, to supplement the "Technology Readiness" assessment of the TRL metrics [6]. Specifically, EMRLs were designed to address the problem that "there is nothing in the description of [any TRL] … that requires that the technology be producible, reliable, and affordable". EMRLs were intended to be integrated with TRL assessments, in particular with later stage development programs. Five EMRL stages were defined (EMRL 1 through EMRL 5), starting after a technology has met TRL 4 or TRL 5, component or breadboard validation in a laboratory or relevant environment. Programs enter EMRL 1 at the point designated in the Defense Acquisition System (DAS) framework as Capability Knowledge Point (CKP) 1, or Milestone B. Figure 4-1 shows how EMRL stages fit into the DAS framework.

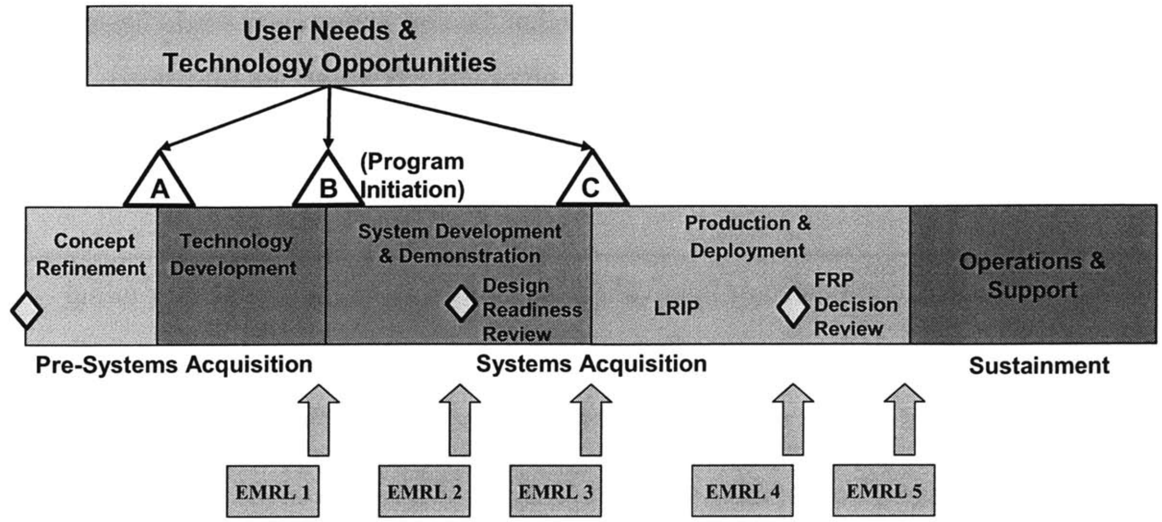

Figure 4-1. Integration of EMRLs into the Defense Acquisition Systems framework, from [20].

The EMRL methodology has evolved since 2001 to include highly quantitative metrics for design readiness and manufacturing readiness for each step in the EMRL process. For example, at EMRL 1 at least 50% of the physical and functional interfaces must be defined and at least 75% of the major subsystems representing about 80% of cost must meet the requirements of CKP 2 (Design Readiness Review) (see Table 4-3 for the complete definition of EMRL 1). Similar criteria are defined for the more advanced EMRLs. These criteria can be considered clear, consistent, and objective and to a large extent they do define activities, tasks, and methods for the process, so they meet many of the criteria of good NPD gates. A Missile Defense Agency EMRL implementation guide also indicates that gatekeepers have been at least considered within the EMRL process: although certification authorities are not identified for the EMRL assessments, they are specified for the TRL hardware assessments included in the EMRL assessments (see Table 4-4) [19]. Finally, the EMRL process introduces the key concept of precedence relationships in the work breakdown structure. Drilling down through the layers of system, sub-system, and component, each entity is required to be at an EMRL that exceeds the EMRL of the layer of the system in which it resides. These precedence relationships are designed to avoid the problems of technology development occurring concurrent with product development. If a new system is in development, the subsystems are expected to already be in low rate initial production (LRIP) and components are expected to be in full rate production (FRP), so that the new system is not held hostage to an unproven component technology. Effective precedence relations are illustrated schematically in Figure 4-2. The implications of including an immature core component in a system are also shown.

EMRL 1: "System, component or item validation in laboratory environment or initial relevant engineering application/breadboard, brassboard development."
"System, component or item validation in initial relevant engineering application and ready to enter Development Phase. Technologies must have matured to at least Technology Readiness Level (TRL) 4 or 5. Satisfying exit criteria metrics for Capability Knowledge Point (CKP)1 (Milestone B) and successful completion of system Preliminary Design Review (PDR) indicates readiness for the Product Development Phase. This is the initial level of engineering and manufacturing readiness. Technologies must have matured to at least TRL 4 or 5. At this point all system engineering/design requirements defined and 50% validated. Component physical and functional interfaces 50% defined at system level. Manufacturing processes and system level integration demonstrated. 75% of major subsystems representing approximately 80% of cost meet requirements of CKP2. Overall quality and reliability levels and key characteristics identified and established for 50% of the system. Failure modes effects and criticality analysis required for all levels. Safety assessment plan initiated. Design to Cost goals established."

Table 4-3. EMRL 1 Definition, excerpted from [20].

Level	**Certification Authority**
TRL 1	Principal Investigator (PI)
TRL 2 – 3	PI + Funding Agency Project Sponsor
TRL 4 – 6	Deputy(ies) external to the Project
TRL 7 – 9	Cognizant Development Deputy in conjunction with SE

Table 4-4. TRL certification authorities defined within the MRL framework.

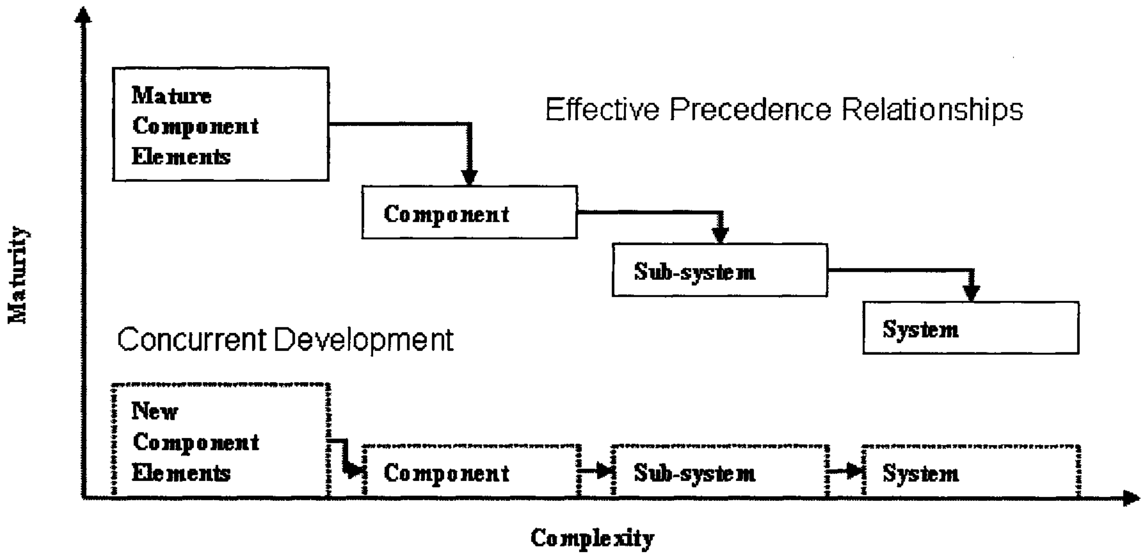

Figure 4-2. Illustration of maturity precedence relations, adapted from [20].

We can see from these characteristics that the EMRL framework is fairly well designed as a set of NPD gates, when compared with Cooper's criteria, and EMRL assessments are in fact being implemented by the MDA. We do note, however, a few limitations to the EMRL model, which are of concern. Our first reservation is that EMRL 1 is reached in parallel with Milestone B, the end of Technology Development, so it does not truly integrate manufacturing readiness with the early product R&D design phase during which most product costs are determined. Second, although the EMRL framework does provide much more objective criteria than the TRL framework, it runs a risk of going too far in the direction of checklists more representative of early NPD processes. By 2006, the EMRL evaluation criteria had grown to include 61 Program Maturity factors, and 353 Criteria and Metrics [20] and a web-based software tool was being developed for EMRLs. The developer clarified that criteria may be shortened or tailored for particular applications and that the detailed criteria are "intended for people with less experience" [21], but the risk remains that project teams may see the extensive list of criteria as bureaucratic without adding value. In the view of one senior defense scientist, such processes operate on "the fundamental tenet that people are not smart enough to do the design" and they "slow productivity to a trickle." Although this is surely not the intent of the detailed criteria, it is important to recognize that the EMRL requirements may be perceived as demonstrating a lack of respect for the people counted on to execute the EMRL process, and this perception may undermine EMRL efficacy.

4.3 Manufacturing Readiness Levels (MRLs) – DoD

Manufacturing Readiness Levels provide an alternative DoD metric which is also designed to assess hardware maturity. MRLs were developed and introduced after EMRLs but build significantly on the material introduced by the EMRL framework. As of mid-2006 the MRL framework was about 90-95% complete, and was being strongly supported within the DoD and in particular within the Man Tech division. Directives were issued in 2005 to carry out Manufacturing Readiness Assessments (MRAs) within programs overseen by the AFRL [22]. Similar assessments are being carried out within the Army Research Laboratory (ARL). The Defense Science Board Task Force on the Manufacturing Technology Program also recommended in 2006 that MRLs be incorporated into the DoD 5000 series acquisition regulations as a program evaluation requirement [12]. This proposal reportedly has Congressional support [7] and it is expected that this change to the 5000 series regulations will occur.

MRLs are designed to evaluate the "manufacturing readiness" of a product, supplementing the existing TRL framework [7]. The primary goal is to enable rapid, affordable technology transitions to acquisition programs. MRLs seek to answer underlying questions not addressed by the TRL framework, such as reproducibility of technical performance, product cost, and materials availability. Recognizing that most technologies are developed by highly skilled scientists, MRLs raise the issue "Can [devices] be made in a production environment by someone without a Ph.D.?" In answer to the question of many developers as to whether "production" and "reproducibility" are really relevant in often low-volume defense products, MRLs also specifically target performance reproducibility "in items 2 – 1000." By the time the 1000^{th} item is produced, the cumulative volume produced has doubled almost 10 times. There is in fact the most opportunity for moving down the learning curve in the early stages of production.

To ensure cost effective technology transitions, MRLs establish a structure which directly parallels the nine-level TRL structure, from as early as TRL 3. Figure 4-3 shows the alignment of MRLs with TRLs and with the DAS milestones. MRL evaluations start much earlier than EMRL assessments, including four assessments prior to Milestone B (EMRL 1). MRL proponents emphasize that early intervention is critical, since about 85% of costs can be locked in by Milestone B [7]. For this reason, in fact, pilot MRL programs today are all Advanced Technology Demonstrators (ATDs), which the AFRL hopes to take from MRL 3 through MRL 5 or ideally MRL 6 [24].

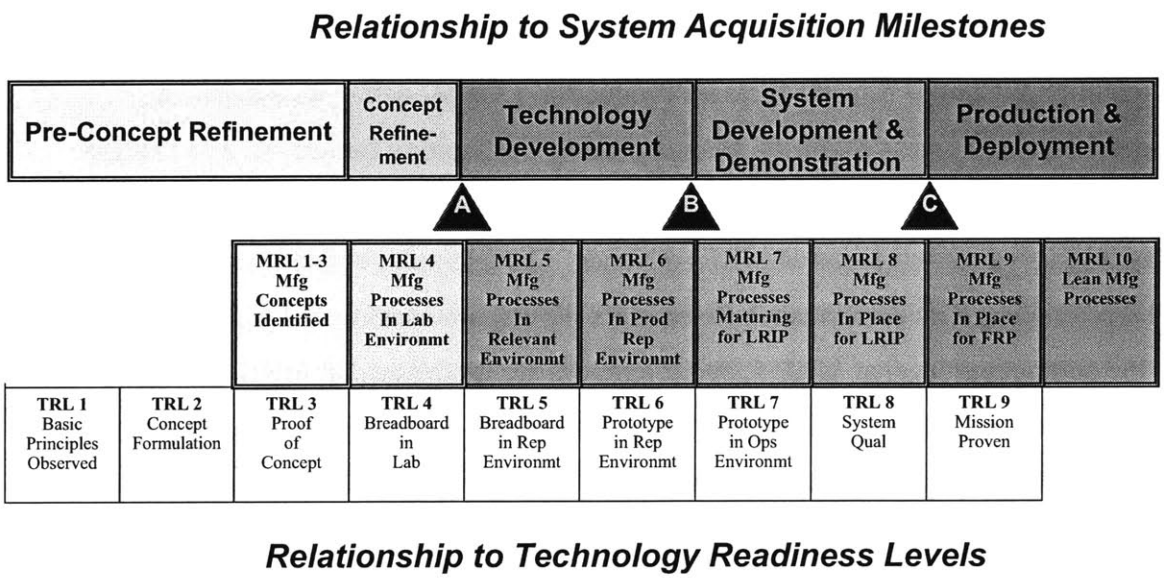

Figure 4-3. MRL relationships, reproduced from [7].

4.3.1 MRL definitions

The MRL framework is actively evolving today as pilot programs are run, so one challenge is finding specific MRL definitions. The best available sources appear to be an electronic document repository actively maintained and updated within the Defense Acquisition University (DAU) web site (acc.dau.mil) and various presentations from members of the AFRL Man Tech Division. We review the overview of the MRL metrics from the DAU website below. We then provide detailed criteria for the first few MRL gates, which are most relevant to our goal of identifying appropriate gating criteria for early stage defense contract funded R&D programs, using fairly straightforward lists covering MRL 3 through MRL 6 from the AFRL Man Tech program.[3]

[3] Much more extensive electronic checklists are also available through the acc.dau.mil website. Like the 61 Program Maturity factors and 353 Criteria and Metrics of the EMRL software tool, though, these detailed checklists may have too many "boxes to check" in them. There is a risk that the fundamental intent (and

The DAU website includes a detailed matrix of MRL requirements outlining nine primary threads with specific criteria at each MRL. Threads include Technology & Industrial Base, Design, Materials, Cost & Funding, Process Capability & Control, Quality Management, Manufacturing Personnel, Facilities, and Manufacturing Management. Each thread is then broken down into more detailed areas. For example, the Design thread addresses Producibility, Form, Fit, & Function, Unique Components, and Key Characteristics. The Materials thread addresses Maturity, Availability, Sources, and Special Handling (including safety and hazardous materials issues). The Process Capability & Control thread addresses Production Line Modeling & Simulation, Manufacturing Process Maturity, Manufacturing Technology Initiatives, and Process Yields and Rates. Each sub-thread then has specific requirements which become progressively more rigorous as MRLs advance. For example, within Design: Key Characteristics, Key Performance Parameters (KPPs) are identified at MRL 4, allocated at the component level at MRL 5, and tolerances are established at MRL 6. In parallel, the Process Capability and Control: Process Yields and Rates thread requires yield assessments on similar processes at MRL 4, identification of yield/rate issues and plans for improvement at MRL 5, and evaluation of yields in a production representative environment at MRL 6. On the supply chain side, the Materials: Sources thread requires identification of sole/single/foreign source vendors at MRL 4, planning to minimize sole/single/foreign source vendors at MRL 5, and justification for any remaining sole/single/foreign sources at MRL 6; sourcing stability is assessed and monitored from MRL 7 through MRL 10.[4] More details within each level are explored below.

4.3.1.1 MRL 3 – Identification of Manufacturing Concepts

Table 4-5 lists three fundamental requirements for certification at MRL 3, the simplest gate. The primary requirements are identification and documentation, all of which should be fairly straightforward to achieve, provided that the program also meets TRL 3. MRL 3 also starts to identify, though, areas which may contribute to difficulty or

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benefits) of the MRL framework may be obscured by the extensive detail in these documents, so we have instead focused here on the more general questionnaires being actively used today.

