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Zonal Ship Design

ABSTRACT

Modern ships typically have a number of distributed systems. Distributed systems are used because it's simpler, cheaper, and better to centrally produce a commodity such as electricity or chill water, than to locally produce it with the users of the commodity. For naval warships, in addition to cost, two measures of performance are very important: Survivability and Quality of Service. Survivability relates to the ability of the distributed system, even when potentially damaged by a threat, to support the ship's ability to continue fulfilling its missions to the degree planned for the particular threat. Quality of Service measures the ability of the distributed systems to support the normal, undamaged operation of its loads. This paper defines a number of key terms, details a number of different zonal architectures, describes the situations where the architectures are best suited and proposes a framework for zonal ship design that promises to satisfy survivability performance requirements and quality of service requirements.

INTRODUCTION

The advantages of zonal systems design have long been recognized and documented (Petry and Rumburg 1993)(Shiffler 1993). Since then, zonal a.c. electrical distribution systems have been used in the DDG 51 class, LPD 17 class, and LHD 8. The next advance in zonal electrical distribution, Integrated Fight Through Power (IFTP) featuring d.c. zonal electrical distribution is being developed for the Navy and is a candidate for future installation on DD(X) and CG(X). (Ciezki and Ashton 1999)(Roberts 2002) (Hiller 2003) (Walsh 2003) (Zgliczynski et. al. 2004)

To date, zonal design concepts have been applied to distributed systems (usually just the electrical system) in an ad hoc fashion. A systematic study of zonal architectures has not been published. Likewise, the impact of zonal system design on total ship design has not been adequately addressed. This paper defines a number of key terms, details a number of different zonal architectures, describes the situations where the architectures are best suited and proposes a framework for zonal ship design that promises to satisfy survivability performance requirements and quality of service requirements.

The views expressed in this paper are those of the author and are not necessarily official policy of the U.S. Navy or any other organization. The intent of this paper is to foster dialogue to gain a better understanding of zonal system design and zonal ship design.

BACKGROUND

Modern ships typically have a number of distributed systems. Distributed systems are used because it's simpler, cheaper, and better to centrally produce a commodity such as electricity or chill water, than to locally produce it with the users of the commodity. For naval warships, two measures of performance are very important: Survivability and Quality of Service.

Survivability relates to the ability of the distributed system, even when potentially damaged by a threat, to support the ship's ability to continue fulfilling its missions to the degree planned for the particular threat. The threats for which a ship is designed to are its Design Threats, and the residual capability following exposure to the Design Threats is the Design Threat Outcome.

While survivability measures the ability of the ship to continue to function during damage, Quality of Service measures the ability of the distributed systems to support the normal, undamaged operation of its loads. Quality of Service is measured in terms of a Mean Time Between Failure (MTBF) where a failure is defined as any interruption in the supply or deviations outside of normal bounds of commodity characteristics that prevent the load from performing its assigned function.

Although survivability and quality of service are usually not the source of design conflicts, design

features may impact one more than the other. For example, the routing of cables in an electrical distribution plant will have little impact on Quality of Service, but will have a tremendous impact on Survivability. On the other hand, the reliability of generator sets has a bigger impact on Quality of Service than on Survivability.

In the design of distributed systems, cost is always a major consideration. Because the relative costs and capabilities of different distributive system components differ from system to system, a universal zonal design that applies to all cases does not exist. In selecting an architecture, the following strategies for reducing acquisition costs (while still meeting performance requirements) should be considered:

a. Eliminate hardware and software

b. Substitute expensive hardware and software with cheaper hardware and software. This includes increasing cost and capability of device A to enable the reduction in cost and capability of device B as long as there is a net savings.

c. Enable the hardware to be installed more easily

d. Enable the hardware to be tested before installation onboard ship

e. Reduce the engineering effort needed to design the ship

Because this paper does not address specific distributed systems, these cost reduction strategies will be addressed only in general terms.

DEFINITIONS

Zone

A zone is a geographic region of ship. In a general sense, the boundaries of the zone can be arbitrary, but to maximize survivability, the zones of multiple distributed systems as well as damage control zones should be aligned. For shipboard distributed systems, this typically means the zone boundaries are the exterior skin of the ship and selected transverse watertight bulkheads. The zone boundaries may rise above the watertight bulkheads into the superstructure, or the superstructure may be composed of one or more zones independent of the zones within the hull.

Adjacent Zones

Adjacent Zones are zones that could simultaneously be damaged by a design threat. Zones are typically sized so that usually only 2 zones are simultaneously damaged by a design threat, although in some cases a third zone (such as the superstructure) may also be damaged.

Zonal Survivability

For a distributed system, 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 a service interruption. Zonal Survivability assures damage does not propagate outside the adjacent zones in which damage is experienced. For many distributed system designs, zonal survivability requires that at least one longitudinal bus remains serviceable, even through damaged zones.

At the ship level, zonal survivability facilitates the ship, when experiencing internal faults in adjacent zones due to design threats, to maintain or restore the ships primary missions as required by the Design Threat Outcome. Ship level zonal survivability focuses restoration efforts on the damaged zones, simplifying the efforts required of the ship's crew to maintain situational awareness and take appropriate restorative actions. Ship level zonal survivability requires sufficient damage control features to prevent the spreading of damage via fire or flooding to zones that were not initially damaged.

Compartment Survivability

Zonal Survivability only addresses loads outside of the damaged adjacent zones. For some important loads, including those implementing mission systems, providing redundant capability across multiple non-adjacent zones may prove to be infeasible. This situation often arises in the superstructure where the sensor masts are located in the same or adjacent zones. In some cases, these loads may be perfectly functional

although damage has reached into its zone. Likewise, maximizing the probability of maintaining loads that support damage control efforts within the damaged adjacent zones also assists in preventing the spread of damage to zones not initially impacted. Examples of such loads include emergency lighting and power receptacles for portable dewatering pumps. In these cases, providing Compartment Survivability for the distributed systems for the specific loads is warranted.

Compartment Survivability requires that every distributed system required by a specific load provide independent normal and alternate sources of its commodity (power, cooling water, etc.). For the specific design threat, one of the sources of the commodity should be expected to survive if the specific load is expected to survive. The point at which the in zone distribution of the commodity merge (such as with an Automatic Bus Transfer – ABT) from the normal and alternate sources should be within ½ of the expected damage radius of damage centered at the specific load.

