Electric Ship Power and Energy System Architectures

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IEEE ESTS 2017
August

Agenda

- Naval Power (and Energy Systems)
- Existing Ships
- MVAC Architectures
- MVDC Architectures

Dec 8, 2016: DDG 1000 and LCS 2
(US Navy Photo by Ace Rheaume)

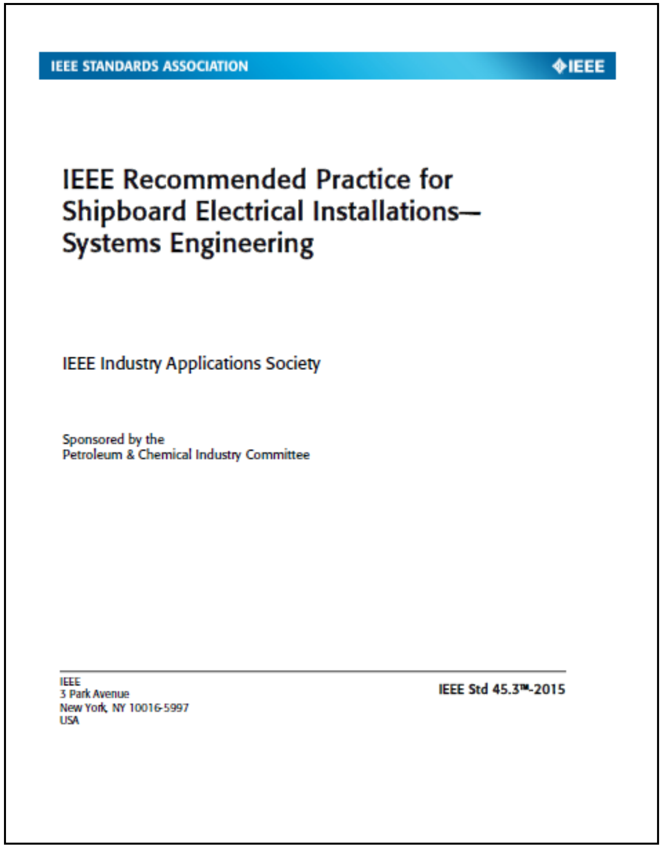
Properties of a Naval Power (and Energy) System

- Limited rotational inertia – AC frequency is not a constant
- Lack of Time Scale Separation
- Load sharing vice Power Scheduling
- Short electrical distances
- Load dynamics very important
- System behavior dominated by controls

Systems Engineering (IEEE 45.3)

Systems studies, analysis and reports

- Electrical Power System Concept of Operations (EPS-CONOPS)
- Electric load analysis
- Load-flow analysis
- Transient analysis
- Short-circuit / fault-current analysis
- Harmonic / frequency analysis
- Stability analysis
- Failure Modes and Effects Analysis (FMEA)
- Electromagnetic Interference (EMI) analysis
- Thermal analysis
- Electrical power system data for life-cycle cost analysis
- Electrical power system data for signature analysis
- Safe return to port / survivability analysis report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IEEE Recommended Practice for Shipboard Electrical Installations— Systems Engineering

IEEE Industry Applications Society

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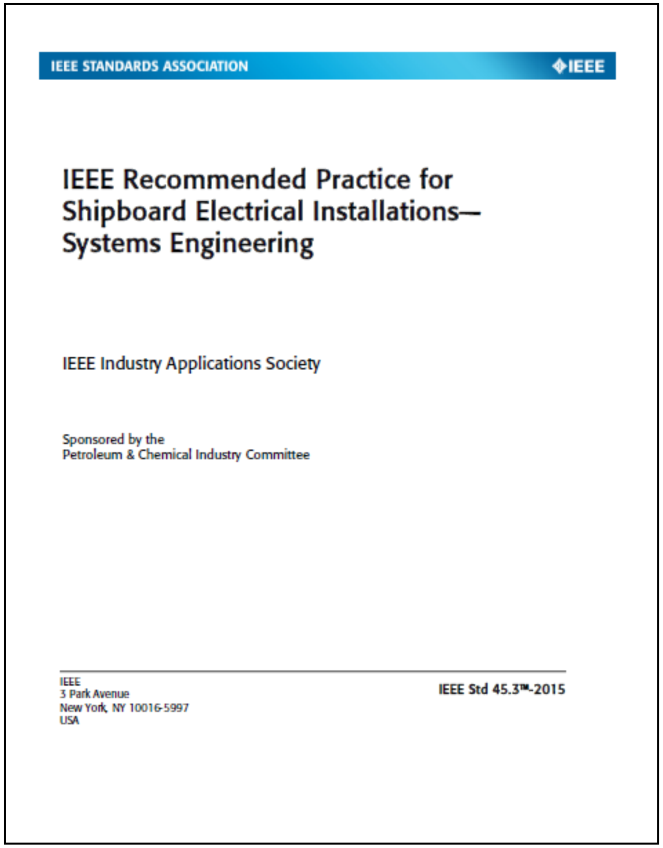
IEEE Std 45.3™-2015

Systems Engineering (IEEE 45.3)

Systems studies, analysis and reports (continued)

- Electrical power system one-line diagram
- Future power growth assessment
- Protection system design report
- Grounding system design report
- Electrical power system corrosion control report
- Electrical power system equipment section of the ship's weight report
- Auxiliary system requirements derived from the electrical power system
- Electrical power system section of the master equipment list
- Electrical power system input to machinery and ship arrangements
- Electrical power system input to endurance fuel calculations
- Incident energy analysis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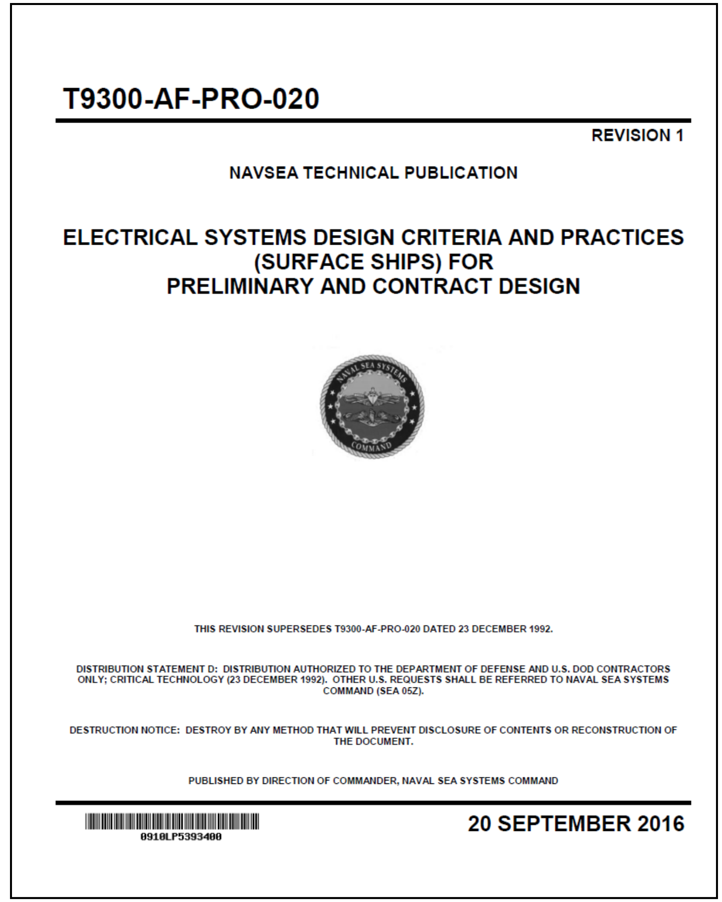
Naval Power (and Energy) System Design Objectives

- Power Reliability
  - Power Quality
  - Quality of Service
- Power System Survivability
  - Zonal Survivability
  - Compartment Survivability
- Zonal Design
- Complexity
- Acquisition Cost
- Operating and Support Cost



T9300-AF-PRO-020

REVISION 1

NAVSEA TECHNICAL PUBLICATION

ELECTRICAL SYSTEMS DESIGN CRITERIA AND PRACTICES (SURFACE SHIPS) FOR PRELIMINARY AND CONTRACT DESIGN

THIS REVISION SUPERSEDES T9300-AF-PRO-020 DATED 23 DECEMBER 1992.