[4] A takeaway from the Materials section is also the reminder that prime contractors are responsible for ensuring that their suppliers also meet MRL criteria. The prime contractor is responsible for its own materials and anything it sources externally.

cost later, by highlighting areas which will need "new or significantly different resources."

MANUFACTURING READINESS LEVEL 3
TRL 3 – Analytical and experimental critical function and/or characteristic proof of concept. *Applied Research – Demonstration of technology functionality for potential applications.*
MRL 3 – Manufacturing Concepts Identified 1. Identify the high-level manufacturing flow for producing new technology 2. Identify materials / resources needed 3. Highlight key areas which will require new or significantly different manufacturing capability or resources

Table 4-5. Criteria for MRL 3, reproduced from [23].

4.3.1.2 MRL 4 – Identification of Manufacturing Processes

MRL 4 should occur with TRL 4, when performance has been validated in a laboratory environment. At this point, more detail on the processing side is required, including planning for process integration, resources, requirements, and costs. Table 4-6 provides a set of detailed questions to be answered in six primary areas. At MRL 4 planning is begun for future work, including a roadmap and cost projections, as it becomes more likely that the technology will be successful.

MANUFACTURING READINESS LEVEL 4
TRL 4 – Component and/or breadboard validation in laboratory environment *Applied Research – Demonstration and/or breadboard validation in laboratory environment*

MRL 4 – Identify the key manufacturing processes
1. Manufacturing flow concept detailed:
    a. What are the processing steps?
    b. Any processing steps new, different, or specialized?
    c. What are the manufacturing capabilities requirements?
    d. Capture detailed flow of new processing
    e. Identify manufacturing runs for critical processes
2. Process integration planning
    a. Identify interactions between independent processes
3. Resources required: capabilities, facilities, expertise, materials?
    a. Are there new resources required beyond current industrial base?
        i. Identify new processing resources
        ii. Identify new materials required
        iii. What are the requirements for new / different resources?
4. Identify key design requirements / key design characteristics
5. Identify the high-level manufacturing flow of the system level or major sub-system (integration of the new technology)
    a. Identify who could potentially produce a system that integrates the new technology
6. Roadmap
    a. Develop plan showing progression from MRL 4 through MRL 6
    b. Identify critical milestone decision points for insertion systems
    c. Show planned MRL maturity in relationship to insertion system milestones
    d. Cost targets / drivers identified

Table 4-6. Criteria for MRL 4, reproduced from [23].

4.3.1.3 MRL 5 – Manufacturing Process Development

MRL 5 begins the focus on manufacturing process development, once the technology has been demonstrated to meet performance requirements in a relevant environment (see Table 4-7). The intent of MRL 5 is to start process development so that future production of the device or system will be successful. MRL 5 thus introduces the concepts of process capability and control, and requires a test plan for manufacturing runs. MRL 5 also introduces some of the less technical issues in Cooper's criteria, such as requiring a viable preliminary business plan and a make versus buy (make/buy) analysis.

MANUFACTURING READINESS LEVEL 5
TRL 5 – Component and/or Breadboard validation in relevant environment *Advanced Technology Demonstration - Demonstration in a high-fidelity hardware-in-the-loop facility*
MRL 5 – Manufacturing processes development 1. Technology prime planning a. Process capability i. Establish process capability requirements ii. Document definition of the control subject 1. Select measurement units 2. Identify key process input variables iii. Define boundary values b. Process control i. Identify factors contributing to process variation c. Update plans for manufacturing runs of critical processes d. Update plans for manufacturing runs to demonstrate process interaction e. Review of technology manufacturing concepts and key processes f. Value stream map g. Make / buy trade-offs h. Preliminary Business plan / viability i. Facilities ii. Personnel iii. Tooling iv. Materials v. Cost and schedule projections i. Demonstrate technology capability to produce prototype item 2. Roadmap update a. Process capability and control goals documented b. Add cost projections for technology to MRL milestones c. Update key design requirements / key design characteristics

Table 4-7. Criteria for MRL 5, reproduced from [23].

4.3.1.4 MRL 6 – Demonstration of critical manufacturing processes

MRL 6 requires demonstration of critical manufacturing processes and demonstration of baseline process control by the time the system or subsystem performance is validated in a relevant environment (see Table 4-8). With this information, yield goals can be established and the business plan can be updated to include appropriate cost and schedule projections.

MANUFACTURING READINESS LEVEL 6
TRL 6 – System / subsystem model or prototype demonstrated in a relevant environment *Advanced Technology Demonstration - Demonstration of actual flight ready hardware set in a high-fidelity hardware in the loop facility under expected levels of shock, vibration, altitude, and temperature*

MRL 6 – Critical Manufacturing Processes Demonstrated
1. Process capability and control baselined for critical steps
    a. Manufacturing runs of critical processes executed
        i. Analyze process
            1. Failure modes and effects analysis
        ii. Improve and control
        iii. Yield goals reconciled with business plan costs and schedules
2. Plans for manufacturing process integration executed
    a. Critical process interactions run / demonstrated
3. Production line development
    a. Implementation planning completed
        i. Lean production plan developed
        ii. Investment requirements identified
4. Reconciled with business plan costs and schedules
5. Roadmap update
    a. Process capability and control goals confirmed
    b. Cost projections for technology updated
    c. Key design requirements / key design characteristics updated
    d. Business plans updates

Table 4-8. Criteria for MRL 6, reproduced from [23].

4.3.2 MRL evaluation

We can see from the specifications for MRL 3 – 6 that the MRL framework does in general meet many of the criteria required for good NPD gates. Criteria for each MRL are clear, consistent, and objective, and visible deliverables are specified at each level. Metrics are not quite as directly quantified as the EMRL metrics, in that MRLs do not specify a percentage of drawings to be complete, but key issues such as process capability and control are addressed. MRLs also emphasize costs and viable business plans much earlier in the process than for EMRLs. EMRL 1 occurs at the same point, Milestone B, as MRL 6. By incorporating four gating points up to and including MRL 6, the MRL framework gives visibility into possible future issues before EMRL 1. Finally, of the three frameworks, the MRL framework appears to have the broadest view of a program, looking at how the program fits within the industrial base, requiring a make/buy evaluation, and considering issues such as sole/foreign/single sourcing. By including not only the two dimensions of product and process, but supply chain as well, the MRL framework starts to approximate a three-dimensional concurrent engineering (3-DCE) approach, the use of which can provide firms with significant competitive advantage [25]. Effectively the MRL framework seeks to require that firms develop capability in multiple dimensions, so that over the long run they may "work smarter" [11].

Comparing the MRL criteria to the best practices decision criteria identified by Cooper, we see that the MRL framework does address many of the must-meet criteria. Technical feasibility is verified through the parallel TRL requirements. Market need and positive returns are somewhat covered by the business plan requirements at MRL 5 (although this may not be early enough in the process for the contractor). Safety, health, environment, and legal requirements are covered through much of the materials and manufacturing planning. Show stoppers and potential killer variables are explored through identification of critical processes, interactions between processes, and sourcing verification. Leveraging of core competencies could possibly be said to be indirectly treated through investigation of the industrial base. On the other hand, MRLs do not explicitly address strategic alignment, product advantage, or organizational structure, all of which are also required for success. MRL proponents themselves clarify that "MRLs are not designed to be go/no-go gates, but rather to assist leaders in making informed risk decisions at Milestone reviews" [7]. It will thus likely still be in the contractor's best interest to evaluate capabilities against other metrics in addition to MRL criteria.

4.4 Choosing a readiness level metric

Our review of the three hardware-specific DoD readiness level metrics has shown that either EMRL or MRL metrics, but not TRL metrics alone, could likely be used as partial gating criteria for NPD in the defense industry. In order to choose which one of these is preferable, for our purposes, we consider a few more criteria, notably the voice of the customer and the stage of technology development.

We saw in Chapter 2 that good NPD processes emphasize market orientation and "the voice of the customer." We saw in Chapter 3 that many of the gating decisions in the defense industry, particularly go/kill decisions, are also made by the customer, not the contracting firm. It follows from these two considerations that the contractor should prepare for gate reviews according to criteria which are set by the customer. Thus the choice between EMRL and MRL metrics today to a large extent comes down to the primary source of contract funding. For firms with significant investments from the MDA, it will make most sense to follow development steps consistent with EMRL metrics. Firms with significant DoD funding from AFRL or ARL will likely want to follow MRL metrics. In both cases, firms have an incentive to pro-actively prepare for EMRLs or MRLs becoming part of their contractual obligations. In fact, firms likely have an incentive to prepare for a composite of the two metrics to be instituted. It is expected that eventually the two programs will be reconciled into a single structure. This ultimate integration is evidenced by frequent use of EMRL examples in some areas of the MRL implementation guide, where the development of the equivalent MRL step (for example subsystem/component roll-up charts) lags EMRL development [26]. The most likely integration will merge the two processes where they are similar and will incorporate benefits from each that do not have a parallel in the other. For example, since the early stages of the MRL process (MRL 3 through MRL 6) are not as fully developed in the EMRL process, these would be expected to be retained. Likewise, since the EMRL framework has more explicit requirements for maturity precedence relations and has a more developed visualization metric (rollup charting), these might be expected to survive in the final system.

Our case study is focused on an optical component which has been developed on contract R&D funds from both DARPA and AFRL. The AFRL is currently implementing MRLs on ATD programs and has plans to implement these on an additional 16 programs in the near future. In fact, the "AF ManTech office is establishing the capability to conduct manufacturing readiness assessments for all hardware-intensive AFRL ATDs" [7]. All of these programs will be at levels under MRL 6. The 16 programs on the current list include two which could incorporate the technology in our case study, which today is at approximately TRL 3. Thus for our purposes, it is most appropriate to apply the MRL methodology, both for customer satisfaction and due to the early stage technology maturity. As an added carrot, AFRL Man Tech staff confirmed that ATD programs which undergo MRL evaluations become candidates for Man Tech funding. Although DoD Man Tech programs represent less than 0.5% of DoD research, development, test and evaluation (RDT&E) budget, in a competitive funding environment, more potential sources of funding are always desirable. A typical small Man Tech program might provide $1M for one year, while a larger program might provide $15M over four years. We will see in our case study that this level of funding could help to establish market attractiveness.

4.5 Summary of defense readiness level metrics

We have seen that the defense acquisition environment appears to be changing today to formally incorporate best practices for manufacturing readiness in addition to its standard focus on technology capability. The older TRL metrics are insufficient by themselves to serve as sufficient gating criteria. The EMRL and MRL metrics being developed by the MDA and the DoD are much better aligned with commercial best practices. They incorporate manufacturing design into the early stages of development where costs can be impacted the most, and they do this through the use of clear objective criteria. It is expected that one or both of these metrics will soon be incorporated formally into defense acquisition regulations. Defense contractors who prepare for this change are likely to come out ahead in development of upcoming DoD systems, and those who do this, plus integrate other "softer" commercial best practices are likely to do best.

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Chapter 5: Application of Best Practices: Case Study Analysis

With a set of best practices and gating metrics applicable to the defense industry now in hand, we will now see how these practices and metrics might be applied to a current R&D program funded by defense contracts at a major U. S. defense contractor. A technology transition study of an optical component was carried out as part of an MIT Leaders for Manufacturing (LFM) internship with an LFM partner company. The internship spanned six and a half months, from June 2006 through December 2006. The primary objective of the internship was to provide recommendations to the firm's divisional management on how to bring up production capabilities for the device under development. These recommendations were to address questions including if, how, when and where the firm should make capital investments to support production capabilities, and what best practices the firm should follow in order to ensure a successful new product transition. The best practices frameworks presented in Chapters 2 to 4 were studied to find a set of metrics appropriate to the defense industry, both for this program and more generally for other technologies that the contractor might develop in the future.

In the next two chapters we use the frameworks developed in previous chapters to both understand the state of the device development today and to provide the firm with recommendations for the future. Background information is first provided to position the technology and the development group within the organization and the changing defense environment. In this chapter, we then explore non-technical ("soft") aspects of the NPD project including strategic fit, organizational structure, financial options, and competitive position. To understand the business and project environment, we review perceived commitment levels from management and the government, and the current organizational structure. To understand fit, we explore how the proposals for new capital expenditures support the firm's strategy and how they fit with the firm's core competencies. For finances, we summarize results from financial models for four proposed investment scenarios, including best- and worst-case scenarios. Finally, we review the competitive component landscape.

In the next chapter, technical Manufacturing Readiness Assessments (MRAs, "hard" criteria) are presented for three elements of the component: one externally sourced material and two internally sourced processes. Because MRLs are new and contracts do not yet require compliance with MRL requirements, it is not expected that the component elements will be at a specific MRL. The MRAs serve broadly to identify areas for focus in future contracts.

Taken together, the results of the "soft" and "hard" evaluations were used to provide an ensemble recommendation for future steps in program development. Because of the proprietary nature of the details of the study, much of the specific data in both evaluations has been modified in this work to provide representative illustrations. Data for the study was gathered through 6.5 months of on-site work for the contractor, including interviews, surveys, site-visits, and review of existing company documentation and processing records.

5.1 Background

The device under development is an optical component first conceived of by scientists in the R&D division of the firm in the mid-1980s. The device can be used in applications including free-space optical communications and high energy laser delivery, all of which have been maturing in concurrent defense programs for a few decades. It relies on a liquid crystal optical element which is controlled by complex electronic circuits. As a liquid-crystal-based device, the component uses technology and processes common to the flat-panel and liquid crystal display (LCD) industries. These include fabrication methods and equipment common to the semiconductor business, such as photolithography and thin film deposition technologies. Like both LCDs and semiconductors, the devices require fabrication in a clean room.

Investments in the technology were funded in initial years through corporate R&D dollars and in later years through various government contracts, including funding from DARPA and AFRL. The development team achieved several "firsts" in technology development under these contracts, including demonstrating record device size at one or more times. The group or its members also received various internal and external technology and publication awards.

Recent years brought several changes to the contractor and to the development team which are relevant for our study. The most fundamental change was the dissolution of the corporate R&D division several years ago. This restructuring organizationally realigned former R&D groups under specific business divisions and physically relocated groups when the original corporate R&D site was closed. At this time, the technology was identified as a potential enabler for laser communications, a new growth area being driven by the Transformational Satellite (TSAT) Communications vision of the Under Secretary of Defense. As funding opportunities opened up in the TSAT area, the component group was realigned under a communications-focused business unit of the firm and was relocated to available clean-room space rented from another business division, about an hour's drive from the regional headquarters of the parent communications business unit. For clarity below, this clean-room location is referred to as Site A and the regional headquarters location for the communications business unit is referred to as Site C. Most of the R&D group was physically located at Site A, while business division management, program management, and systems integration staff were located at Site C. The R&D group in Site A received government contracts sufficient to make it nominally self-supporting in 2003 and 2004, excluding the capital outlays required to transfer the clean room equipment. More recently, though, many factors have made the funding environment more difficult. These include re-allocation (and reduction) of government funds across the board due to the expenses of the ongoing war in Iraq and an overall slippage of the TSAT program. The initial champion of the TSAT program has also left the DoD, and proponents of existing satellite communications programs (MilStar) are lobbying for alternate approaches which may further reduce the size of available programs in the laser communications space. In 2006, the R&D team was actively working on two contracts, and the next phase of a third expected contract had been indefinitely postponed.

In this challenging environment, the firm needed to make some key decisions, both for the long and short term. Looking out a few years, and assuming continued success in device development, the firm wanted to decide at what location to enter into production and where capital investments should be made. Complicating the issue was a request for capital equipment expenditures at Site A in the short term to upgrade or replace older equipment which the development team had been using for two decades. At the outset of the internship, it had largely been assumed that expenditures could and would be made in two locations: the common view was that investments would be made to grow and upgrade the capabilities of the existing R&D group at Site A, but that investments for manufacturing at a product level would probably occur in a different facility already dedicated to component manufacturing. This second facility is referred to below as Site B. In this hypothesis, personnel at Site B would be responsible for producing product while the R&D group at Site A would continue to develop next generation devices. In the initial assumptions, it was also assumed that Site B, with a stand-alone profit and loss statement, would foot the bill for any capital expenditures required to give it all the technology capabilities needed for fabrication of this particular component. One justification for transferring production to Site B was that Site B already had some existing processing equipment for other products with some technical capabilities that exceeded the capability of the existing equipment at Site A.