Mission System

A mission system consists of the hardware and software dedicated to the performance of a Primary or Secondary mission of the ship. Examples of mission systems include aircraft launch and recovery equipment (ALRE), propulsion systems, combat systems, and C4ISR systems. Ideally, the mission systems of a ship should be designed such that the capability to perform the ship's missions is not lost if mission system equipment in adjacent zones are not operational. Unfortunately, ship design constraints will often preclude the level of redundancy required to ensure continuous capability. If mission capability can not be assured continuously, then the ability to restore capability to achieve the Desired Threat Outcome must be provided.

Distributed System

A distributed system moves a commodity from one or more sources to multiple loads distributed through-out the ship. Examples of commodities include electrical power, cooling water, firefighting water, and fuel. For a given commodity, distributed systems can generally be described by an architecture consisting of the following functional elements:

GENERATION

A generation element produces the commodity. Examples include Gas Turbine Generator Sets, firepumps, and chill water plants. Generation elements for one distributed system are generally loads for other distributed systems.

DISTRIBUTION

A distribution element transports the commodity between other functional elements. For zonal distribution systems, the longitudinal buses are instances of distribution functional elements.

CONVERSION

A conversion element converts the commodity from one form to another. An example of a conversion element is a transformer in an electrical system. A transformer changes the voltage level of it commodity, electrical power.

LOAD

A load is a consumer of the commodity. A load for one distributed system can be a generation element for another distributed system. For example, a chill water plant is a load to the electrical distribution system and a generation element for the chill water distribution system.

STORAGE

A storage element stores the commodity for later use. In some systems, such as fuel systems, storage elements (fuel tanks) functionally replace generation elements. In other systems, such as electrical systems, storage elements (Uninterruptible Power Supplies) serve as buffers to prevent power disturbances from propagating to loads.

CONTROL

A control element coordinates the other elements of a distributed system to enhance quality of service and to facilitate the restoration of service following a casualty. For new designs, the Control Element typically consists of software that resides within the total ship computing environment.

For an example of this architecture as applied to an Integrated Power System, see Doerry and Davis (1994) and Doerry et. al. (1996).

Design Threat

A design threat is a threat to the ship where a Design Threat Outcome has been defined. Examples of Design Threats could be specific cruise missiles, torpedoes, guns, explosives, weapons of mass destruction as well as accidents such as main space fires, helicopter crashes, collisions, and groundings.

Design Threat Outcome

The design threat outcome is the acceptable performance of the ship in terms of the aggregate of susceptibility, vulnerability, and recoverability when exposed to a design threat. Possible Design Threat Outcomes include:

a.   Ship will likely be lost with the loss of over 25% of embarked personnel.

b.   Ship will likely be lost with the loss of 25% or under of embarked personnel.

c.   Ship will likely remain afloat and not be capable of performing one or more primary mission areas for a period of time exceeding one day.

d.   Ship will likely remain afloat and be capable of performing all of its primary mission areas following restoration efforts not exceeding one day using only that external assistance that is likely available within the projected operating environment.

e.   Ship will likely remain afloat and be capable of performing all of its primary mission areas following restoration efforts not exceeding two hours using only organic assets.

f.   Ship will likely remain afloat and would be capable of performing all of its primary mission areas following restoration efforts (if needed) not exceeding 2 minutes using only organic assets.

g.   Ship will likely remain afloat and would likely be capable of performing all of its primary mission areas without interruption.

h.   The threat weapon is not considered a significant threat because the probability that the threat weapon would have been defeated before striking the ship is greater than 98%.

Note: The term "likely" should be assigned a specific probability of occurrence. A reasonable choice would be to specify that "likely" refers to a probability of occurrence greater than 86%.

The levels of survivability for the design threats can be evaluated using Total Ship Survivability Assessment (TSSA) methods. Yarbrough and Kupferer (2002) provided an example of the TSSA process as applied to a naval ship (JCC(X)) during the concept / feasibility stage of design.

Over-Matching Threat

An over-matching threat is a design threat where the design threat outcome includes likely loss of the ship.

Quality of Service

Quality of Service is a metric of how reliable a distributed system provides its commodity to the standards required by the users. It is calculated as a Mean-Time-Between-Failure (MTBF) as viewed from the loads. A failure is defined as any interruption in service, or commodity parameters outside of normal parameters, that results in the load equipment not being capable of performing its function. The time is usually measured over an operating cycle or Design Reference Mission. Quality of Service is a reliability metric, as such the calculation of QOS metrics does not take into account survivability events such as battle damage, collisions, fires, or flooding. Quality of Service does take into account equipment failures and normal system operation transients. A typical cause of normal system operation causing a QOS failure is the shifting of sources for the commodity such as shifting to/from shore power (without first paralleling) or manually changing the source of power using a manual bus transfer (MBT). Also note that not all interruptions in service will cause a QOS failure. Some loads, such as refrigerators and chill boxes, will keep their contents cold even if power is interrupted for several minutes. In this case, a QOS failure will

not occur as long as power is restored in time to prevent significant heating of the contents. Note that the optimal configuration of a distributed system may be different for QOS considerations and for survivability considerations. In the electric plant for example, the most important QOS consideration is the ability to preserve power to loads when a generation element trips off line while damage to the distribution system and the ability to preserve power to vital mission systems loads is of major interest in the survivability analysis. For QOS reasons, many ships operate with their electric plant paralleled in peacetime steaming and only shift to the more survivable split plant configuration under threat conditions.

Longitudinal Bus

Longitudinal buses are means to transport a distribution system commodity across zone boundaries.

The design of a zonal system can be greatly simplified if one can protect the longitudinal buses sufficiently such that the expected damage in a zone will not result in the failure of all the longitudinal buses crossing the zone. Typically, for a dual bus system, locating the two buses as far apart transversely and with several deck separations vertically will provide adequate protection. Ultimately, Total Ship Survivability Assessments should be used to ensure zonal survivability has been achieved.

ZONAL SYSTEM DESIGN

Zone Size

The size of a zone is a compromise between increased survivability and cost. In general, damage from threats that are not over-matching should be limited to one or two adjacent zones. However, zones should not be so large that a significant amount of mission system equipment will remain undamaged but inoperative due to a lack of required services from damaged distributed systems. For most combatants, about 6 or 7 zones is a good starting point, resulting in each zone being roughly 15% of the length of the ship. The actual zone boundaries should be aligned with watertight bulkheads whose positions are established based on damage

stability criteria. A zone can however, span multiple watertight subdivisions.

