Analyzing the Effects of Component Reliability on Naval Integrated Power System Quality of Service

by

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Abstract

The Integrated Power System (IPS) is a key enabling technology for future naval vessels and their advanced weapon systems. While conventional warship designs utilize separate power systems for propulsion and shipboard electrical service, the IPS combines these functions. This allows greater optimization of engineering plant design and operations and leads to significant potential lifecycle cost savings through reduced fuel consumption and maintenance. Traditionally the focus of power system design has been survivability, with the assumption that service continuity was inherently provided. A new probabilistic metric, Quality of Service (QOS), now allows the power continuity and quality delivered to loads to be addressed explicitly during the design of IPS vessels. This metric is based both on the reliability of the power system components and the system architecture employed.

This thesis describes and implements a method for modeling and evaluating the effects of component reliability on the QOS performance delivered by a current generation IPS architecture. First a representative "ship" is created, based largely on the U.S. Navy's *ZUMWALT* class destroyer (DDG-1000), including electrical loads, an operating profile, and Integrated Fight Through Power system architecture. This simulated ship is then run through a reliability analysis model employing Monte Carlo Simulation techniques to evaluate the QOS performance of the power system. By treating the reliability of power system components as a variable, the model gives insight into the role component reliability plays within the given system architecture. A method is then proposed for extending this analysis to comparative studies between future IPS architectures or components, with the ultimate goal of allowing research and development efforts to better focus precious funding and resources on areas with the greatest potential for high-value improvement.

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Biographical Note

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Chapter 1 - Introduction

Motivation

For much of the history of the modern warship, the archetypal design has consisted of a set of engines dedicated exclusively to propulsion and an additional set of engines dedicated to function as generators to supply electrical power to the vessel. This approach made sense initially, when electric loads required only a tiny fraction of the power necessary to propel the ship. The increasing role of electronics, computers, and power-intensive weapon systems has led to a steadily growing demand for electrical power on warships, to the extent that a new model has emerged and is rapidly gaining acceptance. The integrated power system (IPS) takes the two ultimate destinations for power generated on a vessel and allows power from all the vessel's engines to be used for either purpose. The basic principles of this concept are now well understood, but constant advances in the technology utilized by IPS systems (as well as traditional shipboard electrical systems) present new challenges for designers. Additional complications arise from the increasingly finicky nature of the sophisticated computer systems that make up more and more of the electric loads. These systems require high quality power, and have little or no ability to tolerate interruptions in this power. Survivability has been the driving factor in nearly all previous electrical system designs, but can no longer be the sole focus for designers of future warships. While survivability obviously remains crucial for any future system, increasing importance must be placed on what can be called electrical system quality of service (QOS). The motivation for this study is to examine several of the factors which influence this quality of service in IPS ship designs and assess their roles and relative importance in order to aid designers in focusing future design efforts and research initiatives on the areas in which they can be most effective.

Background and Prior Work

Traditionally, the primary focus of naval electrical system design has been on survivability during battle or other damage scenarios. The continuity and quality of the power delivered during normal operations was seldom considered explicitly. Instead designers relied on basic rules of thumb and simplistic redundancy rules to ensure the day-to-day power system operating characteristics would be acceptable. For a long time, this approach was perfectly acceptable, as electrical systems were only a small portion of the overall ship, were limited in scope to command and control or combat systems roles, and were generally designed from the ground up for their specific platform and function. Over the past few decades, however, the role and nature of shipboard electronics have undergone drastic changes. Warships have come to rely increasingly on computers and other electronics in nearly all ship systems. Additionally, to reduce development and procurement costs, more and more systems are being adapted for naval use from non-military designs - commonly referred to as commercial-off-the-shelf (COTS) systems. These new systems are considerably less rugged and much more demanding in terms of the quantity and quality of power they require. At the same time their near ubiquity means that for a new ship to function effectively, its power system must be designed to meet the increased demands of its electrical loads, not vice versa. The situation is further complicated when considered within the framework of an integrated power system. The propulsion motors demand large quantities of electrical power in an inconsistent and highly unpredictable manner, and can also create significant harmonic distortions and other impacts to power quality if not properly addressed in the system design. Clearly the traditional way of doing business is no longer adequate.

While the ultimate purpose is not new, the idea of service quality as a design variable was not broached until 2005, when CAPT Norbert Doerry and Mr David Clayton, both of the Naval Sea Systems Command addressed “the practical design issues associated with providing continuity of service under other than combat damage conditions and [proposed] a Quality of

Service (QOS) metric to aid in the design, design certification and operation of shipboard power systems" and further defined the metric as "based on the probability that the power system will provide the continuity of power that each load needs to support the ship's missions" (2005, p. 1). This paper, presented at the IEEE Electric Ship Technologies Symposium, represented a first step in addressing the issues created by the evolution of naval power systems. Since its publication, although the authors have continued to refine the concept of QOS in several papers, little attention has been paid to the subject in other published work. The need for additional work to examine the role of QOS, and the factors that influence it, is clear. Doerry lists several of these factors, stating "the reliability of power system equipment, the systems architecture of the power system, and the power system concept of operation are the primary drivers for QOS provided by the power system" (2007, p. 29). The first two of these factors will be the focus of this study, in an effort to explore the nature of QOS and recommend ways to use and improve this new metric in future ship design efforts.