5.2 Commitment and organizational structure

New product development efforts work best when an assigned team of players with a clearly accountable leader are supported in their NPD efforts by solid commitments from management, as discussed in Chapter 2. To understand how well the existing organizational structure for this component met these criteria, we surveyed employees in Sites A, B, and C with connections to device development. On-line surveys were completed by 24 of 36 invitees (67%) for a first survey and by 19 of 35 invitees (54%) for a second survey run a few months later: these high response rates are indicative in and of themselves of a high level of commitment to the program.[5]

Survey results did indeed confirm strong commitment and motivation among employees. 87% of respondents agreed or strongly agreed with the statement "I am motivated to do my best to support [device] development efforts." Motivation was uniform across all locations, with only one employee dissenting. Respondents also agreed or strongly agreed with the statement "I personally have a vested professional interest in the success of the [device]" at a 79% rate. Thus the firm had in place a committed team of players dedicated to making the product successful.

[5] A rule of thumb is that typical survey response rates are around 30%, so both of these response rates are considered quite successful.

On the other hand, employees in general felt that commitment and support was lacking both from firm management and from U. S. government programs. On a one to five scale (1 = too little, 3 = the right amount, 5 = too much), device R&D support from firm management was rated only 1.7 on average, and support from U. S. government programs was rated 2.2 on average. Only a few respondents seemed to believe that government support slightly exceeded management support, but all were worried about funding. "Failure to invest" and "program uncertainty" were rated as the top two non-technical risks to device success. The second survey followed up on the perceived lack of government support by asking "how well does the firm publicize or advertise device capabilities?" Only 21% of respondents believed publicity was sufficient, with the majority (58%) responding "not enough" and an additional 21% responding "way too little."

Despite these worries, though, there was significant optimism that program and management support would still warrant a high level of device-related activity in multiple locations. A series of questions asked staff to predict what level of device-related activity would be present in a 5-10 year timeframe in seven different processing areas (device fabrication through system level assembly), either at the current R&D site (Site A) or elsewhere within the company. Allowed responses started at no activity (0) and moved up through conceptual design (1), research (2), development (3), new product pilot line (4), small volume production line (5), and manufacturing (6). The mean predicted activity level was 4.0 at Site A and 4.3 elsewhere, with maximum expectations of 4.9 at Site A and 5.8 elsewhere. Respondents thus strongly believed that the firm would be supporting a pilot line in the current Site A location, as well as production line in either low or high volume elsewhere in the firm.

These responses together highlight a contradiction between what staff believed would be the case in the future and the level of support that they felt they had at present. Best practice is to have a clearly defined project leader who communicates upwards and downwards, so we wondered what message was being given by program leadership. Since the component work spanned several different government programs, we needed to first identify the person responsible for the overall maturation of the component technology. Since the organization had both business and technical arms, in both surveys we asked respondents to name the individual who "owned" the device business case and the individual who "owned" the device technology development.[6] Respondents were instructed to leave the response blank if they did not know. In the first survey, two names were given for business ownership: 74% of respondents correctly named the business unit manager in charge and others named the scientist who had invented the technology, but who also now had some business development responsibilities. On the technical development side, four different names were provided, and several respondents independently filled in the equivalent of "no one is in charge." Of the four people named, only one thought he was responsible for development, and this was not the same person deemed responsible by management at Site C. In a detailed look, it was also noted that 56% of self-identified technical contributors at Site A either left the technical leader answer blank (an implicit "I don't know") or explicitly wrote in the equivalent of "no one is in charge." A follow-up survey was run a few months later. Since a few respondents had indicated that ownership and leadership meant different things to them, the technical ownership question was split to ask separately "who owns technology development?" and "who is leading technology development?" to see if this would provide more consistent responses. Again however, four different names were put forth for each question (six unique names in total) along with several "no one" and "I don't know" answers. One person was named as both owning (42%) and leading (32%) technical development, but again the person deemed responsible by management at Site C was named only 21% of the time for both questions. Overall these results pointed to an area in need of improvement, namely the clear designation of a project leader responsible for maturing the component technology itself.

We concluded from our organizational and leadership analysis that many of the key attributes needed for successful NPD were present, especially a committed team, but that there was an opportunity for organizational improvement. Many of the discrepancies between what was perceived at present and what was expected in the long term are very

[6] In the best practices literature, the project leader should be dedicated to only one NPD project (in our case component development) and should have formal authority to make day-to-day decisions. This means the appropriate "leader" here is the technology development leader. However, since the culture of this firm is to somewhat split responsibility between a business unit manager who oversees multiple technologies, and program teams, we used two separate questions to differentiate between these roles.

likely linked to the lack of clarity in technical leadership. Without a clearly responsible technical leader in place, the team did not have a representative to air concerns regarding funding and publicity to management. Likewise, no one had responsibility to challenge the assumption that there would be significant investments in the component technology over the next several years. The physical distance between management in the regional headquarters at Site C and the satellite clean room at Site A likely also increased the difficulty of effective communications. Finally, no one had the key responsibility for ensuring that the technology was maturing as planned, and that the strategy and resource requirements were consistent with the firm's goals and capabilities.

5.3 Strategic fit and core competencies

New products have a better chance of succeeding when they fit the business strategy of the firm or business unit in a manner synergistic with the business unit's strengths and core competencies. The proposed paths to production for this component involved two related business units with slightly different charters. We therefore compared the fit of the component and its production requirements to the goals and strengths of these two units, to see which path might provide the most synergy in the future. We started our evaluation by looking at the mission of the firm as a whole, and then drilled down into the details of the two specific subsidiary units. We then made qualitative assessments of the strategic fit and ability to leverage core competencies. We emphasize that in practice, these assessments should be made by the designated leadership team, against agreed-upon criteria with agreed-upon weights. The assessment presented here is thus only intended to be illustrative of one possible view and was primarily designed to spur the management team to increase discussions of strategic fit and leverage in their own decision-making process.

From the top down, the corporate objective is to be the leading defense and aerospace systems supplier. In defense, as in many industries, companies have come to believe that more value can be captured by working "further up the food chain" in systems integration activity instead of in component and device supply. Consistent with this view, this firm's objective now emphasizes being known for "mission systems integration," a shift from previously being known more as a provider of components and sub-systems.

Divisions within the corporate structure focus on providing mission systems integration in specific areas. For example, the parent division in our study is responsible for providing mission solutions for networked communications, including command and control and battlespace communications. Other divisions are responsible for space- and aero-space-based systems, missile systems, and integrated air-, land-, and sea-based defense systems. Business operating units within each division have further defined mandates, usually supporting the parent divisions and occasionally crossing several divisions where broad support is needed.

In our study, the component R&D team (Site A) was aligned with a communications systems business unit (Site C) whose objective is to provide military communications solutions at the system level, with core competencies in systems integration. We saw positives and negatives in this alignment for the component R&D team. On the positive side, the systems integration development group was able to leverage the component when preparing bids for next generation communications systems. A key customer confirmed that the firm does today have "a competitive advantage by having in-house component development" although he would like to see multiple component suppliers. There is thus a match in strategic fit on the communications side, and some leveraging of component competencies. On the other hand, the component group itself is less able to leverage the core competencies of its parent business, since component development requires different skill sets and expertise than systems integration. A component developer must know how to manage and control fabrication processes, qualify a component for space or airborne operation, and deliver a completed device to the customer. However, interviews with systems integration personnel at Site C confirmed that steps in component process control, qualification, and manufacturing are foreign to them; once a system is specified by the systems integration group, the design is typically transferred to another location for production, and already-qualified components are obtained from vendors both internal and external to the firm. The result of this is that the component group has no local strategic partner within its own division to guide it in moving from R&D to production and it cannot leverage core manufacturing competencies in its own organization. Also, as a component fabrication group reliant on high tech capital-intensive equipment, it is an anomaly in a systems integration organization which is not used to its costs[7] and cannot easily absorb its skilled technical workers. Finally, one last drawback is that current programs for the component extend beyond communications, for example to high energy laser delivery for laser-based weapons. Weapons applications are not within the mandate of the parent communications business unit, so these programs are considered "step-out" projects from the perspective of this unit, even if they are consistent with the mandate of the firm as whole.

We next checked to see whether a better fit would be obtained with the second proposed organization at Site B. This second organization is an independent unit with responsibility to support several major corporate divisions by developing and producing electro-optic components for communications, missiles, and weapons systems. The unit has a wide variety of product lines based on several primary technology areas and ships tens of thousands of space- and military-qualified devices each year to internal and external customers. Most products are made with high tech capital-intensive equipment like semiconductor processing machines. As an exception to the general corporate mission to focus on mission systems integration, Site B has an explicit mandate to develop component technology. Understanding this mandate, we find a better strategic fit for the optical component with Site B (component technology) than with Site A (communications systems). As an active component supplier, Site B has core competencies in component engineering, manufacturing, and qualification which could be directly leveraged in maturing the optical component. These abilities should also make leveraging the component in systems integration bids easier for the firm, since they could demonstrate production experience to systems customers. With a mandate to support several divisions, Site B also can readily support non-communications applications such as high energy laser-based weapons and could potentially facilitate use of the component by other divisions. Finally, the fact that Site B supports multiple product lines means that it has less vulnerability to long term drops in demand. In the

[7] In addition to capital equipment depreciation, rent on the clean-room space increases the rate structure of the entire regional systems integration group significantly, according to the regional director.

event of a drop in demand for one product, highly skilled workers may be transferred to work on a different product, since multiple products rely on the semiconductor processing equipment and associated skills.

One specific concern worth addressing was frequently raised whenever the question of transferring technology from Site A to Site B was discussed: what about employees, their expertise, and the firm's capacity for future innovation? In an expertise evaluation, it is clear that the specific knowledge and the specific ability to produce the component currently reside at Site A. Staff at Site B have comparable training and skill, though, and can be expected to easily learn the required production techniques, if processes are mature enough to transfer, or to appropriately re-engineer product design for robustness and manufacturability where processes are not mature enough to transfer. In this case, knowledge transfer should strengthen, not weaken, the firm. Again, this comes down to a question of versatility and breadth of contribution. Cross-trained employees and teams help firms to cope in downturns because they can be re-assigned to other product lines. The absence of any other product development work on Site A equipment and the absence of additional component-level innovations coming out of the group in the years since the original device invention blocked us from concluding that the firm would lose substantial device innovation capability if the component work were ultimately transferred from Site A to Site B. Clearly knowledge transfer would require cooperation and assistance of staff in Site A.[8] Such cooperative knowledge transfer occurs routinely in firms and between firms in all industries today. The division would, however, also need to make sure that such a transfer would not jeopardize ongoing systems-level innovations for uses of the component in subsystems and systems relevant to the parent communications division at Site C.

5.4 Financial options

A third criterion for a successful new product introduction is financial attractiveness, including market attractiveness, market need, and positive return versus risk. Cooper emphasizes that firms should not make NPD decisions on financial assessments alone, but financial criteria should still be included as part of a complete

[8] It was estimated that the assistance of about four key staff members would be needed for about one year in order to effectively transfer the product. These costs were included in financial analyses.

assessment. The more robust the financial expectations from a new product even in the event of adverse circumstances, the more confident a firm may be that it is a good investment. We thus considered four financial scenarios, under a variety of best- and worst-case conditions, to see which investments could make the most sense for this firm. Scenarios evaluated included (I) investment and activity at Site A only, (II) a hybrid of investment and activity at both Sites A and B (the assumed approach), (III) production investments at Site B with no additional investments at Site A, and (IV) limited investment at Site A with potential future investments for production at Site B delayed by a few years. These scenarios are summarized in Table 5-1. Options I – III assume immediate investment at the relevant site(s), while Option IV assumes delayed investment. The outcome of Option I would be both R&D and production capability at Site A. The outcome of Option II would be enhanced R&D capability at Site A with production capability at Site B. Option III would result in full production capability at Site B, but no enhancements to the R&D capability at Site A. Option IV would make no immediate R&D-level investments and would delay production-level expenditures until a make/buy decision at a later date, with an option to invest for production capability at Site B in the event of a decision to make the component internally.

Option	Captial investment description	Resulting R&D Capability	Resulting Production Capability
I	Immediate investment at Site A only	Site A (production equivalent)	Site A
II	Immediate investment at both Sites A and B	Site A (enhanced)	Site B
III	Immediate investment at Site B only	Site A (limited upgrades)	Site B
IV	Delayed investment at Site B, if make/buy decision is to make.	Site A (limited upgrades)	Delayed option to invest at Site B

Table 5-1. Summary of the four financial scenarios modeled.

Scenarios were evaluated on the basis of net present value (NPV) and internal rate of return (IRR) from cash flow projections over a 10 year period. Key inputs to the models included required capital expenditures and expected profits from expected future contracts. A financial model including all capital expenditures requested for Option I had already been developed before the start of the internship. This model had an extremely complete associated capital equipment list due to the expected obsolescence of older Site A equipment and the inclusion of equipment for a proposed capacity expansion. This Option I model was used as the foundation to develop Options II – IV. Capital equipment lists and processing run sheets were reviewed line-by-line with staff from Site B to identify specific capital investments which would be needed at Site B. Ongoing capital expenditures for maintenance of the clean room infrastructure were included based on the experience of the team at Site B. All capital investments were depreciated using 150% declining balance converting to straight line depreciation over a 10 year life. Best- and worst-case scenarios for capital needs were also developed for each option based on the probability that certain equipment would or would not be required as a result of ongoing technical work.

Some of the most important numbers in financial analyses are the projected sales that a firm expects to get. Entrepreneurs notoriously overestimate projected revenues and revenue growth rates. To mitigate the problem of overestimating returns, this firm uses a system of "factored" and "unfactored" sales. Usually, unfactored sales represent the total addressable market, while factored sales represent the fraction of the market contracts that the firm realistically expects the government to fund and the firm to win. Factored sales are the appropriate revenues to use in financial calculations, because they take risk and market share into account. In the case of this particular component, though, a slightly different definition was being used, perhaps since the total addressable market was less well known. For this product, factored sales represented the full amount of known optical system-level contracts within the firm's 5-year plan that the firm expected to win and to which the business unit had committed in its 5-year plan. Sales in years 6-10 followed a growth rate projected by a detailed analysis of the market conducted in 2004, with an allowance for some slippage observed in government funding since 2004. Unfactored sales were then backed out of the given factored sales, using a confidential internal factor. This approach is not in and of itself worrisome, except that in some cases the unfactored numbers had been used to justify capital expenditures, as they provided a more optimistic return on investment. To be consistent with the firm's past analyses and to be rigorous in the numbers presented to management, we ran models using both sets of numbers, but we emphasize here our belief that the factored sales to which the business unit leadership team had committed are the appropriate numbers to use.

All financial analyses were also done from the rolled up perspective of the firm, with the perspective of the individual business units included only where appropriate. This was critical to correctly understand the impact of investment options at Site B. As noted in section 5.1, it had originally been assumed that Site B would foot the bill for any capital investments made there to support the component, because it was assumed that Site B would earn profit from making the device. In fact, however, as a wholly-owned subsidiary of the firm, at the corporate level Site B was prohibited from taking any profit from the divisions that it was designed to support. Consistent with standard corporate financing practices to avoid double marginalization, product sold internal to the firm by Site B is transferred at marginal cost, i.e., labor plus materials, while product sold externally is sold at market or government contract pricing. Since Site B would only be producing devices for internal consumption,[9] Site B would only receive funding for component-specific labor hours. Thus the critical question for Site B became whether there was sufficient labor volume in future contracts to balance the additional capital depreciation that it would have to take on. For this, we compared the ratio of annual labor to annual depreciation against a confidential internal threshold. Since revenues in the model were at the system level, we also made a very rough estimate of the fraction of each system-level contract which was expected to go towards component production.