Single Bus Architectures

A single bus architecture is generally advantageous if storage is not cost effective and the relative cost of the generation elements is less than the cost of the distribution elements. This single bus architecture (Figure 1) normally has sufficient generation capacity in each zone to satisfy its own requirements. The longitudinal bus is capable of being segmented between zones. To configure the system for maximum Quality of Service, the bus is not isolated, but only enough generation capacity is provided to service the existing loads plus, if desired, an online reserve capacity to account for fluctuations in load and the possibility of an online generation element dropping offline. When a threat is identified, or damage is detected, the control system automatically isolates every zone and starts all generation elements. If the generation element in one zone is not operative, or not capable of servicing its zonal loads, cross-connecting with adjacent undamaged zones is possible. In this manner, continuity of service, or at least restoration of service, to undamaged zones will be provided. Shiffler (1993) describes the implementation of a single bus architecture for the firemain of a combatant.

If zonal storage is provided in every zone to provide continuity of service while the longitudinal bus isolates damaged segments and available generation elements come on line, then the requirement to have generation elements in each zone can be relaxed (Figure 2). To achieve zonal survivability in a single bus architecture, generation elements must be in the forward-most and aft-most zones. If locating a generation element in either the forward-most or aft-most zone is not feasible, consideration should be made for using a hybrid architecture discussed below.
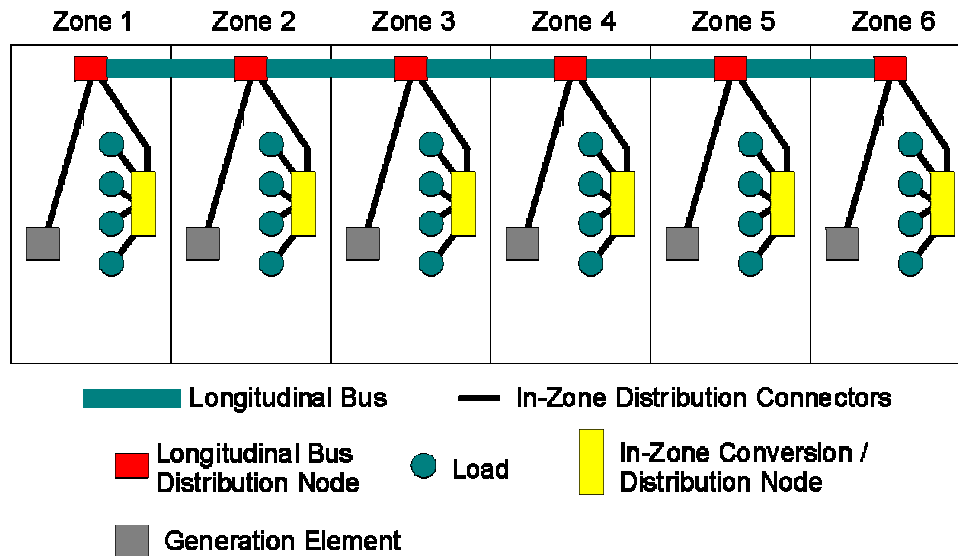
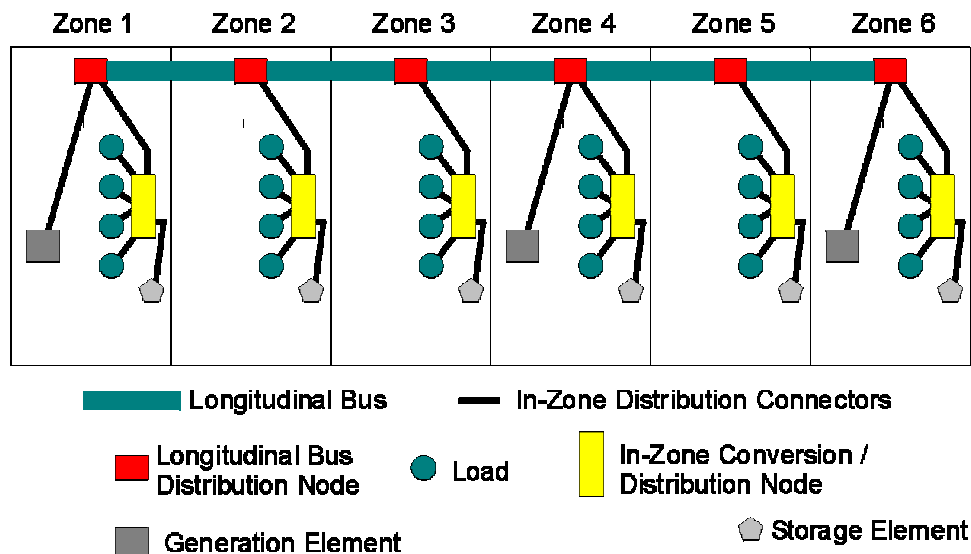**FIGURE 1: Single Bus Architecture with zonal generation**

FIGURE 2: Single Bus Architecture with zonal storage

Dual Bus Architectures

If the cost of generation elements is high relative to the cost of conversion and distribution elements, then a dual bus architecture should be considered. Figure 3 shows a typical dual bus architecture. Typically, generation elements are only provided in some of the zones. Service for the other zones is provided solely by the distribution system. For survivability considerations, the longitudinal buses must be widely separated and protected from damage to minimize the possibility that both buses will be out of service at the same time. The longitudinal bus distribution node where the longitudinal bus distributes the commodity to the in-zone distribution system must additionally have provisions to prevent damage from the in-zone distribution system to negatively impact the operation of the longitudinal bus. In the example shown, if one longitudinal bus is damaged, the In-Zone Conversion / Distribution Node automatically shifts the source for all the loads to the other longitudinal bus. Typically, at least three generation elements are provided to

allow one element to be taken out of service for either damage (Survivability) or maintenance (Quality of Service) while the other two service the two longitudinal buses. For survivability, generation elements should be separated to ensure that remaining capacity after loss of the worst case adjacent zones is sufficient to service the remaining loads. If a generation element can not be brought online in time to prevent a QOS failure, the generation elements serving each longitudinal bus must have the capacity to service all of the loads. If this is not the case, when one of the longitudinal buses goes out of service, loads must be shed quickly enough to ensure the remaining generation elements do not trip offline from overloading caused by all the loads drawing the commodity from the other longitudinal bus.