Objectives

Since it is a new concept that has not been included in previous design efforts, there are no tools available to the author to model QOS effects specifically. Therefore, the first goal of this project is to develop a basic modeling approach to simulate power system operation and QOS effects in an IPS ship. The model must replicate the major components of the power system, as they pertain to QOS, including the power system architecture, component characteristics, propulsion and ship's service loads, and operating profile. While it is important to generate a fairly representative model of the ship, it is not necessary to model any particular ship or to reproduce any system exactly. This is in fact impossible in an academic setting due to the classified and/or proprietary nature of much of the information required for such detail. The key is instead to develop a model that includes representative system elements and is scalable, providing a building block for future work, where access to exact system and component specifications may not be an issue. The model also does not need to extend beyond the realm of QOS. It should be used to simulate QOS performance, but other unrelated power system evaluations would be left for different programs. This model is envisioned as simply a QOS module within a broader power system design and evaluation tool.

Once a functional model has been developed, the next objective will be to study the role of component reliability throughout the power system. As hard reliability data is difficult to obtain, and what is available is often suspect due to the varying methods and assumptions used in its estimation, reliability will be treated as a variable. One goal of this portion of the study will be to locate critical component levels where reliability is very important. In other words, to determine the system elements whose individual reliability level impacts QOS the most. In the same way, the study will attempt to locate component levels whose reliability has a markedly small impact on system QOS. The purpose of both these efforts will be to find areas of high-value reliability, where small local improvements can lead to greater global system benefits, or conversely where small global QOS sacrifices could yield great costs savings through reduced component reliability. These areas would then be recommended as focal points for future reliability research in order to improve QOS and cost performance.

The third objective will be to propose methods and applications for evaluating the influence of changes in component characteristics or the IPS system architecture on QOS performance using the developed model. This will include the effects of changes in redundancy, such as shifting from an N+1 approach to another method. It will also involve investigating the impacts of proposed technologies, particularly new power conversion elements, on the IPS architecture and QOS. Possibly the most significant impact would be the switch from medium voltage AC to medium voltage DC or high-frequency AC as the primary source power. Again the goal is to develop a method for finding high-value aspects of IPS system architecture that can be recommended for future efforts to improve QOS and cost performance.

Thesis Outline

1. Review relevant theory and concepts
    a. IPS Concepts
    b. QOS Concepts
    c. Reliability
2. Modeling and Simulation
    a. Ship Model Design

    b. IPS System Design
    c. Computer Simulation Model
    d. DOE simulation plan
3. Simulation Results and Analysis
4. Evaluation and Conclusions
    a. Model Evaluation
    b. Applications for the Model
    c. Conclusion

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Chapter 2 - Concepts & Theory

Integrated Power Systems

From the first introduction of electric systems onboard a naval warship, the USS Trenton and its electric lighting installed in 1883, the dominant design paradigm has consisted of large main engines providing propulsion power and separate, usually much smaller engines generating electrical power for the use of other ship systems. Even on ships with a common power source such as steam, separate turbines or other systems are used to power propulsors and electric loads, resulting in limits on each. For a long period of time, this dichotomy presented few problems. The relative amount of power necessary to propel a ship through the water has not changed that significantly since the late 19th Century. The same cannot be said, however, of electrical power. Shipboard electrical systems evolved gradually at first from lighting to radio communications, to radar and sonar and other early electric systems. As the computer age dawned this growth began to accelerate rapidly. Figure 1 illustrates the rapid increase in generation capacity, which corresponds with electric loads, over the past few decades. On a modern warship, the electric loads can be expected to make up easily ten percent or more of the total power produced by a ship's engines (propulsion and ship's service combined).

As the demand for electrical power continues to grow, the separation of the propulsion and ship's service power functions creates increasing inefficiency. Both electrical service and propulsion loads tend to be highly variable in warships, depending greatly on the type of operations being conducted, specific systems involved, and the maneuvers required. Both types of power system must be sized for worst case scenarios, resulting in a ship that has far more power generation capacity than it needs at nearly any time. This leads initially to higher acquisition cost for more or larger engines, and ultimately to higher operating costs due to more engine hours and frequent operation at suboptimal loading points. There is no reason to believe electrical load demands will stop growing at anytime in the foreseeable future. Thus continued adherence to the traditional design paradigm will lead these inefficiencies to climb well beyond acceptable levels.

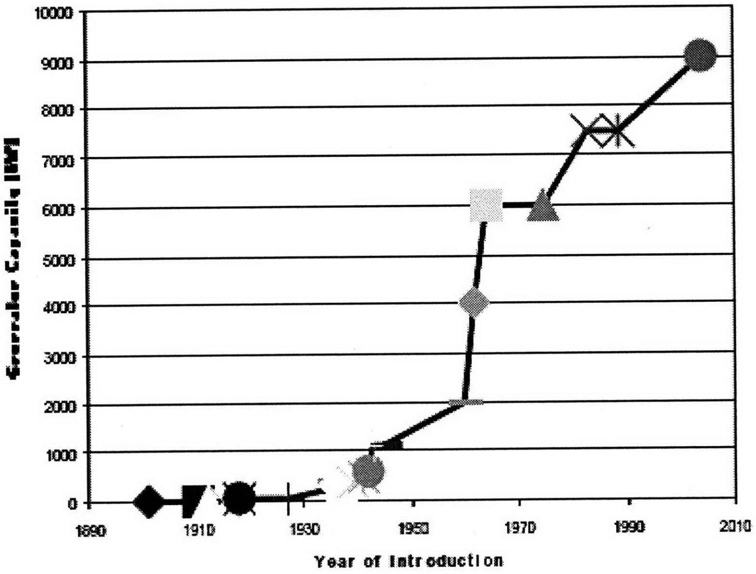


Figure 1 - US Navy Destroyers Installed Electric Generating Capacity (Amy, 2002, p. 331)

