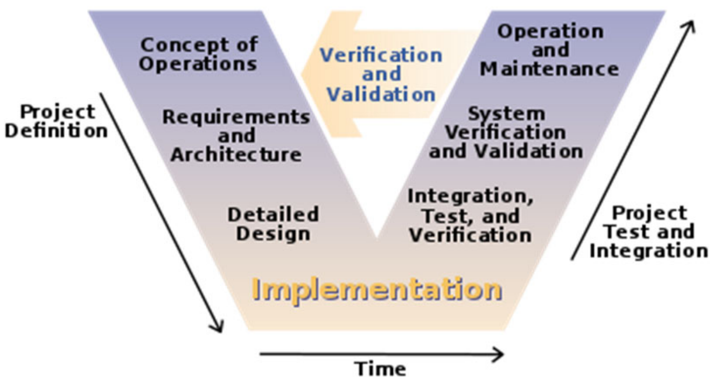
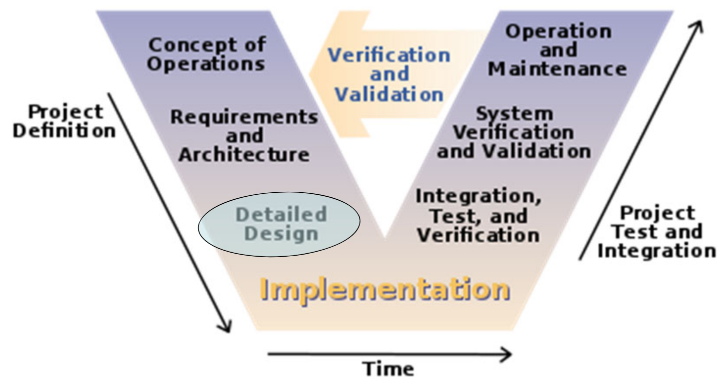
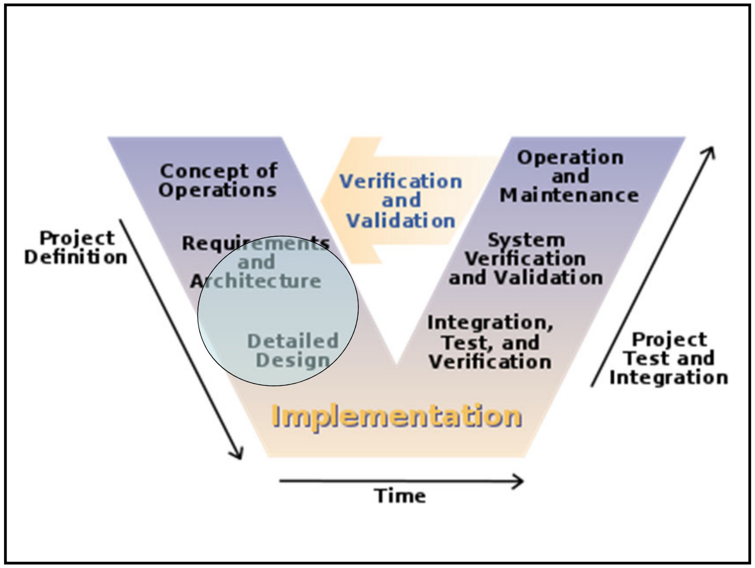
Lecture 21 - Role of Test and Measurement In Good Systems Engineering

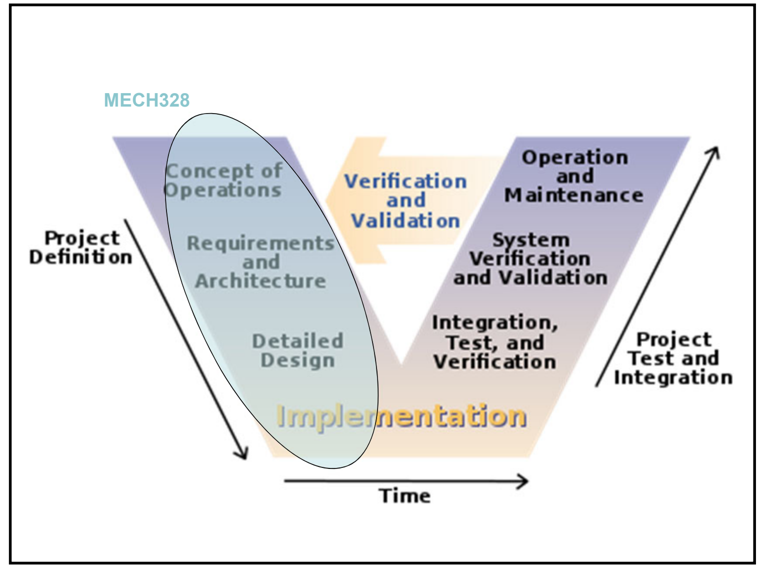
Prototyping

- What is it?
- Why do it?