In unattractive feature of Figure 3 is that if load shedding is not desired, the total capacity of the generation elements must be 3 times the total load. This can be very expensive. To improve the architecture, storage elements can be added to provide the commodity for the short time needed to bring the third generation element on line. There are two logical areas to insert storage into the architecture: At the Longitudinal Bus Level (Figure 4), and on a Zonal level (Figure 5). At the Longitudinal Bus Level, each storage element and each generation element must have the capacity of one half the total load (usually margined). The storage element must be capable of providing its commodity at its capacity rate for the time it takes for the remaining generation element to come on line. Depending on the capability of the in-zone conversion / distribution node, the capacity of the zonal storage unit need only be 50% to 100% of the capacity of the zonal loads. Hence the total capacity of the zonal storage elements could be 50% to 100% of the total capacity of the longitudinal bus level storage. Which storage method to use should depend on cost or other naval architectural concerns.
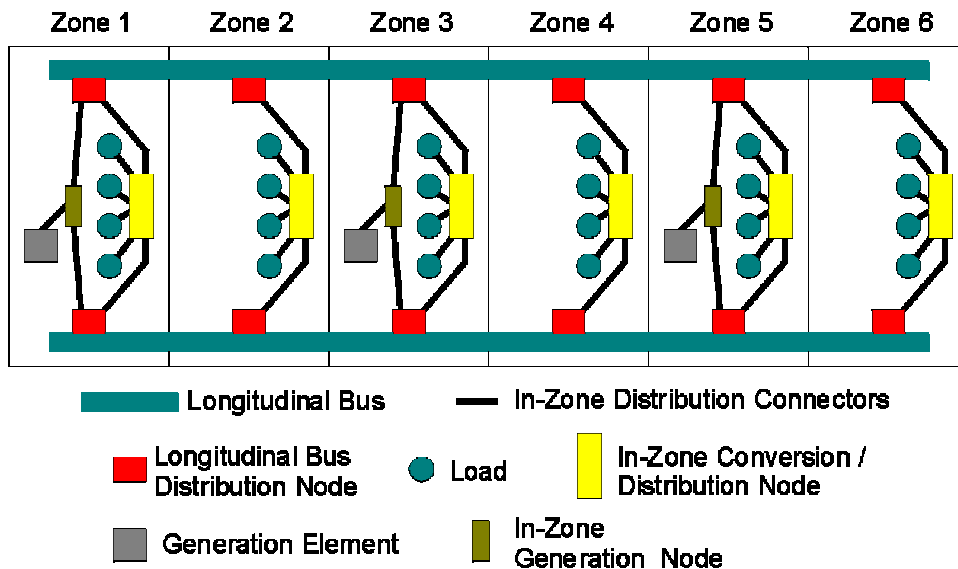

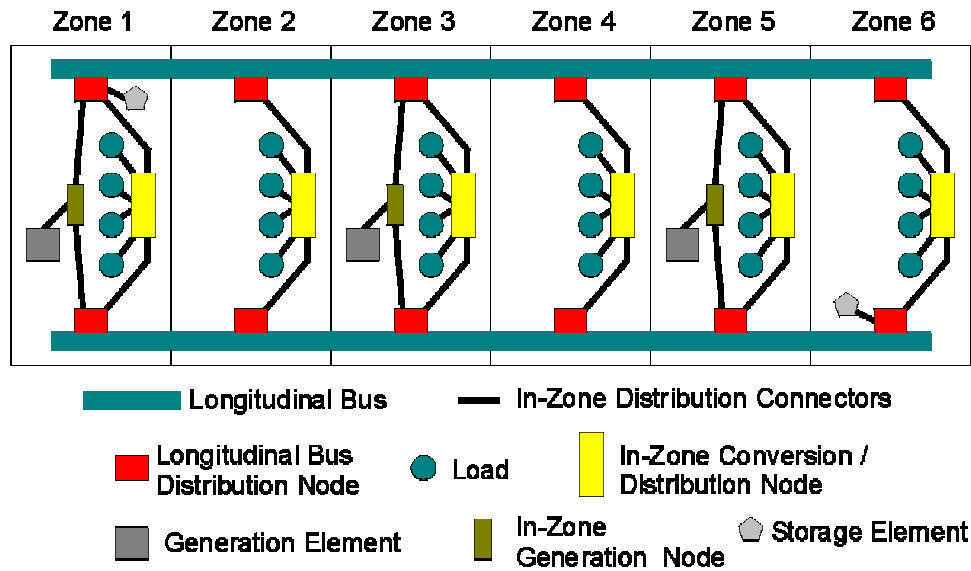**FIGURE 3: Dual Bus Zonal Distribution System**

FIGURE 4: Dual Bus Zonal Distribution System with Longitudinal Bus Level Storage
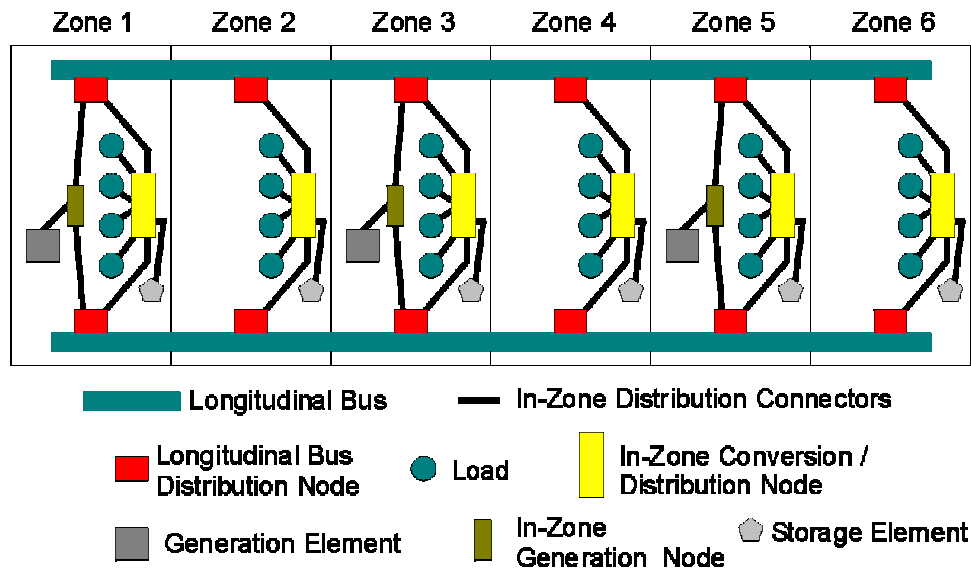