DISTRIBUTION STATEMENT D: DISTRIBUTION AUTHORIZED TO THE DEPARTMENT OF DEFENSE AND U.S. DOD CONTRACTORS ONLY; CRITICAL TECHNOLOGY (23 DECEMBER 1992). OTHER U.S. REQUESTS SHALL BE REFERRED TO NAVAL SEA SYSTEMS COMMAND (SEA 05Z).

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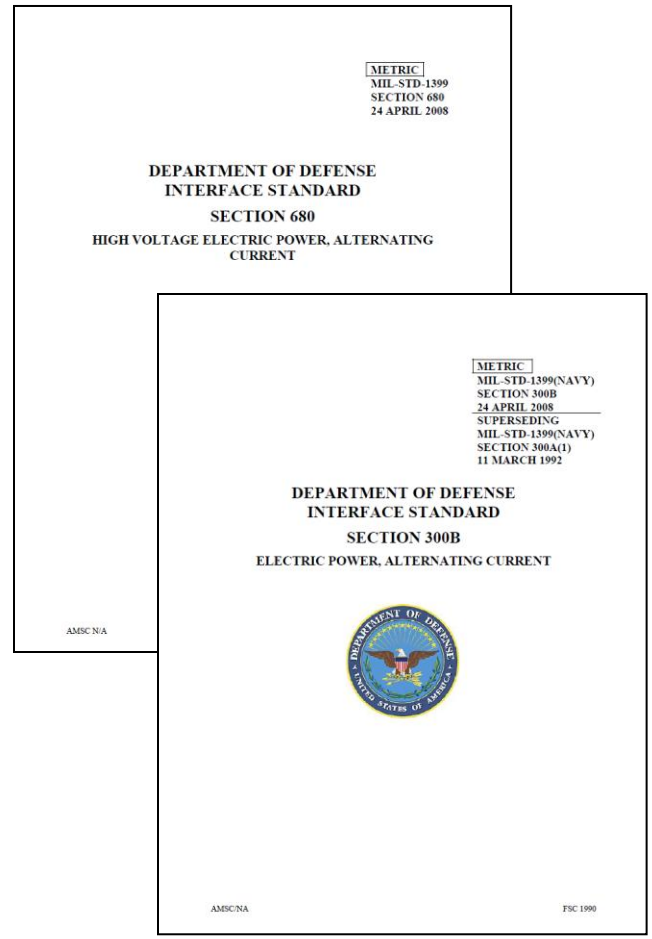
0910LP5393400

20 SEPTEMBER 2016

Power Quality (AC Systems)

- Interface Standards
  - MIL-STD-1399-300B
  - MIL-STD-1399-680
- Paradigm
  - Loads responsible for Energy Storage
  - Limited Pulse Loads
  - Rotating Machine source of power


METRIC
MIL-STD-1399
SECTION 680
24 APRIL 2008

DEPARTMENT OF DEFENSE
INTERFACE STANDARD
SECTION 680
HIGH VOLTAGE ELECTRIC POWER, ALTERNATING CURRENT

AMSC N/A

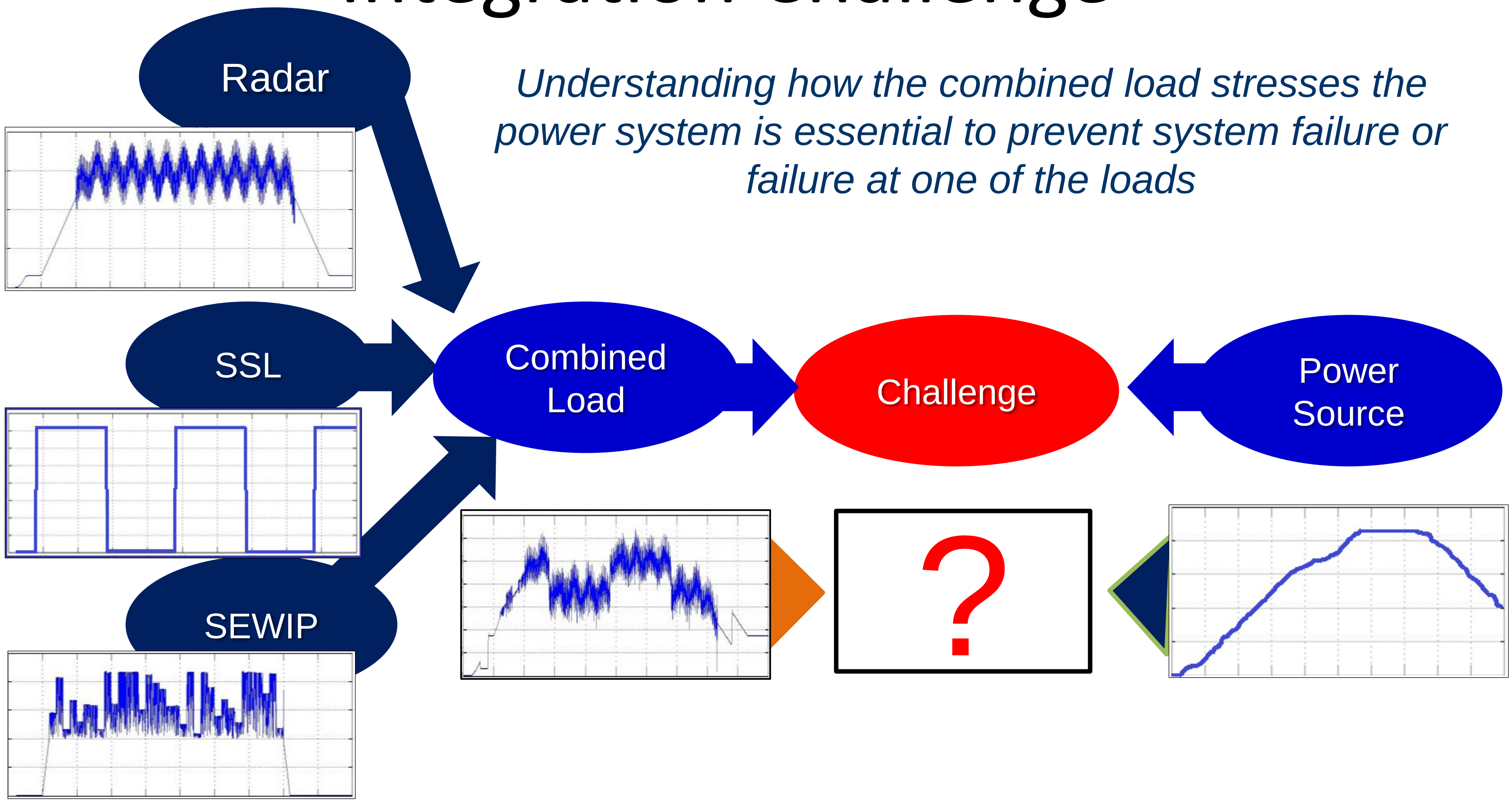
METRIC
MIL-STD-1399(NAVY)
SECTION 300B
24 APRIL 2008
SUPERSEDING
MIL-STD-1399(NAVY)
SECTION 300A(1)
11 MARCH 1992

DEPARTMENT OF DEFENSE
INTERFACE STANDARD
SECTION 300B
ELECTRIC POWER, ALTERNATING CURRENT

AMSC/NA
FSC 1990

High Energy Mission Systems Integration Challenge

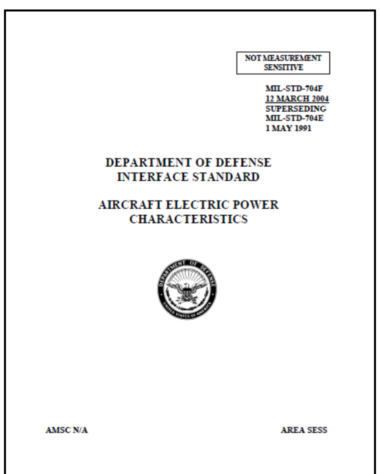
Understanding how the combined load stresses the power system is essential to prevent system failure or failure at one of the loads



Ships cannot support High Power Systems without modifications to the ship's Electric Power System and other ship systems