As the impending problems with current power system design became apparent, a solution to the inefficiencies of dual systems emerged in the form of the integrated power system (IPS), which began to garner widespread support starting in the 1990s. While the idea of electric propulsion is not new, recent advances in power electronics were necessary to make it a feasible option for large, high speed vessels. Although it goes by several different names, including Integrated Electric Propulsion (IEP), Integrated Full Electric Propulsion (IFEP) and Integrated Electric Drive (IED), the basic IPS concept is the same. Several prime movers (engines), potentially of different types and sizes, are used to generate electrical power, which is then sent via a common distribution system to both the propulsors (now electric, not mechanically driven) and the ship's service loads. This arrangement allows tremendous operational flexibility and great potential gains in operating efficiency over traditional separated systems. The concept has already gained commercial acceptance in several areas, including cruise ships, ferries, and many other vessel types. Now several navies, including the US, UK, France, and the Netherlands, all have programs exploring (and building) IPS warships.

There are several key benefits to the IPS architecture. The first advantage comes from the improvements in operational efficiency and lifecycle cost. By operating the lowest number of prime movers necessary, engine hours are cut for all engines, thus reducing wear and maintenance. The engines in operation can also be run at higher loading levels, maximizing their fuel efficiency. Additionally, due to the more efficient operation, with proper planning the total number of installed prime movers can be reduced. This can result in considerable savings of volume and complexity, as well as to both acquisition and lifecycle costs. Another advantage is the ease of reversing the direction of shaft rotation using power electronics. This eliminates the need for the complex, fragile, less efficient controllable-pitch propeller (CPP) common in modern warship designs. Although electric transmission is less efficient than mechanical transmission at full power (89% vs. 93% for a CPP ship), this is mitigated by improved low speed efficiency that can match or even exceed CPP transmission (Hodge & Mattick, The Electric Warship, 1996). A final advantage comes in the form of design flexibility. With electric transmission, there is no need for long, heavy shafts between engine and propeller. Besides allowing engine placement for operational and survivability considerations, this also saves considerable weight and volume, while reducing design and construction costs. The primary disadvantages of an IPS warship involve the size and cost of currently existing propulsion motors and power conversion equipment. Presently these downsides effectively cancel out a fair portion of the gains from IPS. However efforts are underway to overcome these obstacles, and the ever-advancing state of power electronics technology bodes well for success in the near future.

Architecture of Integrated Power Systems

The current US Navy IPS architecture consists of several functional modules that perform the various roles within the power system. These modules were defined by CAPT Norbert Doerry, USN of the US Naval Sea Systems Command in establishing a program known as the Next Generation Integrated Power System (NGIPS). In two reports, “Establishing The Next

Generation Integrated Power System Baseline Architecture" (2007) and "Next Generation Integrated Power System Technology Roadmap" (2007), Doerry laid out and then refined the functional modules that make up a notional IPS system.

The first module is the power generation module (PGM). The function of the PGM is fairly self-explanatory; it converts fuel into electrical power. The PGM would typically consist of a prime mover and a generator set, as well as the necessary power rectification, auxiliary support, and control equipment. While gas turbine or diesel engines are the most common concept for the prime mover, hydrogen fuel cells and nuclear power represent other realistic options for future PGM use.

The next module is the propulsion motor module (PMM). Its function, naturally, is to convert electrical power into rotational motion to drive the vessel's propulsor. It generally consists of a motor drive and an electric motor. The current state of the art is known as the Advanced Induction Motor (AIM), but future IPS systems may use more advanced motors using permanent magnets or high-temperature superconductors. The goal of these new technologies is to increase power density, a necessity for employing IPS in smaller, high-speed warships.

While the PMMs are the destination for much of the generated power, the power load module (PLM) represents the remaining loads, and will continue to grow in size relative to the PMM portion of the overall demand. More of a function placeholder than a specific system, the loads that make up the PLM are designed for their role within the ship's mission, with little regard for their place within the overall power system. The key task within the PLM therefore is not design but organization. The ship loads must be classified in terms of several different schemes, including power type, mission priority, and QOS. The various categories each PLM load falls into are then used for sizing generation and distribution equipment as well as load shedding in the event of failure or damage. Classifying loads within the PLM will be complicated even further as new sensor and weapon technologies are developed and fielded. The immense power requirements and unique load profiles of the advanced radar systems, rail guns, and directed-energy weapons envisioned for future warships will cause them to interact with the IPS system in ways unlike any current PLM loads. It is likely that a new Special Loads Module will be necessary to account for these exceptional loads within the IPS framework.

Power is transferred between various modules by elements of the Power Distribution Module (PDM). The PDM function is carried out by the cables, switchgear, and fault protection equipment necessary for each type of power encountered through the system. Because the PDM encompasses all power at all transfer points, there is considerable variation in the requirements it must meet. It consists of everything from simple cables to complex load centers.

For power to be distributed and used effectively, it must assume different forms. The power conversion module (PCM) is where power is converted from one such form into another. PCMs are connected to other modules and each other by PDMs. Generally PCMs consist of either transformers or solid state conversion elements. Where conversion is necessary as part of another module's basic function, such as power generation or motors, it is included within that module, and not considered to be a separate PCM.