FIGURE 5: Dual Bus Zonal Distribution System with Zonal Storage

In the event that damage results in the loss of both longitudinal buses, the ability to segment the longitudinal bus to isolate damages segments can significantly improve the time to restore service to undamaged zones following severe damage. If a segmented bus is paired with zonal storage, then the requirement that one of the longitudinal buses remain undamaged in a damaged zone can be relaxed in the zones after the forward-most zone containing a generation element and forward of the aft-most zone containing a generation element. The ability to segment the longitudinal bus can be incorporated into the Longitudinal Bus Distribution Node as shown in Figure 6. This architecture matches the current architecture of the Navy's Integrated Fight Through Power (IFTP) concept. Alternately, if segmentation devices are provided independently at the zone borders as shown in Figure 7, segments can overlap and still provide zonal survivability for damage to both longitudinal buses in all zones but zone 5. Because Zone 6 does not have its own generation element, it relies on one of the

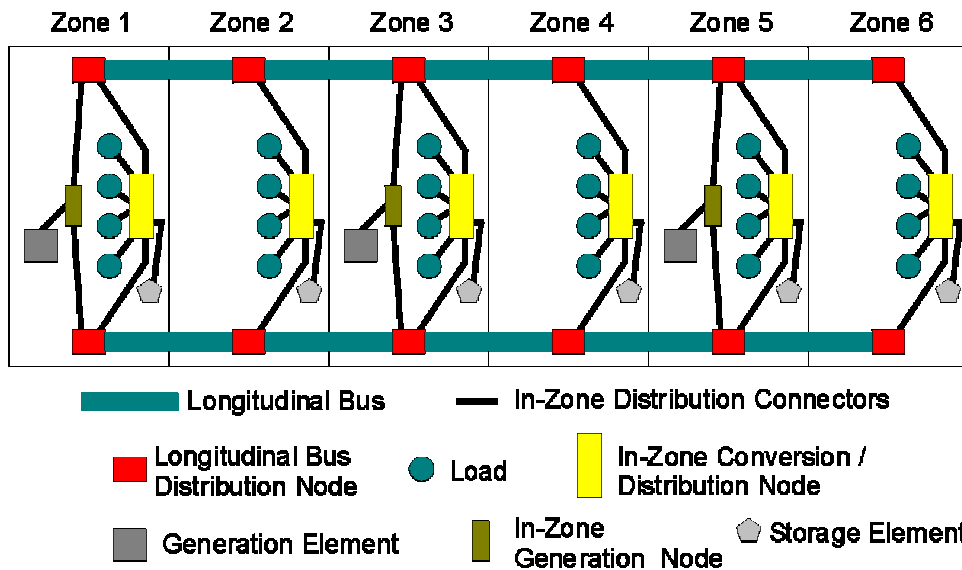two longitudinal buses remaining undamaged in zone 5.

FIGURE 6: Dual Segmented Bus Zonal Distribution System with Zonal Storage and Integral Segmentation
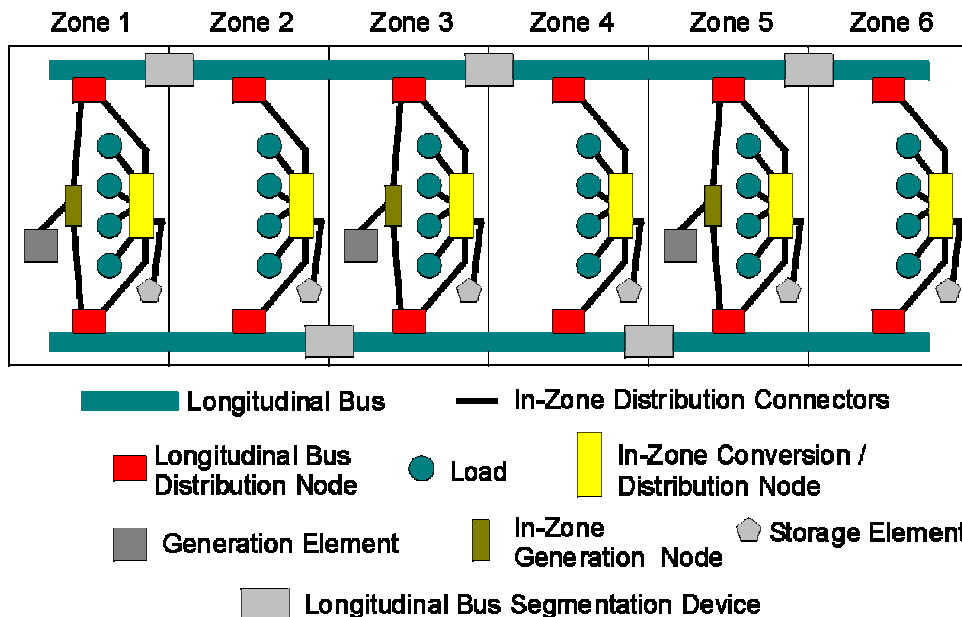

FIGURE 7: Dual Segmented Bus Zonal Distribution System with Zonal Storage and Independent Segmentation

Hybrid Bus Architectures

The single bus architecture described in Figure 2 required generation elements in the forward-most and aft-most zones. If this is the only condition that can not be met, then a hybrid bus architecture as shown in Figure 8 can work. In this case, zone 6 does not have a generation element and is therefore provided a second source via an abbreviated bus that connects up to an in-zone generation node or the longitudinal bus distribution node in a zone at least 3 zones

away. The three zones are required because the zones in between are adjacent zones and both could be damaged (If zones 3, 4, and 5 were all adjacent zones simultaneously, then the bottom bus would have to continue to zone 2).
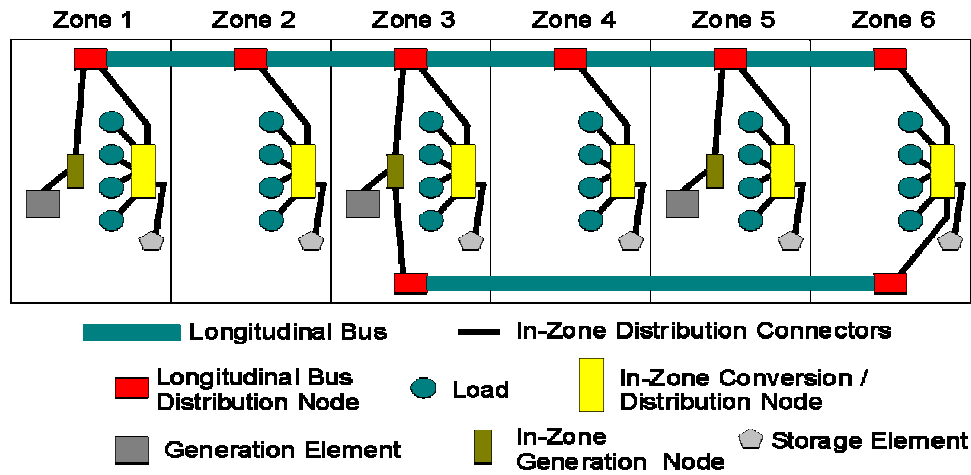

