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WHAT IS A SYSTEM? NASA's PHASED PROJECT DESCRIPTION

From the MSFC Systems Engineering Handbook (1991)

Systems engineering is defined in MIL-STD-499A as

> . . . the process(es) required to transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test and evaluation. It includes the integration of related technical parameters and ensures compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design. In addition, systems engineering integrates reliability, maintainability, safety, survivability, and other such efforts into the total engineering effort to meet cost, schedule and technical performance objectives. (*Engineering Management*, May 1, 1974)

Systems engineering is a continuous, iterative process that has a built-in feedback mechanism. It is used throughout a project or program's life cycle to arrive at the best system architecture and design possible. Just when systems engineering began to be practiced as a separate discipline is open to debate, but there seems to be general agreement that formal recognition and definition of the process started after World War II. Large, complex post-war development projects such as the first U.S. ballistic missiles and NASA's Apollo program exhibited the characteristics which created the need for systems engineers.

Among these project characteristics are:

- Large design teams with many highly specialized designers
- Many contractors involved, widely separated geographically, complicating communications
- Many hardware and software systems in concurrent development
- Complex operational and logistic support requirements
- Constrained development time
- High level of advanced technology (*Systems Engineering Management Guide*, U.S. Government Printing Office, 1986).

There are many definitions of a system. Two of these are listed below:

- A system is a set of interrelated components working together toward some common objective. (Blanchard, Benjamin S. and Fabrycky, Wolter J., *Systems Engineering and Analysis*, Prentice Hall, Inc., 1990)
- A system is a grouping of parts that operate together for a common purpose. For example, an automobile is a system of components that work together to provide transportation. An autopilot and an airplane form a system for flying at a specified altitude. (Forrester, Jay W., *Principles of Systems*, Wright-Allen Press Inc., 1968).

Systems engineering is a cyclical process as depicted in Figure 1. The terms shown in this figure are explained in the following paragraphs.

1. *Project and Mission Requirements/ Need Definition* can also be termed as "customer engineering." It is the process by which the needs of the customer (the principal investigator or other significant parties, such as Congress or other budgetary authority) are determined. This allows the systems engineer to define requirements for a system that will meet the needs of the customer.

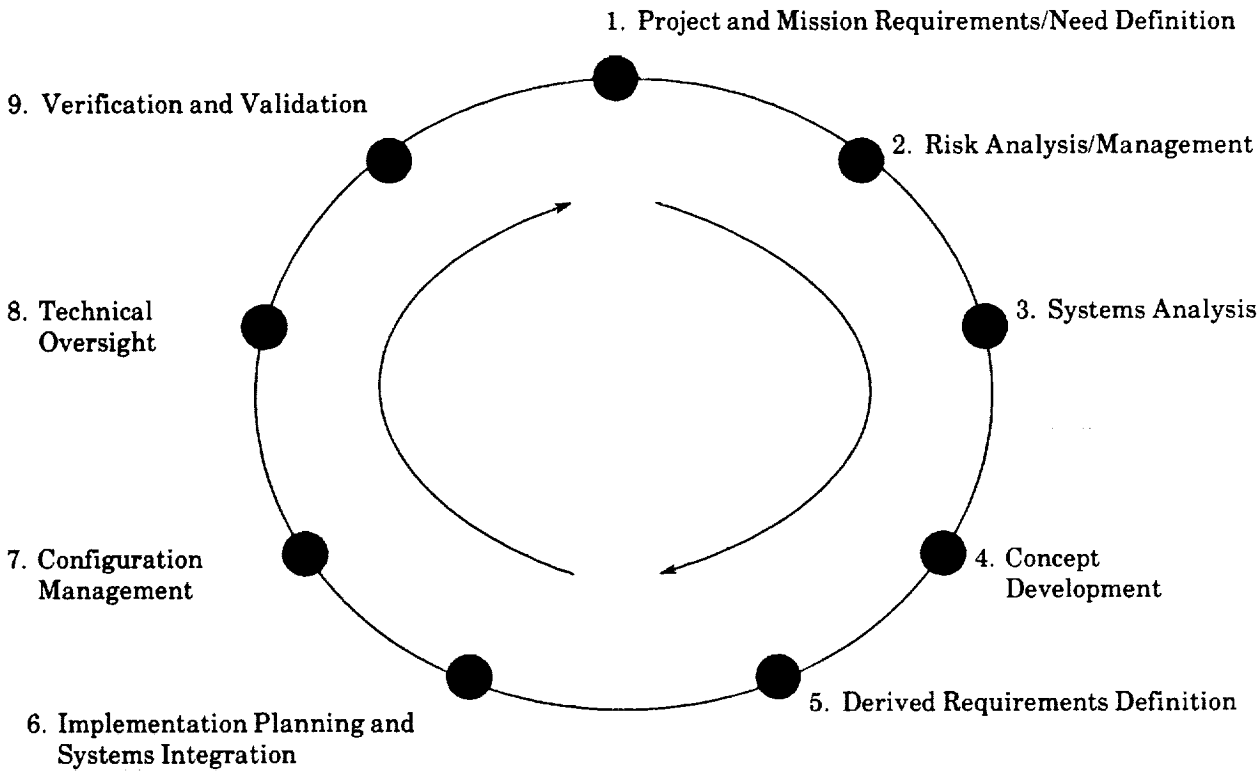


Figure 1 Systems Engineering Cycle

2. *Risk Analysis/Management* is a continuing process to identify and assess the risks involved with the development and operation of the system. These include technical, schedule, cost and organizational risks. Following the identification of the risks involved, the system engineer then develops an implementation plan to control and, if possible, reduce risks.