The relative internal rate of return from the four scenarios under study is shown in Figure 5-1. All options appeared to have high IRR when unfactored (total potential) sales were used, but only Options III and IV had IRR above the corporate hurdle rate (dashed line) when factored (expected) sales were taken into account. NPV results were similar. Note that Option IV also implicitly included a possibility of purchasing components externally (not shown), rather than investing at Site B, in which case returns on Option IV would be higher. Options I and II both yielded negative NPV values for factored sales, indicative of undesirable investments. Option II is clearly the least desirable option

[9] No external component sales were assumed, in order to maintain the perceived systems-level advantage of having an in-house component supplier with a unique capability.

from a financial standpoint, requiring almost 60% more capital expenditures than Option III, on the same revenue base. Option I, investing heavily at Site A only, was also not viable in the factored sales case. All net profits from systems-level contracts were insufficient to justify the requested immediate component-level capital expenditures at Site A.

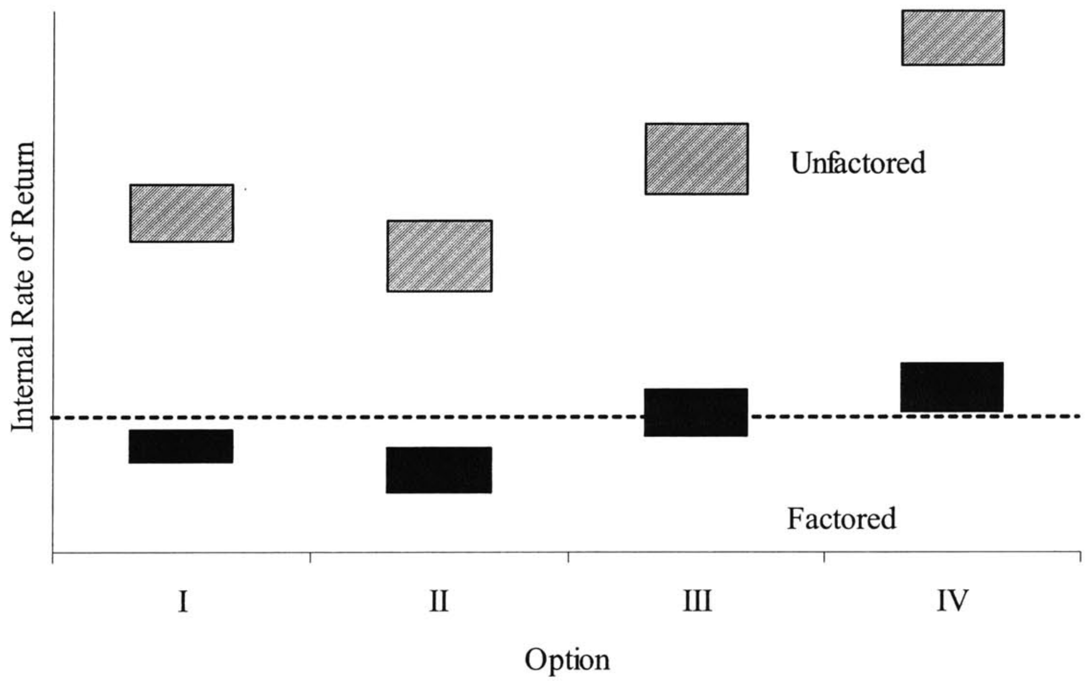

Figure 5-1. Internal rate of return ranges for the four financial options under study, for both factored (solid) and unfactored (hatched) revenues.

Options III and IV appeared to be the most desirable from a pure NPV and IRR standpoint, at the corporate level. Since these involve internal transfers, though, site specific metrics for Site B must be checked. For Option III, we found that the amount of component fabrication labor predicted in the factored sales cases was insufficient to justify Site B taking on the associated capital expenditures. This was also true for the first several years of the unfactored sales analysis. These results implied that unless there was a corporate level change in the metrics by which Site B was evaluated, it would not make sense for Site B to invest. Only Option IV appeared viable from both corporate and individual business unit perspectives. By delaying purchase of capacity expanding equipment for a few years and investing at Site B where some existing equipment was already in place, IRR and NPV were both maximized, and the risk to Site B was minimized by starting Site B participation at a point when device volumes could justify capital expenditures. An exemplary metric illustrating the ratio of new labor hours to new capital depreciation for Site B is schematically shown in Figure 5-2. As volume increases in later years, labor is sufficient to carry the associated capital depreciation expenses.

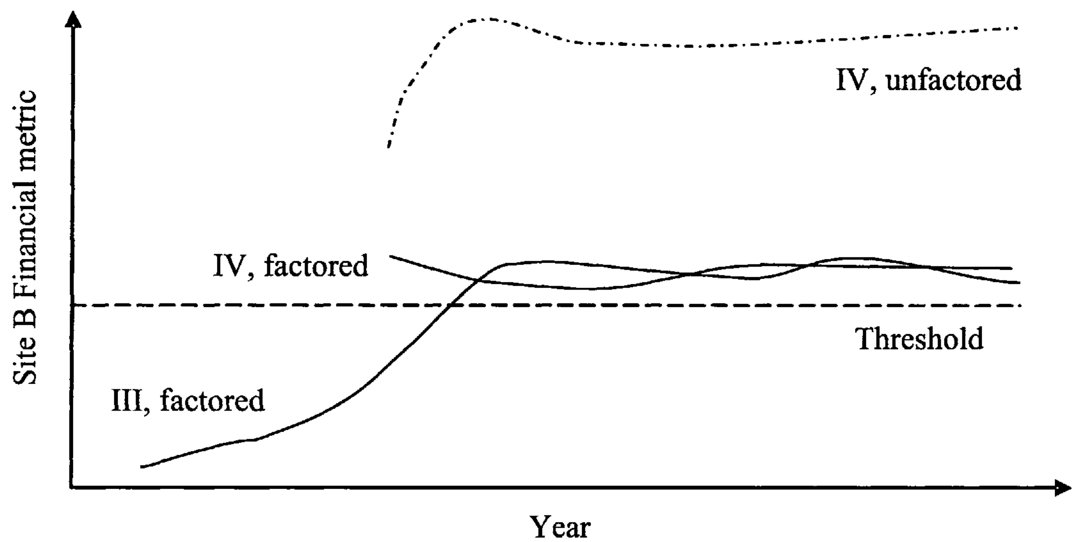

Figure 5-2. Schematic representation of financial metrics for Site B.

5.4.1 Potential additional revenue

The financial options above would all be more desirable if more revenue could be brought in to offset the capital expenditures. However, only revenues which can directly be accessed as a result of investments belong in a financial capital justification. A few other revenue generating ideas were discussed within the firm, including intellectual property (IP) sales, licensing and/or production of the component for non-defense purposes, for example as part of a telecommunications switch, and sales to other defense contractors. We briefly discuss these here, to acknowledge them and also to explain why those revenues, with the exception of possible external sales for other defense purposes, do not in fact belong in the financial models above.

The most prominently discussed "opportunity" was to generate several million dollars in one-time sale or royalty fees by licensing IP for a non-defense application. In fact, an outside consulting firm had recently provided a very optimistic assessment of potential IP-related revenues, and significant short term receipts had been included in previous financial models. We excluded those revenues from our analysis not only because of the uncertainty of these receipts, but also because whether or not the firm receives these revenues is independent of whether the firm spends today on capital equipment, so they do not belong in the capital justification.[10]

A similar argument holds for revenues which would be generated from non-defense sales of the component. The idea was proposed, internally and also externally by a primary customer, that it would be desirable for the firm to produce components for example for a telecommunications application, in addition to producing them for defense. This is similar to the "dual-use manufacturing" proposal for civilian and military operations [12]. There are two problems with this idea. First, non-defense component applications clearly do not fit within the business strategy of any of this firm's business units. The firm lacks core competencies in producing for or selling to a non-defense market and it would be extremely difficult to justify such a step outside of the norm for this one small component. Second, even in the event that the firm chose to invest for a non-defense production line, or convinced a non-defense partner to do so, competition in commercial products, especially telecom devices, is so severe that there is little probability that military and commercial devices would ever be made on the same line. Today labor accounts for over 90% of the cost of a single device, which rate is untenable in the commercial component market. For telecom, the device would require significant re-engineering to reduce costs and would in all likelihood ultimately be fabricated in Asia, a location which is out of bounds for defense work. The firm might be able to benefit from the faster learning curve that the commercial group would see, if a deal were structured to allow this knowledge capture, but investments would have entirely separate financial justifications.

The last possible option for additional revenue generation is to sell devices to other defense contractors to build volume and utilize equipment capacity. A key

[10] If the firm wants to find its return on investment going all the way back to the 1980s and 1990s, these revenues could be included as returns on the intellectual property developed at those times, and would offset some of the earlier capital expenditures. Just as "sunk costs" are excluded from the financial analysis for today's investment decisions, though, "sunk revenues" are also excluded.

customer thought that in an ideal scenario, the firm could still "make the best device" and integrate it with a slight advantage in-house, but still sell them outside to other defense contractors. This option has not been discussed significantly in the past, but is worth evaluation in the future. Here the application (and cost structure) would be consistent with the firm's strategy and capabilities but the firm would give up some "uniqueness" on the systems side. The initial goal of using the component to open the door to the business unit for systems-level communications contracts has largely been fulfilled, though, so this might be acceptable. The division is now a credible supplier in the systems space and has additional contracts which use other technology approaches. In the future, when expenditures under Option IV are to be authorized, the firm may want to evaluate in more detail the trade-offs between facilitating competitors on the systems side and capturing value on the component side.

5.5 Product uniqueness and advantage

A final key requirement for new product success is "Having a superior differentiated product that delivers unique benefits and better value to the customer." This means both that the product must be superior and differentiated, and that the firm must be able to uniquely provide it. In this study, we took at face value the commitments from existing customers and the results of previous market studies as confirmation that the technology does indeed deliver unique customer benefits. The component technology enables communications networks with no moving parts and has advantages in terms of size, weight, and power handling capability over more conventional technology approaches. As long as the promised technical performance can be delivered, this advantage will be preserved.[11] For our discussion here, we limit our analysis to whether or not this firm has a unique superior product, relative to other potential component providers. To assess the firm's competitive advantage in providing this technology we considered the firm's IP position, "sole source" contract justifications, and published reports of comparable devices provided by competitors. Here we found that the firm has had a competitive advantage in the past, but that the relative advantage has decreased in recent years, so the firm does need to be more wary of competition.

[11] Ongoing systems-level trade studies (internal to the firm and out of the scope of this study) will also serve to validate or challenge this assumption.

Intellectual property ownership is often cited to back up a claim that a company has unique control of a product. For this to be the case, the firm must have a comprehensive IP position and must be able to defend its ownership. This is difficult to claim for this product for two reasons. First, it is fundamentally very difficult to defend IP in the defense world: if a contractor believes that another supplier is infringing a patent while providing product at the government's request, the wronged contractor can only sue the government, not the other supplier. Since the government is the firm's customer, there is a disincentive to sue. IP protection is thus not very strong for defense components. Second, although the firm does own some of the original patents in this technology space, its relative portion of the patent portfolio is decreasing and aging. To qualitatively determine IP strength, we searched the U. S. Patent and Trademark Office (USPTO) database to find IP relevant to the technology, starting first with the firm's own patents and then conducting backwards and forwards citation searches. This generated over 600 cross-citations referencing about 450 patents. From these we checked almost 200 specific patents to qualitatively assess relevance. From this search, we found that the IP space was in fact fairly well populated. The firm holds the largest fraction, about one-quarter, of the most relevant IP, primarily covering device design and applications. A key competitor (Competitor A) holds about one-fifth of the relevant IP, with strengths in particular processing elements such as thin film designs. This leads to the conclusion that the firm has a strong, but not unique IP position. Its position is also weakening as the patents from the early 1990s expire.

Without strong IP protection, the firm needs to justify uniqueness based on other criteria, such as technical superiority. In fact, the team has received at least one contract based on a "sole source" justification, as the only contractor capable of providing the technology at the time the contract was awarded. To find out if this advantage still held, we interviewed a key customer who had been involved in that award. He confirmed that indeed at the time, the firm did have a unique capability. However, since the contract award, Competitor A had also demonstrated comparable device performance, and in the eyes of this customer, Competitor A would now be a credible supplier. A "sole source award" would possibly not be made in the next contract award phase. Consistent with the DoD goal to not be dependent on a single supplier, this customer was also very interested in developing other firms to produce comparable technology. Although work at Competitor A was not being actively funded right now, he "would like to send them a contract." Overall, the customer saw the firm in our study as being in first place in technology development but identified two credible competitors and a few potential new entrants.

Finally, we reviewed public information covering the two credible competitors to develop an understanding of their technical capabilities. Competitor A only entered this particular optical component space in the late 1990s but has been working on other liquid crystal based devices for many years. Synergies with these other devices seem to have made it somewhat easy for them to enter the optical component space. They published record device performance in 2004. They utilize an extensive collaboration network including many of the same people collaborating with the R&D group in our study, in defense, industry, and academia. Competitor A is primarily focused on component development and supply, not on systems. Published news reports indicate Competitor A has invested in large new clean-room manufacturing facilities in recent years. Like Site B of the partner firm, this competitor has a wide product line spanning many technologies, so they are well positioned to survive fluctuations in market demand. The optical component would only represent a small fraction of their sales. Competitor A does not appear to be making a strong push into the optical component space at present, but they have demonstrated competency that will likely make them a credible supplier should they choose to enter. The firm has recently been acquired by another firm, so there is some uncertainty regarding their future.

The second competitor (Competitor B) actively produces components based on similar technology for both the commercial and the defense market. Competitor B has been in the industry since the late 1980s, but is still quite small, with fewer than 20 employees. They focus primarily on component design and assembly, outsourcing much of the capital-equipment-intensive portions of processing to an external foundry. The firm's products in the OEM commercial market are fairly simple devices. Competitor B can probably benefit from its manufacturing learning in these simpler products to bring down its overall manufacturing costs for more complex products. In the defense world, the firm is a small player, but has received on the order of $10.5M in DoD Small

Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) funding over a 15 year period [27]. Again, they collaborate with many of the same groups, including commercial and academic liquid crystal suppliers. They should be considered a credible entrant into component supply if and when this becomes profitable. Their reliance on an external foundry will likely help them to wait out delays in system deployments since their lower capital investment structure means they are not overly reliant on immediate returns. Competitor B holds two relevant recent patents but since their issue has been content to put work into the public domain.

5.6 "Soft" conclusions

The review above indicates that the market for this particular component will possibly be somewhat competitive in the future. The firm seems to be the strongest competitor today, but should keep competition in mind as investment plans are made. Much of the firm's original "first mover" advantage has been lost in the twenty plus years since the original invention. The firm itself is actually now facing a capital-based "barrier to entry" into component production, since it needs to expand or replace aging equipment.

If the firm chooses to source components internally, our analysis of strategic fit and core competencies indicates that an ultimate alignment of component production with Site B would probably put the firm in the strongest competitive position. However, comprehensive investments should not be made in the near term at any site, unless the firm is prepared for financial losses. Because of the highly capital intensive nature of the component fabrication processes, the firm is in a position where automatic profitability through defense contract margins does not apply. Until volumes are sufficient and sufficiently certain to justify large capital expenditures, the firm should focus on optimizing processes in the current facility, to prepare for a technology transfer at a later date. In the mean time, it was recommended that improvements could also be made in the organizational structure by designating a clear technical leader responsible for component technology development. This appointment has since been made and reports are very positive regarding recent progress that the R&D team has made under this new leadership.

The firm should also continue to monitor potential alternative component suppliers who have shown credible capabilities. These firms could either enter as suppliers to competitor systems providers in the future, or a partnership could be formed to source component supply from one of these firms at a later date. A make/buy decision will need to be made in the future based on a comprehensive trade analysis of the costs and benefits of an external supply against the costs and benefits of investing in a captive in-house supply.

