Preliminary Manufacturing Assessment

Bryan D. Smith[1]
Northrop Grumman Space Systems, Promontory, Utah, 84302, USA

Northrop Grumman's Propulsion Systems has transitioned recently from a largely heritage product manufacturing division to developing many new large-scale solid rocket boosters that support a variety of customers. In order to better support this new position, Propulsion Systems has created an initiative to establish a new culture of manufacturable design. PMA is a strategy for all design and manufacturing teams to work together throughout the design and development cycles to ensure a product design can be manufactured and that it will meet all external and internal requirements for safety, quality, schedule, cost, and reliability. This paper discusses the key elements in the execution of PMA. It includes successes, failures, lessons learned, and how to sustain the culture of change for the long term. As the business continues in its new cultural transformation, it recognizes that it requires constant attention to revise the strategy, always looking for new ways to improve and adapt to new challenges.

Nomenclature

CAD	=	Computer-Aided Design
CAM	=	Computer-Aided Manufacturing
CBS	=	Common Boost Segment
CDR	=	Critical Design Review
CE	=	Collaborative Engineering
DoD	=	Department of Defense
GBSD	=	Ground Based Strategic Deterrent
IPT	=	Integrated Product Team
MBOM	=	Manufacturing Bill of Material
MRB	=	Material Review Board
MRI	=	Magnetic Resonance Imaging
MRL	=	Manufacturing Readiness Level
NASA	=	National Aeronautics and Space Administration
PDR	=	Preliminary Design Review
PFMEA	=	Process Failure Modes and Effects Analysis
PMA	=	Preliminary Manufacturing Assessment
SIS	=	Safety Improvement System
SPC	=	Statistical Process Control

I. Introduction

In 2018, Northrop Grumman's Propulsion Systems determined a significant transition was needed in the company culture. The business had moved from steady heritage production programs to several new development, large-scale solid rocket booster designs required to meet growing customer needs. Division leadership undertook a new cultural initiative to help drive this transition. Key stakeholders met to establish an initiative that became known as Preliminary Manufacturing Assessment (PMA).

The overarching goal of PMA is involving key personnel on the manufacturing team early enough in the design development to ensure all external and internal safety, reliability, quality, schedule, and cost requirements can be met during manufacture of the motor. This paper discusses the cultural transition Propulsion Systems made in order to meet the demands of this new environment.

[1] Staff Engineer, Propulsion Systems Research Operations Process Engineering

II. What is PMA

The traditional method of designing product is illustrated in Figure 1 below.

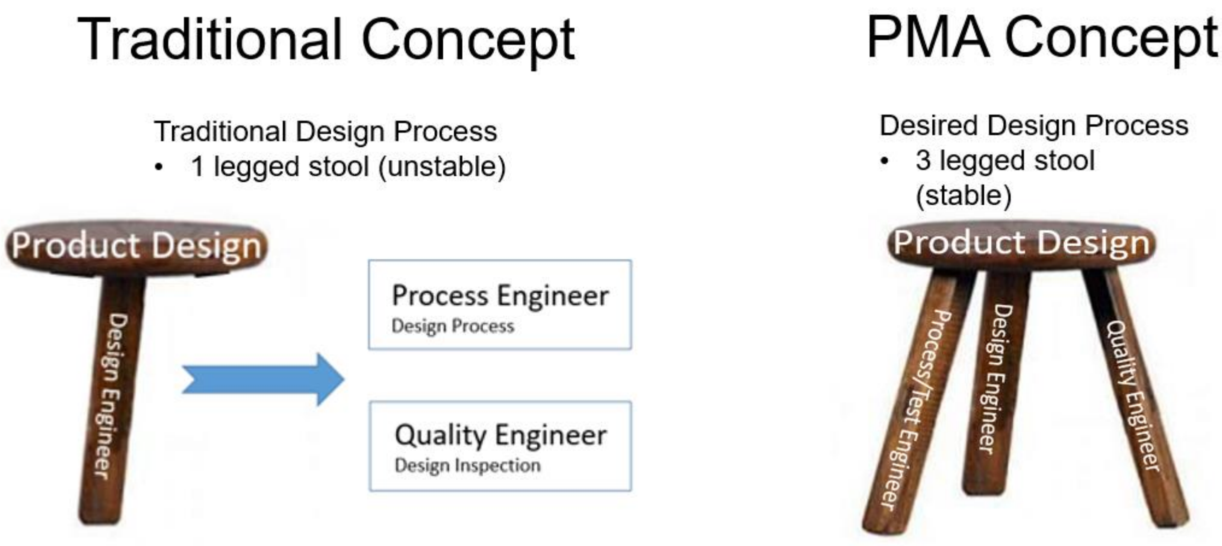

Figure 1. Three Legged Stool

Historically, the design engineer receives requirements from the customer for a new product. The new product is designed and drawings and specifications are provided to the process and quality engineers who establish processes to build and inspect the product. This is illustrated using a stool with one leg, which is unstable. The PMA concept utilizes a three-legged stool concept by establishing a design team that adds the process and quality engineer in the product design, resulting in a much more stable stool. Manufacturability,inspectability, and procurement are considered to be equally important as the design features that result in functionality and performance.