3. *Systems Analysis* involves understanding how the key mission and system functional elements interact. The mission analysis translates the users' needs into functional/performance requirements and design constraints. A functional analysis takes these requirements and breaks them down into specific tasks.

4. *Concept Development* is the process of making informed trade-offs among the various options to select the one that best meets the requirements and design constraints. Preliminary design and performance requirements and implementation architecture are the results.

5. *Derived Requirements Definition* is the process of translating mission and functional analysis results, system operational concepts, and the selected system architecture into a set of system performance and interface requirements. At this level, the requirements must specify either functional or interface criteria only, without presenting design solutions. This gives the detail designers the flexibility needed to arrive at design solutions that meet the requirements.

6. *Implementation Planning and Systems Integration* is a complex activity resulting in a coherent, integrated set of implementation tasks and responsibilities for the design, development, fabrication, verification and operation of the required system. It requires negotiation between the system requirements definition personnel and the system implementation (development) personnel. The plan must also consider the project constraints of schedule and budget while avoiding unnecessary risk.

7. *Configuration Management* activities ensure that controlled definition of all engieering documentation is maintained and correct information is distributed to all appropriate parties in a timely manner. This is one of the most important responsibilities of the systems engineering organization. On larger programs that have large numbers of people involved, this process becomes even more critical. This activity is also the mechanism by which the system development process is documented (i.e., design knowledge capture).

Configuration Management establishes the system to control the requirements and configuration of hardware and software, evaluate changes, and maintain the definition of the configuration via baselined documentation and released drawings.

8. *Technical Oversight* serves two functions. First, it ensures that all the subsystems work together. Second, it implements mechanisms to guarantee that the developed and documented architectural concept is not inadvertently changed during the development process. This allows the developer to certify that the system, which is ultimately tested, will meet the customer's requirements. Technical oversight consists of the technical reviews and audits that gather consensus from all parties involved to ascertain that the effort at any given time is correct and adequately planned for the continuance of the work.

A specific task for the systems engineer to perform is assuring that the systems requirements are understood and correctly implemented by the design organizations. This responsibility requires the systems engineer to work closely with the design organizations throughout the program. At the same time, the systems engineer must recognize that the initial set of systems requirements will not be perfect. During design evolution or because of the inability of a subsystem to meet its intended functional requirements, changes in the systems requirements will be necessary, and the systems engineer should view these changes as a normal part of the design process. Avoid the tendency to view the Systems Requirements Specification as something, once baselined, that is final and unchangeable.

9. During the *Verification and Validation* portion of the development activity, the characteristics and performance of the system are compared to the requirements and specifications. Tests, analyses and demonstrations are performed to verify that the hardware and software satisfactorily meet the performance requirements of the system specifications.

NASA PHASED PROJECT DESCRIPTION

In the planning of major projects, critical requirements must be well defined and the necessary technology must be available. If these criteria are met, there will be an acceptable level of risk in meeting technical goals with reasonable cost and schedule.

To ensure that the program is at a proper level of maturity when Congress approves major funding for design and development, projects go through various phases of analysis and definition. There are five phases in the life cycle of a typical successful project: pre-Phase A (concept study), Phase A (preliminary analysis), Phase B (definition), Phase C (design) and Phase D (development/operations). Depending on the complexity of the system, funding availability and launch schedules, a project may combine phases or add intermediate phases. Common variations would include combining pre-Phase A and Phase A, adding an advanced development phase between Phase B and Phase C, combining Phase C and Phase D into Phase C/D, or moving operations out of Phase D into a separate phase. As a further example, the Space Shuttle program had both a Phase B' (B prime) and Phase B" (B Double-prime) in order to further refine the definition and requirements of the system before proceeding into Phase C. Figure 2 depicts a typical phased project flow in which