Concept of Operations
Verification and Validation
Operation and Maintenance
Project Definition
Requirements and Architecture
System Verification and Validation
Detailed Design
Integration, Test, and Verification
Project Test and Integration
Implementation
Time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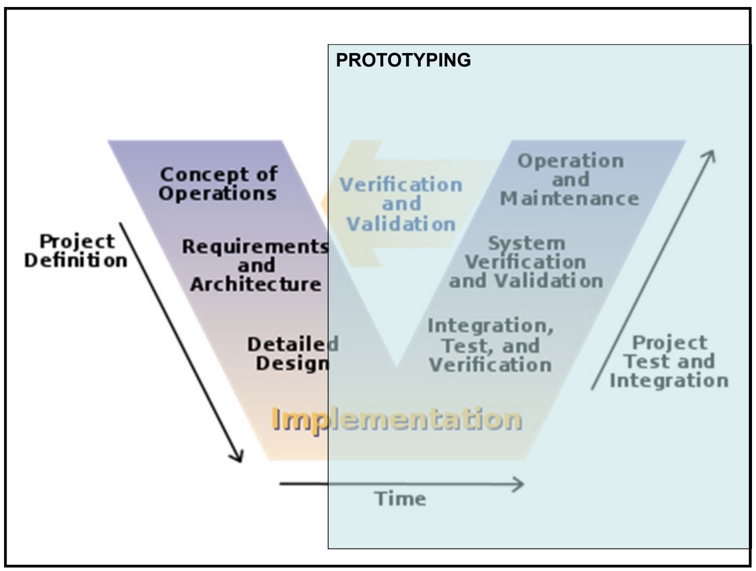
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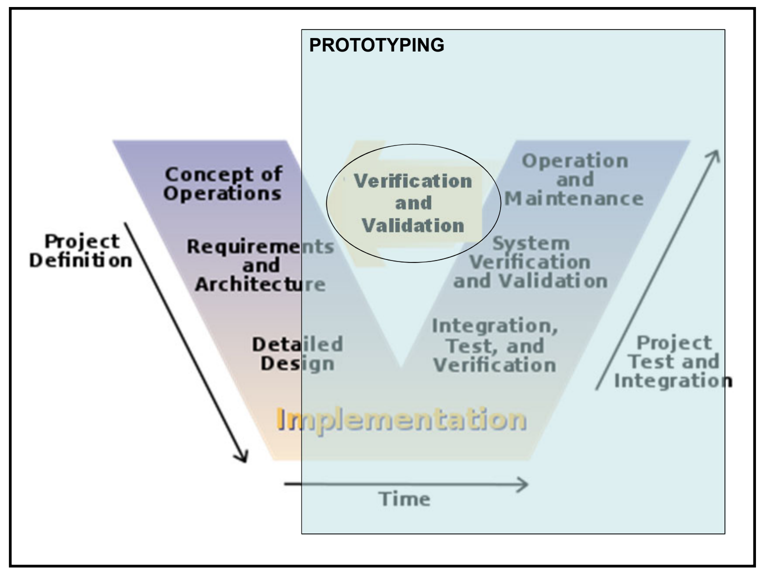
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A NASA Perspective

- Modern systems engineering instruction puts a lot of focus on process
  - Requirements functional decomposition, interface control, systems modeling, hazard/risk management etc…
- From my perspective, modern systems engineering instruction does not put enough emphasis on test and a measurement
  - A requirement without a test is just marketing
  - A test without a measurement is just a demonstration of a design operating at a point
- Good systems engineering cannot exist without test and measurement
  - Cooking analogy – would you want to eat a cake prepared by bakers who only prepare and bake the cakes but never taste them ?

V&V

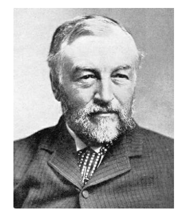
- **Verification**: The process of confirming that a system or requirement is *compliant* – does it do the job?
- **Validation**: Confirms that a design or system, or set of requirements, meets the *intent* of the stakeholder or customer – is it the right job?

V&V

- **Verification**: The process
  that a system or requ
  – does it do the
- **Validatio** sign or
  syst ents, meets the
  ider or customer – is it

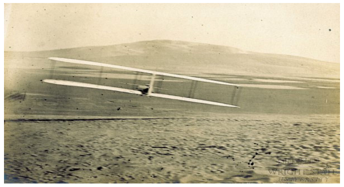
When is the right time to taste the cake?