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Chapter 6: Case Study: Manufacturing Readiness Assessments

We now turn to the technical evaluation of the component to supplement the organizational, strategic, financial and competitive analysis. In this part of the case study, the objective was to build a picture of the manufacturing readiness of the component. Fabrication of the component could be broken down into eight primary areas, including thin film deposition processes, photolithography, liquid crystal alignment layer preparation, fabrication of the liquid crystal itself, assembly, electronic controls, packaging and test. A detailed investigation of all aspects of fabrication would not have been feasible within the timeframe allotted to the internship, so we selected a few exemplary processes to evaluate: the externally supplied liquid crystal, internally supplied thin films, and various steps in the assembly and final test process. We assessed capability in these areas using the DoD MRL criteria of Chapter 4, since AFRL is the primary customer for the device today. As noted above, since no compliance with MRLs has yet been required by contracts, the intent of the MRA is only to provide the firm with a benchmark and to identify areas for focus in the future. The firm is not yet expected to have completed any MRLs.

6.1 TRL baseline

Manufacturing Readiness Levels incorporate Technology Readiness Levels into their metrics, so we started by trying to find consensus regarding the device TRL capability. Unfortunately, as noted in Chapter 4, there are no explicit certification authorities specified by the TRL metric, so we found a wide variety of opinions as to the maturity of the device. In our first survey, we asked respondents familiar with TRL metrics to indicate the TRL of the simplest form of the device, a component built on a glass substrate with a specific liquid crystal. The nineteen responses ranged from TRL 1 to TRL 6, with a mean of 3.4. Many in the organization expressed surprise at the range of responses, although others did not. One interpretation of the high variability of opinion is that it is consistent with the uncertainty regarding technical leadership. Another interpretation is that variability is attributable to a possible lack of training in this area. Five respondents did indicate they were "not familiar" with TRL metrics and chose not to respond to the question. Responses to the same question on the second survey, after some internal discussions regarding TRL metrics, showed more consensus: 79% of respondents chose TRL 3 or TRL 4 and the remaining 21% selected TRL 5. Only one respondent to the second survey indicated insufficient familiarity with TRL metrics.

TRL 3 encompasses "Analytical and experimental critical function and/or characteristic proof-of-concept" while TRL 4 requires "Component and/or breadboard validation in laboratory environment." Consensus was ultimately reached in discussions with the R&D team that the device today is in qualification for TRL 3. These discussions led to the acknowledgment that precedence relations require that the component cannot be at a higher TRL than the least mature of its subcomponents. Although past devices using a commercially available liquid crystal and a different assembly process have met TRL 4 criteria, a new specialty liquid crystal and a new assembly method are both being developed on current contracts. The critical function of this new material and new method was yet to be tested as of the end of the internship, so the maturity of the current design reverts to below TRL3. Since devices with other materials and assembly processes have indeed been validated in a laboratory environment, though, as long as the new processes and materials under development are demonstrated successfully, the program should move quickly from TRL 3 to TRL 4.

6.2 Externally supplied liquid crystal

The liquid crystal is the most fundamental enabling technology for the optical component in our study, so it is appropriate to use it as a subject for an MRL assessment. Further, the liquid crystal material and supply, along with the methods for filling and sealing the liquid crystal cavity, were identified by survey respondents as the two highest risk elements in device fabrication. To evaluate the liquid crystal, we applied the MRL criteria of Chapter 4. Data was gathered from available data logs in the R&D laboratory and also from discussions with firm and supplier personnel. At present, the liquid crystal used in the devices is provided through a research subcontract with an academic researcher at a U. S. university. As the prime contractor on communications systems contracts using the component, the defense firm will be responsible for ensuring that its liquid crystal supplier complies with MRL requirements.

6.2.1 MRL 3: Identification of liquid crystal manufacturing concepts

The primary requirements of MRL 3 are identification of processes and materials. In our study, we found very limited existing liquid crystal-related documentation aside from sparse log book records. However, discussions with the university researchers allowed us to fairly easily construct a first cut at identifying manufacturing concepts for MRL 3. For example, the high level manufacturing flow for producing a new liquid crystal consists of (1) designing molecules, (2) synthesizing or purchasing compounds, (3) synthesizing mixtures, (4) testing formulations, and (5) testing devices. Steps (1), (3), and (4) are usually carried out at the U. S. university. For step (2), one or more specialty compounds are typically sourced externally from an Engineering, Chemistry, and Physics Department at a foreign (usually European) university. Materials and resources needed include these specialty molecules, approximately $40K of testing equipment, and preferably a clean room environment for synthesis and mixture formulation. We also found that the R&D team at Site A has not yet designated a point person in-house who is responsible for understanding liquid crystal characterization, for tracking liquid crystal performance, and for tracking incoming quality and consistency. We listed this person as a required resource to be developed, since we believe this will be necessary to meet the requirements of MRL 4.

MRL 3 also starts the process of highlighting areas which will require new or different manufacturing capabilities or resources. Here we stress that all liquid crystal work today is done in a university research laboratory with no formal manufacturing capability and where many requirements are not met. For example, the university lab is not in fact in a clean room. It also has limited testing capability. The current university measurement capabilities include only a single wavelength laser source and a small temperature range. The actual component operating temperature is expected to be quite high, and at least two other different wavelengths will be used in defense applications. Liquid crystal performance is highly sensitive to both wavelength and temperature and a single point measurement is insufficient to predict performance. In order to meet MRL 4 requirements for identification of key design requirements and characteristics, performance at operating wavelength and temperature will be needed, so we highlight the need for future investments in test and measurement equipment. We also highlight the longer term need, which will reappear in MRL 4, for a commercial liquid crystal supply. The firm has been in discussions with a few specialty chemical companies and believes that a supplier can be found. The primary challenge will be making the work financially attractive. The number of devices being made is in fact very small today. This fact, coupled with the fact that over 500 devices can be filled with only 5 g of liquid crystal, means that manufacturing the material will probably be unattractive to large liquid crystal suppliers such as Merck or Sigma Aldrich and that a "boutique" supplier will be necessary.

Overall, we do not expect significant hurdles to the firm in meeting MRL 3 metrics, provided that TRL 3 is met with the newly designed materials. Compliance with MRL 3 will likely require more detailed documentation than what we have summarized above, but this documentation should be straightforward for the firm to produce or to request from the university research team as today's liquid crystal supplier.

6.2.2 MRL 4: Identification of the key liquid crystal manufacturing processes

MRL 4 presents more challenges to the liquid crystal than MRL 3. MRL 4 focuses on identification of manufacturing processes: flows, materials, and risks. It also requires identification of key design characteristics as a precursor to demonstrating performance against those requirements at MRL 5. For the liquid crystal, this will mean identification of technical parameters such as optical birefringence and figure of merit (FoM) requirements, operating temperature requirements, speed requirements, and reliability needs (hermeticity, radiation, etc.). Building a database to monitor performance and correlating device performance to key design characteristics (to validate these requirements) will be necessary. In addition, more specific criteria will likely need to be provided to the university research team. Today, the university team has only been given the objective of developing a liquid crystal with the fastest possible response. Additional requirements for performance against critical environmental criteria (temperature, radiation) also need to be included in design requirements.

MRL 4 incorporates TRL 4 as a base requirement: "basic technological elements must be integrated to establish that the 'pieces' will work together to achieve concept-enabling levels of performance for a component and/or breadboard." In addition to this, MRL 4 also requires identification of interactions between processes. At present, a chemical interaction between the tolane-based liquid crystal and something in the device assembly process has been observed and has been under investigation for a few years. The interaction causes undesirable degradation of the liquid crystal, i.e., the pieces do not yet work together. To reach TRL 4 and MRL 4, this degradation will need to be eliminated, and the solution will need to be documented for future program stages. Similarly, the liquid crystal today is known to interact with ultra-violet (UV) light. Some processing steps have been modified to eliminate UV exposure of the liquid crystal. MRL 4 will require documentation of UV exposure risks so that future process modifications do not reintroduce the problem. Note that achieving MRL 4 is not blocked by these documentation notes, but awareness is raised regarding potential future risks.

MRL 4 also starts to build information for sourcing. Evaluation of the industrial base will likely indicate that development of a non-university source will be required. Similarly, when MRL 4 starts the process of identifying sole source, single source, and foreign source vendors, foreign source concerns may be raised over the foreign supply of key liquid crystal molecules. Foreign sourcing is in fact expected to be one of the primary concerns for government adoption of the technology, independent of which defense contractor provides it. The university research team is also the primary liquid crystal source for competitors, and according to the U. S. university team, the European university is the primary supplier of high tech specialty molecules to most liquid crystal suppliers, including commercial firms such as Merck and Sigma Aldrich. It is thus expected that most paths today will lead back to a single foreign source for key liquid crystal elements. This state will need to be approved by the defense customer throughout the manufacturing progression. Alternatively, the defense customer may choose to support development of U.S.-based expertise equivalent to that at the foreign universities. For the time being, the firm in our study should be able to meet MRL 4 requirements, since these do not yet require mitigation of sole/foreign sourcing, and the customer today is aware of off-shore sourcing for liquid crystal materials. Still, reaching future levels may be challenging, depending on the customer's wishes.

Finally, MRL 4 starts requirements for planning and for funding commitments. This includes both manufacturability of the component (here the liquid crystal) and of the system (here the optical device). Cost drivers must be assessed and a plan for maturation from MRL 4 to MRL 6 is required. Funding sufficient to reach MRL 5 must be available. A detailed assessment of the liquid crystal against MRL 4 metrics was provided to the firm. Many steps in MRL 4 are not yet started, as would be expected for an early stage technology development effort. Meeting these requirements will require contributions from both the firm and from today's university source. As the prime contractor, the firm will be responsible for ensuring that the university (or any other liquid crystal supplier) meets the documentation requirements where appropriate.

6.2.3 MRL 5: Liquid crystal manufacturing process development

MRL 5 focuses on manufacturing process development. This includes establishing process capability and control, value stream mapping, and make/buy tradeoffs. A viable business plan is required, along with cost and schedule projections. For the liquid crystal, this will mean identification of a viable supplier. At MRL 5, this includes beginning planning to minimize sole/single/foreign sources. MRL 5 also requires planning for maturation to MRL 7, and available funding to reach MRL 6.

On the technical performance side, MRL 5 also requires TRL 5: "Component and/or Breadboard validation in relevant environment." The optical component will be subject to harsh operating and non-operating conditions. Ambient operating temperature ranges vary with application, but a rough study of several applications indicates that operation from about 15 °C to 65 °C and storage from about -30 °C to + 70°C will be required. Liquid crystals are characterized by phase transition temperatures at which they transition from crystalline form to smectic phase, smectic to nematic phase, and nematic to isotropic phase (clearing temperature). The optical device operates in the nematic phase and heaters are included to control operating temperature. However, devices stored at -30°C will clearly go into the crystalline state, passing through the smectic state. Today, when crystallization occurs, devices are heated to above the clearing temperature in order to realign liquid crystal molecules with the inner cell surface alignment layer. It is an open question whether including a high temperature cycle at startup is a viable long-term option from the customer standpoint, and what repeated high temperature cycles will do to device reliability. Liquid crystal research goals today do include development of isomers that do not have a smectic phase, and that form a true eutectic mixture. Such future liquid crystals could eliminate some of the issues above, but these liquid crystals will need to be built into devices and validated on their own. To avoid limiting (by maturity precedence requirements) the maturity of the component to the maturity of these yet-to-be developed isomers, customers assume that success will be possible with liquid crystals available today.

Work towards MRL 5 has not been started today at the liquid crystal level. Achieving MRL 5 will require a significant increase in rigor, including data collection and analysis, establishing a requirements flow-down from the optical device, and modeling of interactions with component tolerances. It will also require significantly more detail in business planning, both for a non-university source for the liquid crystal, and for reducing dependence on the foreign source.

6.2.4 Liquid crystal summary

The liquid crystal is clearly a high risk element in the component, considering technical and manufacturing concerns. Maturity today is limited by the introduction of a new mixture, which keeps maturity below TRL 3 and MRL 3 until proof-of-concept is demonstrated. On the technical side, the chemical interaction issue must be solved in order for the device to meet TRL 4 (and MRL 4) requirements. More detailed technical requirements must also be flowed down to the supplier to make sure that the liquid crystal will meet all requirements. Adding more detailed specifications and verifying performance against these criteria represents a shift in mindset for the R&D team, which has focused more in the past on achieving "hero" performance along a single dimension. On the manufacturing side, sourcing is the most serious issue, since the current source is not commercial and relies on foreign-sourced components. Meeting MRL 5 criteria is likely to be challenging.

6.3 Internal wafer processing

Manufacturing readiness of internal wafer processes was assessed to understand the maturity of processing steps controlled by the R&D team and to identify areas which would need to be improved to mature the device towards MRL 6 within the next few years. Wafer processing includes several thin film deposition processes. Anti-reflective

(AR) coatings, transparent electrodes, and isolating dielectric layers are all deposited on optically transparent wafers as part of the fabrication process. Below we present a general overview of the wafer processing maturity according to MRL 3, MRL 4 and MRL 5 metrics. Select results from specific processes are also presented to illustrate control charting and yield prediction techniques which will be useful for assessing yields at MRL 4, and meeting process capability and control requirements at MRL 5 and MRL 6.

6.3.1 MRL 3: Identification of wafer processing manufacturing concepts

MRL 3 requires technical performance at or above TRL3 supplemented by identification of manufacturing flows, materials, and resource requirements. In thin film processing, most criteria for MRL 3 are met today, with one reservation regarding TRL 3.

Starting with the TRL assessment, whether thin film processing meets TRL 3 hinges on a question of whether the final target performance must be demonstrated at TRL 3 or if performance close to target is sufficient. Most early stage R&D contracts require experimental critical function and characteristic proof of concept only on a "best-effort" basis. The team has delivered devices which meet most optical performance criteria, so TRL 3 has in general been believed to have been met. Our process control analysis indicated one parameter of concern, though, which will be discussed in section 6.4. Once analytical modeling is done to demonstrate a thin film design which meets this parameter requirement, TRL 3 should be considered complete.

On the manufacturing side, the team already has in place many of the requirements called out by MRL 3. Manufacturing flows are detailed in process documentation "run sheets" for all device builds. Material requirements and resources are also called out in these run sheets, which specify the particular equipment used for each step and the source materials for each thin film layer. Material requirements are all standard semiconductor processing materials such as silicon dioxide, aluminum oxide, and other thin film oxide materials. Base materials are usually glass substrates with tight specifications for surface flatness and optical transparency. Regarding new or different resources, the team has already identified through the capital equipment list reviewed above the new or additional manufacturing resources which will be required.

The primary issue which we identified in the manufacturing-specific criteria was the frequency with which documenting run sheets were updated. Some process changes were not recorded in updated run sheets resulting in discrepancies between reported and actual target levels (to be discussed further in section 6.3.4). To fully meet the intent of MRL 3, we recommend reconciling process documentation with actual device targets.

6.3.2 MRL 4: Identification of key thin film manufacturing processes

MRL 4 presents more challenges in thin film processing than MRL 3. MRL 4 focuses on identification of manufacturing processes: flows, integration, resources, key design requirements and characteristics, and initial roadmapping to MRL 6. Yield assessments are also completed on similar processes. Here the primary challenges are expected to be in understanding the manufacturing capability requirements, critical processing requirements, and key design characteristics. This challenge comes primarily from the R&D nature of the work done to date, not from an intrinsic design limitation, though, so this is an addressable problem. Overall, many of the steps towards MRL 4 have not yet been started.

The primary limitation found in our MRL 4 assessment was an overall shortage of comprehensive data analysis. As noted above, most early programs had focused on demonstrating "best effort" performance, typically on a small number of devices. In general, no device-to-device performance analysis was carried out, nor was device performance correlated back to processing parameters. Likewise, no uniformity studies had been done within at least the past five years. Yields were not determined using performance criteria, but instead only on whether a device made it through the assembly process. Consistent with these trends, no database existed with current or past processing data. Most processing records were only kept manually on the run sheets.