III. The Case for PMA

Using the PMA concept has been shown to reduce the cost. In addition, product scrap and rework are reduced, and quality and schedule are positively impacted during manufacture. Figure 2 below demonstrates how the cost to make a design change increases as you move right in the design cycle.

It has been found that costs for a change can increase as high as 1000x if done late in the design cycle, or after manufacturing has begun. This could be due to new testing, qualification, and customer approvals that are required, all of which are very expensive when considering rocket motor design. Additionally, Figure 2 shows what percentage of a program's lifecycle costs are committed by different milestones. As can be seen, up to 90% of the program's lifecycle costs are committed by Critical Design Review (CDR), meaning very little ability for production cost reductions to occur without expensive design updates.

Figure 3 also demonstrates the relative cost if Design for Manufacturability and Assembly (DFMA) and Collaborative Engineering (CE) are not used. Cost savings as high as 80% can be realized using these concepts. The role and use of DFMA and CE in PMA is discussed later.

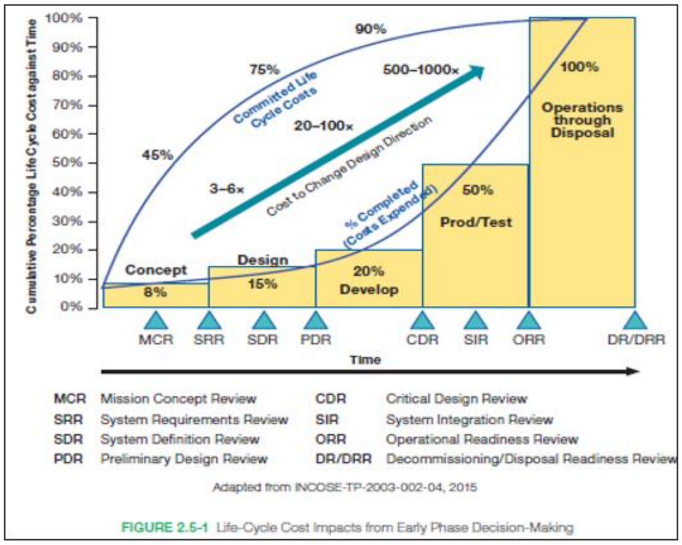

Figure 2. The Costs of Design Changes [1]

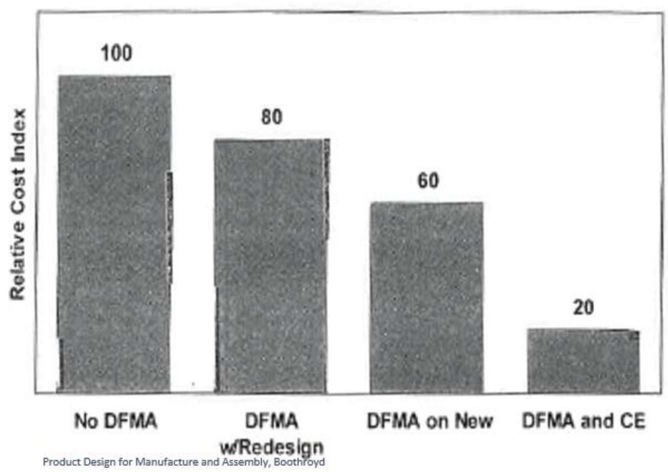

Figure 3. Cost Savings of Collaborative Engineering [2]

IV. How to Do PMA

Figure 4 below shows how the PMA activity occurs early in the design process, beginning prior to Preliminary Design Review (PDR). It is important for the success of PMA to have the meeting months prior to CDR, where the design becomes firm and is presented to the customer.