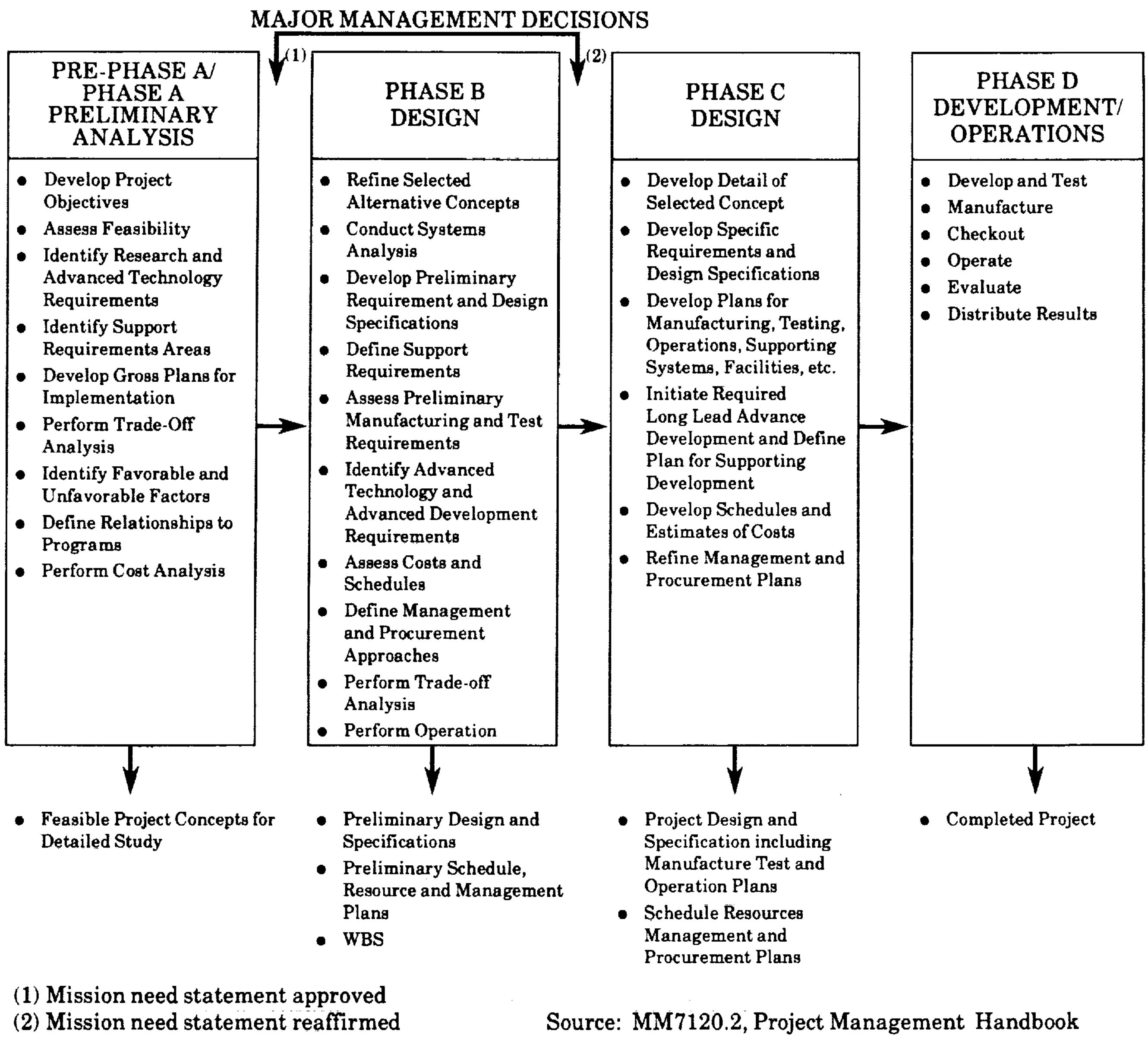


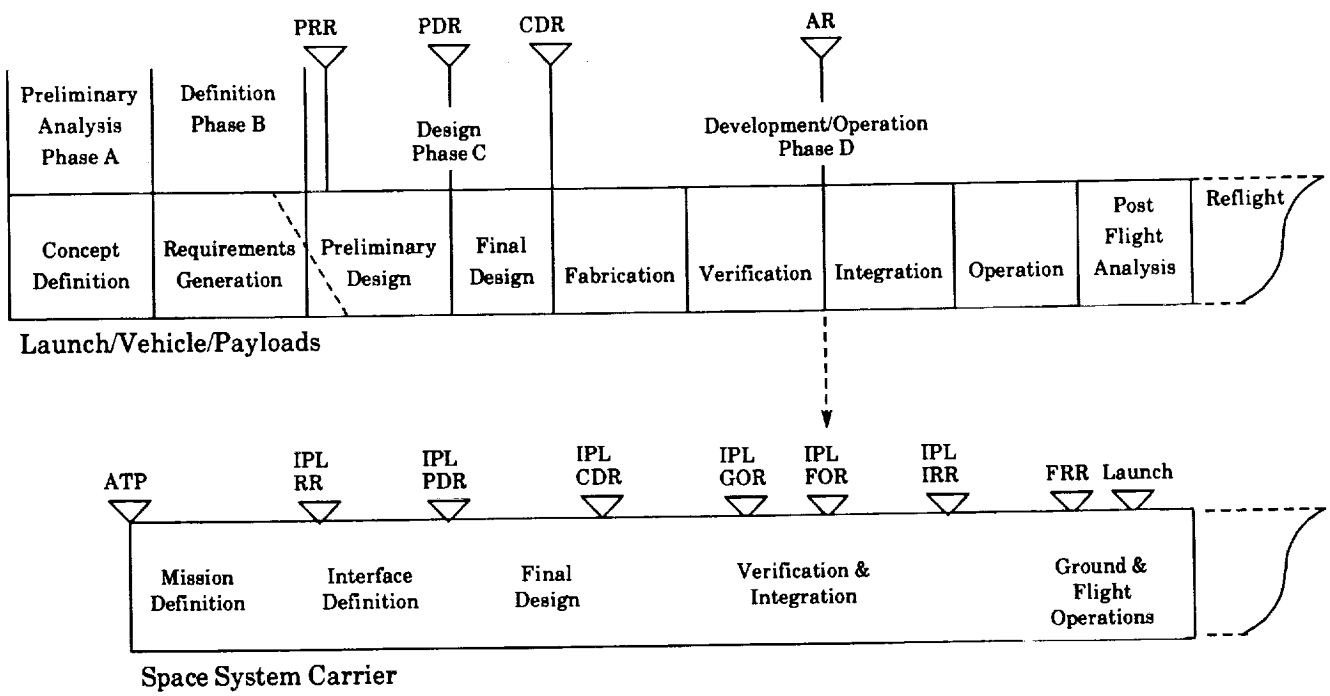
Figure 2 NASA Program Phases

pre-Phase A has been combined with Phase A.

Safety is a critical systems engineering function that must be considered during all program phases and in all studies and analyses. In short, although safety is organizationally the responsibility of S&MA, it is a responsibility of all program participants and should be a primary consideration throughout the systems engineering process.

Figure 2 shows the major activities in each phase, as well as the outputs and major decision points. Note that this description pertains to the typical program, in which NASA contracts with industry to do the Phase C/D activity. Other types of programs include small, contracted efforts, as well as both large and small in-house programs where NASA may retain all or part of the design and development responsibility.

The typical program review phasing includes many more activities and formal reviews than are shown in Figure 2. For completeness, these are introduced here and



Notes:
PRR - Preliminary Requirements Review
PDR - Preliminary Design Review
CDR - Critical Design Review
AR - Acceptance Review
ATP - Authority to Proceed
IPL - Integrated Payload
RR - Requirements Review
GOR - Ground Operations Review
FOR - Flight Operations Review
IRR - Integrated Readiness Review
FRR - Flight Readiness Review

Figure 3 Typical Program Review Phasing

shown in Figure 3. This figure also serves to relate the major reviews to the project phases and to show the more detailed integration activities associated with attached payloads and Spacelab-kinds of experiments.

At MSFC, the Program Development (PD) Directorate is responsible for nurturing new projects from idea conception through concept definition supporting preliminary design. Systems engineering is emphasized and utilized throughout this process, both in-house and during contracted studies. Typically, concepts that have matured through this process and gained Congressional new start approval to become official projects are then moved into project offices. The new start review and approval process begins approximately two years in advance of Phase C/D authority to proceed (ATP) at which point funds are applied to begin a major design and development effort. That two-year period is used to execute the definition phase (Phase B) and prepare the request for proposal (RFP) for Phase C/D. The new start approval process includes a definition review or non-advocate review (NAR) generally conducted during the Phase B activity at a time when the project manager, Center management, and Headquarters program office deem appropriate. Results of the NAR are factored into the Phase C/D RFP, as well as the budget approval process. Note that this timeline pertains principally to large programs which include in-house and contracted efforts. The timeframe could be *much shorter* for smaller projects such as experiments. Figure 4 shows the overall systems engineering process flow in Program Development (PD).

In the course of developing the preliminary systems requirements and the conceptual design, PD uses many of the same