The manufacturing flow concept requirements of MRL 4 include a requirement to assess yields and identify manufacturing capability needs, critical processes, and interactions between processes. For thin films, this means identifying requirements for optical transmission, thickness targets, sheet resistance, etc., with regards to uniformity across the area of a wafer, wafer-to-wafer uniformity within a run, and run-to-run uniformity. Requirements should include definitions of acceptable ranges as well as target values. Processes such as annealing and subsequent deposition steps are also known to change the performance of previously deposited films, so the interactions between these processes must be documented and in-process shifts tracked through the run sheets. Further, the net effects of all thin film deposition layers needs to be considered together, for example by budgeting for optical losses between the AR coating layer and the transparent electrodes. Building a database and correlating device performance to processing characteristics will clearly be necessary.

Finally, MRL 4 also starts requirements for planning and for funding commitments. Cost drivers must be assessed and a plan for maturation from MRL 4 to MRL 6 is required, including funding sufficient to reach MRL 5. Again, data will be critical, since cost-drivers imply an understanding of yield issues.

6.3.3 MRL 5: Thin film deposition manufacturing process development

MRL 5 focuses on manufacturing process development. This includes establishing process capability and control, value stream mapping, and initiating make/buy tradeoffs. A viable business plan is required, along with cost and schedule projections. Considering the financial analysis from section 5.4, MRL 5 will be the appropriate point for the firm to decide whether to invest in production capability at Site B, or if devices should instead be sourced externally. On the technical side, MRL 5 will require an understanding of uniformity across wafers and devices, and impacts on device yield, whether these are used as steps towards manufacturing within the firm, or as steps towards qualifying an external provider. Yield/rate improvement studies are initiated. MRL 5 also requires planning for maturation to MRL 7, and available funding to reach MRL 6.

Thin film work towards MRL 5 has for the most part not been started today. Achieving MRL 5 will require a significant increase in rigor, including data collection and analysis, establishing a requirements flow-down from the component, and modeling of interactions with component tolerances. It will require routine process monitoring, such as in-process control charting. MRL 5 will also require that all specifications and control limits be established.

6.3.4 Wafer process control analysis

The manufacturing readiness assessment of wafer processing showed that a shortage of data collection and analysis will probably become an issue at MRL 4 and MRL 5. Specifically, the MRL analysis highlights the questions that the DoD and AFRL wanted to promote, such as "can more than one device be made reproducibly?" Trying to answer this question, and attempting to set the stage for the team in future device builds, we analyzed existing data from previous builds to see what level of understanding we could gain. One frequently heard refrain was "we do not do batch data analysis because the volumes that we produce are too small for process control analysis to be useful." Thus, we also sought to see if indeed data volumes were too small, or if useful information could be obtained. In fact, our analysis did allow us to identify processes which are likely to be critical for MRL 4 or MRL 5. It also highlighted ways in which more controlled design-of-experiment (DOE) approaches may be taken in the future in order to increase the value of the data that is available through low volume builds. Finally, full analysis of the data indicated potential areas in which time (and cost) may be saved by identifying non-conforming material at early processing stages. These savings will be critical as volumes increase in the near future.

6.3.4.1 Test population and method

To provide a meaningful framework for future process control monitoring, we needed to develop a model with a population of comparable devices. Specifically, we needed to make sure we did not include devices for which the R&D team had intentionally varied processing parameters. With the help of the R&D team, we identified a set of devices for evaluation which had been built during a six month period to nominally identical design specifications, as part of a final build for a previous program. Specific thin films were then selected for analysis based on the R&D team's expectations of processes that should be in control. A detailed report including the full analysis of all films was provided to the firm. Here, we show only sample results including behavior of an in-control film (Film A) and an out-of-control film (Film B), for illustration purposes. We used the Film B data to look for trends across a wafer, and show how a trend analysis might be used to remove at least one out-of-control wafer. We also identify correlations between measurements of Film B early in the fabrication process and performance at the end of processing, and show how this could be used to yield wafers early in the process before additional fabrication expenses are incurred. As with other data, potentially proprietary numerical values have been omitted.

The test population consisted of 14 discrete substrate wafers and 12 unique superstrate runs used to assemble 23 devices of three different sizes and two different types. Up to five discrete thin films are deposited on each substrate or superstrate in a series of coating runs. In general for this device population, most series were unique to one or two wafers. For example, two wafers might be processed together for Film A, Film B, Film C, and Film D, and then another two wafers would be processed together for Film A′, Film B′, Film C′, and then might be split into two batches for Film D′ and Film D″, where ′ denotes a different deposition run. The 14 substrate wafers were processed in 7 unique series. Each superstrate was processed in a single unique series. These unique series unfortunately prevent meaningful analysis of the full film stackup, but controlled builds using a DOE process were identified as a potential next step for future builds. We limit our analysis below to only single films with equivalent processing targets.

For each selected process or parameter, we set up sample control chart analyses to identify natural control limits and to compare these limits to nominal specifications. Two commercially available software packages were used for data analysis: SPC Excel[12] and JMP.[13]

6.3.4.2 Film A results

We first illustrate behavior of an in-control process using data from one type of deposition run (Film A). Figure 6-1 shows the individual (a) and associated 2-point moving range (b) control charts generated by measurement of Film A as deposited. Individual measurements are shown as points. Natural control limits, shown as heavy dashed lines, are computed based on the mean (heavy solid line) and the sum of the moving range data. The 95% confidence interval for the mean is also shown (thin dotted lines).

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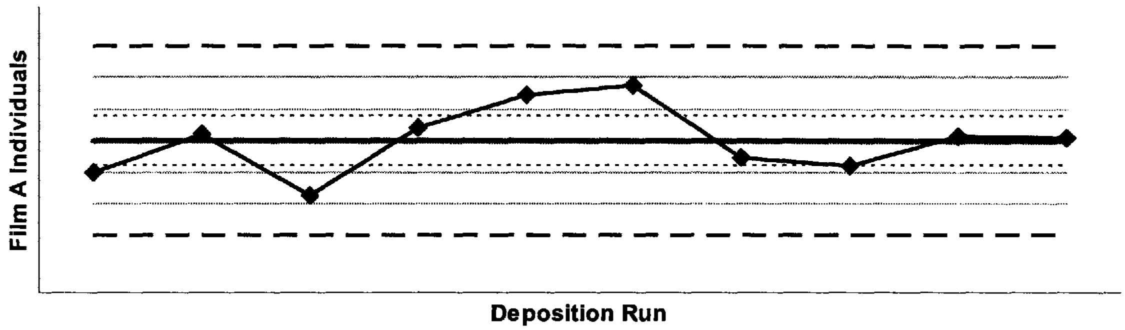
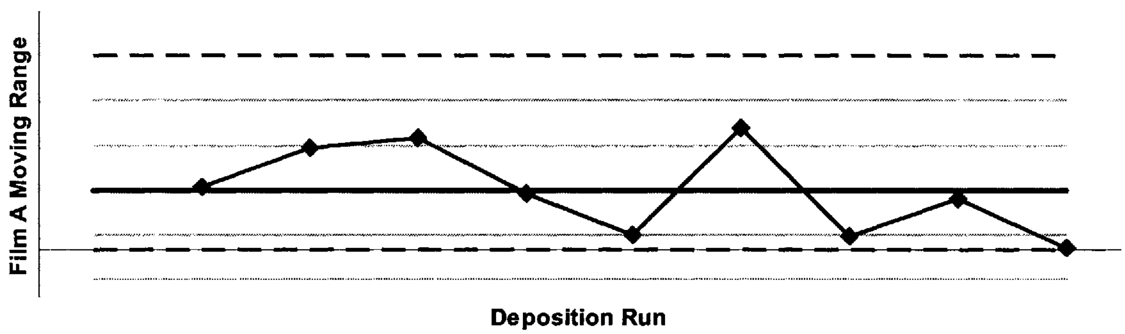
[12] SPC Excel is a Microsoft Excel add-in with SPC (Statistical Process Control) capabilities. http://www.sigmazone.com/spcxl.htm

[13] http://www.jmp.com/



(a) Individuals control chart



(b) 2-point moving range control chart

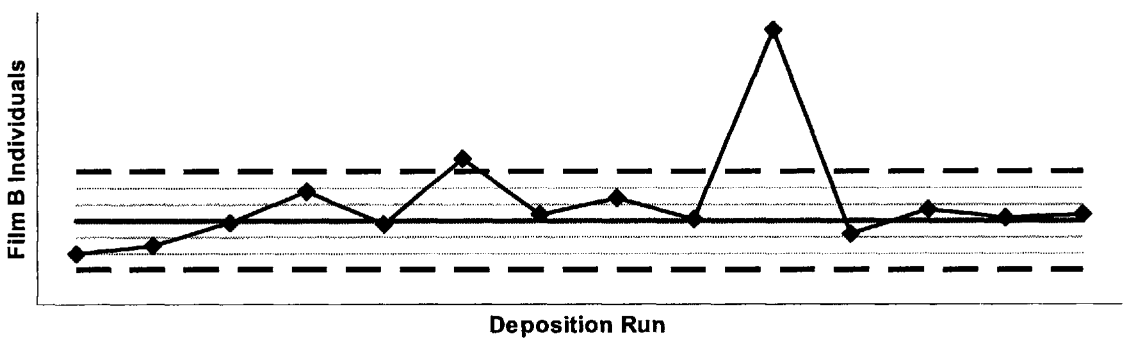
Figure 6-1. Film A control charts including (a) an individuals control chart, and (b) a 2-point moving range chart.

The data indicate that the process for Film A is under control, within the natural control limits shown, and the 95% confidence limit for the mean contained the target value, which is good, although this interval is wide due to the small number of data points. Processing documents did not contain upper and lower specification limits for Film A, so we could not evaluate whether the process was also within specifications, but this can in the future be done in a straightforward manner by the development team.

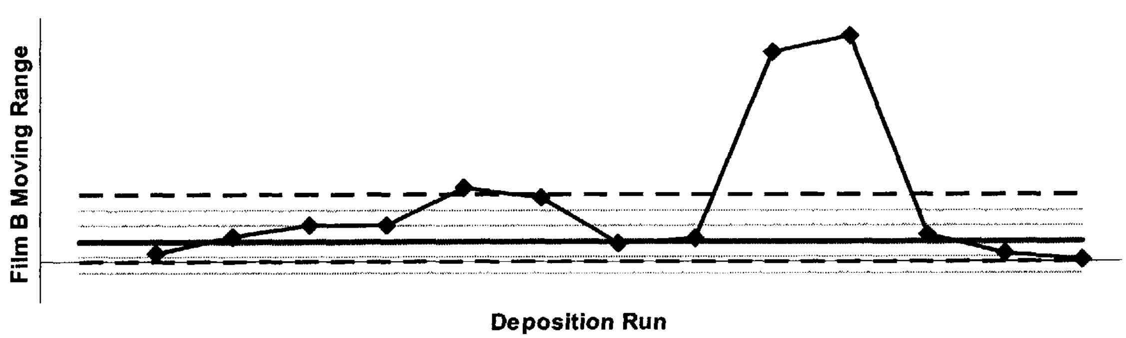
The primary unknowns for this process are now the within-wafer uniformity and within-run uniformity, since we only have one measurement per run, taken on a witness coupon placed in the chamber with the wafers. Historically, non-uniformity is reported to be less than a percent. In the future, this non-uniformity should be confirmed. This value, together with the few percent variation observed run-to-run in Figure 6-1, could be used to construct the boundaries of the process capability required for MRL 5 compliance. These serve as a start towards baselining process capability and control for Film A at MRL 6.

6.3.4.3 Film B results

Other films were not in as good control as Film A. Figure 6-2 shows the individual (a) and 2-point moving range (b) control charts generated by measurement of a witness coupon from Film B deposition. Again individual measurements are shown as points, and natural control limits are included as heavy dashed lines. Two data points show up as "out-of-control," above the upper control limit. These points indicate that this process should probably be monitored more closely to determine what may be triggering these events.



(a) Individuals control chart



(b) 2-point moving range control chart

Figure 6-2. Individuals (a) and 2-point moving range (b) control charts for Film B.

Two other concerns were raised from the analysis of Film B. First, the natural control limits computed, even with the two outlying data points removed, were more than a factor of two wider than the nominal specification limits listed on the wafer processing run sheets. Second, although the run sheets contained specification limits, these limits were not used to yield wafers during fabrication. Only about 60% of the data in Figure 6-2 met specifications and yet all wafers were processed and used to build devices. Together, these observations lead to the conclusion that the existing documentation does not accurately reflect design requirements or processing rules today. If, on the one hand, specification limits are incorrectly too narrow, they should be widened to avoid unnecessary scrap in the manufacturing process and unnecessarily tight equipment requirements. If, on the other hand, specification limits are actually correct, and final device performance will be impacted, then the process needs to be improved. Reconciliation between documentation and actual practice should be done to truly comply with MRL 3 requirements.

6.3.4.4 Within-wafer uniformity and within-run uniformity

Thus far we have only looked at single point measurements on witness coupons included in the deposition chamber. We now examine process control data measured at several different points on a wafer, to understand issues associated with within-wafer uniformity. We will also briefly investigate within-run uniformity here. For this purpose, we used another set of measurements of a parameter determined by Film B, but measured at the end of the process (EOP).

Characterization of within-wafer uniformity requires measurements at multiple locations on the wafer. Wafers for our device are circular. Nominally square optical apertures are distributed across a wafer, in a configuration determined by the size of the aperture and the available size of the wafer. Test structures are included in the photolithography mask pattern at specific locations across the wafer so that a "map" of the film uniformity can be constructed. For process monitoring, it is in general desirable to map as much of the wafer surface as possible, by placing test structures at representative locations across the wafer, both close to the center and close to the outer edges. The number of data points along a particular axis determines what order of fit may be applied to the data. For example, to get a measure of curvature in film thickness, measurements would typically be taken at center, and at least two other points $\pm r$ along the x- and y- axes, where r is a radial distance from the center $(x, y) = (0, 0)$. For our optical devices, test points were unfortunately less than ideal, but some measure of across wafer uniformity can still be obtained. Three different photolithography mask sets were used for the three different aperture sizes. Of these, two masks had four test structures at coordinates approximately equivalent to $\{(x, y)\} = \{(x_0, y_0), (x_1, y_0), (x_1, y_1), (x_0, y_1)\}$ where x_0 and y_0 were approximately in the center, and x_1 and y_1 were towards the periphery. These locations probe less than half the wafer since they are only effectively in a single quadrant. The third mask, however, had five test structures at coordinates approximately equivalent to $\{(x, y)\} = \{(x_0, y_0), (x_1, y_1), (-x_2, y_1), (-x_2, -y_2), (x_1, -y_2)\}$, where x_0 and y_0 were as before, and x_1, x_2, y_1, and y_2 were about 1/3 to 1/2 the distance from center to edge. Together, this ensemble of measurements allows us to look at some film variability across a wafer. The third mask also allows us to estimate some measure of curvature across the wafer, even though test structures were not balanced evenly from the center and a single axis cannot be drawn through any three points. Overall, the mappings were unfortunately insufficient to allow 1:1 assignment of specific values to specific devices within a wafer. Designing future masks with more comprehensive test locations was suggested as a future improvement.

An X-bar chart of the EOP measurements across each wafer is shown in Figure 6-3. In this plot, each wafer is represented by a point showing the mean value of the four or five measurements. The box plots around each point show the maximum, minimum, 75th percentile, 25th percentile, and median for each wafer. Every pair of points with the same symbol represents a pair of wafers processed in the same deposition run. The solid lines represent the computed upper control limit (UCL), mean, and lower control limit (LCL) computed from the data.