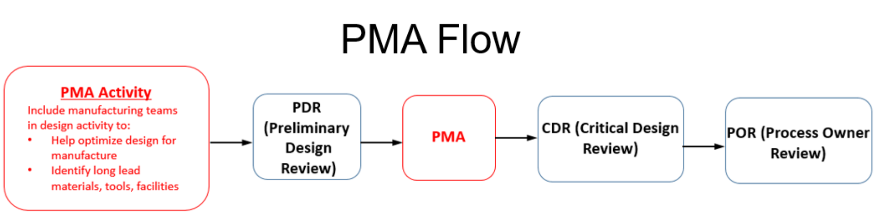

Figure 4. PMA Flow [3]

A. Established Procedure and Standard Work

Figure 5 is a snapshot of the procedure and standard work that were written to guide teams in performing PMA. The procedure documents the purpose, requirements, and roles and responsibilities of each team member. The standard work is a PowerPoint template the teams use to present the results of the PMA activity to the PMA board.

Figure 5. PMA Procedure and Standard Work [3] [4]

B. Training and Follow-up

All team members are trained in the elements and expectations of PMA. Several months prior to the PMA meeting, training sessions are held so the teams understand the expectations and roles they play, with the Board Chair performing the training. Lessons learned and examples from previous PMA board meetings are shared, including examples of actual presentations and actions so the teams better understand the expectations.

Regular follow-up is required to ensure the team is on the right path. Regular PMA meetings and reminders of roles and responsibilities for PMA elements leads to a successful PMA. Attendance at weekly Integrated Product Team (IPT) or project team meetings can be a method to evaluate progress.

C. Increased Communication and Collaboration

One of the critical elements of a successful PMA is improved communication. During a PMA meeting with the Igniter Team, the process engineer raised a concern about the joint design of the igniter and how during assembly, the joint seal could be displaced. The concern had been largely ignored by the design team. The program manager had not heard of this issue before and directed the design team to further test and study the problem to determine if the joint design could be changed. PMA aids in getting information to decision makers that can see the bigger picture to ensure the design is being optimized not only for performance, but for production as well.

Often individuals are not sure who their key team players are, and in some instances, roles have not been assigned. Escalation of this issue to managers occurs to ensure teams are fully staffed. It is typical that during the training phase, managers are asked to assign individuals to fill roles. PMA training sessions are a good time to introduce team members, and for them to understand one another's role.

An example of the criticality of communication in rocket motor design was demonstrated by a failure of a motor soon after launch. Investigators found that the motor design team had not accounted for movement of the nozzle in the aft direction during motor initiation, even though their counterparts 90 miles away knew that this phenomenon would occur. This lack of communication amongst the team required activation of the self-destruct sequence of the motor soon after liftoff.

In many companies, teams have learned valuable lessons and experienced the challenges of creating and developing new product. Sharing those lessons across various organizations through collaboration can reduce issues and leverage a company's knowledge. PMA connects organizations and individuals by asking the question "Who has built this design", and then requiring communication with that team to learn the lessons already learned without "reinventing the wheel".

D. PMA Board Meetings

The PMA Board meeting is the culmination of months of work by the teams. It is an opportunity to reinforce the new culture. It provides accountability, ensures the team is on track, or may point out a need to shift resources. It allows management to see the big picture and to shift attention to areas that may need it. Frequently, board members have many years of experience designing and manufacturing rocket motors and have knowledge that can be shared with less experienced teams.

In the PMA Board meeting, the team begins by orienting the board to the program and motor under consideration. It is helpful to present to the board at the outset a comparison of the new design to heritage designs. (Figure 6). This helps create the bigger picture and how company knowledge can be leveraged to the new design.

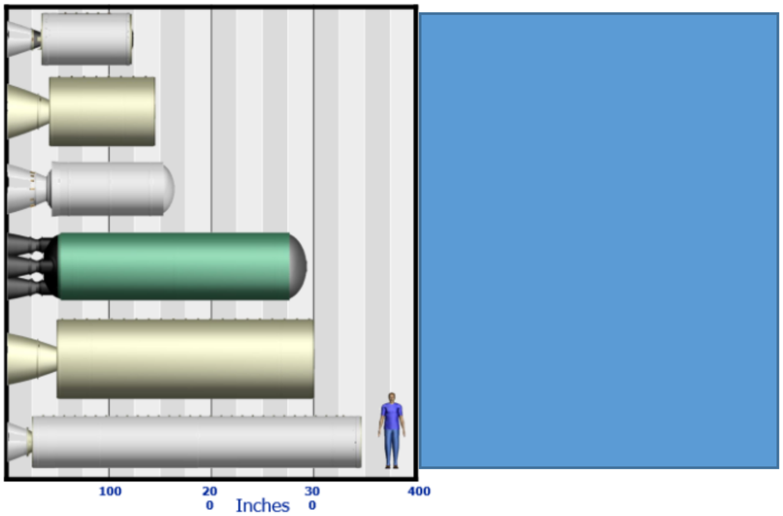

Figure 6. Heritage to New Design Comparison

E. Engagement

Engaged leadership and key team members that are influential in their organizations are important to the success of any cultural change. Every organization has recognized leaders, regardless of titles, that influence their organization. Taking time to engage and convince those leaders of the value and importance of PMA to the company's short and long-term viability is critical.