A crucial aspect of any integrated power system is system control. The module responsible for coordinating the actions and responses by and between other functional modules is the power control module (PCON). Unlike the other modules, the PCON is not necessarily a physical entity, but instead is comprised of the software needed to control and monitor the remainder of the system. Portions of the PCON module may lie within the physical domain of other modules, or they may reside in a separate hardware system (such as a central control console). Some portions of the PCON may be automatic, while others will involve a human interface. The functions defined for PCON within the NGIPS framework include: remote monitoring and control of other modules, mobility control, resource planning, system configuration, fault detection and isolation, load shedding (based on mission priority or QOS), supporting maintenance and tag-out efforts, and training.

The final functional module is the energy storage module (ESM), which is responsible for storing excess power to be used later or to accumulate large quantities for special purpose loads. Although not part of any currently planned IPS system, ESMs are expected to play a crucial role in fielding many new technologies aboard IPS vessels, including fuel cell PGMs and high power directed energy or electromagnetic weapon systems. There are numerous forms that an ESM could take, including a simple battery bank, a flywheel, or a large capacitor. Future IPS systems may employ ESMs only for special loads or use them as system-wide sources of standby power.

Power Conversion Modules

Within the context of this paper, the only functional module necessary to discuss in detail is the power conversion module. There are currently three main types of PCM used within the IFTP framework, delineated by number, PCM-1, PCM-2, and PCM-4; and their proposed follow-on PCMs, PCM-1A and PCM-2A, and PCM-4A. An excellent description of each PCM is found in the "NGIPS Technology Development Roadmap":

> PCM-4: Transformer Rectifier to convert MVAC power to 1000 VDC power. The rating of the PCM-4 must be greater than ½ of the maximum margined electrical load and greater than the total un-interruptible load. Under normal operation, two PCM-4s will be operational, each supplying power to one of the port / starboard longitudinal busses.
>
> PCM-1: Converts 1000 VDC Power from PCM-4 to 800 VDC power, 650 VDC Power, or another user-needed DC voltage. Also segregates and protects the Port and Starboard 1000 VDC Busses from in-zone faults. 650 VDC Power used to supply power to motor controllers for large motors and for large resistive heating applications PCM-1 contains a number of modular Ship Service Converter Modules (SSCM) that can be paralleled to provide redundancy and the requisite power rating. Each SSCM currently has a rating of 300 kW and uses a proprietary interface with the PCM-1 cabinet. SSCMs can provide power to segregated outputs. For each segregated output, with one SSCM out of service, the remaining SSCMs shall be able to supply the greater of 50% of the maximum margined load or 100% of the maximum margined un-interruptible load serviced by that segregated output. (The 2_{nd} PCM-1 in the zone will supply the other 50% of the load)
>
> PCM-2: Converts 800 VDC power from PCM-1 into 450 VAC Power at 60 Hz. or 400 Hz. Although a zone may have multiple PCM-2s, cost savings can be realized by limiting the number of PCM-2s necessary to achieve survivability requirements. PCM-2 contains a number of modular Ship Service Inverter Modules (SSIM) that can be paralleled to provide redundancy and the requisite power rating. Each SSIM currently has a rating of 300 kW and uses a proprietary interface with the PCM-2 cabinet. SSIMs can provide power to segregated outputs. For each segregated output, with one SSIM out of service, the remaining SSIMs shall be able to supply the maximum margined load serviced by that segregated output.
>
> PCM-4(A): Transformer Rectifier to convert MVAC/HFAC/MVDC power to 1000 VDC power. The functionality of the PCM-4 may be incorporated into PCM-1A.
>
> PCM-1A: A PCM-1A converts 1000 VDC Power from PCM-4 or power from MVAC/HFAC/MVDC to 750-800 VDC power, 650 VDC Power, another user-needed DC voltage, or 450 volt 60 Hz AC Power. Also segregates and protects the Port and Starboard busses from in-zone faults. 650 VDC Power is used to supply power to motor controllers for large motors and for large resistive heating applications For DC loads, PCM-1A contains a number of modular Ship Service Converter Modules (SSCM) that can be paralleled to provide redundancy and the requisite power rating. Similarly, for AC

> loads (short-term and long term interrupt 60 Hz loads) PCM-1A contains a number of modular Ship Service Inverter Modules (SSIM) that can be paralleled to provide redundancy and the requisite power rating.
>
> PCM-2A: Converts 750-800 VDC power from PCM-1 into 450 VAC Power at 60 Hz, 400 Hz, or variable frequencies and voltages to drive variable speed motors. PCM-2A would be used to service un-interruptible AC loads as well as loads with special power requirements. One notable difference from the current PCM-2 is that the PCM-2A would incorporate the features of a load center – individual loads, or sets of small loads, would have individual power converters. To enhance survivability, a zone could have multiple PCM-2As collocated with the serviced loads. In general, the number of loads serviced by PCM-2A should be minimized due to:
>
> 1. The efficiency of the current generation air-cooled input and output modules for the PCM-2A is considerably less (~85%) than the efficiency of the water cooled PCM-1A (~ 97%)
> 2. Since each of the output modules of the PCM-2A directly drives a load, N+1 redundancy is not provided. The reliability of the output modules of the PCM-2A will directly impact the QOS provided to loads.
> 3. The cost of providing power to loads from PCM-1A will be less than the cost of providing power from PCM-2A via PCM-1A. (Doerry, 2007, pp. 24-26)

Zonal Electrical Distribution and Integrated Fight Through Power

A key enabling concept for the integrated power system is zonal electrical distribution (ZED). Shipboard electrical distribution traditionally involved a radial system wherein AC power generation units fed power through switchboards and then directly out to load centers throughout the ship. This approach involved considerable complexity as well as large quantities of cable and other distribution equipment to ensure sufficient survivability and service continuity (Hegner & Desai, 2002). Figure 2 shows a typical radial AC power distribution system.