Power Quality (DC Systems) Naval Surface Combatants

- DDG 1000 re-introduces DC power to Naval Surface Combatants
- Standard DC voltages defined in T9300-AF-PRO-020
- Power Quality Standards for voltages above 270 V are under development


NOT MEASUREMENT SENSITIVE

MIL-STD-704F
12 MARCH 2004
SUPERSEDING
MIL-STD-704E
1 MAY 1991

DEPARTMENT OF DEFENSE
INTERFACE STANDARD

AIRCRAFT ELECTRIC POWER
CHARACTERISTICS

AMSC N/A
AREA SESS

- Low Voltage
  - 28 V (MIL-STD-704) note 1
  - 155 V (MIL-STD-1399-390)
  - 270 V (MIL-STD-704) note 1
  - 375 V
  - 650 V
- High Voltage (aka Medium Voltage)
  - 1 kV
  - 6 kV
  - 12 kV
  - 18 kV

Note 1: for interfaces with vehicles and systems designed for vehicles or modules

Quality of Service

- Metric for how reliable a distributed system provides its commodity to the standards required by the user
  - Measured as a MTBF
  - Not all service interruptions are QOS failures
  - Uses Reliability type analysis, but in different ways.
- QOS does not take into account Battle Damage, collisions, fire, flooding, etc.
- QOS ensures the ship can perform its mission under normal conditions (when it is not damaged).

Survivability

- Design Threats & Design Threat Outcomes
  - Key differentiation between commercial and naval ships
- Survivability Elements
  - Susceptibility
  - Vulnerability
  - Recoverability
- A Survivability Strategy
  - Zonal Survivability
  - Compartment Survivability

USS Howorth (DD 592) sunk as target (8 March 1962)

SURVIVABILITY IS A PROPERTY OF THE TOTAL SHIP
SHOULD BE ADDRESSED BY AN OVERALL SURVIVABILITY STRATEGY

Survivability Elements

- Susceptibility
  - A measure of the capability of the ship, mission critical systems, and crew to avoid and or defeat an attack and is a function of operational tactics, signature reduction, countermeasure, and self-defense system effectiveness.
- Vulnerability
  - A measure of the capability of the ship, mission critical systems, and crew to withstand the initial damage effects from conventional, CBR or asymmetric threat weapons, or accidents, and to continue to perform assigned primary warfare missions, and protect the crew from serious injury or death.
- Recoverability
  - A measure of the capability of the ship and crew, after initial damage effects, whatever the cause, to take emergency action to contain and control damage, prevent loss of a damaged ship, minimize personnel casualties, and restore and sustain primary mission capabilities.

OPNAV INSTRUCTION 9070.1A : Survivability Policy and Standards for Surface Ships and Craft of the U.S. Navy

Susceptibility in Naval Power System Design

- Signatures most influenced by power system
  - Infrared
  - Magnetic
  - Acoustic
- Quality of Service (Reliability) helps ensure mission systems are available to defeat weapons before they affect the ship

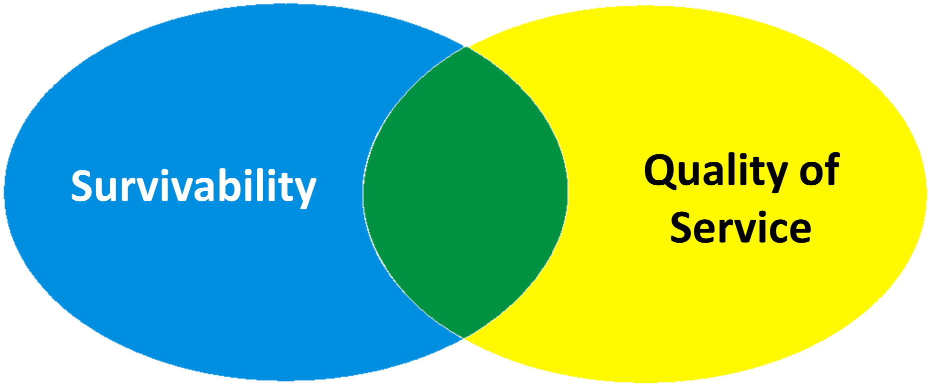
Zonal and Compartment Survivability as applied to Distributed Systems

- Zonal Survivability
  - Zonal Survivability is the ability of the distributed system, when experiencing internal faults due to damage or equipment failure confined to adjacent zones, to ensure **loads in undamaged zones do not experience an interruption** in service or commodity parameters outside of normal parameters
    - Sometimes only applied to "Vital Loads"
- Compartment Survivability
  - Even though a zone is damaged, some important loads within the damaged zone may survive. For **critical non-redundant mission system equipment and loads supporting in-zone damage control efforts**, an increase level of survivability beyond zonal survivability is warranted.
  - For these loads, **two sources** of commodity should be provided, such that if the load is expected to survive, at least one of the sources should also be expected to survive.

ZONAL SURVIVABILITY addresses VULNERABILITY
COMPARTMENT SURVIVABILITY addresses RECOVERABILITY

Interaction of Survivability and QOS

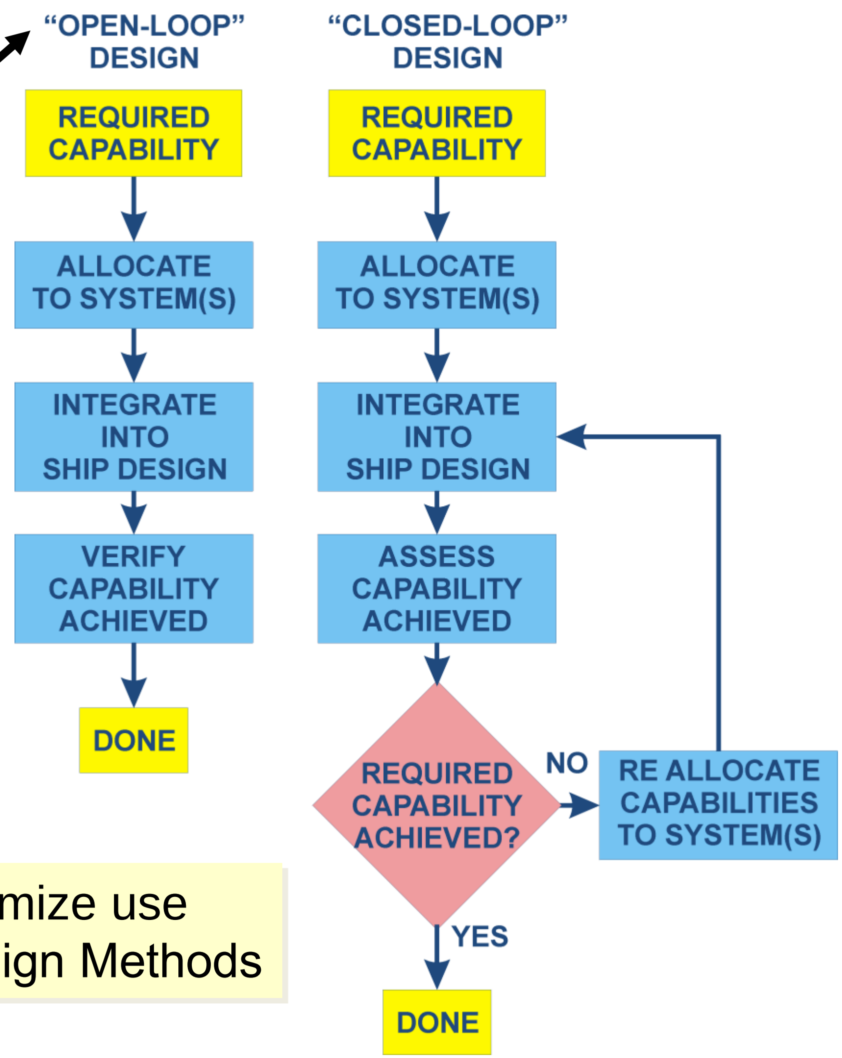
- Many design decisions that impact Survivability will also impact QOS
  - Redundancy
    - May be added for either Survivability (Vital Load) or for QOS
  - Rating of equipment
- Exceptions
  - QOS is not sensitive to equipment location.
  - Survivability is not very sensitive to reliability of equipment.
  - System line-ups can impact one more than the other.
    - Parallel vs. Split Plant



Zonal Design

- Goal: Reduce complexity and cost of ship design while still meeting survivability requirements.
- How: Use a disciplined Systems Engineering Approach that inherently reduces complexity and achieves survivability objectives

Open Loop and Closed Loop Design



Accelerates Convergence Of a Design

For Speed: Maximize use Of "Open Loop" Design Methods

Naval Concept Essential Task List

- A disciplined approach to defining ship concept capabilities
- Based on the Universal Navy Task List (UNTL) defined in OPNAVINST 3500.38
- Naval Concept Essential Task List (NCETL) Elements
  - Tasks
    - "Actions or processes performed as part of an operation"
    - Describes a discrete activity visible outside the command
    - Does not define who, or how the activity is accomplished.
  - Conditions
    - Variables of the environment that affect the performance of tasks in the context of the assigned mission.
    - Includes physical environment, military environment, and civil environment
  - Standards
    - Describe how well an organization or force must perform a task under a specific set of conditions for a specific mission.
    - Differs from a Measure of Performance (MOP) in that a Standard in an input to the design while an MOP is an output from the design (What the design is capable of doing).