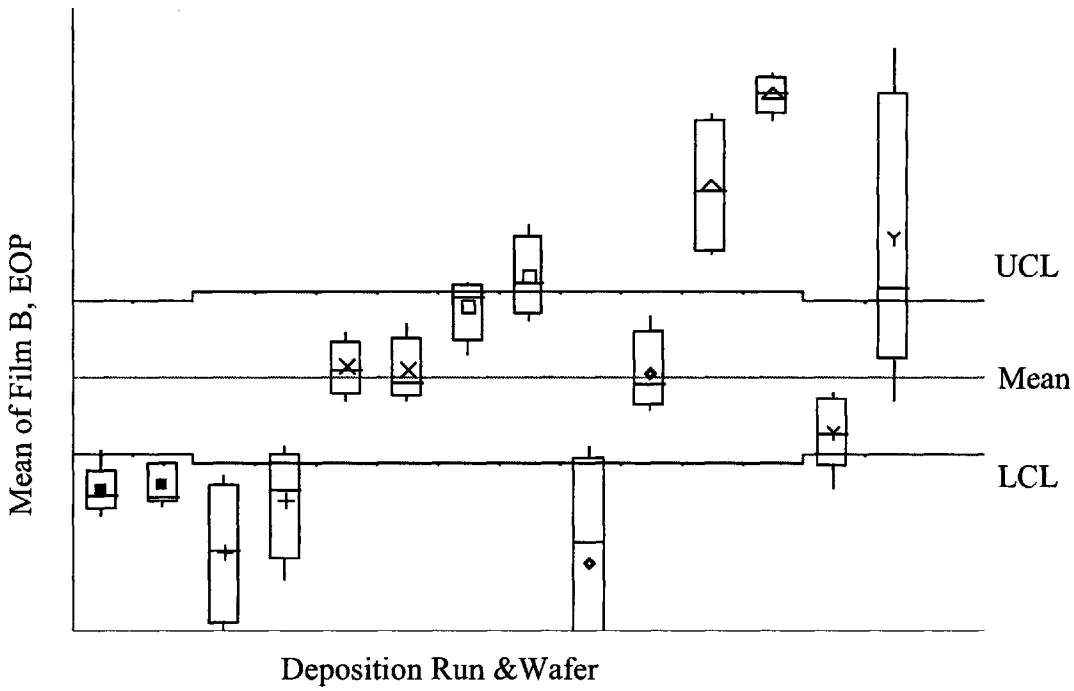
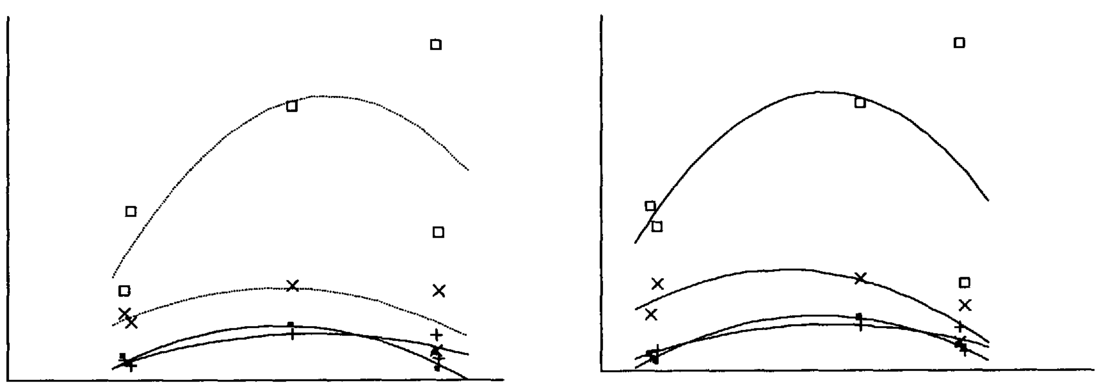


Figure 6-3. X-bar chart of Film B, EOP across several wafers.

The data in Figure 6-3 prompt several observations. First, we see that the overall process was not in control during the entire build, consistent with the results already reported for Film B. Second, the first four pairs of wafers still appear to perform very similarly within each pair. Although the data indicate that the process is not in control and varies significantly from run-to-run, the mean values for the paired wafers in groups 1 (square dots), 3 (x's), and 4 (squares) are fairly close to each other. This might indicate that the process had been running in control at an earlier date, but that there was slippage at an early point in this build. The mean values for nine of the wafers fall outside of what should be the control limits. Third, wafer-to-wafer variation within a run appears to increase during the build. Finally, for this parameter, actual performance again did not agree with nominal specification limits in the documentation. Overall, this data indicates that in-process control charting and monitoring should probably be implemented on future builds, so that appropriate changes can be made when process control degrades.

The high level of variability within each wafer leads to the question of whether there are observable trends in film characteristics across a wafer or within the testing chamber. To explore this, we examined the four wafers for which five data points were available. These were the first and last pairs of data from Figure 6-3. We estimated the *x*- and *y*-coordinates of the test points from wafer maps in the documentation and plotted the measurement results as a function of these coordinates. We then checked for quadratic trends in the data, since wafer rotation during deposition will often produce radially varying film thickness. These results are shown in Figure 6-4. The first two wafers (A and B) do show some quadratic behavior. R^2 values for the 2nd order fits (solid curves) are 0.87 in *x* and 0.96 in *y* for Wafer A (dots), and 0.66 and 0.69 for Wafer B (+'s), indicating that about 90% of the variation in Wafer A and slightly less than 70% of the variation in Wafer B might be explained by radial variation. Within the second pair of wafers (dashed curves), we find similar quadratic behavior in Wafer C (x's), although with less convincing fitting parameters (R^2 was only 0.30 in *x*, but 0.55 in *y*). More importantly, though, we see very anomalous behavior in Wafer D (squares). Behavior for Wafer D diverges significantly from the previous trends and the total variation across the wafer is much greater. This is important not so much to determine the form of the actual variation for Wafer D,[14] but to point out that in a manufacturing setting Wafer D would probably be eliminated from the processing group based on this anomalous behavior.



(a) Film B, EOP by x-coordinate

(b) Film B, EOP by y-coordinate

Figure 6-4. Film B, Msmt #2 results as a function of test coordinates x (a) and y (b).

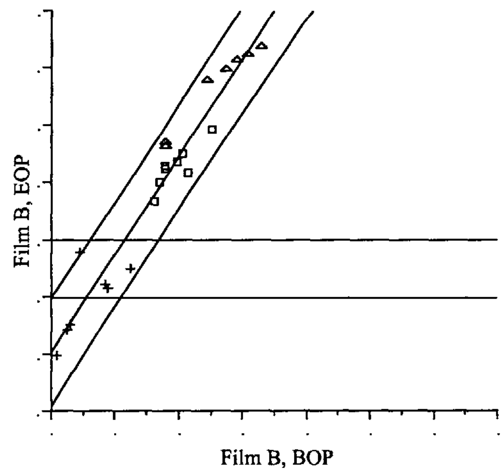
[14] The quadratic fit in pure x-y coordinates for Wafer D is admittedly not particularly appropriate but is retained in the figure for illustration. In fact, the measurement values increase monotonically along a nominal southwest/northeast axis from $(-x_2, -y_2)$ through (x_0,y_0) to (x_1, y_1), but rise and fall along a nominal northwest/southeast axis from $(-x_2, y_1)$ through (x_0,y_0) to $(x_1, -y_2)$. Since no three measurement locations lie on a straight line, though, we did not do an axis transformation to make the fit to the nominally rotated axes.

Finally, the ensemble of the Film B results from the witness coupon measurements (Figure 6-2) and from the actual wafer data at end-of-process (Figure 6-3 and Figure 6-4) indicate the witness coupon measurements are not particularly reliable when there is significant variability within a deposition run, between wafers or across a wafer, because the coupon only samples one location in the chamber. If we do want to scrap wafers during a manufacturing process in order to avoid processing non-conforming material, a wafer-specific measurement is likely to be most appropriate.

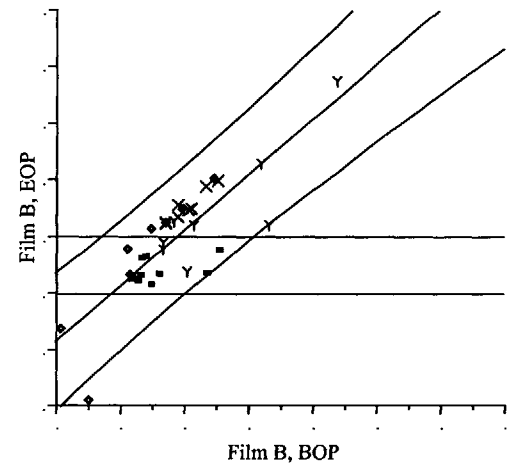
6.3.4.5 Correlations through the process

In order to reduce costs and avoid unnecessary effort, it is preferable to remove non-conforming material from the processing queue as soon as it can be identified. In our analysis above, we identified non-conforming material at the end of processing. We demonstrate here how this material could in fact be identified at an earlier point in fabrication.

Measurements equivalent to the EOP data of Figure 6-3 and Figure 6-4 are in fact taken at four separate times during processing, once after the initial patterning at the beginning of process (BOP), and then after each additional thin film is deposited. We compared the data from each set of measurements to the data and found that the data at EOP can be well predicted from the data at the previous steps, allowing for process induced shifts. As an example, Figure 6-5 shows the correlation between BOP and EOP measurements for wafers of Type I (in (a)), to which four additional thin films are added, and for wafers of Type II (in (b)), to which two additional thin films are added. In both cases the EOP data can be predicted well by a simple linear fit (solid line). The slope of the line for the Type I devices is steeper, indicating a larger relative in-process shift, due to the additional thin film applied to the Type I devices. Both fits are quite good and the 95% individual confidence curves (short dashed lines) contain all but one or two extreme values. The R^2 value for the Type I fit is 0.94, and the R^2 value for the Type II fit is 0.68. The slightly lower R^2 value for the Type II fit probably comes from the presence of two groups of wafers with slightly different patterns, grouped together here to ensure a large sample size.



(a) Type I devices



(b) Type II devices

Figure 6-5. Correlation between beginning of process and end of process measurements for Film B, for (a) Type I wafers and (b) Type II wafers.

These data show that the thin film performance at the end of the process can in-fact be predicted from the first set of measurements taken after the wafer is patterned. This means that out-of-specification wafers could in the future be pulled from processing almost immediately, without the expense of applying the three remaining thin films.

One final piece of information is required before wafers could be yielded at the initial patterning step. We need to know the correct specification limits for the step at which wafers are down selected. The horizontal dashed lines in Figure 6-5 show the specification limits for Film B as documented in the process run sheets. However, as mentioned above, these specification limits are entered with the same values for the as-deposited witness coupon, the as-patterned film (BOP), the two intermediate test steps, and the EOP film. They are also entered with the same value for Type I devices as for Type II devices. For these specification limits to be useful, they need to take into account the shifts induced at each step and the differences in device type. Designed experiments need to be performed to validate the correct specification limits by correlating final device performance with in-process performance. Hopefully these experiments will also be able to demonstrate that a wider specification range will be acceptable. As shown in Figure 6-5, yields to the current narrow specification limit will be extremely low.

6.3.5 Thin film process summary

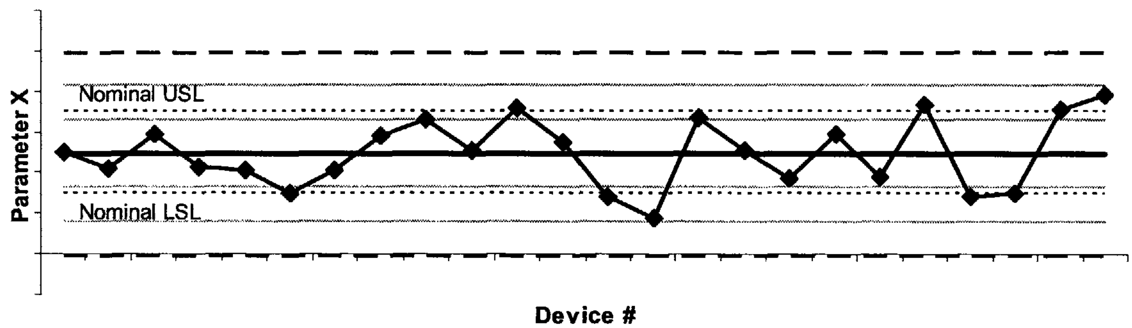
The manufacturing readiness analysis and in-process data analysis of representative thin film deposition processes show that while some steps towards manufacturing readiness have been taken, many more remain to be done. On the positive side, existing process documentation will help the team to meet the documentation portion of the MRL requirements, in particular for MRL 3. On the negative side, a lack of a database infrastructure and missing batch data analysis was identified as a possible hindrance to reaching MRL 4 and beyond. A retrospective analysis of previous data showed that processes were not as well controlled as had initially been believed, and that many specification limits in the documentation needed to be updated and/or corrected. However, this analysis also showed that statistically significant data can be obtained from even small processing runs. As a consequence, the R&D team at Site A has since implemented real-time on-site control charting and is developing a database for monitoring process parameters. Processing documentation is also being updated. Initial reports indicate very positive results from these efforts. As more devices are built on current and future contracts, the team will have the opportunity to implement meaningful pro-active SPC controls to improve processes and yields on the way to MRL 5 and MRL 6. This type of effort should improve performance and reduce costs, making the component more competitive overall.

6.4 Assembly and final test

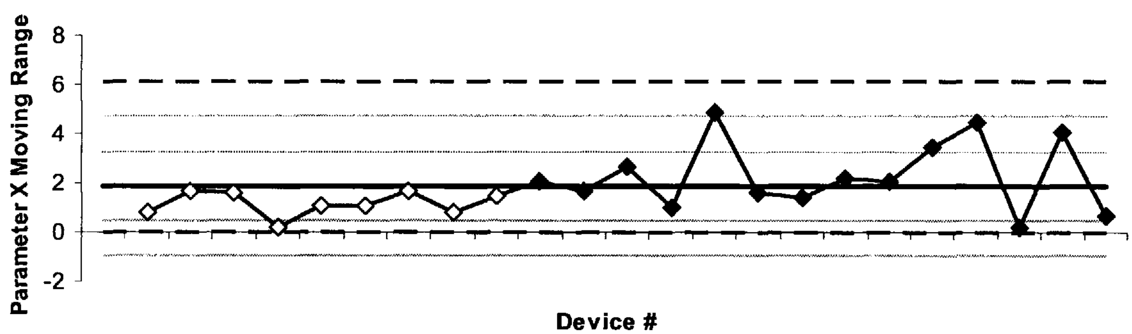
To supplement the liquid crystal and thin film analyses, we also completed one more review in the area of assembly and final test. Many of our findings were similar to those from the first two studies, so rather than present a detailed analysis of compliance with MRL criteria, we summarize key learnings here.

First, the assembly process today is highly manual and non-standard. In some cases it requires artisan-like skills known today by only one employee. In other cases, qualitative assessments determine when a process is "complete." A comparison of processes used in the firm with the industrial base also shows many steps for which the processing technique used by the firm is different from the industry standard process. Proprietary techniques may be warranted in cases where they provide superior technical performance at an acceptable cost, but the cost-benefit analysis needs to be completed. The customer expects the firm to use as many industry-standard techniques as possible, to benefit from existing knowledge, so proprietary or unique techniques will undergo special scrutiny. Overall, from a manufacturing standpoint, although the assembly flow can be identified today, the actual device design will need to be significantly re-engineered in order to produce a robust and manufacturable device. In our first survey, respondents thought on average that the device would need from 45% to 70% redesign or reengineering in order to meet manufacturability requirements. In the second survey, 69% of respondents also thought the current plan to meet these redesign needs was insufficient, and only 21% thought the plan was sufficient. The team may be able to meet MRL 3 by documenting the need for this redesign, but an actual redesign should be started before MRL 4.

Second, on the assembly side, we found some existing documentation, but we also found a need for updates and reconciliation of nominal requirements with actual process capability, as in the case of thin films. For example, Figure 6-6 shows process control data for an assembly related parameter (X). The process is in control, but the nominal specification limits fall inside the control limits. A capable process, e.g., one with $Cpk \geq 2$, has specification limits that are much wider than the control limits. In this case, as in the thin film data analysis, it turns out that the nominal specification limits are merely quoted, but are not acted upon. In other words, devices outside of specification are routinely processed. For these devices, the team also reports no apparent adverse performance from devices outside of the nominal specifications. For parameter X, the appropriate action is probably to confirm that wider specification limits would be acceptable, and to update documentation accordingly. If wider limits are not acceptable, process improvements will be needed. In this case, the team should probably look more closely at process settings for the first several devices, which seem to follow a tighter distribution (with smaller moving range values, open diamonds) than the later devices. The process may indeed have been under better control at an earlier date.