A considerable improvement over radial distribution was introduced aboard USS OSCAR AUSTIN (DDG-79), launched in 1998, in the form of the AC ZED. This system supplies power to several electrical zones via longitudinal busses. Load centers within each zone then distribute the power to loads inside the zone. This architecture results in a much simpler system due to the much shorter and more direct cable runs within the zones, saving weight and also construction cost since cables can be run within zones before they are joined together. Figure 3 shows a typical AC ZED system with four zones.

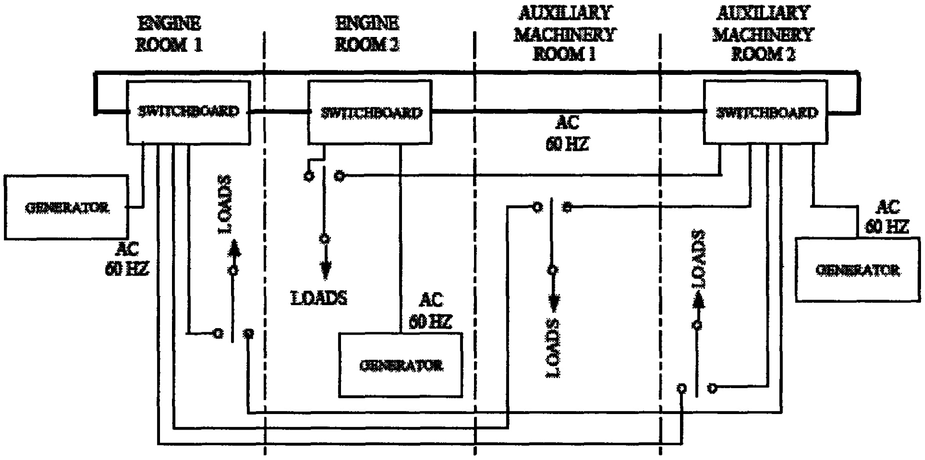


Figure 2 - AC Radial Distribution (Hegner & Desai, 2002, p. 336)

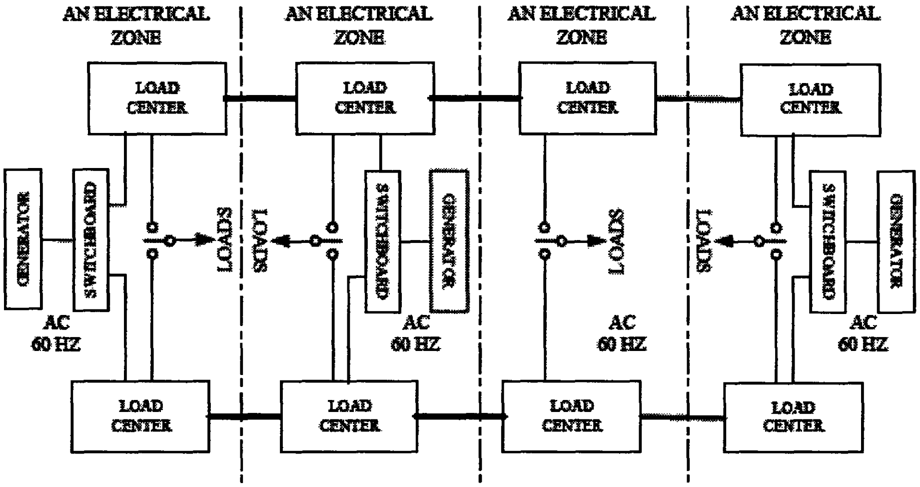


Figure 3 - AC ZED (Hegner & Desai, 2002, p. 337)

From the AC ZED came the inspiration for the latest distribution scheme, a DC ZED system known as Integrated Fight Through Power (IFTP). In IFTP power from the generation modules is converted from medium voltage AC (MVAC) power, usually either 4.16kV or 13.8kV, into 1000 VDC power by PCM-4s, one for each of the two longitudinal DC busses. Within each zone, the tie in to each bus is a PCM-1, which converts the power to lower voltage DC using modular SSCMs and also isolates the bus from in-zone disturbances. From the PCM-1, power is either distributed to DC loads or transferred to the PCM-2. The PCM-2 converts 800 VDC power from the PCM-1 into 450 VAC at 60Hz or 400Hz using modular SSIMs. From the PCM-2 power is distributed via a load center to the AC loads within the zone. Within each zone, the PCM-2 and any DC loads requiring multiple power sources are connected to both PCM-1s and receive power via auctioneering diodes. A three zone IFTP system is shown in Figure 4.