F. PMA Elements

<u>Schedule</u>

A NASA manager that worked on the Space Shuttle design once said that if you give engineers unlimited budget and time, they will do trade studies, iterate, test, and analyze, but never come to a conclusive design and never build anything. At some point, decisions have to be made and actually making the product must happen at some point. The schedule is what drives the work.

PMA requires a detailed program (Figure 7) and manufacturing schedule (Figure 8). These schedules are used by teams and managers to determine if key milestones are being met, or if resources may need to be shifted in order to meet those milestones.

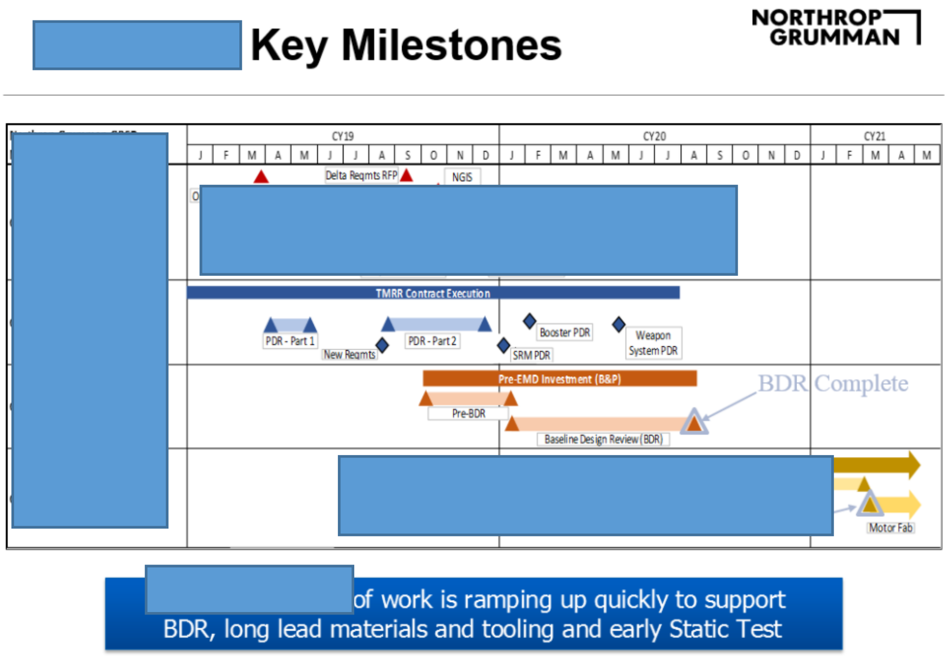

Figure 7. Program Schedule

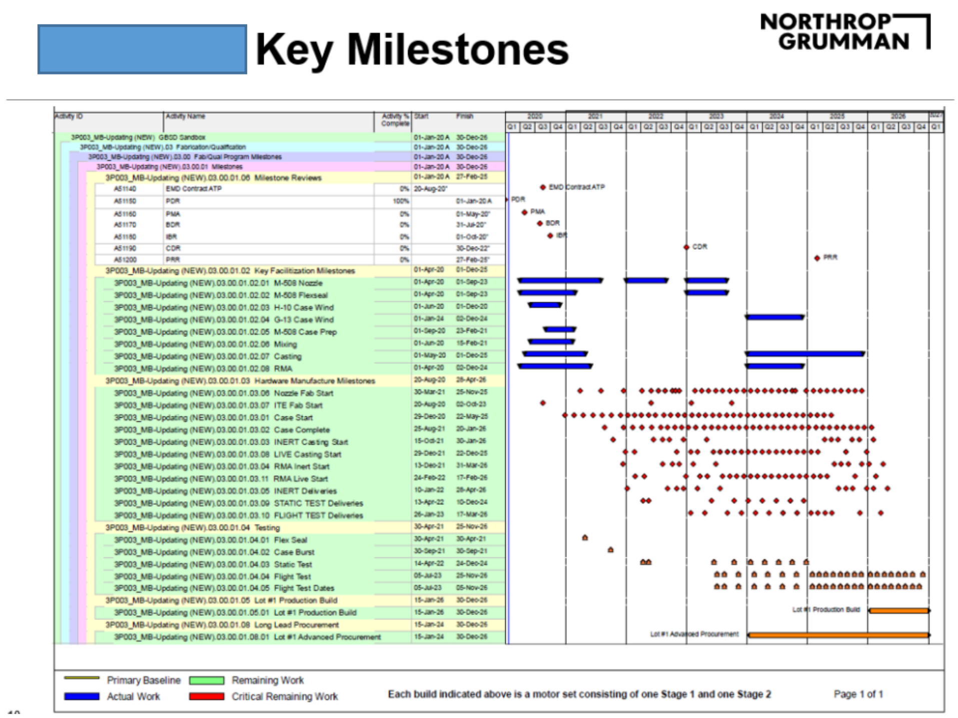

Figure 8. Manufacturing Schedule

During initial production of a new motor program, the design of the exterior insulating cork resulted in significant increases in manual layup processes. Major unanticipated times to process the insulation resulted in increased costs and production delays. PMA evaluates the effects of new designs and attempts to predict changes in cost and schedule.

Cost

The cost of the rocket motor must be considered. Customers increasingly are looking for competition and ways to get more for each dollar spent. Programs establish budgets and require teams to design and build to cost. Teams are challenged to find ways to design efficient processes, which may include modifying the original design, purchasing automated equipment, or designing better tooling. Engaging the manufacturing team early is key to efficient processing and recurring cost savings. Program cost allocations and team expectations for cost are presented (Figure 9).

Cost Allocation (Program)

Component	FS Cost (K)	SS Cost (K)	Assumptions
Case	$XXX	$XXX	
Loaded Case	$XXX	$XXX	• New material not included
Nozzle	$XXX	$XXX	
Igniter	$XXX	$XXX	• Commercial igniter
Final Assembly	$XXX	$XXX	
Total	$XXX	$XXX	• Average recurring cost for 35 motors

Touch Assumptions	Support Assumptions	Materials Assumptions
• Based on actuals from E123, E234, and E456 (~50 motors/yr) • Top down estimates validated by functional orgs • Learning curve assumptions	• 24x5 operations; assumed same level of support from actuals for condensed PoP	• 80% materials based on PO history with escalations based on timeframe • 5% blanket challenge issued by PMO

Figure 9. Cost Allocation [4]

Personnel

In order to successfully manufacture rocket motors, sufficient personnel are required. Qualified individuals must be available in time to perform the work. PMA asks the question early enough to hire and train employees so that schedules can be supported with trained and qualified workers. Managers are provided with program information so they can evaluate their organizations and determine potential employee training or hiring needs.