Common Language for defining Requirements

Tasks

- Navy Tactical Task List (Subset of UNTL) Structure
  - **NTA 1 DEPLOY/CONDUCT MANEUVER**
  - **NTA 2 DEVELOP INTELLIGENCE**
  - **NTA 3 EMPLOY FIREPOWER**
  - **NTA 4 PERFORM LOGISTICS AND COMBAT SERVICE SUPPORT**
  - **NTA 5 EXERCISE COMMAND AND CONTROL**
  - **NTA 6 PROTECT THE FORCE**
- Universal Joint Task List (UJTL) defines Operational and Strategic Tasks
  - Specified in CJCSM 3500.04C

Task Structure Example

- **NTA 1.1 Move Naval Tactical Forces.**
  - **NTA 1.1.1 Prepare Forces For Movement**
  - **NTA 1.1.2 Move Forces**
    - **NTA 1.1.2.3 Move Units**
      - **NTA 1.1.2.3.3 Conduct Flight Operations.**
        - » **NTA 1.1.2.3.3.1 Conduct Aviation Qualification**
        - » **NTA 1.1.2.3.3.2 Launch Aircraft**
        - » **NTA 1.1.2.3.3.3 Recover Aircraft**
- **NTA 1.2 Navigate and Close Forces**
- **NTA 1.4 Conduct Countermobility**
- **NTA 1.5 Dominate the Operational Area**

Reference: NTTL 3.0 draft
Of November 2004

Task Definition

NTA 1.1.2.3.3.2 Launch Aircraft.

To launch aircraft from ships. This task covers all fixed-wing, tilt-rotor, and helicopter aircraft launch operations from ships, surface combatants and all other applicable sea vessels. This task requires the safe and efficient execution of all procedures applicable to launch, including: pre-launch procedures, launch procedures, instrument and visual departure procedures, departure communications procedures, departure rendezvous procedures, emergency recovery procedures, tanker procedures, and procedures for diversion of aircraft. **(JP 3-04.1, MCWP 3-31.5, NWP 3-04.1M, 3-22 Series)**

Reference: NTTL 3.0 draft
Of November 2004

Conditions

1.0 PHYSICAL ENVIRONMENT

1.1 Land
1.2 Sea
1.3 Air
1.4 Space

2.0 MILITARY ENVIRONMENT

2.1 Mission
2.2 Forces
2.3 Command, Control, & Communications
2.4 Intelligence
2.5 Deployment, Movement & Maneuver
2.6 Firepower
2.7 Protection
2.8 Sustainment
2.9 Threat
2.10 Conflict

3.0 CIVIL ENVIRONMENT

3.1 Political Policies
3.2 Culture
3.3 Economy

Condition Definitions

- **C 1.2.1.1 Ocean Depth**
  - The depth of ocean water at a point or for an area.
  - *Descriptors*: Shallow (< 100 fathoms); Limited (100 to 500 fathoms);
  - Deep (500 to 2500 fathoms); Very deep (> 2500 fathoms).
- **C 1.2.1.2 Ocean Currents**
  - A steady, generally predictable flow, present either in open ocean waters or in littoral coastal ocean waters.
  - *Descriptors*: Strong (> 3 knots); Moderate (1 to 3 knots); Little or no (< 1 knot).
- **C 1.2.1.3 Sea State**
  - Roughness of seas caused by wind or disturbances.
  - *Descriptors*: Calm to slight (Beaufort Force < 5, Sea State 3 or less, seas 4 ft or less); Moderate (Beaufort Force 5, Sea State 4, seas 4-8 ft); Rough (Beaufort Force 6-7, Sea State 5-6, seas 8-16 ft); Very Rough (Beaufort Force 8-9, Sea State 6, seas 17-20); High (Beaufort Force 10, Sea State 7, seas 20-30 ft); Extremely rough (Beaufort Force above 10, Sea State above 7, seas above 30 ft).

Measures, Criterion, and Standards

STANDARD - A standard provides a way to express the degree to which a ship must perform a task under the specified set of conditions. A standard consists of:

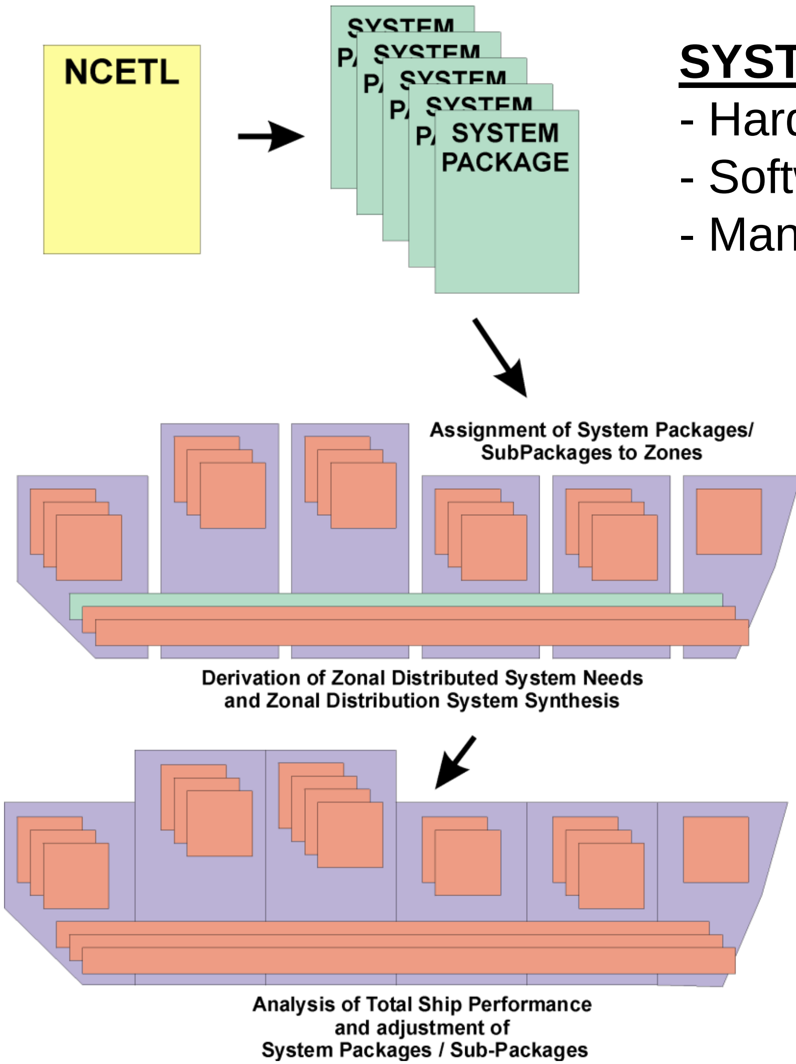
- **MEASURES** - Measures provide a dimension, capacity, or quantity description to a task. A measure provides the basis for describing varying levels of task performance and is therefore directly related to a task.
- **CRITERION** - A criterion defines acceptable levels of performance. It is often expressed as a minimum acceptable level of performance.