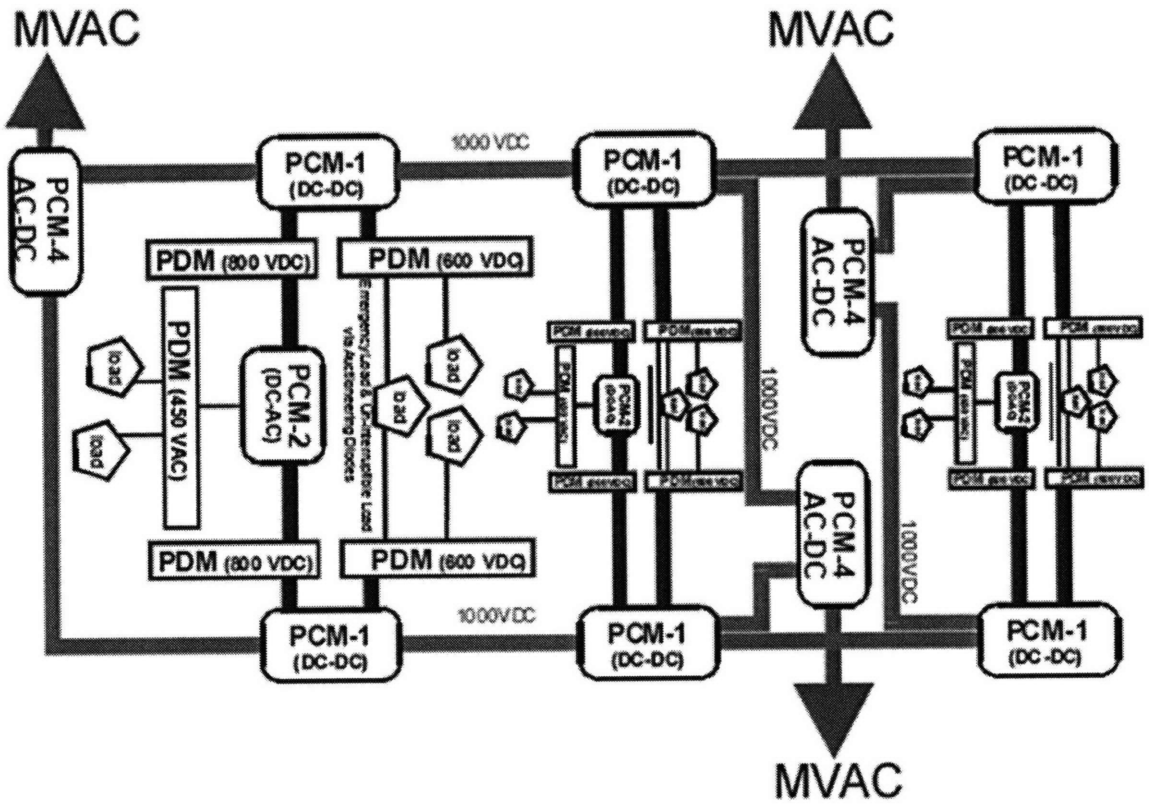


Figure 4 - Current Generation IFTP System (Doerry, 2007, p. 25)

IFTP provides several advantages over AC ZED systems. The first results from cost savings from removing the large electromechanical switchgear needed for AC distribution and instead using power electronics to perform fault protection. The "fight through" capability comes from the zonal isolation afforded by the PCM-1s connecting each zone to the longitudinal DC busses. Additional savings are realized by eliminating the need to generate and distribute high quality AC power to the entire ship. This means that the generator operating frequency is less constrained, allowing the use of smaller, less expensive rectification equipment. By converting to the necessary power type within zones, power quality delivered to the loads is also higher than when converted at the source as in either AC distribution scheme. Another benefit is in the simplicity and speed of the auctioneering diodes used to transfer power between port and starboard buses (via PCM-1s), which are smaller, cheaper, and faster than the bus transfer switches utilized in AC ZED. A final, and perhaps the most significant, benefit of IFTP is its potential to take advantage of the rapid advances in power semiconductor technology to improve both capacity and performance (Hegner & Desai, 2002, pp. 337-338).

While the present IFTP system possesses a number of significant advantages over previous AC distribution schemes, the proposed next generation IFTP architecture, utilizing PCM-1A, PCM-2A, and possibly PCM-4A, will offer even greater benefits. If PCM-4A is not used but instead incorporated within PCM-1A, only the high power bus (as opposed to both high power and 1000 VDC busses in the current IFTP) will need to cross zonal boundaries, reducing cabling and improving survivability. It will also result in lower total required transformer rectification capacity between the PCM-1As than the PCM-4 (since each PCM-4/4A must be sized for 50% of the maximum margined ship's service load). In addition to potentially eliminating many types of special purpose load conversion equipment, savings are realized by reducing the total number of SSCMs required in the PCM-1A, since SSCMs are no longer required to power all SSIMs downstream in the PCM-2A (Doerry, 2007, p. 27). Figure 5 shows the nominal in-zone architecture of this system.