Motor Design

Because PMA is a manufacturing-focused review, it is important to limit the discussion on the product design. PDR and CDR reviews are used to review the design, but PMA should be 80 to 90% about the production of the product. Just enough of the product design should be presented to the board to allow enough understanding for evaluation of the manufacture of the motor.

Design for Manufacturability, Assembly, and Inspection

Various computer-aided design (CAD) and computer-aided manufacturing (CAM) tools are available to verify tolerances and interferences that may occur in a design. PMA reports on the outcome of those analyses. In addition, Quality Engineering analyzes requirements, paying greatest attention to key and critical characteristics discussed below. Thought is given to how parts will be inspected and if expensive equipment may be needed to verify critical design requirements. For example, new or modified X-ray or magnetic resonance imaging (MRI) equipment may be needed to reduce the possibility of critical flaws in the case or propellant. Due to the long lead-time required for this type of equipment, inspections processes need to be evaluated early to determine any long-term equipment needs.

Collaborative Engineering

Collaborative engineering is the interactive, inter-organizational process of engineering whereby multiple interested stakeholders initiate change, resolve conflicts, bargain for individual or collective advantages, agree upon courses of action, and/or attempt to craft joint outcomes that serve their mutual interests. It asssesses manufacturability, inspectability, and material procurement early enough in the engineering cycle to influence recurring costs and to minimize cost and schedule impacts. Northrop Grumman has procedures and processes in place to perform collaborative engineering. Results of the effort is presented at PMA at a high level.

Key/Critical Characteristics and Process Control

Quality and manufacturing teams often spend effort and time inspecting and assessing items that are not critical to the performance of the rocket motor and may miss critical characteristics. Establishing key and critical characteristics assists in identifying those things that are important to inspect, as well as assessing whether or not they can be inspected. In addition, processes can be established and tooling created to ensure data is collected, monitored, and analyzed to ensure processes are in control. The company process control plan is used to guide teams in establishing process control parameters, including statistical process control (SPC). Key and critical design characteristics are established jointly by the design, process, and quality engineers and the plan is presented at PMA.