System Packages

- Current Design process independently assesses Hardware, Software, and Manpower
  - Requires considerable coordination, adding complexity to design process
- System Packages proposed to link Hardware, Software, and Manpower
  - Can be composed of "sub packages"
  - Allocated from NCETLs
  - Includes derived requirements
  - Ensures manpower, software and ship concept are all consistent
- Ideally, manpower requirements (and software) can be estimated solely from the collection of Systems Packages comprising a ship concept.
  - May be refined from synthesized ship concept
- Hardware elements of System Packages integrated through a ship synthesis tool (such as ASSET) into a ship concept

Packages Link Capabilities to Synthesis

Zonal Design Process



SYSTEM PACKAGE:
- Hardware
- Software
- Manpower

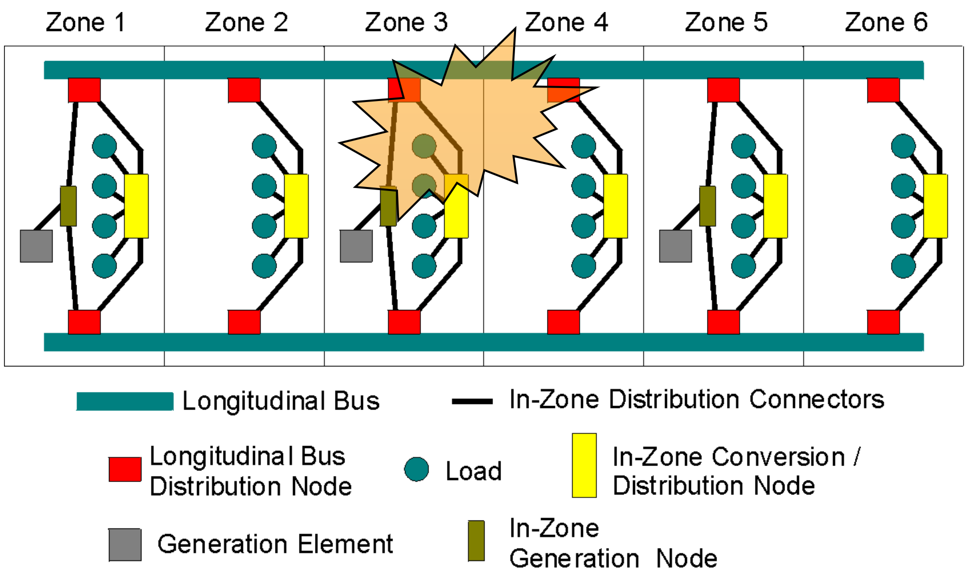
Zonal Design:
For capabilities that are required to survive, assign associated redundant Packages / Sub-packages such that loss of any 2 adjacent zones will leave sufficient functionality in undamaged zones.

Goal:
Make Survivability an "Open Loop" Design Process rather than a "Closed Loop" Process

Zone Definitions

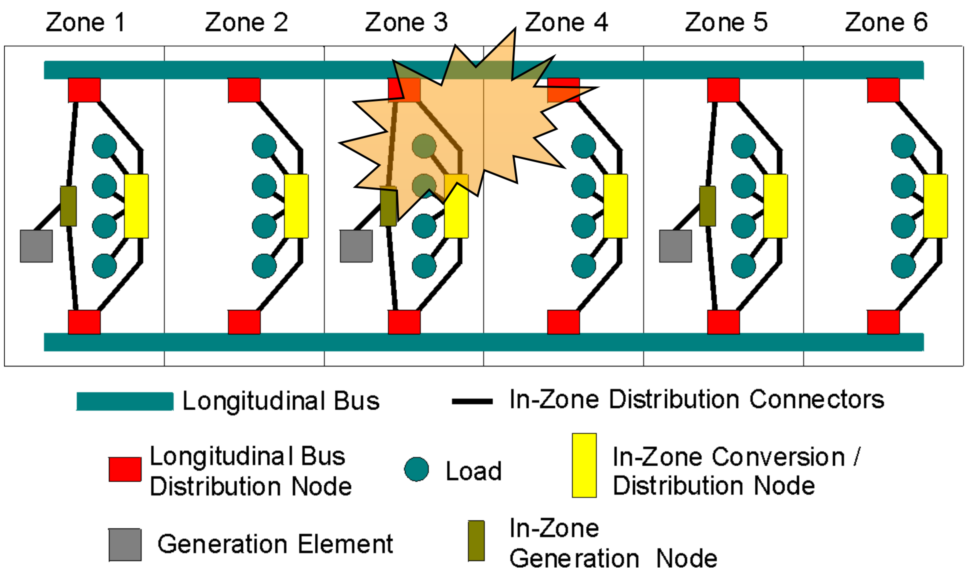
- Recommend ships about 120 m or longer to have 5 to 7 zones.
  - Provides sufficient opportunity to allocate redundant components in non-adjacent zones.
  - Reduces probability that more than two adjacent zones will be damaged due to weapons effects.
- Zone Boundaries should align with water-tight bulkheads
- Distributed System architecture should align with zone boundaries.
  - Some systems may split a zone into sub-zones.

Zonal Survivability Review



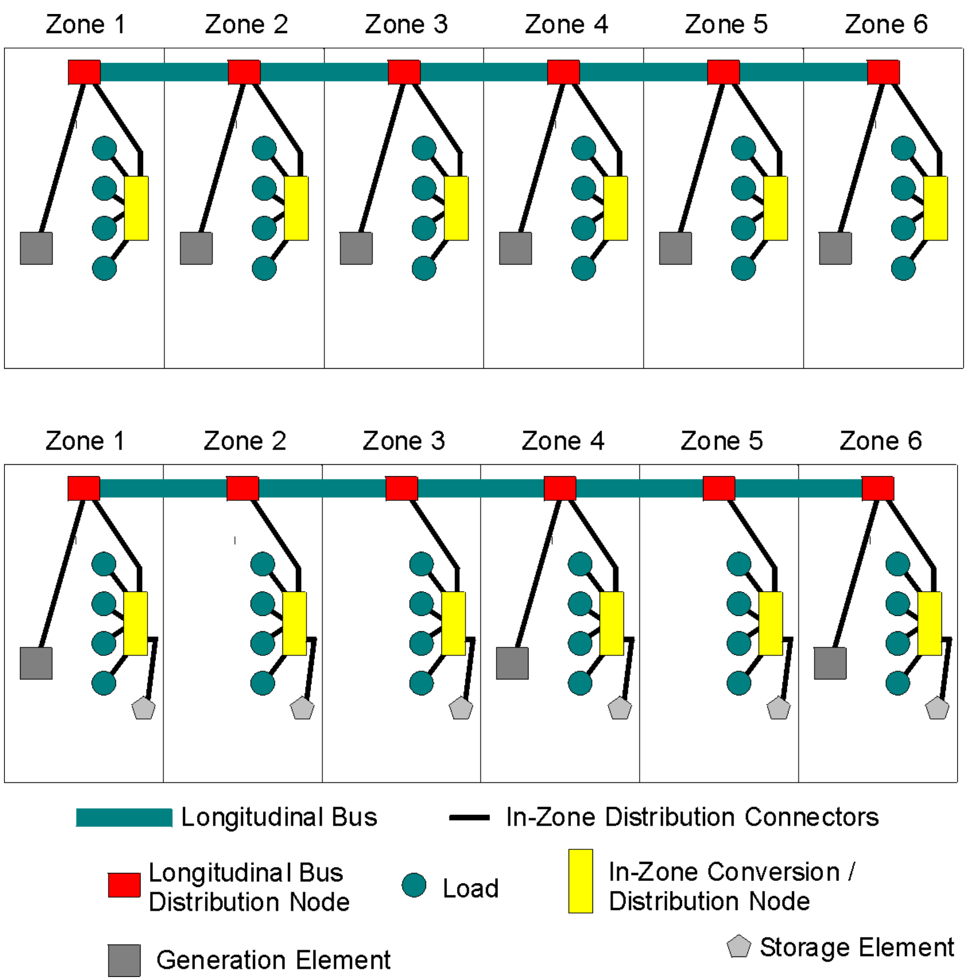
- The ability of a distributed system, when experiencing internal faults, to ensure loads in undamaged zones do not experience a service interruption.
  - Sometimes applied to only Vital Loads.
  - Usually requires one longitudinal bus to survive damage.
- Limits damage propagation to the fewest number of zones.
  - Enables concentration of Damage Control / Recoverability Efforts.