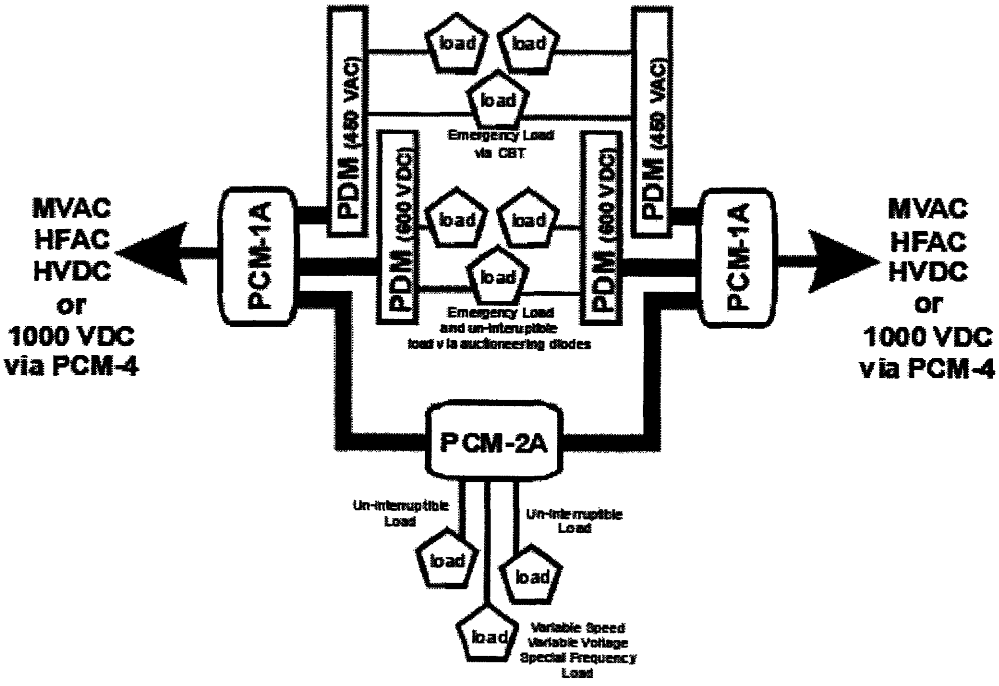


Figure 5 - Proposed Next Generation IFTP Zonal Architecture (Doerry, 2007, p. 27)

Quality of Service

Doerry and Clayton (2005) define Quality of Service as a metric to evaluate the continuity of service provided by the power system. It is based on the probability that each load will be provided with the level of continuity it needs to effectively fill its role within the ship's mission. The major factors involved with QOS include the capacity rating, reliability, and failure mode of the PGMs, PCMs, and PDMs, and their respective submodules, as well as the overall system architecture and the current operational configuration of the power system.

This definition of quality is in contrast to the concept of power quality from a terrestrial power grid perspective. In this sense, power quality refers to variations in the characteristics of the actual voltage delivered from the ideal prescribed voltage (generally a perfect sine wave at 60Hz). These variations can include electrical noise, momentary interruptions, momentary sags or surges, transients ("spikes"), and harmonic distortion (Salem & Simmons, 2000). These characteristics of the voltage delivered are of great importance for terrestrial power supplies which must generate and transmit large quantities of power over long distances to many users. They are still important considerations in shipboard systems, but are less critical for engineers, particularly in an IFTP system where the needed power is created (or, more properly, converted) in close proximity to the load and in relative isolation.

At its simplest, Quality of Service can be viewed as a failure rate of the power system from the perspective of its loads. A failure would consist of any power interruption or departure from the required power quality (in the terrestrial sense) that causes the load to be unable to perform its required function. The causes of such failures might include equipment failure in any of the IPS modules or submodules or transient conditions resulting from normal system operations. While these conditions might occur to some degree with relative frequency, they will not necessarily result in a QOS failure as defined above. If the system is able to maintain the required level of service through another path or temporarily shedding loads, no failure will have occurred. Likewise if the load's mission does not require urgent restoration of power, manual corrective actions or even repairs could bring the system back online before a QOS failure occurs. This might be the case for temperature control loads, such as heaters, air conditioners, or refrigeration, where significant time periods can elapse before the temperature in their compartments changes appreciably (Doerry & Clayton, 2005).

QOS Load Categories

To account for these variations in tolerance, Doerry and Clayton (2005) proposed a set of load categories based primarily on the time before a QOS failure can be considered to have occurred.

A. Uninterruptible Load

Uninterruptible (UI) Loads are electrical loads which cannot tolerate a power interruption lasting 2 seconds. These loads generally require a source of standby power, whether through an uninterruptible power supply (UPS) or some sort of alternate path control by fast automatic switches like auctioneering diodes. These loads should be capable of withstanding interruptions on the order of 10 ms while switching to the standby power supply.

B. Short-Term Interrupt Load

Short-Term Interrupt (STI) Loads are loads capable of tolerating a 2 second service interruption, but incapable of tolerating interruptions longer than 5 minutes in duration. These loads are generally provided with standby power through slower electromechanical switchgear, which imposes the minimum 2 second requirement. This allows switching, fault clearing, and load shedding of Long-Term Interrupt Loads before power is guaranteed to the STI Loads. The 5 minute limit is considered to be the nominal startup time for a standby generator to be brought online.

C. Long-Term Interrupt Load

Long-Term Interrupt (LTI) Loads are loads which are capable of tolerating interruptions longer than 5 minutes. They may be provided with a source of standby power, but not necessarily. LTI loads are the first loads to be shed in order to maintain service to STI and UI loads. While bringing a standby generator online will often result in power being restored to all loads in less than 5 minutes, the LTI loads may be subject to additional load shedding if necessary due to continued limits on the power, for instance if the standby generator is smaller than needed.

D. Exempt Load

Exempt Loads are not quite the same as the three previous load categories. Exempt loads can be considered a second class of LTI load, and only exist for the purpose of generator sizing. While ship's service loads must fall into one of the three standard QOS load categories, propulsion loads may not. A certain quantity of propulsion power might be designated as STI, perhaps to maintain steerage or some minimum speed. The rest would be considered LTI or exempt. The portion of this remaining propulsion load that cannot be delivered with the largest generation module out of service would be categorized as the exempt load.

Load Shedding

In the event of a failure within the power system, the available power may be less than the power required by the online loads. In order to provide power to the most important online loads, it may be necessary to deny power to certain loads in a process called load shedding. Doerry and Clayton (2005) define two types of load shedding that may be conducted by an integrated power system.

A. Quality of Service Load Shedding

QOS load shedding is based on the QOS load categories defined above. When a power interruption first occurs within the system, affected UI loads receive power from their UPS or fast-switching standby immediately. The system then conducts load shedding of LTI loads in order to provide sufficient power to the STI loads online. During this period repairs can be made or additional generation capacity can be brought online, with the goal of restoring sufficient power to all loads within the 5 minute Long-Term Interrupt limit. If this process occurs without further mishap, there is a high likelihood that a QOS failure will be avoided.