Process Failure Modes and Effects Analysis

Process failure modes and effects analysis (PFMEA) is a tool to identify, assess, mitigate, and/or eliminate risks in the manufacturing process. Propulsion Systems has a PFMEA procedure that contains documentation and elements required to conduct an effective PFMEA. The PFMEA begins during preliminary design and is revised as the manufacturing process matures. It is important to perform the PFMEA during preliminary design in the event that a high-risk item can be mitigated by the product design. As processes mature, the PFMEA is updated and a final report released once all processes are finalized. Key findings of the PFMEA are presented at PMA, as well as the plan to complete all required PFMEAs.

Tooling and Facilities

Many tools and facilities require long-lead times for design and construction or modification. Attention needs to be given to connect manufacture of the new product to tool and facility space and availability. PMA teams are provided checklists that ensure all items are considered when planning and designing tooling and constructing facilities.

Many new motor programs are long-term contracts that take many years to complete. It is important to consider whether sufficient facility space and tooling exists to meet rate for the long term. Is there sufficient storage to house components? Is the quantity of energetic materials planned for storage acceptable and within the limits established for a facility?

Quality

Heritage rocket motor designs are frequently leveraged to provide the advantage of manufacturing experience and historical motor performance data. What is often forgotten is to review the problems with those existing designs. Quality engineers can review Material Review Board (MRB) history to determine the stability of a process and provide input into the need to change the process or design that will result in stable processes. Unachievable requirements should be uncovered and should be changed early in the design process.

Safety

Manufacturing rocket motors is hazardous. Rocket motor propellants can be explosive or easy to ignite and handling rocket motors due to the sheer size makes them inherently challenging. Rocket motor customers understandably desire manufacturers to understand safety risks and continuously address incidents or close calls. Northrop Grumman uses a variety of systems and initiatives to ensure safe operation, including Safe Start, and the Safety Improvement System (SIS) to track and address safety risks. Safety and Hazards Analysis can assess heritage designs and processes to determine if minor changes to design requirements can have large impacts on the safety of personnel. This could include materials that are less hazardous or implementation of engineering controls that brings safety risks down to acceptable levels.

Manufacturing Readiness Level

The Department of Defense (DoD) has established standards to identify the level of maturity of a manufacturing process. These standards are found in the DoD Manufacturing Readiness Level (MRL) Deskbook [5] and have been adapted for Northrop Grumman. (DoD MRL website www.dodmrl.com) For PMA, it has been established that an MRL of 6 is required at the PMA meeting. If a 6 is not achieved, resources should be reallocated in order to develop the process to be ready for manufacture.

An example of the value of MRLs in rocket motor design was demonstrated during a failure of a component during a rocket motor static test. An evaluation of the process after the failure found that the process of making the part was not well understood. The failure would not have occurred if more process development and testing were done prior to the static test to understand the process and establish process controls.

Manufacturing Bill of Material)

The manufacturing bill of material (MBOM) is created to identify all materials needed to build the rocket motor. Many components in rocket motors require significant lead time. For example, large and complex forgings may require several months to procure. It is important to identify those items and ensure a process is in place to connect sales orders to each material and to establish dates when those items are required.

G. Critical Risks

In order to be successful in rocket motor manufacture, critical risks must be addressed and resources allocated to mitigate those risks. At times, customer negotiations may be required to modify unreasonable or unachievable requirements. It is important to ensure risks are handled at the appropriate level with decision makers who have a stake in the outcomes. PMA accomplishes this by having teams present their respective risks during the PMA meeting and key stakeholders evaluate and assess those risks. Resources can be allocated and risks are tracked to closure by the board chair.

H. Actions

The board chair establishes due dates for actions and tracks items to completion. Time is taken at the end of the meeting to review the action verbiage, to document the actionees, and who gave the action in the event that further clarification is required later.

The Action Register (Figure 10) is used to document actions from the PMA board. It is important to include required due dates to ensure actions are completed in time to support milestone due dates. The board chair is responsible to follow up with actionees and to escalate problems that may arise in working and closing actions.