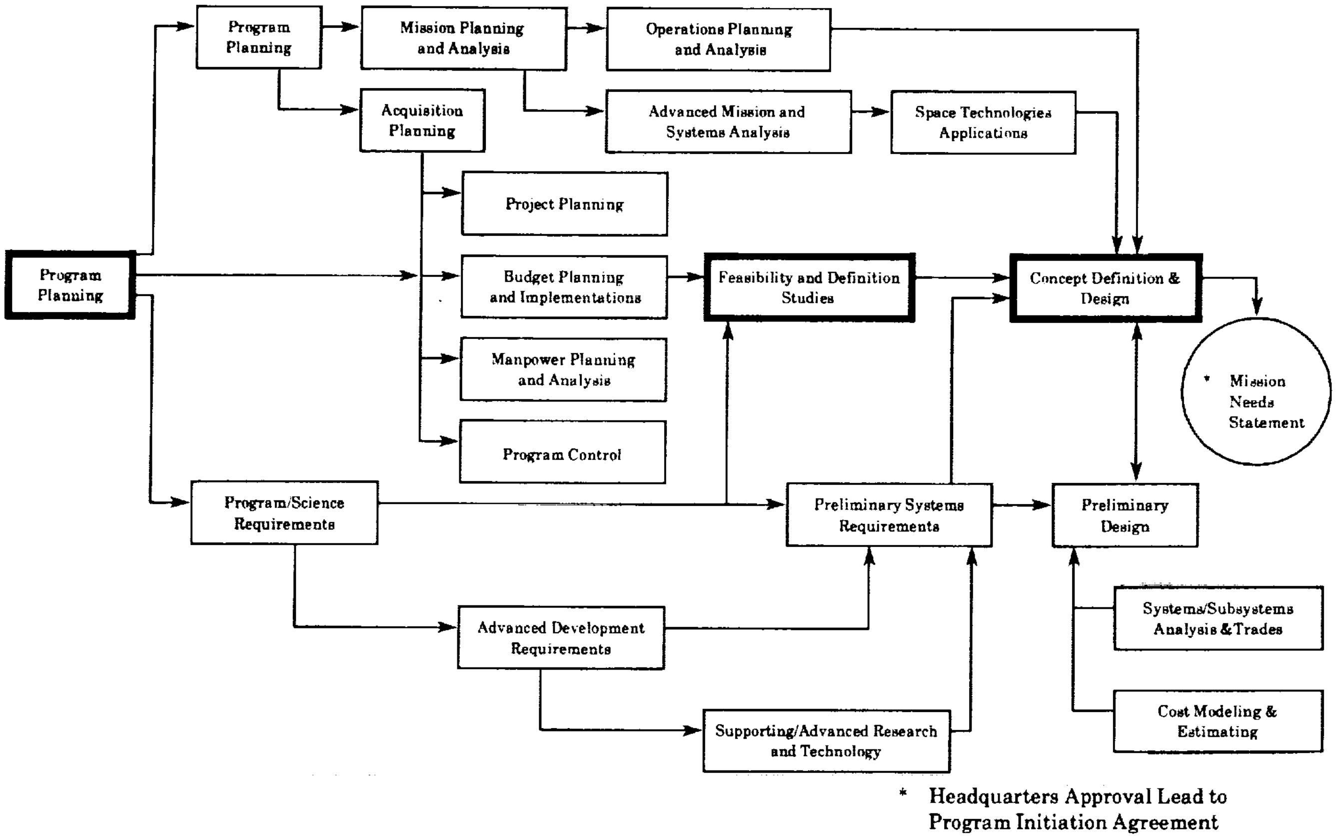


Figure 4 Systems Engineering Process Flow in Program Development

analysis tools and techniques that are employed by Science & Engineering (S&E) in later program phases. The principal differences in the outputs of the two organizations are the quantity, format and maturity of the documentation and the level of detail in the analyses. In summary, the analyses and trade studies by S&E are to refine, not repeat, the concepts developed by PD in support of design implementation. PD develops the conceptual approach and S&E develops the design implementation.

PRE-PHASE A (CONCEPT STUDY)

A pre-Phase A study may be accomplished within the engineering capability of Program Development or contracted with funding from one of the major NASA Headquarters offices. Successful results from this study would provide justification to initiate a Phase A study or additional pre-Phase A studies. The genesis of new ideas requiring further study can come from a variety of sources: industry, the scientific community, university and research centers, MSFC contractors and associates, or even from within MSFC itself. Typically, such ideas receive a top-level examination by cognizant MSFC/PD personnel. A quick assessment of objectives, requirements and the total mission concept is performed. Often, new ideas are shared with colleagues through proposals (either in response to an RFP or unsolicited), technical papers at professional society meetings, or "white papers" propounding the new idea/concept. From an MSFC in-house weeding out process, concepts are identified for further (Phase A) study.

System functional concept trades are performed during the pre-Phase A period, generally at a fairly cursory level of detail. This process eliminates architectures that are too costly or time-consuming to develop. They are conducted at a level sufficient to support the definition of the top-level system requirements. Architectural options are the result. Some of the primary sources for this identification of concepts include brainstorming, past experience, examination of other systems and intuition.

Cost estimates are developed in pre-Phase A and are usually at a very preliminary level due to the lack of detailed systems definition. These estimates are based primarily on parametrics adjusted for the new program, taking into account differences in mission, size, complexity and other factors.

PHASE A (PRELIMINARY ANALYSIS)

A Phase A study is the preliminary analysis of a space concept. These concepts could have come from a pre-Phase A study or from other sources within or external to NASA. The majority of concepts that are studied at MSFC are assigned by NASA Headquarters and funded accordingly. Documentation in this Phase usually consists of study reports and briefing charts.

Schedules are developed during Phase A studies by Program Development in conjunction with the organization performing the study (contractor, PD, S&E). The schedules include an overall program schedule provided by MSFC and a detailed technical schedule developed by the contractor.

The overall program schedule depicts important milestones that establish the start and finish dates of each study phase, including design, development, launch, and operations. Programmatic milestones are also shown. These are dependent on the federal budget cycle plus proposal preparation and evaluation time. The contractor schedule depicts the major activities and phasing required to develop the hardware in time to meet the scheduled launch date. Since this is a concept study, the detail schedule is still at a relatively high level and would not show activity below the system level.