Samuel P. Langley, curator of the Smithsonian

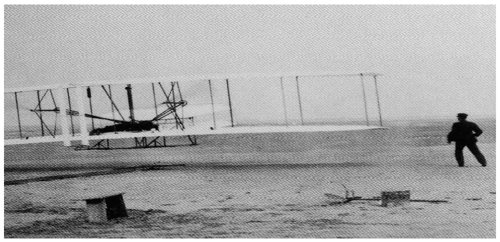


Legacy:

- Langley Gold Medal by the Smithsonian Institution
- NASA Langley Research Center
- Langley Air Force Base
- Langley Hall at the University of Pittsburgh
- Langley High School in Pittsburgh
- Langley Memorial Aeronautical Laboratory
- Langley unit of solar radiation
- Mount Langley in the Sierra Nevada
- USS Langley (CV-1)
- USS Langley (DE-131)
- USS Langley (CVL-27)
- Seadrome Langley
- SS Samuel P. Langley, U.S. Liberty Ship
- Samuel P. Langley Elementary School in Hampton, VA.

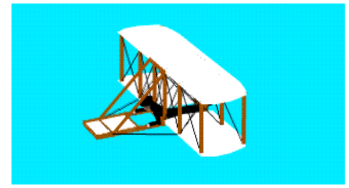


1902 Glider – first coordinated turn



1903 – first successful heavier than air flight

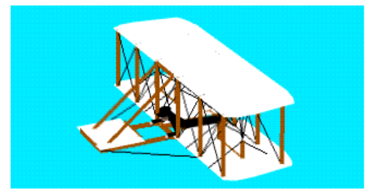
Wright Brothers



1900

17 ft span, 165 sq ft area
50 lbs – empty weight

Flown mostly as a kite
< 12 glider flights
~ 300 ft max distance

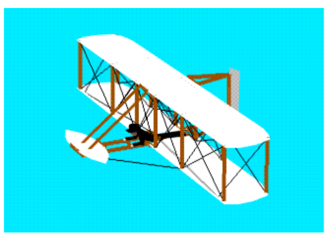


1901

22 ft span, 290 sq ft area
100 lbs – empty weight

Flown mostly as a glider
> 50 glider flights
~ 400 ft max distance

http://wright.nasa.gov/discoveries.htm

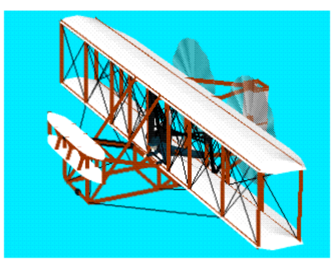


1902

32 ft span, 305 sq ft area
115 lbs – empty weight

First aircraft with control in all three directions

> 1000 flights
~ 650 ft max distance
~ 25 sec. max duration

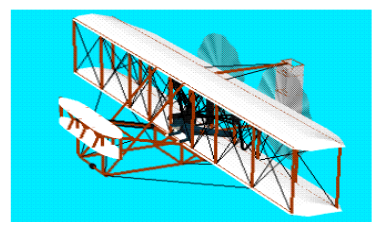


1903

40 ft span, 505 sq ft area
750 pounds with pilot
12 hp motor

First powered aircraft to fly under pilot's control (Dec. 17, 1903)

4 flights
850 ft max distance
59 sec max duration

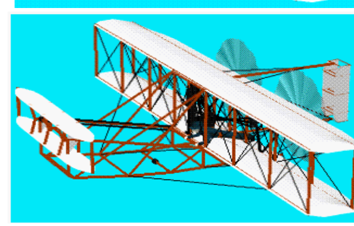


1904

40 ft span, 505 sq ft area
900 lbs with pilot
18 hp motor

First aircraft to fly a complete circle. (Sept. 20, 1904)

> 100 flights
> 3 miles max distance
> 5 minutes max duration

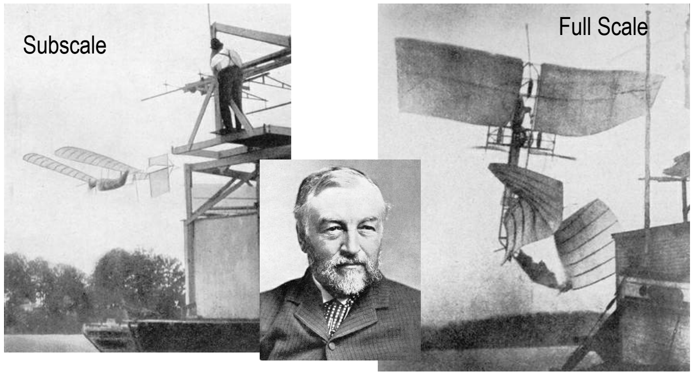


1905

40 ft span, 505 sq ft area
860 pounds with pilot
18 hp motor

First practical aircraft
altitude > 50 ft
circles and figure 8's

~ 50 flights
> 25 miles max distance
> 35 min. max duration



Samuel Langley, convinced his subscale model success was sufficient understanding of the problems of flight, pressed directly to full scale with horrible results just days before the Wright Brothers succeeded

- When do we taste?