NG GBSD Program Site ▸ GBSD PMA Actions Updated.xlsx — Microsoft Excel Web App — Smith, B

FILE EDIT WORKBOOK SHARE DATA FIND

Action Item #	Action	Owner	Requested By	Responsible group	Status	Due date	Estimated Completion Date	Notes
GBSDPMA-01	Obtain concurrence from LV at BDR before we start manufacture.			PMO	Closed	09/15/2020	09/01/2020	
GBSDPMA-02	Create a Secret Security clearance plan with GBSD employees. Get clearances in work now. Scott Lusk to provide info already collected.			Integrated Operations	Closed	09/01/2020	08/31/2020	
GBSDPMA-03	Look at implementation of GEM 63 cost reduction methodology for GBSD			PMO	Closed	07/01/2020	07/01/2020	
GBSDPMA-04	Establish/release Quality plan prior to first build. Document in the program management plan.			PMO	Closed	07/31/2020	07/06/2020	
GBSDPMA-05	Strengthen security plan to include: 1) list of processes/areas that need security clearance, 2) approach for security (SCG efforts)			PMO	Closed	06/15/2020	06/19/2020	
GBSDPMA-06	Address MRB Authority approach as soon as possible to bound MRB issues and provide a path to timely resolution. We need			PMO	Closed	06/30/2020	06/08/2020	
GBSDPMA-07	Need a Quality Plan TIM with LV & Customers to talk through challenges we will experience on MRB, HAR, ... Consider this kind of discussion with LV and customers on this, SCG, and other such areas (change control, ...).			PMO	Closed	06/30/2020	11/20/2020	
GBSDPMA-08	Safety Plan needs to be approached just like the Quality plan - establish approach and recommend to LV with impacts if requirements not changed			PMO	Closed	06/30/2020	07/20/2020	
GBSDPMA-09	Define plan to refine design and understand/address risks associated with development of Key Characteristics and process controls			Nozzle	Closed	06/01/2020	06/01/2020	

Figure 10. Action Register

The action burn-down plan (Figure 11) is a visual chart used to show progress in completion of PMA actions. It is a good tool to assist in getting actions worked and closed. The y-axis shows the number of PMA actions given and the x-axis shows the dates for closure. It is typical to have a majority of actions closed early with some actions that are more difficult or time consuming taking months to complete. In some cases, actions may be transferred to a program-level action list to be monitored and tracked.

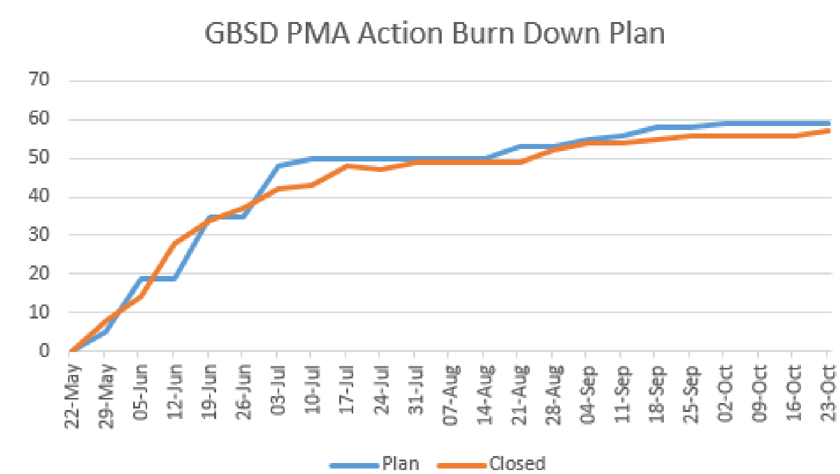

Figure 11. Action Burn-Down Plan

I. Additional Points

<u>PMA Must Be Tailorable</u>

Programs are unique and require distinctive approaches. It must be communicated to teams that they must continually ask the question “Is this value added” as they perform their work, and that milestone dates work for the program. An example of this is on the Ground-Based Strategic Deterrent (GBSD) program. PMA typically occurs three months before CDR, which occurs three months prior to manufacturing start. Because the majority of the design activity is occurring years prior to manufacturing start, PMA was held years prior to CDR and production start. The critical part of tailoring is that key stake holders work together to establish milestone dates and determine if PMA requirements can be altered to best support program goals.

Sustainment

There are several keys to ensure the PMA culture is sustained and not just one of many initiatives soon to fade. They are:

1. PMA meetings must be a priority, are attended by required board members, and are not delegated unless absolutely necessary.
2. Management provides resources for teams to perform the work, are supportive, and ask routinely about progress.
3. Successes are celebrated and teams are rewarded for good work performed.
4. PMA is continuously adapted (see below).
5. The PMA chair stays abreast of new program developments and ensures PMA procedures are followed.
6. PMA training is ongoing and occurs routinely.

Continuous Adaptation

PMA requires constant attention and a culture of continuous improvement in order to adapt to new customer and program needs. The PMA procedure and standard work are updated regularly to incorporate changes in company directions, goals, and lessons learned from on-going program PMA's.