Cost estimates developed during Phase A are generated using a parametric cost analysis system in conjunction with the cost database discussed above. The has access to several cost estimating systems, both government and commercial. One example is the GE/RCA Price Model. Each model is unique with special capabilities and limitations. Complexity factors and Cost Estimating Relationships are applied to the estimating software using system weight as the independent variable. A factor is applied to the hardware/software costs to account for wraparounds such as project management, test and verification, percent new design, operational complexity, hardware complexity, similarity to other projects or development activities and others. As each system is defined in more detail and the system weight is further refined, the cost estimates become more realistic and provide a higher confidence level in the results.

A cost/risk analysis and assessment is usually completed near the end of each Phase A study. The analysis is accomplished with special software that uses statistical techniques, including a Monte Carlo simulation. The results predict the probability of completing the program within the estimated cost. A risk assessment, which follows the analysis, should identify areas of high risk that require further cost analysis or possibly further trade studies to look at alternate systems that would lower the potential costs without sacrificing technical capability.

As part of the study activity, the contractor provides a detailed risk analysis and assessment to establish a high level of confidence for the program cost. The cost estimate established during this phase will provide NASA Headquarters with the funding requirements to be approved by Congress before the development program can begin.

The processes occurring during Phase A include:

- Development of project objectives
- Assessment of project feasibility
- Identification of research and advanced technology requirements

- Identification of support requirements areas
- Performance of trade-off analyses
- Identification of favorable and unfavorable factors
- Definition of relationships to other programs
- Selection of systems concepts
- Identification of maintenance, technology insertion, and disposal concepts of payload and orbital debris
- Environmental Impact Analysis.

The outputs from Phase A, which become the inputs to Phase B, are in the form of reports or annotated briefing charts and include information on:

- Concept definition
- Preliminary system requirements
- Preliminary configuration layouts
- Point designs
- Preliminary implementation plans
- Preliminary schedules
- Preliminary cost estimates
- Environmental impact.

PHASE B (DEFINITION AND PRELIMINARY DESIGN)

This phase of the project consists of the refinement of preliminary requirements, cost estimates, schedules and risk assessments prior to starting final design and development.

Once the feasibility of an idea is established, the concept definition phase is begun to explore alternatives to meet the documented mission need. Competition and innovation should be employed to ensure that a wide variety of alternatives are identified and examined. Modeling and computer analysis are required to assess the best concepts.

The goal of a concept definition activity is to determine the best and most feasible concept(s) that will satisfy the mission and science requirements. Generally, the requirements available at this point in time are Level I (NASA Headquarters) requirements from preliminary activities.

Level I requirements are broad mission needs and objectives. Occasionally, there may be some Level II (project office level) requirements at this time.

The mission need determination is the first step in a multifaceted preliminary concept definition activity. This is the step that is first performed at a NASA Headquarters or Center level (or industry, university, etc.) and is the precursor to concept development. The mission need determination is that part of early mission planning that identifies a scientific knowledge need or gap that could be met with some kind of NASA sponsored activity. A set of Level I requirements is generally developed during or just prior to the activities described in the following paragraphs.

A feasibility analysis is conducted to determine the viability of the project. The study report usually includes requirements, objectives, problems, opportunities and costs.

A utility analysis is then conducted to determine the value of a project. The following criteria may be considered during this study: the needs met, the scientific knowledge acquired, the political benefits, or potential spinoffs and applications.

Certain satellites and/or instruments are selected for a more detailed level of design. The Preliminary Design Office of Program Development performs these studies. This office is a miniature replication of the capabilities of the laboratories at MSFC: Propulsion, Guidance, Navigation and Control, Electrical Power, Avionics, Structures, Operations, etc. One difference is the emphasis by Program Development in developing credible cost estimates. Cost is an important differential, but often other factors, such as mission risk or incompatibility with other instruments that may be grouped on a common satellite, may predominate.

Throughout the Phase B period the concepts that were developed during Phase A are iteratively reviewed and analyzed. Using trade study techniques, the concepts' capabilities are compared to the system requirements. Those concepts that consistently satisfy the requirements are identified and refined. Any concepts that do not meet performance and other requirements are scrutinized very closely for possible elimination. Following the examination of those that do not perform well, assessments are made regarding their augmentation to discover the degree of change necessary to bring their performance into scope. The concepts that have to change too much or would experience severe budgetary and/or schedule impacts are deleted from the concept definition and analysis cycle. This allows the analysts' energies to be focused on those concepts that are valid and workable.

These trade studies provide a more detailed look at the architectural concepts and result in a narrowing of the field of candidates. Trades performed during this time consider such things as cost, schedule, lifetime and safety. The evaluation criteria used to assess alternative concepts are developed to a finer level of detail than for earlier system trades.

Cost estimates from Phase A are refined as further detailed requirements are identified during Phase B. The cost estimating process is still dependent on parametric analysis. The Program Development cost office works closely with the study contractor in evaluating costing methodology and continuously compares government cost estimates with those of the study contractor. Should a large discrepancy occur, the assumptions and schedule inputs of the study contractor are examined. If this examination yields valid assumptions and schedules, the NASA estimates are adjusted. The cost estimation process goes through continuous iterations during the study to reflect the evolution of detail resulting from trade studies.