Compartment Survivability Review



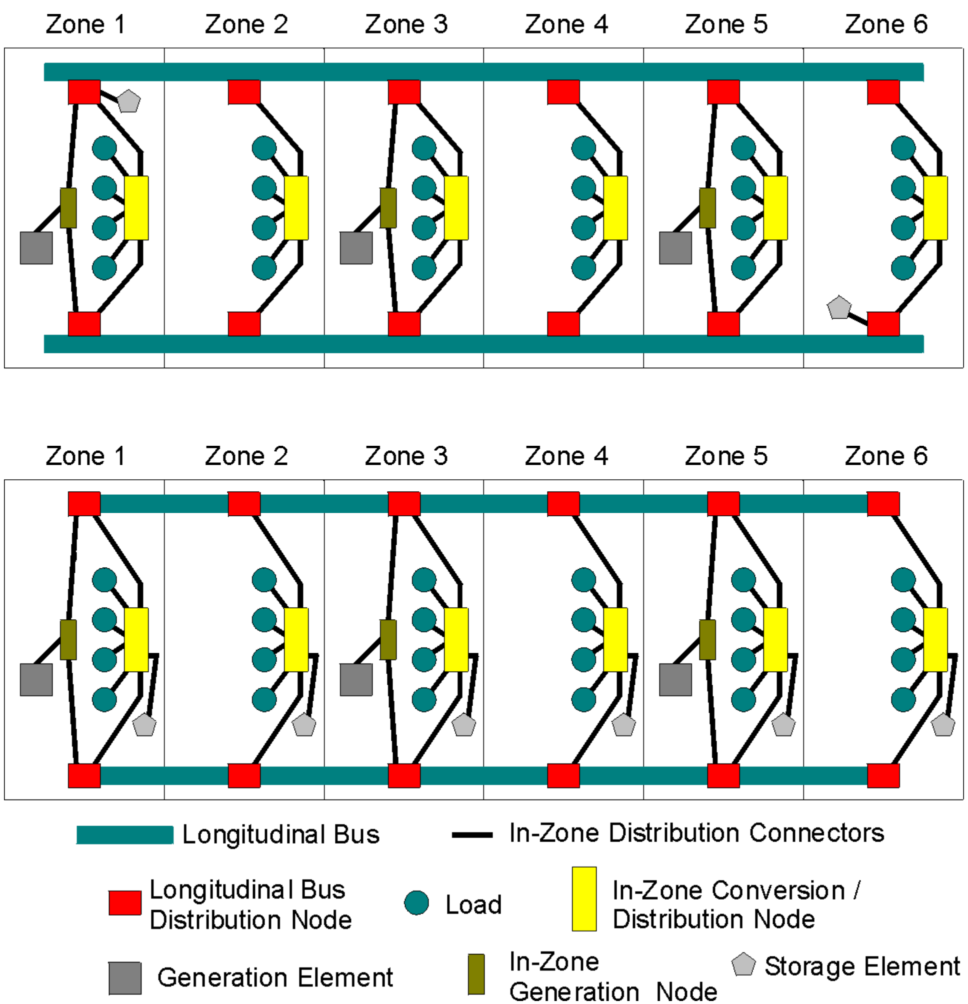
- Provide capability to recover selected undamaged loads in a damaged zone.
  - Often requires redundant feeds.
- Which Loads to Select?
  - Non-redundant Mission Systems
  - Loads supporting damage control efforts

Single Bus Architectures



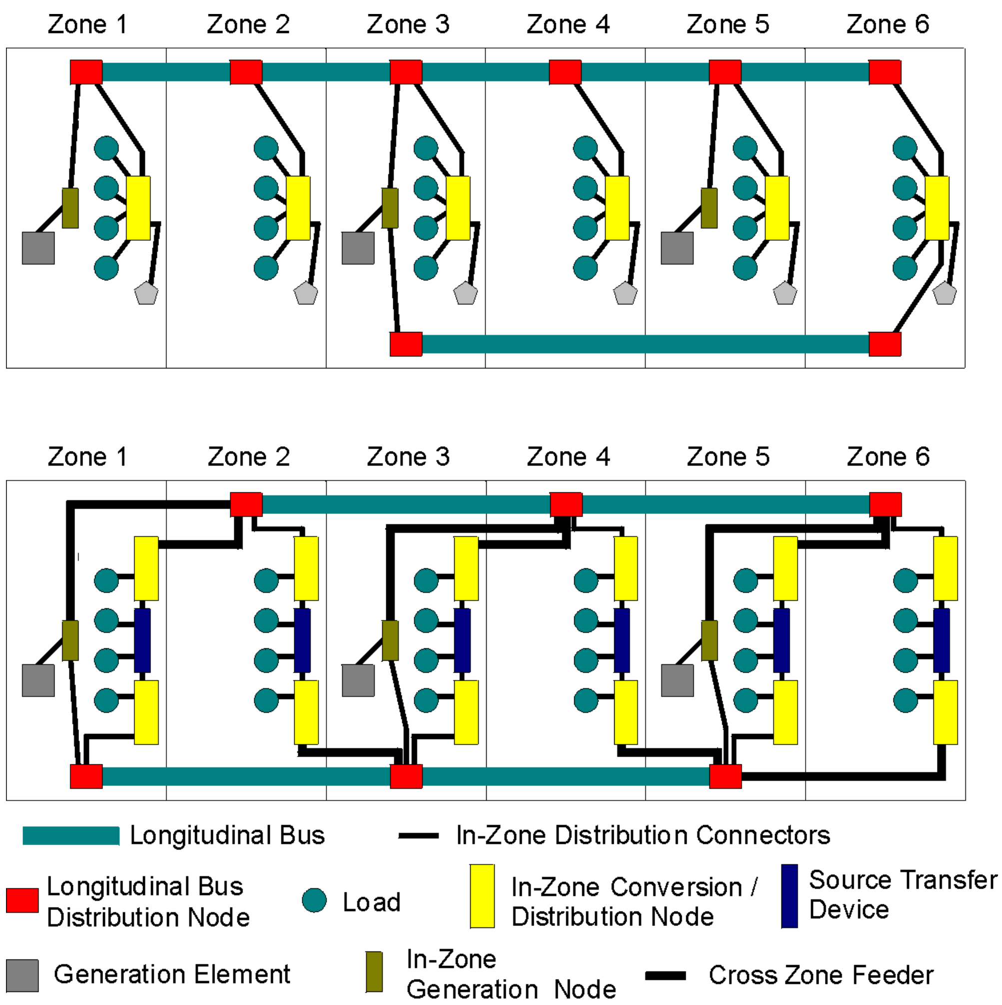
- Can achieve Zonal Survivability if Generation or Storage is in every zone.
  - Generation must be in First and Last Zones
  - In-Zone Distribution must be buffered from disturbances on longitudinal bus
- Attractive if Generation / Storage is less expensive than distribution.