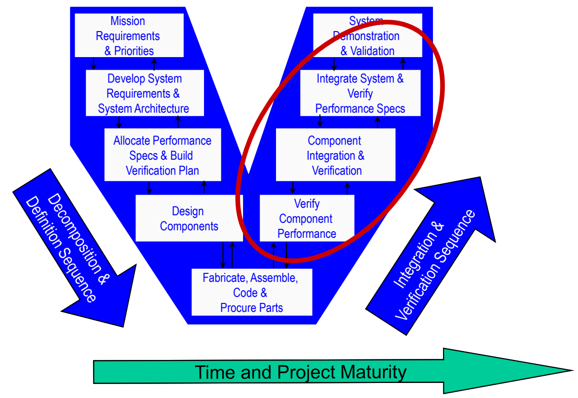
- When do we taste?
  - FREQUENTLY

- When do we taste?
  - FREQUENTLY
- What do we taste for?

More on System Validation and System Verification

- **Verifying a system**: Building the *system right*: ensuring that the system complies with the system requirements and conforms to its design.
- **Validating a system**: Building the *right system*: making sure that the system does what it is supposed to do in its intended environment. Validation determines the correctness and completeness of the end product, and ensures that the system will satisfy the actual needs of the stakeholders.

Verification is Intertwined with the Integration of Components and Subsystems



Templates Help Capture Verification Technique, Rationale, Significance and Traceability

Requirement Definition Card					
Requirement ID#:	*Unique alphanumeric*		Requirement Origin (Spec, Conop, etc.):	*Pointer to origin*	
Requirement:	*Requirement statement*				
Source:	*Author*		Date:	*Origination Date*	
Verification:	*How will the requirement be tested? One or two sentences.*				
Customer Satisfaction:	*(1-5) 5=essential to have, 1=indifferent to capability*		Customer Dissatisfaction:	*(1-5) 5=very dissatisfied if not implemented, 1=not concerned if not implemented*	
Estimated Implementation Cost:	(1-5) 5=expensive to build, 1=inexpensive to implement		Estimated Implementation Risk:	*(1-5) 5= very high risk to implement, 1=no risk, 2= low risk*	
Related Requirement(s):	*Identifier*		Conflicting Requirement(s):	*Identifier*	
Rational:	*Pointer to info*		History:	*Origin, changes, or deletion (as applicable)*	
Customer Approval:	*Name*	*Date*	Provider Approval:	*Name*	*Date*

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The Final Verification Matrix

The verification matrix specifies:

- Requirement
  - Example: "Space vehicle first-mode natural frequency shall be greater than 35 Hz."
- Associated verification requirement, including success criteria
  - Example: "The space vehicle first-mode natural frequency shall be verified by test. The test shall conduct a modal survey of the vehicle using a vibration table. The test shall be considered *successful* if the measured first-mode is greater than 35 Hz."
- Method of verification: Inspection, Analysis, Demonstration, Test
  - Example: test
- Level verification is to be performed: Part, component, subassembly, assembly, Subsystem, System, Vehicle
  - Example: vehicle
- *Who performs the verification.*
- *The results of the verification as they become available.*

Example Verification Matrix

Requirement No.[a]	Document[b]	Paragraph[c]	Shall Statement[d]	Verification Success Criteria[e]	Verification Method[f]	Facility or Lab[g]	Phase[h]	Acceptance Requirement?[i]	Preflight Acceptance?[j]	Performing Organization[k]	Results[l]
P-1	xxx	3.2.1.1 Capability: Support Uplinked Data (LDR)	System X shall provide a max. ground-to-station uplink of…	1. System X locks to forward link at the min and max data rate tolerances 2. System X locks to the forward link at the min and max operating frequency tolerances	Test	xxx	5			xxx	TPS xxxx
P-i	xxx	Other paragraphs	Other "shalls" in PTRS	Other criteria	xxx	xxx	xxx			xxx	Memo xxx
S-i or other unique designator	xxxxx (other specs, ICDs, etc.)	Other paragraphs	Other "shalls" in specs, ICDs, etc.	Other criteria	xxx	xxx	xxx			xxx	Report xxx