Schedules are developed during Phase B by the task team program control personnel and by the study contractors. Schedules developed by the task team are expanded from the Phase A overall program schedules. In addition, other schedules are developed that include Phase C and D procurement strategies, cost phasing and project manning requirements. The study contractor schedules are expanded to lower levels of the work breakdown structure (WBS) to include subsystem development, program management, manufacturing, verification, logistics planning, operations planning and other technical areas. The schedule detail would show the phasing of all major activities through launch and the follow-on operations.

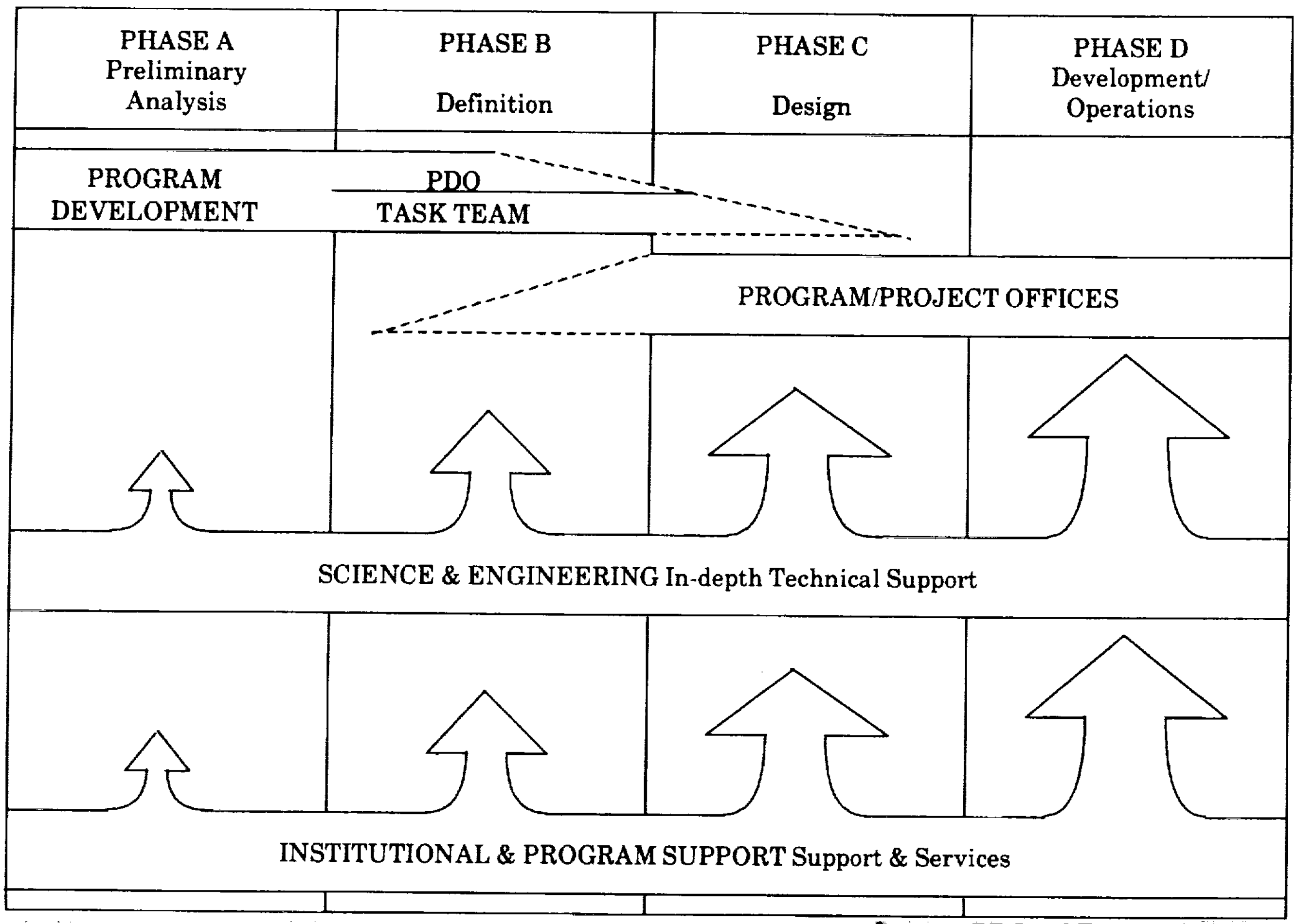
As in Phase A, the typical documentation of this phase consists of reports and briefing charts.

The processes occurring during Phase B include:

- Refinement of selected alternative concepts
- Performance of trade-off analyses
- Performance of system analyses and simulations
- Definition of preliminary system and support requirements
- Definition and assessment of preliminary manufacturing and test requirements
- Identification of advanced technology and advanced development requirements for focused funding
- Refinement of preliminary schedules
- Refinement of preliminary cost estimate and trade study results which support selection of baseline for cost estimate
- Assessment of technical, cost, and schedule risks
- Assessment and refinement of the Mission Need Statement.