FIGURE 8: Hybrid Bus Zonal Distribution System

Multiple Bus Architectures

In AC Zonal systems with medium/high voltage longitudinal buses, the Longitudinal Bus Distribution Node consists of a medium/high voltage switchboard, a transformer, and a 450 VAC Switchboard. Because the Longitudinal Bus Distribution Node is large, heavy, and costly, the architecture is modified somewhat to minimize the number of such nodes. Figure 9 is an example of using cross zone feeders (essentially small longitudinal buses) to provide zonal survivability for vital loads. Note that non-vital loads are not connected to the Source Transfer Device and are therefore not provided zonal survivability. In some cases damage outside a zone could prevent a non-vital load from being serviced. A variation of this architecture is used in LHD 8 (Dalton et. al.).

If the cost of the Longitudinal Bus Distribution Node is very expensive, then an architecture similar to Figure 10 could be called for. In this architecture, the Longitudinal Bus connects the generation elements together. Normal and Alternate supplies of the commodity for every zone are provided via feeders from two Longitudinal Bus Distribution Nodes located fore and aft. As with the previous example, only loads connected to the Source Transfer Devices are provided zonal survivability.
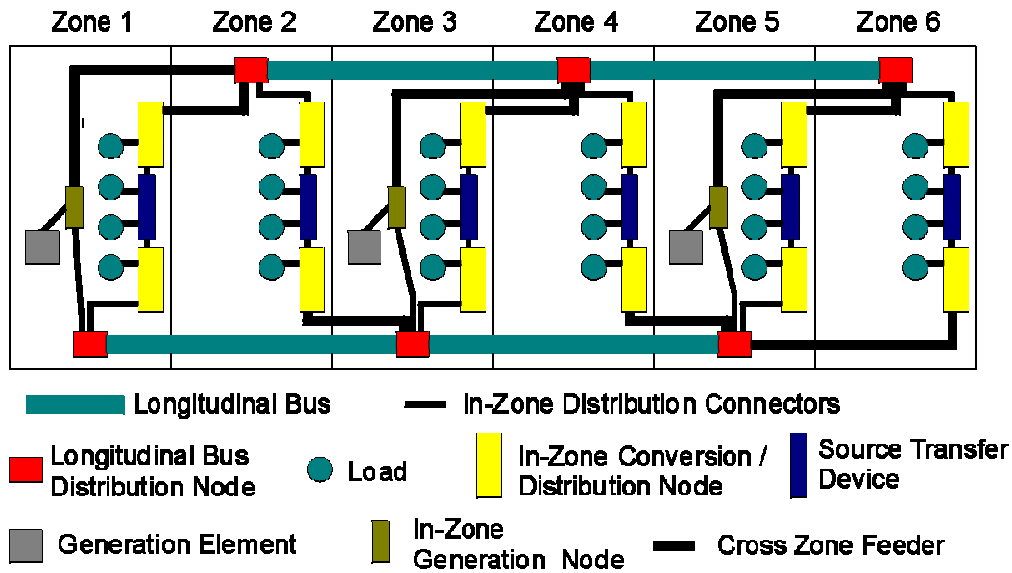
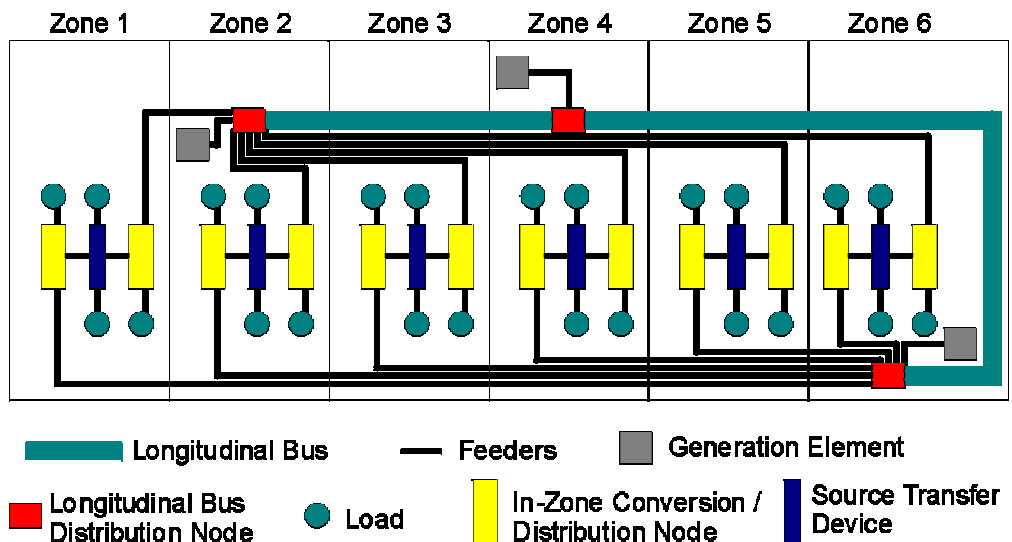**FIGURE 9: AC Zonal Electrical Distribution System example**

FIGURE 10: Multi Bus System Example

Non-zonal mission systems and in-zone emergency loads

As stated previously Zonal Survivability only addresses loads outside of the damaged adjacent zones. For some important loads, including those implementing mission systems, providing redundant capability across multiple non-adjacent zones may prove to be infeasible. In some cases, particularly if zone sizes are large, these loads may be perfectly functional although damage has reached into its zone. Likewise, maximizing the probability of maintaining loads

that support damage control efforts within the damaged adjacent zones also assists in preventing the spread of damage to zones not initially impacted. Examples of such loads include emergency lighting and power receptacles for portable dewatering pumps. In these cases, providing Compartment Survivability for the distributed systems for the specific loads is warranted.