Verification Plan

- System engineers develop a *verification plan* when writing the verification requirements.
- Importance:
  - To document a project's approach to executing verification, including people, schedule, equipment, and facilities.
  - To ensure not breaking irreplaceable test units or endangering any of the staff.
- The *verification plan* includes system qualification verification as well as launch site verification, on-orbit verification, and post-mission/disposal verification.
- Support equipment is specified in the *verification plan*, including
  - Ground support equipment
  - Flight support equipment
  - Transportation, handling and other logistics support
  - Communications support infrastructure (e.g., TDRSS, DSN)

The Methods of Verification

There are 4 fundamental methods for verifying a requirement:

1. Inspection
2. Analysis
3. Demonstration
4. Test

Often joked that the top three verification methods are test, test, and test - to emphasize the importance of objective, measurable data in verifying a requirement.

Alternatively it is joked that one test is worth a thousand expert opinions - for equal emphasis.

Inspection

- Inspections determine conformance to requirements by the visual examination of drawings, data, or the item itself using standard quality control methods, without the use of special laboratory procedures or equipment.
- Inspections include a visual check or review of project documentation such as, drawings, vendor specifications, software version descriptions, computer program code, etc.
- Inspection includes examining a direct physical attribute such as dimensions, weight, physical characteristics, color or markings, etc.
- The kind of language used in the item requirement that usually indicates verification by inspection is:
  - "…shall be at least 24 inches long…"
  - "…shall have the NASA logo in accordance with…"
  - "…shall be painted white…"

Analysis

- Analysis is the evaluation of data by generally accepted analytical techniques to determine that the item will meet specified requirements.
- Analysis techniques: systems engineering analysis, statistics, and qualitative analysis, analog modeling, *similarity*, and computer and hardware simulation.
- Analysis is selected as the verification activity when test or demonstration techniques cannot adequately or cost-effectively address all the conditions under which the system must perform or the system cannot be shown to meet the requirement without analysis.
- The kind of language used in the item requirement that usually indicates verification by analysis is:
  - "…shall be designed to…"
  - "…shall be developed to…"
  - "…shall have a probability of…"

Demonstration

- Demonstration determines conformance to system/item requirements through the operation, adjustment, or reconfiguration of a test article.
- Demonstration generally verifies system characteristics such as human engineering features, services, access features, and transportability.
- Demonstration relies on observing and recording functional operation *not* requiring the use of elaborate instrumentation, special test equipment, or quantitative evaluation of data.
- The kind of language used in the item requirement that usually indicates verification by demonstration is:
  - "…shall be accessible…"
  - "…shall take less than one hour…"
  - "…shall provide the following displays in the X mode of operation…"

Test (1/2)

- Test is a verification method in which *technical* means, such as the use of special equipment, instrumentation, simulation techniques, or the application of established principles and procedures, are used for the evaluation of the system or system components to determine compliance with requirements.
- Test consists of operation of all or part of the system under a limited set of controlled conditions to determine that *quantitative* design or performance requirements have been met.
- Tests may rely on the use of elaborate instrumentation and special test equipment to measure the parameter(s) that characterize the requirement.
- These tests can be performed at any level of assembly within the system assembly hierarchy.
- The analysis of data derived from tests is an integral part of the test program and should not be confused with "analysis" as defined earlier.

Test (2/2)

- Testing is the preferred method of requirement verification and used when:
  1. Analytical techniques do not produce adequate results,
  2. *Failure modes* exist which could compromise personnel safety, adversely affect flight systems or payload operation, or result in a loss of mission objectives, or
  3. For any components directly associated with critical system interfaces.
- The kind of language used in the item requirement that usually indicates verification by test is:
  - "…shall provide 50 Hz…"
  - "…shall be settable over a range of 0 to 30 degrees C…"
  - "…shall not be larger than 10 microns, at once per rev frequency…"

Prototyping

- A requirement without a test is just marketing
- Every requirement should have a V&V plan
- Every subsystem or component has its own V&V plan in order to ensure that the system is right
- Every piece of your TrailRider… "n" pieces?
- Every requirement in your Report… "m" requirements?
- n x m tests?

Overview

- This lecture is a set of odds and ends
- They are things that you need to know about
- They are things that other courses might spend a lot of time on
- They tend to be more process based than technical
- My rubric for topics here has been to give you a top level introduction to any topics that we haven't previously discussed that would be considered as mandatory knowledge for a systems engineer
  - I don't want anyone to turn to you and say "I thought you said that you took systems engineering?"