V. Examples of PMA Outcomes

Common Boost Segment Motor Forward Segment Grain Design

During a design review of the Common Boost Segment (CBS) forward segment propellant grain on one of the new motor designs, the design engineer had planned to use the heritage design of a motor with significant history of successful performance. The manufacturing team had knowledge of the difficulty and significant costs associated with the complex core tooling and maintenance required for the process. With a minor change in the grain geometry that still met all customer performance requirements, hundreds of thousands of dollars were saved in the casting core tooling and significant recurring savings were realized in the propellant casting process. This occurred because the team met very early in the design cycle where this change could be made with the least impact on the program.

Motor Raceway

During PMA of a new Northrop Grumman motor, the team escalated to the PMA board that the customer had provided unachievable requirements for the raceway brackets (the raceway is used to house critical electrical components on the exterior of the motor). Months of negotiations by engineers with the customer resulted in little progress and no workable solutions to the issue. The team was ready to move ahead knowing that requirements would not be met and the parts would be documented by Quality as a discrepancy. The PMA board directed the team to create a plan to assemble raceway hardware and collect data on what was achievable. This data would be used to escalate the issue with the appropriate Northrop Grumman and customer personnel.

VI. Lessons Learned

To be successful, PMA requires full management support and engagement. Management and working teams must be convinced that PMA activity is valuable and required for the new rocket motor program to be successful. There should not be a lot of "new" work or requirements for PMA. The goal is to drive accountability for the work already required earlier in the program where decisions can be made early enough to affect outcomes. It also holds teams accountable for work required by scheduled need dates. Key leaders that are influential across organizational boundaries at all levels must be engaged.

Story: "We don't design it, we figure out how to build it."

During PMA training, two of the engineers with significant experience with the company did not appear to be very open to the "Three-Legged Stool" metaphor that describes a team effort in new product design. Further discussion ended with one of the engineers crossing their arms, sitting back in their chair, and proclaiming, "We don't design it, we figure out how to build it." It should be anticipated, as with all change, that some employees will struggle to do things differently. In his book "Who Moved My Cheese" [6], Spencer Johnson says, "I guess we resist change because we are afraid of change". He talks about how a strong organization works best when the organization has all types of people. The organization needs those that resist change to bring stability, as well as those always looking for a better way.

In the case of the PMA culture, the organization has evaluated how business was done and how changes are critical to sustaining the company. Input from multiple organizations at various levels was evaluated and a well thought-out direction was determined and moved forward.

VII. A Word of Caution

PMA may be seen as a way to impress the boss and to provide an opportunity for promotions. This may be acceptable to some degree and can provide incentive to work hard on the issues. However, if it becomes the overarching purpose, the PMA can become more of a show, rather than an important purpose - to bring to light the challenges all teams face in meeting the many external and internal requirements imposed. It is important the teams adequately communicate risks and real problems so the issues can get the attention and resources required to solve them.

Are all team members on the same page? Is there discord and disunity because workable win-win solutions have not been found for the entire team? Often, issues such as these are swept under the rug and end up surfacing later with costly consequences to budgets and schedules. If the picture seems to be too rosy, or no problems are discussed, it is probably too good to be true, and requires further inquiry.

VIII. Conclusion

PMA is a valuable tool that assists teams in being successful in designing and building a new product. Although the elements of PMA could be used for any new product, use on complex and critical rocket motors is particularly useful to ensure expectations and requirements are achieved for the customer and program. At a time when access to space is increasing, and ensuring adequate strategic and defense goals are achieved to ensure a safe and connected world, PMA can ensure efficient and reliable systems are designed and built to achieve those goals.

IX. Acknowledgments

The author thanks Tony Robinson and Earl Benson for their review of the material presented in this paper and to Dixon Brockbank for being an ardent supporter and driver of PMA at Northrop Grumman.

X. References

[1] Systems Engineering Handbook, 4th Edition, INCOSE-TP-2003-002-04 2015, David D. Walden, Garry J. Roedler, Kevin J. Forsberg, R. Douglas Hamelin Thomas M. Shortell

[2] Computer-Aided Design, Volume 26, Issue 7, July 1994, Pages 505-520 Product Design for Manufacture and Assembly, Geoffrey Boothroyd

[3] Northrop Grumman Management Procedure OP-77 Issue 1, Jim Nichols, 11 February 2020

[4] Northrop Grumman Standard Work Document SWI-OP-0017 Issue 1, Dixon Brockbank, 27 January 2020

[5] Manufacturing Readiness Level (MRL) Deskbook, version 2.0, May 2011, Prepared by the OSD Manufacturing Technology Program in collaboration with the Joint Service/Industry MRL Working Group.

[6] Who Moved My Cheese, Spencer Johnson, September 7, 1998, Publisher Putnam Adult, ISBN 0-399-14446-3