Dual Bus Architectures



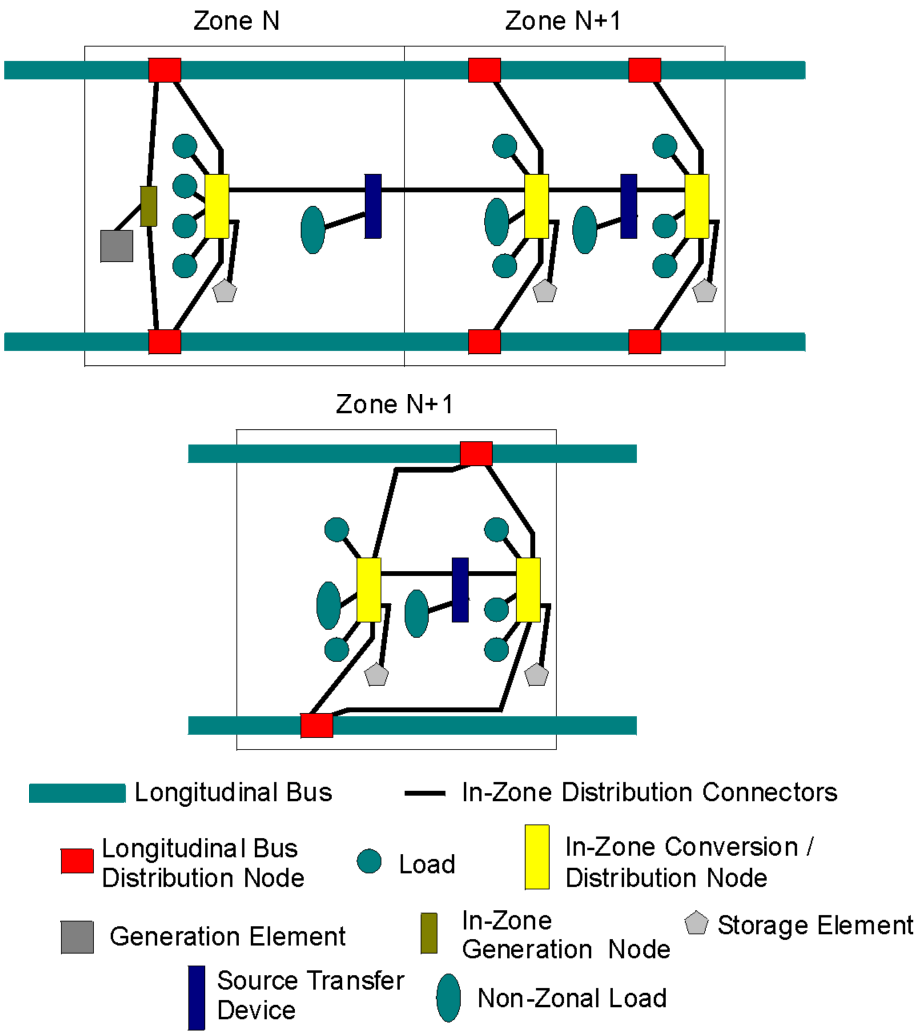
- Generation / Storage is not required in every zone.
- In-Zone Distribution must be buffered from disturbances on longitudinal bus
- Longitudinal buses must be physically protected to prevent loss of both buses from same event
- Without sufficient storage elements, generation and distribution elements must be rated to account for shifting of loads on loss of a longitudinal bus.
- Attractive if Generation / Storage is more expensive than distribution

Hybrid / Multiple Bus Architectures



- Variations to single and dual bus architectures can optimize cost for specific applications.
  - Inability to locate generation in “end zones” in single bus architecture
  - Minimize cost of longitudinal bus distribution node

Loads requiring Compartment Survivability



- Requires junction of main and alternate sources to be within damage volume of load.
- Multiple ways of providing "Compartment Survivability"
  - Most require additional equipment beyond that needed for Zonal Survivability.

Zonal Design Recap

- Zonal Ship Design must be done from a Total Ship perspective.
  - Mission Systems and Distributed Systems must be designed synergistically
- Distributed System Design must account for both Survivability and Quality of Service.
- The choice of Distributed System Architecture depends on survivability and QOS requirements and the relative cost of different elements of the distributed system.

Complexity

Complexity is a function of …

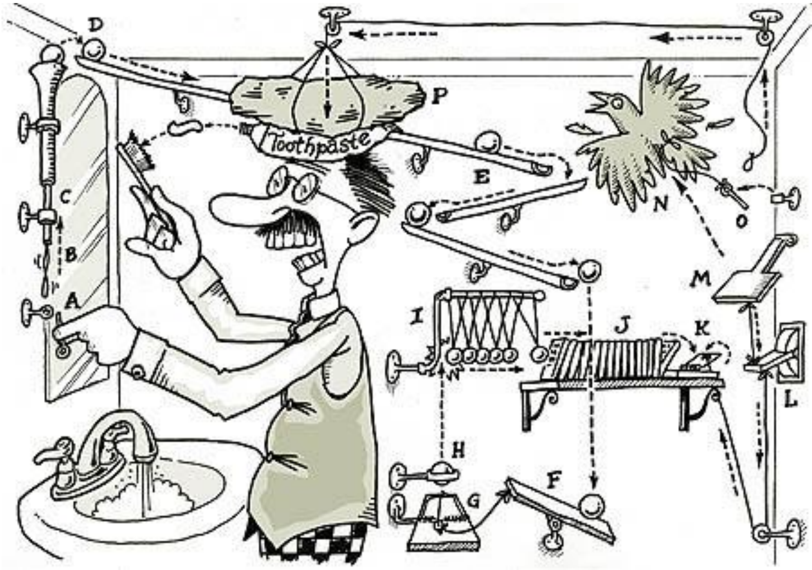
- "Number of ideas you must hold in your head simultaneously;
- Duration of each of those ideas; and
- Cross product of those two things, times the severity of the interactions between them."

Bob Colwell

Trying to Define Complexity

Complexity is a function of …
- "Number of ideas you must hold in your head simultaneously;
- Duration of each of those ideas; and
- Cross product of those two things, times the severity of the interactions between them."

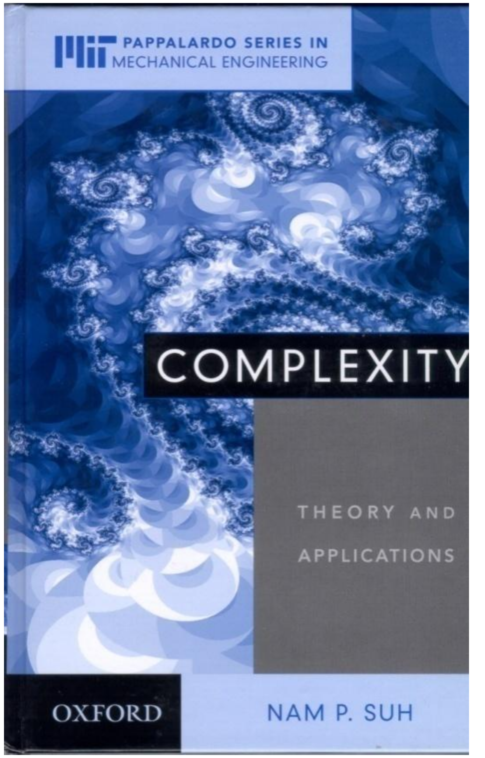
Bob Colwell



Rube Goldberg

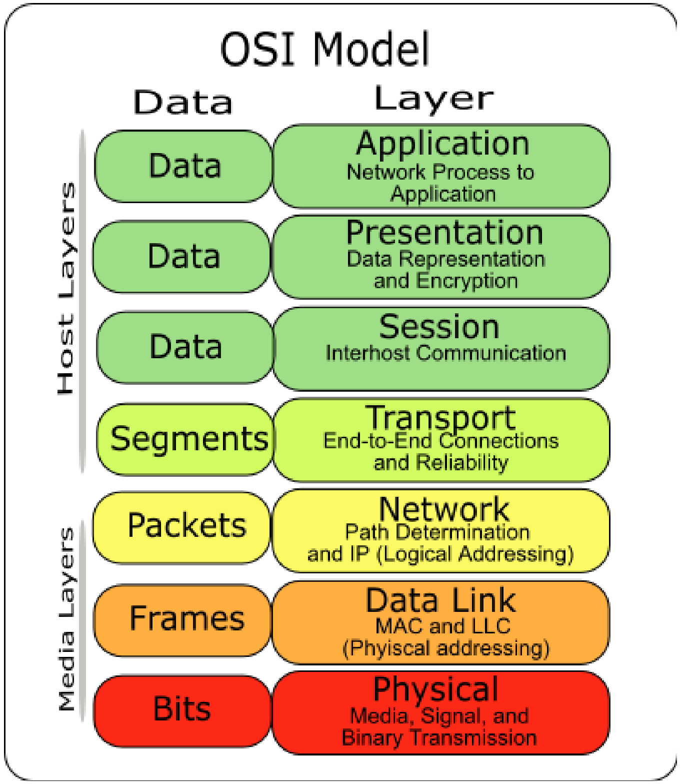
Types of Complexity

- Real Complexity
  - Measure of the uncertainty involved in achieving a task
  - Reduced by reducing variance of the individual tasks and the coupling of individual tasks
  - Lean Six Sigma
- Imaginary Complexity
  - Due to lack of understanding about the system design, system architecture, and/or system behavior (learning curve)
  - Reduced by documenting activities, training, & experience
  - ISO 9000, DODAF, DSM, etc., l
- Combinatorial Complexity
  - The accuracy or properties of the system change with time – either due to internal (wear) or external (threat evolves) reasons such that the system can no longer reliably achieve its objectives. (Diverging ship design)
  - Reduced by converting to Periodic Complexity and by improving robustness (including margin)
  - Maintenance, Modernization, Design Iterations, Architecture, Margin Policy
- Periodic Complexity
  - Systems with Combinatorial Complexity are "reinitialized" based on a "functional period"