(a) Individuals control chart



(b) Moving range control chart

Figure 6-6. Sample assembly-related process control data, including natural control limits and nominal specification limits.

In the final test area, we also found trends similar to those identified for the liquid crystal and the thin films. Again, a comprehensive database was lacking, even where test systems had been fully automated. Individual test results were stored in individual electronic formats (some numeric, some images), but device-by-device test results had to be extracted manually from the individual files. We also had trouble finding documentation on particular tests, especially where fitting routines had been modified multiple times over the years. Databases and documentation will both need to be improved, or called out as required new capabilities, to meet MRL requirements. Development of an appropriate database will be critical for the studies needed to establish appropriate parameter control limits for fabrication processes.

Finally, we used the available final test data as a last check on both liquid crystal and thin film processes. We did not previously have sufficient multiple measurements of a single liquid crystal to estimate liquid crystal uniformity, for example for birefringence. Using final test data, we identified a surrogate parameter (Y) which provides an alternative way to characterize the liquid crystal uniformity, by looking at device-to-device consistency. A control chart for parameter Y is shown in Figure 6-7. The parameter is well controlled and the mean is quite predictable. Variation from lower to upper control limits is on the order of a few percent. Since this parameter depends on the liquid crystal and on specific assembly steps, variability comes from both sources. This gives us confidence that the liquid crystal uniformity is at least better than a few percent. This estimate could be further refined by additional physical measurements of devices during assembly, to get an independent estimate of the assembly-related variability. This data can also be used to benchmark uniformity of future liquid crystals. If the assembly process does not change, but a new liquid crystal is introduced, changes in parameter Y can be attributed to variations in the new liquid crystal.

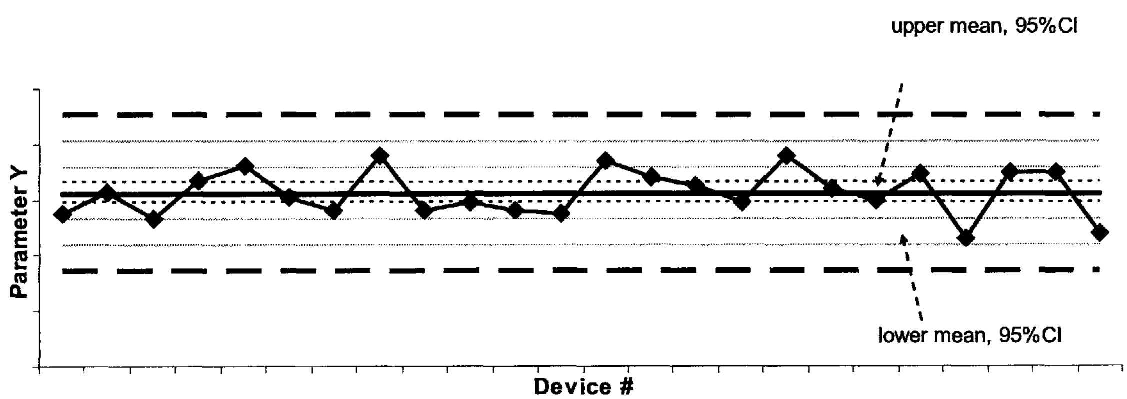
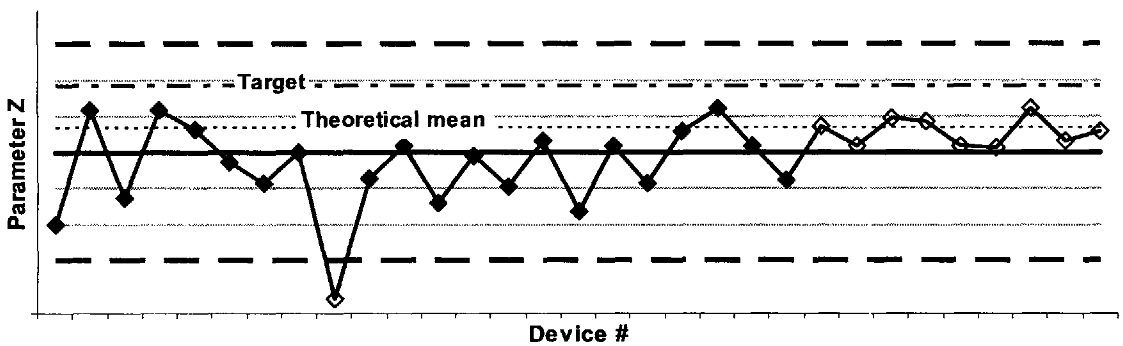
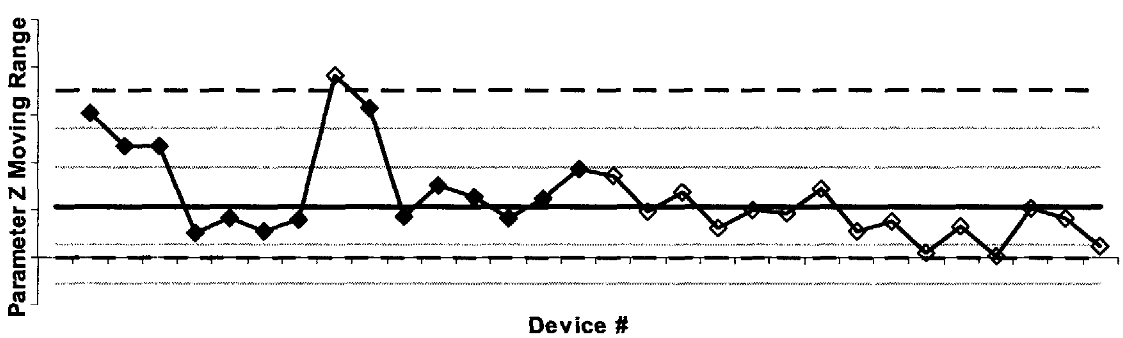


Figure 6-7. Final test results for a surrogate liquid crystal monitoring parameter, Y.

For thin film processing, we also did not have an in-process method to monitor the performance of the final stack of thin films. Final test data allows us to check whether the ensemble of thin film processing steps produces devices with acceptable performance. Figure 6-8 illustrates device capability against one parameter (Z) which is driven by the performance of the ensemble of films together. All but one data point falls between the control limits. The process thus appears controllable, and control limits may even be able to be tightened if the trend in tighter performance of the later devices (open diamonds). This looks positive, but Figure 6-8 also highlights a major risk. Although parameter Z may be controllable, it is not centered on the actual performance target, shown by the dash-dotted line. This is in fact a performance threshold which no device has yet reached. This is what prompts the concern above regarding TRL compliance for the device and ultimately for the system. As noted before, all previous builds, this one included, are contracted on a best-effort basis. Thus the performance in Figure 6-8 is contractually acceptable for these earlier contracts, and may in fact represent state-of-the art achievement. It is, however, non-conforming with future deployed system needs.



(a) Individuals control chart for parameter Z. The target is shown as a dash-dotted line.



(b) 2-point moving range control chart for parameter Z.

Figure 6-8. Thin film-driven final test performance.

The primary concern is that the systems being designed today to use the component assume that the target specification will be achieved, but there is not a clear path towards meeting this goal. The expected performance (theoretical mean, dotted line) of the design today falls below the target. Several devices are close to the theoretical value, but the design itself must be changed in order to reach the target. Analysis of parameter Z on a previous set of devices from a few years earlier shows equivalent performance (the two populations are statistically similar). There have not yet been sufficient design changes from one build to another.

6.5 Manufacturing readiness assessment summary

The review of component manufacturing readiness against MRL metrics to a large extent reinforces the strength of the reasoning that is prompting MRL implementation. Unless manufacturing-specific requirements are made clear early in the product design process, there is a high risk that manufacturing concerns will be left outside the process. This is not because of an intent to ignore them. Instead, it is an outgrowth of the R&D search for a "hero" technical result and a focus on finding the single device which can demonstrate superior performance. We see this in the liquid crystal sourcing, in which the best research is at the university level and the best molecular synthesis is available in Europe, so this supply route is used. We see this in the thin film processing arena, in which batch-to-batch data is not gathered or analyzed and process documentation does not match actual processing, frequently because it is time consuming or cumbersome to perform these task for small volume runs. And we see this in assembly and final test where again it is more advantageous for early stage R&D teams to develop craft-like skills and test protocols geared towards individual devices than to spend time and resources developing robust manufacturable designs.

We hope, however, to have shown through SPC analysis of even small data sets, that there is indeed much to be gained from analysis of process control and capability in the early stage R&D environment. Results from a small number of devices can identify which processes are in control and which are not. Patterns across devices can be used to identify material which may have seen abnormal processing conditions. Correlations from beginning to end of process may be used to identify material to pull to the side to make room for more promising material to be processed. On the design side, it is as important to know which processes are in control as on the manufacturing side. If a process is not in control, then there is no way to conduct controlled designed experiments with intentional changes in the design space.

It is hard to argue that starting many of the best practices called out by the MRL metrics will be detrimental to R&D progress. In fact, one could argue that following many of these practices could ultimately be advantageous to the team. In a competitive funding world where contracts and future investments are uncertain, the team which is more prepared to turn technology into a product will be advantaged. Documenting process capability can be beneficial both when processes are in control, where it demonstrates capability, and when problems may be present, where it may serve as a justification for retaining process improvement funding. The intent of the MRL process is to move funding forwards to address manufacturability concerns, and as long as a credible plan to improve processes is present, it should be more beneficial to spend these dollars early rather than late. Finally, in an environment in which make/buy evaluations are on the horizon, process control data on in-house processing provides a benchmark by which to assess potential competing suppliers, and, in the event that superior performance can ultimately be demonstrated in-house, to potentially retain technology responsibility.

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Chapter 7: Conclusions

To conclude, we return to several of the questions posed at the outset of our study. What could be the effect of independently applying commercial best practices for new product development from the very early stages of technology creation, on the part of the defense contractor, in a bottom up approach? If a product development team uses the MRL framework, will the contractor be better positioned in the long run? Is this framework sufficient? If not, what other types of concerns should be addressed during technology development? We review first how these questions are answered for new product development in defense in general, and then how the answers are validated by the learnings from our case study.

7.1 Learnings for New Product Development in Defense

We have seen in this work that commercial best practices coupled with relevant defense industry metrics can indeed be integrated to provide a set of NPD metrics for defense contractors, even in early stage R&D programs. Metrics such as Manufacturing Readiness Levels can provide defense-relevant criteria against which to evaluate new technology programs. These evaluations successfully allow identification of key issues critical to delivering a quality product in a cost-effective and time-effective manner. By reviewing relevant issues early in the design cycle, firms should be able to avoid costly work-around fixes later in system deployment stages.

Contractors who use MRL criteria can expect to gain a competitive advantage by understanding product and processes at an early stage, and by identifying areas for improvement. Using a pro-active general approach with simple criteria may be preferable, in fact, to following a full-blown top-down mandated approach. We saw in our case study that much can be learned from simple manufacturing readiness assessments and process evaluations, without using the detailed web-based checklists being developed for the formal EMRL and MRL roll-outs. NPD processes in defense today lag behind commercial NPD processes by about two generations, as the extensive checklists being developed for the EMRL and MRL frameworks parallel first-generation Stage-Gate™ processes, rather than the more flexible third-generation processes. There is a risk that the higher level of detail and structure in the more extensive checklist formats will slow down learning by making contractors focus more on the evaluation process itself and less on the learning from the evaluation. This risk will need to be monitored closely by the DoD and the GAO as the EMRL and MRL assessment methodologies are formally incorporated into defense acquisition regulations. More gains might be obtained by the DoD by providing additional funds for the Man Tech program or by requiring that its own funding agencies incorporate MRL metrics into contracts, than by further developing extensive methods to monitor MRL compliance.

We do find that the xRL metrics should also be supplemented with additional commercial best practices in order to facilitate project and firm success. As first-generation processes, primarily focused on measuring quality of execution at the contract level for an external customer, the xRLs do not address critical success factors internal to the firm. Firms should thus also conduct independent assessments of programs, to make sure they fit strategically with the firm's business goals, that they are financially viable, and that the firm itself will have a competitive advantage. To a large extent, this implies that firms need to take back some of the responsibility which they have deferred to the contract funding agencies, re-activating their own responsibility for project down-selection. Finally, firms also have responsibility for structuring programs organizationally for success. Teams must have clear accountable leaders, clear technical objectives to meet, and sufficient support from management to meet them. In cases where a technology is being developed for multiple defense purposes, this may mean that the firm takes it upon itself to define a team responsible for maturing the technology platform as a whole. Such a firm-specific development team may be the best way to avoid the pitfall of focusing too much on detailed changes for individual contracts and of focusing too little on fundamental technology development. This type of approach should help the firm to constantly move forward technically, even in uncertain funding environments, but will need to be carefully balanced with customer desires for individual dedicated teams.

7.2 Learnings for the Firm

We have demonstrated through a case study of an optical component being developed on defense R&D dollars that when best practices are actively applied, the firm can find opportunities to gain a competitive edge in the long run. Specific results from the internship study were incorporated into organizational and contract changes related to the optical component development at the host firm. Organizationally, a key point person has now been designated who is responsible for technical maturation of the optical component itself to support all contract platforms. At a financial level, the leadership team has committed to one specific capital investment path for the next three years and has moved from an "opportunistic" approach to one of measured decisions. At the technical level, in-situ process control monitoring is being implemented within the device fabrication facility, a database is being developed, and process documentation is being updated. All reports to date indicate that the R&D team has made significant progress on existing contracts since these changes were made. Finally, for a key contract, a technology development roadmap incorporating both TRL and MRL milestones and go/no-go decisions for additional capital has now been identified. A pro-active approach is also being taken with this customer to pursue a formal MRL assessment on the contract in 2007.

Overall, the division learned several key lessons from the case study analysis. At a technical level, both the systems engineering group and the R&D group had been unaware of some of the requirements in component manufacturing, such as certification of suppliers. Identification of sole/foreign sourcing issues in the liquid crystal was deemed particularly useful, as was the reminder that the firm is ultimately responsible. The precedence relations highlighted by the EMRL structure clarified that new technology elements cannot be "on-ramped" at a later stage without pulling the entire system back in maturity. Most comprehensively, the analysis tools introduced for strategic, financial, and technical evaluation provided a new framework which the division plans to incorporate into future new technology development plans at the component and system level. The firm sees that it has independent choices to make as it executes on existing and future contracts.

The theme which seemed to resurface over and over in our MRL assessment is that in order to ensure a high level of readiness for future production, there must be a change in mindset from the search for "hero" results to the development of a manufacturable product which meets or will meet key performance metrics. Key to this is a shift from the performance of one to the performance of many. This shift must take place both at the contractor and at the customer level, where the customer must decide on the performance level required. With their early introduction of yield and process control analysis, the MRL metrics can hopefully serve as a tool to start this change. From the firm's standpoint, this shift has to occur. Perpetual returns on low volume early stage R&D contracts are insufficient to justify large capital expenditures needed to support the technology. The firm has to reach the higher volume systems deployment and demonstration contracts at MRL 7 and above in order for it to reap the benefit of investment in the technology. Effectively, while delivery of "best effort" is compatible with early R&D contractual requirements, the firm must make sure that internally it has a clear path to meeting performance targets at later stages.

One finding from our case study is that the firm is in fact further towards the beginning of the product development cycle than originally thought. Although this could be seen as a setback, it also can be seen as an opportunity. Armed now with a better set of tools with which to evaluate technology progress the firm can make more informed decisions as to what paths are in fact the best to follow. Using the best practices reviewed here, the final product should have a better long term probability of success.

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