Figure 11 shows three different strategies for providing compartment survivability within a zonal distribution system. First, in Zone N, a

Source Transfer Device (In electrical distribution systems this would be an Automatic Bus Transfer or ABT) would supply the commodity from either the in-zone conversion / distribution node or from a conversion / distribution node in an adjacent node. The drawback for this method is that a path for distribution system other than the longitudinal buses crosses zone boundaries. Use of this solution should be minimized. Zone N+1 shows two other solutions that are based on creating sub-zone Conversion / Distribution nodes. The first solution locates the sub-zone Conversion / Distribution node in the damage volume of the non-zonal load. This increases the probability that if the Conversion /

Distribution node is damaged, then the non-zonal load will also likely be damaged. The final solution provides a source transfer device between two sub-zone Conversion / Distribution nodes located in the same zone.

A variation of zone N + 1 is shown in Figure 12. In this case, Longitudinal Bus Distribution Nodes are shared between the In-Zone Conversion / Distribution Nodes. The physical routing of the In-Zone Distribution Connectors feeding the In-Zone Conversion / Distribution Nodes should ensure that if the appropriate longitudinal bus survives, the Distribution Connector also is likely to survive.
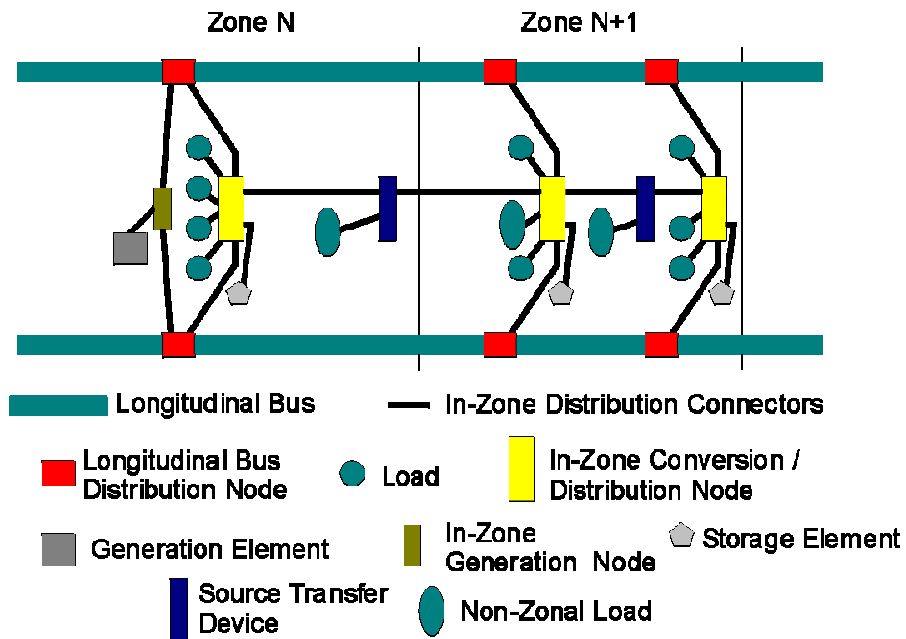

FIGURE 11: Non-Zonal Loads

Zone N+1

Legend:
- ▬ Longitudinal Bus
- ── In-Zone Distribution Connectors
- 🟥 Longitudinal Bus Distribution Node
- 🟢 Load
- 🟨 In-Zone Conversion / Distribution Node
- ⬜ Generation Element
- 🟫 In-Zone Generation Node
- ⬠ Storage Element
- █ Source Transfer Device
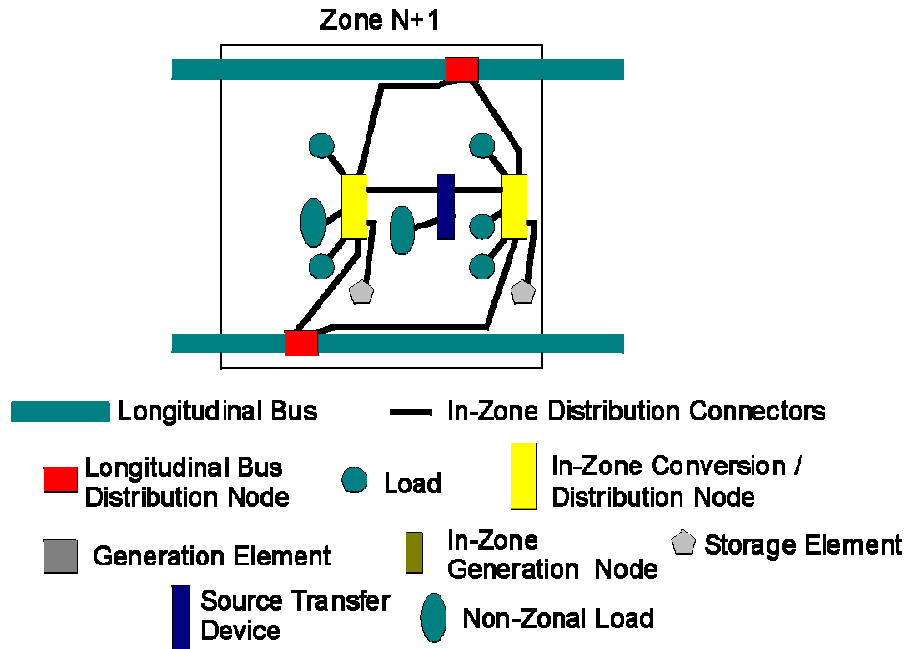- 🟢 Non-Zonal Load

FIGURE 12: Alternate method for supplying non-zonal loads.

Maintenance Considerations

The choice of architecture may also depend on maintenance issues. Quality of Service will be negatively impacted if loads must be secured because of preventative or condition based maintenance of distributive system components. For example, if the longitudinal bus distribution node requires frequent preventative or condition based maintenance, then QOS requirements will likely not be met with a single-bus architecture. A dual-bus architecture will allow one longitudinal bus distribution node to be taken out of service while another provides the functionality. Any "single point of failure" in the distribution system should be extremely reliable.

Interaction with other distributed systems

The ability of a load to perform its function is impacted greatly by its distributed system's Quality of Service and survivability. If a load requires three distributed systems to work properly, but only two of the distributed systems are reliable / survivable, then the weakness of the remaining distributive system will prevail. Ideally, in a balanced total ship design, all of the distributed systems feeding an important load should have the same Quality of Service MTBF

requirements and should have similar survivability performance against the design threats. Too often, distributed systems are developed independently with little consideration for synergy with other distributed systems. In short, total ship distributed system design should be load centric rather than system centric.