Overview

- Systems Engineering Management Plan (SEMP)
- ~~Capability Maturity Model Integration (CMMI)~~
- Change/Configuration Control
- Key Performance Parameters (KPP) and Technical Performance Metrics (TPMs)
- Master Verification Plan

37

Systems Engineering Management Plan (SEMP)

- My experience:
  - If you don't have one, people will insist that you have one
  - If you do have one, and senior management doesn't want to follow it, they probably won't
  - At best, it provides you a mechanism for you to think through how you would like to work
  - At worst, it is another piece of administrative paperwork
- Some people think it is absolutely critical
    - Shuttle Return to Flight was hung up by Stafford Covey until we wrote one
    - The ink wasn't even dry when people started running all over it
- My advice: minimize the parts that don't add value and maximize the engineering value and use it to get your own thinking straight

38

Systems Engineering Management Plan (SEMP) – The basics

- **Foreword**
  Contents
  1. SCOPE
  2. APPLICABLE DOCUMENTS
  3. TECHNICAL PROGRAM PLANNING AND CONTROL
  4. SYSTEMS ENGINEERING PROCESS
  5. ENGINEERING SPECIALTY INTEGRATION
  6. NOTES

http://sparc.airtime.co.uk/users/wysywig/semp.htm

39

SEMP - Technical Program Planning and Control

- Technical program planning and control identifies organizational responsibilities and authority for system engineering management, including control of subcontracted engineering:
  - levels of control established for performance and design requirements and control of the method used;
  - technical program assurance methods (verification-ITAD);
  - plans and schedules for design and technical program reviews;
  - control of documentation;
  - design approval and certification;
- Bottom line – describe how you are going to control the engineering requirement and development process

40

SEMP – Systems Engineering Process

- This section contains a detailed description of the process to be used, including the specific tailoring of the process to the requirements of the system and project:
  - the procedures to be used in implementing the process;
  - in-house documentation;
  - the trade study methodology;
  - the types of mathematical and/or simulation models to be used for system and cost effectiveness evaluations;
  - and the generation of specifications
- Bottom line : describe the tools and methodologies you are going to use

41

SEMP – Engineering Specialty Integration

- The integration and coordination of the program efforts for engineering specialty areas (structures, software, avionics, GN&C, mechanisms, electrical power, hydraulics, etc…), to achieve a best mix of the technical/performance values incorporated in the contract, shall be described with the detailed specialty program (project) plans being summarized and/or referenced, as appropriate.
- The specialty efforts and parameters will be integrated into the system engineering process at each iteration. The process will be described and considerations taken defined.
- *You may have to reduce the performance or capabilities of one part of the system in order to maximize the total performance of the system*
  - *For example, you might have to reduce the cargo carrying capacity of the system in order to reduce weight enough to meet range*
  - *You might have to reduce passenger volume in order to make room for fuel or cargo*
- Bottom line: describe how you are going to integrate different technical disciplines

42

Change or Configuration Control

43

Change and Configuration Management

- If you are going to have an orderly design and development process with many designers working simultaneously, change or configuration management (control) is critical
- Uncoordinated change can create havoc in a development
- Uncontrolled change can have large impacts to a project's ability to maintain cost, schedule or other technical performance goals such as weight
- Once a baseline has been established at a milestone (such as a design review) then it is critical that ALL CHANGES to that baseline are reviewed for technical, cost and schedule impact and communicated to all affected parties
  - Changes need to be approved by the responsible official – typically the chief engineer and the project/program manager
- This review and approval typically takes place at a Configuration Control Board (CCB) where representatives of all of the key organizations are present
  - The change is documented on a Change Request (CR) form with attached presentations and engineering products such as drawings
  - A presentation is normally made by the person/organization proposing the change
- Once approved, paper is signed to authorize a change to drawings, ICDs or other engineering products, to change allocation of moneys or to change schedules
- CCB's may issue actions to gather additional data prior to making a decision or to initiate subsequent changes

44

A Guide to Successfully Running/Presenting to CCBs

- When presenting to a CCB
  - Make a clear and complete statement of the problem you are trying to solve
  - Make a clear and complete statement of your proposed solution and it's entire impact
  - Try to understand the potential impacts and discuss the change with people and organizations that are impacted by the change ahead of time
  - Keep to the topic on hand
  - Just the facts
- When running a CCB
  - Hold them regularly
  - Listen carefully, ask lots of questions
  - Know what your budget and schedule flexibilities are before you commit
  - Gather reasonable data and then MAKE A DECISION – don't keep sending people back for more data or more options