The outputs from Phase B, which become the inputs to Phase C, may include (in the form of study reports and annotated briefing charts) information related to:

- Preliminary WBS
- System requirements
- Preliminary interface requirements



Source: *PD Lead Engineer's Guide*

Figure 5 MSFC Support Relationships in Project Phases

- Management and procurement approaches
- Program Implementation Plans
- Request for Proposal (RFP) inputs, where applicable.

Phase B is normally the final phase of activity within Program Development. A separate core of people is selected to form a task team to manage the Phase B contract. At the beginning of Phase B, a chief engineer is appointed to the task team (or project office) to provide consultation to the task team manager on all related engineering matters. The chief engineer also helps ensure that the study contractor uses acceptable engineering practices and sound judgment during the course of the study. The chief engineer is often the deputy to the task team manager and is usually the first Science and Engineering representative substantially involved in the process. The chief engineer's office has personnel resources available to support the project as needed during the study. Additional engineering support from S&E may be used at the discretion of the chief engineer. The chief engineer plays a key role in determining the state of technical maturity of the project for starting the design and development phase.

At the conclusion of Phase B, the task team is converted to a project office, and it is no longer under the direction of program development. On large projects, such as Space Station, a project office might be created prior to Phase B; in that case, Program Development (PD) support becomes minimal (such as cost estimating and limited programmatics) and S&E plays a major role in the Phase B engineering activities.

At MSFC, it is not uncommon to have more than one directorate providing engineering or technical support to a project throughout its life cycle. The transition of engineering support is depicted in Figure 5.

Figure 5 shows that Program Development typically performs most, if not all, of the technical support during Phase A. As the project life cycle evolves, the S&E Directorate takes on a larger and larger role as PD's involvement tapers off. The exact point at which S&E gets involved varies depending on the size and priority of the project at MSFC, as well as the availability of S&E manpower resources. In every case, however, Phase C and D activities are exclusively the domain of S&E.

The extent of information and the level of detail available at the end of Phase B to begin the Phase C design are variable and become a function of the time and money made available to the PD organization for the conduct of Phase B studies. As a result, significant efforts may be needed at the beginning of Phase C to refine many of the Phase B analyses.

The hand-over of technical responsibility from PD to S&E is an interface which requires a great deal of attention to minimize transition problems and project disruptions. A key issue to be addressed is the type and content of documentation produced in Phases A and B. Since these early phases typically have limited funding and PD's manpower resources are limited, requirements and specifications resulting from Phase B may require substantial refinement and rework by S&E at the beginning of Phase C. It is important that Phase C planning and schedules account for this activity.

PHASE C (DESIGN)

This phase requires Congressional budget approval for projects large enough to be separate line items in the NASA budget submission. Funding must be approved and available at the start of Phase C. Detailed design is accomplished and plans are refined for final development, fabrication, test and operations.

The processes occurring during Phase C include:

- Refinement of work breakdown structure
- Development of Systems Requirements Specification
- Development of design and contract end item specifications
- Development of interface requirements documents
- Completion of preliminary and detail design
- Development of preliminary interface control documents (ICDs)
- Performance of detailed system analyses
- Development of manufacturing, testing verification, integration, operations, supporting systems and facilities plans
- Definition of a development plan
- Refinement of schedules and cost estimates
- Refinement of management and procurement plans.

The outputs from Phase C, which become the inputs to Phase D, include:

- Updated system requirements documentation
- Updated detail design and CEI specifications
- Baseline.

It is typically at the beginning of Phase C, when industry is heavily involved in design and project funding is increased dramatically, that many formal documentation requirements are contractually imposed. This can contribute to large cost increases over previous estimates in Phases A and B, and dictates the need for early inputs from the S&E engineering organization to assure that design and performance requirement specifications and data requirements are incorporated into initial cost estimates.

PHASE D (DEVELOPMENT/OPERATIONS)

During this phase of a project, flight hardware and software are developed, manufactured/coded, tested and qualified for flight. In addition, support is provided for the follow-on flight operations.

The processes occurring during Phase D include:

- Development and test of prototype and protoflight hardware
- Verification/Validation - qualification of hardware and software for flight
- Manufacture and integration of flight hardware
- Checkout of flight systems
- Launch operations
- Flight operations
- Retrieval or disposal of payload and orbital debris.

The outputs from Phase D include:

- A successful mission,
- Documentation and evaluation of the results and anomalies
- Documentation of lessons learned.

In the early days of spaceflight, MSFC provided expendable propulsion systems, so most project activity terminated when launch operations were complete. As the mission of MSFC evolved into payloads and experiments, its role in the area of mission operations and maintenance greatly expanded and now provides an important function in present projects such as Spacelab, the National Space Transportation System, Hubble Space Telescope, the Advanced X-Ray Astrophysics Facility, and Space Station Freedom. These programs involve 15 to 30 years of technology insertion, operations and maintenance activities that would justify a separate independent phase in their life cycles.

At MSFC, the design phase is normally combined with the development and operations phase to form a Phase C/D. The resulting contract takes the Phase B data, refines it into a final design, develops and fabricates the hardware, tests and flight qualifies it, and supports the flight and mission operations.