Restoration of Service considerations

The zonal survivability concept presumes that the ship is hit by only one threat weapon and that only adjacent zones are damaged. In actual combat, a ship may be hit multiple times and experience significant damage dispersed through out the ship. At this point in time, it is impractical to design a ship that can sustain multiple hits in arbitrary points in the ship and still preserve mission capability. It may not even be possible to ensure the ship stays afloat. However, if the ship remains afloat, it is possible to add features that will help the crew to restore critical systems needed for damage control and emergency propulsion.

The most beneficial features are frequent longitudinal bus distribution nodes and segmentation of the longitudinal bus(es). Architectures that have a lot of segmentation

with many longitudinal bus distribution nodes can isolate damaged sections while impacting the fewest loads. From a Restoration of Service viewpoint, the segmentation need not be automatic or rapid. In an electrical system for example, a removable piece of bus-bar may be sufficient to enable segmentation.

From a restoration of service viewpoint, long feeders should be avoided. Long feeders are more likely to be damaged, and without intermediate segmentation and distribution nodes, the undamaged sections of feeders are unusable.

Consideration should be given to providing means for bypassing damaged sections of the longitudinal bus(es) with temporary distributed systems. Provisions may be as simple as reserving the space necessary for routing the temporary distributed system, providing means for patching into the permanent distributed system, and providing a method for the temporary distributed system to penetrate watertight bulkheads. Depending on the desired response time, the materials, manning and expertise for actually installing the temporary distributed system may not even be onboard the ship. The people and materials would be flown to the ship from another location in the battle force, sea base or elsewhere.

ZONAL SHIP DESIGN

Concept / Feasibility Studies

During the early stages of ship design, concept and feasibility studies are used to determine the cost and performance impacts of different sets of user requirements. The level of detail of the ship concepts produced is a function of the questions being asked as well as how similar the concept is to an existing design. For many questions, interpolations or extrapolations of weights, volumes, and performance from existing designs is sufficient to develop the cost estimate. If the concept is significantly different from any existing platform, the ship and its systems must be better defined. If this is the case, the following activities should occur:

a. Identify zone boundaries

b. Define a notional architecture for each distributed system

c. Identify and allocate Mission Systems elements to zones

d. Create a list of equipment to implement the notional architecture and mission systems.

e. Incorporate the equipment from the notional architecture into the appropriate ship synthesis model.

One of the critical tasks that should be completed during this stage of design is the definition of the Design Threats and Design Threat Outcomes. These definitions should be based on force level analysis as well as a notional concept of operations.

Preliminary / Contract Design

During Preliminary and Contract Design, the ship design is matured to enable a budgetary level cost estimate, performance is evaluated to ensure operational requirements can be met, risks are identified and mitigated, and procurement specifications are developed. Zonal design activities that should take place include

a. Establishment of the zone boundaries.

b. Establishment of the zonal architectures for all distributed systems.

c. Identification and Allocation of Mission Systems equipment to zones.

d. Develop distributed system Concepts of Operation that describe the expected plant line-ups and contingency plans for different operational conditions.

e. Develop a list of equipment. Identify the distributed systems required to service it. Identify the distributed system Quality of Service requirements (MBTF and the definition of a Failure) for each piece of equipment.

f. Ensuring the capacities of distributed system components will meet margined load requirements.

g. Arrangement of equipment within zones. Identify routes for longitudinal buses and

major feeders. Effort should be made to locate non-zonal mission system and in-zone emergency loads near in-service distribution / conversion nodes to preclude the need to provide compartment level survivability features. Distributed Systems should be arranged concurrently to increase the probability that a load will be adequately served by all required distributed systems.

h. Perform Quality of Service analysis to ensure the distributed systems can meet Quality of Service requirements for their loads.

i. Total Ship Survivability Analysis should be performed to verify that the Design Threat Outcomes can be achieved against the Design Threats.

j. Consider adding features to enable restoration of emergency services following damage from multiple design threats.

k. Incorporate zonal design requirements into the specifications and statement of work for the detail design and construction contract.

Detail Design and Construction

During the Detail Design and Construction phase, the shipbuilder translates the specifications into production drawings, production plans, and instructions for Computer Aided Manufacturing equipment. If the shipbuilder has not fully participated in the Preliminary / Contract Design stage of design, another iteration of Preliminary Design may take place to optimize the design to be produced at the shipbuilder's facilities before the creation of CAD models and detail drawings takes place. Zonal design activities that take place during this period include:

a. Finalizing the location of all equipment and distributed system routing. The survivability of the zonal system is greatly impacted by how well survivability concerns are addressed during the arrangement of the ship.

b. Evaluating the survivability of the longitudinal buses and applying selective protection where needed. Examples of protection include armor, insulation, and water mist coverage.

c. Evaluating the need for specific equipment to be provided compartment level survivability and providing the necessary provisions within the impacted distribution systems.

d. Verifying the QOS and survivability requirements will be met.

e. Ensuring the capacities of distributed system components will meet margined load requirements.

f. Ensuring Procurement Requests for equipment contain the necessary allocated requirements to meet QOS and survivability requirements.

FUTURE WORK

A number of tasks still need to be accomplished to institutionalize zonal ship design. Among these tasks are:

a. For future ship designs, having the customer (OPNAV) express survivability requirements in terms of Design Threats and Design Threat Outcomes.

b. Developing inexpensive methods to model the impact of survivability and Quality of Service on distributed systems during early stage design.

c. Developing repeatable processes for predicting Design Threat Outcomes during Preliminary / Contract Design as well as Detail Design and Construction.

d. Developing repeatable processes for specifying and predicting Quality of Service metrics for distributed systems.

e. Develop repeatable processes for verifying prior to ship acceptance, that the ship will meet Quality of Service and Survivability requirements.

CONCLUSIONS

From the arguments presented in this paper, it is clear that a "one size fits all" zonal architecture does not exist. The choice of architecture for a given distributed system depends on the Design

Threats, Design Threat Outcomes, Quality of Service requirements, capability of distributed system components, and the relative cost of different distributed system components.

To ensure a successful implementation of zonal distributive systems, the zonal design activities should take place during all stages of design starting with feasibility / concept studies and ending with detail design and construction. A good understanding of zonal architectures and how to implement them in ship designs can contribute greatly to the success of a ship design.

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