45

Systems Engineering Capability Maturity Model Integration (CMMI)

46

CMM

- The **Capability Maturity Model** (**CMM**) is a way to develop and refine an organization's processes. The first CMM was for the purpose of developing and refining software development processes. A maturity model is a structured collection of elements that describe characteristics of effective processes. A maturity model provides:
- a place to start
- the benefit of a community's prior experiences
- a common language and a shared vision
- a framework for prioritizing actions
- a way to define what improvement means for your organization.
- A maturity model can be used as a benchmark for assessing different organizations for equivalent comparison. The model describes the maturity of the company based upon the project the company is handling and the related clients.
- The software CMM was generalized into a systems engineering CMM and then rewritten as the CMMI
- This standard has been developed and maintained by Carnegie Mellon University

Courtesy of Wikipedia

47

Levels of CMMI

- Level 1 – Initial - can do systems engineering, depends on quality of people, hit or miss
- Level 2 – Repeatable – can repeat the process (e.g. write requirements, do a PDR, CDR, etc…)
- Level 3 – Defined – procedures are well documented
- Level 4 – Quantitatively Managed – metrics are maintained to evaluate how well you are doing
- Level 5 – Optimized – you use metrics to identify problems and apply resources to maximize the positive outcome

48

Value of CMMI

- Important for self-evaluation – how are you doing ?
  - I initiated a CMMI audit of Shuttle Systems Engineering and Integration after I took over after the accident
  - It identified the key weaknesses
  - With limited resources at our disposal, I focused our efforts on fixing the key weaknesses found by the audit rather than trying to fix everything
- You can use it to help you continuously improve
- Unfortunately, People use it as a gimmick
  - "we're level 4…."
  - You can almost hear them saying "nyaah,nyaah,nyaah,nyaah"
- To go to the source on CMMI, reference
  http://www.sei.cmu.edu/cmmi/

49

Key Performance Parameters (KPP) and Technical Performance Metrics (TPMs)

50

KPPs and TPMs

- Key Performance Parameters (KPPs)
  - Are the values that a system must attain to meet its most important requirements
  - Example of key performance parameters would be
    - Range
    - Cargo/Passengers
  - In DOD projects the Key Performance Parameters (KPP) are requirements that are so critical to the program, that the failure to meet any KPP would be grounds for program termination.

51

KPPs and TPMs

- Technical Performance Metrics
  - Are the values expressing how well a system is moving towards meeting its KPPs
  - A TPM may have an objective (defined as the goal or required value at the end of the technical effort) or both an objective and a threshold (defined as the limiting acceptable value that if not met can jeopardize the project).
  - A TPM can also have tolerance bands that show the allowed variation, which is based on the projected estimation

52

Master Verification Plan

Master Verification Plan (MVP)

- Identifies the set of facilities and major test environments to verify requirements
- May show relationship between test and analysis by a network diagram (see next few examples)
  - Very important for integrated verification where multiple independent projects need to cooperate to accomplish verification
- Identifies each major system requirement and its verification method (Inspection, Test, Analysis, Demonstration)

FIGURE 3.3.1.1–1

ASCENT AERODYNAMIC VERIFICATION APPROACH

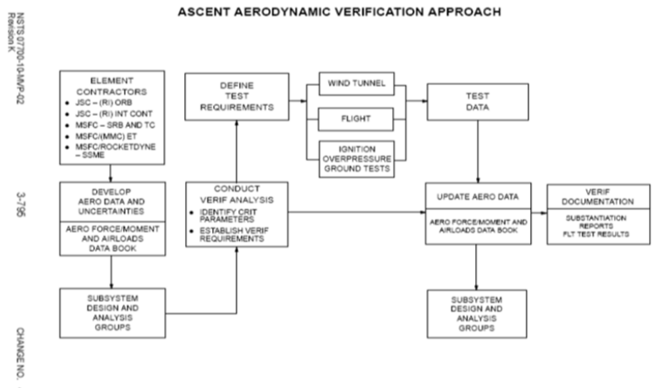
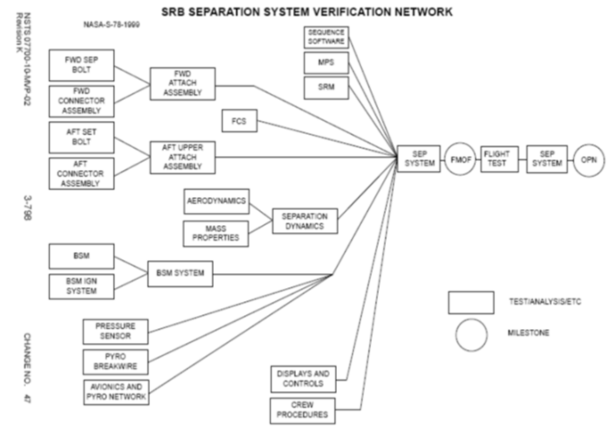