Reduce Complexity through Design Methods and Systems Architecture

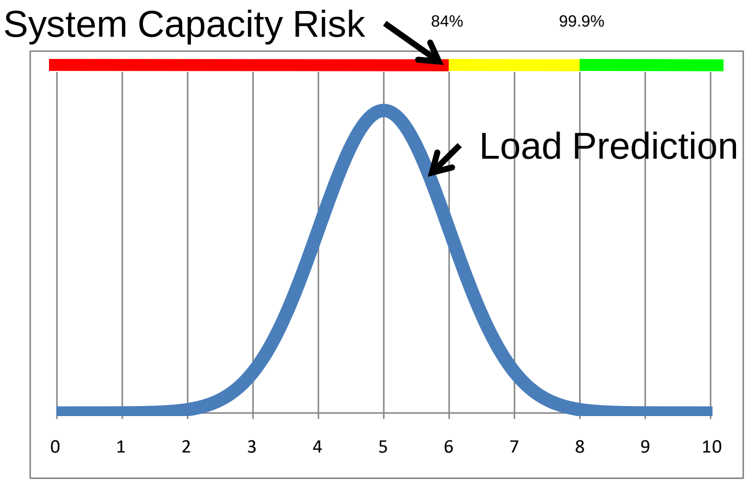
- Nam P. Suh in "Complexity Theory and Application"
  - "For a system to operate stably for a long time, functional periodicity must exist in the system or must be built into the system."
    - In Design, the periodicity is established through gates or design iterations.
  - To reduce the 'real complexity' must create an uncoupled or decoupled design
    - Uncoupled - no interaction between design activities; all design activities can be accomplished in parallel
    - Decoupled – DSM is lower triangular
- Systems architectures that enable decoupling of design activities reduce complexity.

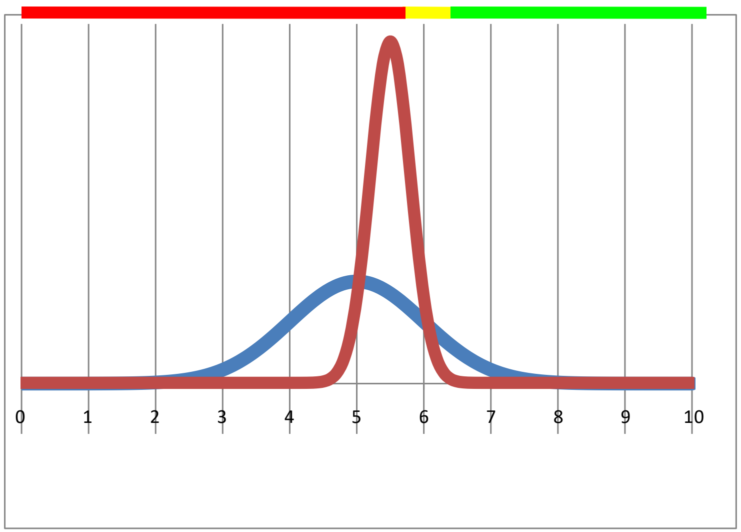


http://www.3mfuture.com/network_security/arp-guard-arp-spoofing.htm

Reduce Design Complexity with Margin Policy

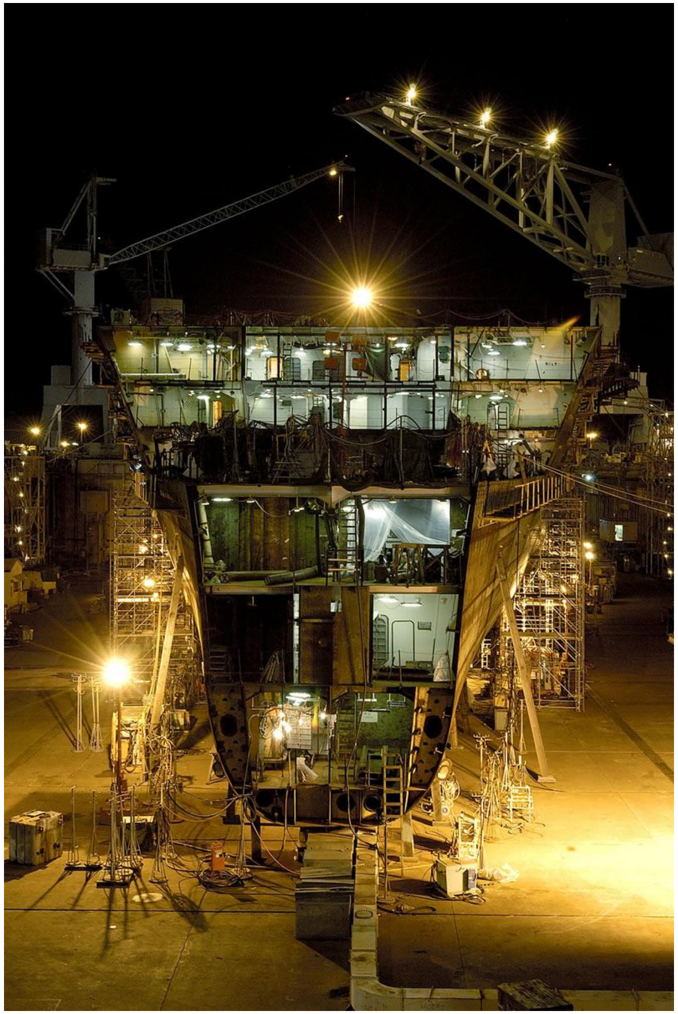
- Margin historically has been based on past performance
  - Tied to historical methods for estimating loads
- Margin accounts for variation in the load prediction.
  - One should be able to calculate the System Capacity risk based on an evaluation of the load prediction uncertainty
- The required system capacity above the mean estimate (margin) to achieve a low risk should be reduced if the prediction methods are improved.
- The number of "sigmas" that mark the boundary of yellow and green risk should be based on the relative difficulty of adding extra capacity. (i.e. risk outcome)





Reduce Production Complexity

- Limit the number of trades that need to work in the same space.
  - Segregate Functions
  - Minimize “through services” in functional spaces.
- Use production processes that enable repeatable, accurate, and testable production.
  - Control the environment
  - Use good tools
  - Train the Workforce
- Use production processes that do not impact adjacent spaces
  - Avoid Hotwork if possible
- Limit components that cross construction boundaries
- Strategically use Modularity
  - Decouple system design/production from ship design/production
  - Enable efficient production and testing



Cost

Strategies to Reduce Acquisition Cost

- Reduce the amount of stuff needed to get the job done.
- Reduce the cost of stuff needed to get the job done.
- Reduce the amount of labor needed to design the stuff
- Reduce the amount of labor needed to install the stuff.
- Reduce the amount of labor needed to test the stuff.
- Reduce Complexity

US Navy Photo by Richard Chaffee (111019-N-ZZ999-001)

Strategies to Reduce Operating and Support Costs

- Improve prime mover efficiency
- Improve propulsor efficiency
- Improve load efficiency
- Reduce hull drag
- Reduce manning
- Reduce maintenance requirements

U.S. Navy photo by Mass Communication Specialist 2nd Class Huey D. Younger Jr. (160222-N-MD297-180)

Naval Power (and Energy) System Design Objectives Recap

- Power Reliability
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ELECTRICAL SYSTEMS DESIGN CRITERIA AND PRACTICES (SURFACE SHIPS) FOR PRELIMINARY AND CONTRACT DESIGN

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