FIGURE 3.3.1.4-1

SRB SEPARATION SYSTEM VERIFICATION NETWORK



Risk Management

In the end, it always comes to the point where it is time to shoot the engineers and go fly the airplane
- Boeing President

57

Risk Management

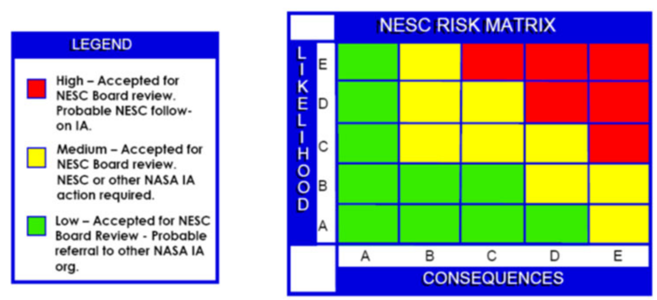
- Use a 5x5 matrix to rate – Very Similar To Hazard Analysis
- Risk mitigation plans established for yellow and red risks
- Allocate resources (money, schedule) to risks –
  - RSS resources to avoid having to hold too much in reserve for covering risks – treat each risk as an independent random variable
  - Multiply risk resources by probability of risk coming true
- Top X list – weekly or monthly review the top risks and their mitigation plans
- Reducible vs irreducible risk
  - Reducible risks are those where you can work harder to reduce or eliminate them
  - Irreducible risks – those were no matter how hard you work, you can't reduce them
    - Good example – combined environments – where you cannot expose an entire flight vehicle structure to the combined thermal, inertial, pressure load simultaneously before you actually fly

58

Advice on Risk

- Irreducible risk – be bold
- Reducible risk – be conservative
  - Control the things you can
- Problem – people say – irreducible risk is greater than reducible so why work so hard on reducible
  - Stupid to lose crew/mission for something you could've fixed
  - Irreducible may be less defined – may not be as large as you or assume
- In our history – people generally die from things we could've anticipated and fixed

59



60

What is the likelihood the situation or circumstance will happen?

LIKELIHOOD

Level	Probability	. . . or –. . .	Example
E	Very Likely	Likely to occur often. Likelihood of occurrence is estimated to be greater than 0.10 (10-1) per operational opportunity	Mortality Rate for Brain Surgery
D	High	Expected to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.01 and 0.10 (10-2 and 10-1) per operational opportunity	Failures per US ELV Launch (1988 - 2001)
C	Moderate	Likely to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.001 and 0.01 (10-3 and 10-2) per operational opportunity	Fatal Crashes per motorcycle trip
B	Low	Unlikely but possible to occur. Likelihood of occurrence is estimated to be between 0.000001 and 0.001 (10-6 and 10-3) per operational opportunity	Fatal crashes per automobile trip
A	Very Low	Likelihood of occurrence is estimated to be less than .000001 (<10-6) per operational opportunity	Fatal crashes per passenger airplane departure

61

What is the Consequence (Safety, Health, Environment, Mission Success, National Significance) of this NESC Risk?

CONSEQUENCE

Level	A	B	C	D	E
Safety, Health, Environment	Minimal/no safety or health plan violations / Minimal to no environ impacts	Could result in injury or illness not resulting in lost work day / Minimal envirnmtl damage	Could result in injury or occupational illness resulting in one or more lost work day / Mit. envirnmtl damage w/o law viol	Could result in permanent partial disability, injuries or occupational illness / Reversible envinmt damage – violates law	Could result in death or perm. total disability / Irreversible severe environ damage that violates law or regulation
Mission Success	Hardware loss between $200K and $1 Million / Failure to any one MMO	Hardware loss between $1M and $10 Million / Failure to meet > 50% of supplemntl objectives	Hardware loss between $10M and $100 Million / Failure to meet any one MMO	Hardware loss between $100M and $250 Million / Failure to meet > 50% MMO's	Hardware loss exceeding $250 Million / Failure to meet all Major Mission Objectives (MMO's)
National Significance	Minimal or no identified National Prestige or Visibility	Low National Prestige and Visibility	Moderate National Prestige and Visibility	Significant National Prestige and Visibility	High National Prestige and Visibility

62

US Army
Pre-mission
Risk Evaluation
For Helicopter Missions

63

Any Questions ?

64