B. Mission Priority Load Shedding

In the event that sufficient power capacity cannot be delivered to all required loads within the 5 minute LTI time limit, the power system shifts its load shedding focus from QOS to Mission Priority load shedding. Mission priority load shedding ensures that the most important load systems, as dictated by the ship's current mission, are given power first, regardless of QOS category. This means that power may be restored to certain LTI loads, while UI or STI loads are shed. The need for Mission Priority load shedding may also arise within the LTI time limit if the available power is insufficient for the online STI and UI loads. In this situation STI loads would first be shed according to Mission Priority, followed by UI loads. By definition, all situations requiring a shift to Mission Priority load shedding also involve a QOS failure (including situations where operators may force a shift to Mission Priority load shedding for tactical reasons).

Basic QOS Calculation

Given the complex nature of any integrated power system, calculating a value of QOS, which can be equated to a mean time between unacceptable service interruptions, from any perspective is certainly a nontrivial exercise. In "Designing Electrical Power Systems for Survivability and Quality of Service," Doerry (2007) suggests a basic method for calculating what he refers to as a Mission System Quality of Service. This model relies on simple summations and several simplifying assumptions, including a known, fixed mean time between failures (MTBF), a small mean time to repair (MTTR) relative to MTBF, and treats component failure as the only source of QOS failure. The goal of this project is to improve upon this basic method, applying stochastic simulation methods and avoiding these simplifying assumptions if possible. The method for accomplishing this will be discussed in detail later in the paper. The basic Mission System QOS model proposed by Doerry is shown below.

> a. Ship Concept of Operations in the form of percent underway time the ship will be in different operational modes. The fraction of time in an operational mode *i* is given by *fom(i)*
>
> b. Mission System Quality of Service model for each operational mode. This model will provide a "1" if a QOS failure has occurred for a given set of power interruptions of specified durations to one or more mission system loads (otherwise provides a "0"). The Mission System Quality of Service model is represented by *qom(i,pi[k])* where *i* is the operational mode, and *pi*[*k*] is a vector of power interruptions for the *k* mission loads.
>
> c. Power System Concept of Operations that determines which power system components are online and in what configuration for each ship operational mode. *pom(i,j)* returns the fraction of time that power component *j* in operational mode *i* is online.

d. Power system Reliability Model that provides the MTBF *rj* for each power component *j* where time is measured in hours that the component is on (operational time).
e. Power System Fault Effects Analysis that determines for each failure of a power system element *j*, the vector of power interruptions for each of the *k* mission loads: *pij* [*k*].

The fraction of time that a QOS failure will occur in response to the failure of power system component *j* is given by

$$f_{qos(j)} = \sum_{i=1}^{n} f_{om(i)} p_{om(i,j)} q_{om(i,pi_j[k])}$$

The fraction of time that component *j* is on is given by

$$f_j = \sum_{i=1}^{n} f_{om(i)} p_{om(i,j)}$$

The MTBF of component j based on calendar time instead of operational time is given by

$$r_{c(j)} = \frac{r_j}{f_j}$$

Since the reciprocal of MTBF is the failure rate, then the QOS failure rate due to each power system component is given by

$$\frac{1}{QOS_j} = \frac{f_{qos(j)}}{r_{c(j)}}$$

Thus the QOS provided to the mission system due to the failures of all power system components (measured as a [mean time between service interruptions]) is given by

$$\frac{1}{QOS} = \sum_{j=1}^{m} \frac{f_{qos(j)}}{r_{c(j)}}$$

$$QOS = \frac{1}{\sum_{j=1}^{m} \frac{f_{qos(j)}}{r_{c(j)}}}$$ (pp. 29-30)

Reliability

Failure and Failure Rates

Central to the quality of service delivered by an integrated power system is its reliability, which is determined by both the architecture of the system and the reliability of the individual components that make up the system. This section will concern itself primarily with the theory necessary to investigate component reliability. A fairly standard definition for reliability in engineering is provided by O'Connor (1991) who defines it as, "the probability that an item will perform a required function without failure under stated conditions for a stated period of time" (p. 3). Given this definition, it becomes necessary to further explore the nature of failure and its expected behavior over time.

When discussing failure, it is often important to distinguish between repairable and non-repairable items. For non-repairable items, the item will only fail once within its lifetime. For such items, the instantaneous probability of this failure occurring is known as the hazard rate. For repairable items, upon failure the item can be restored to functioning condition, and thus may suffer multiple failures through its lifetime. Repairable items are subject to an instantaneous failure probability known as the failure rate, sometimes also termed the rate of occurrence of failures (ROCOF). The difficulty lies in determining what a repairable item is. This is often based on the system level one wishes to examine. Drilling down far enough one will always find a non-repairable item. In practice what we generally consider as the smallest elements of a system are still in reality subsystems made up of even smaller elements. This is particularly true for electronic systems. For the purposes of this study, all components will be treated as repairable. While many elements may simply be replaced within the system following a failure, there is a high likelihood they will be repaired and returned to the system when a similar component fails. The existence of the US Navy 2M/ATE program for conducting electronics repair onboard the ship (as opposed to at maintenance depots ashore) supports this assumption, as does the increasing focus on employing hot-swappable components (e.g. the SSCMs within a PCM-1A) which are replaced immediately and subsequently repaired outside the system to minimize overall system downtime.

Regardless of their reparability, nearly all items exhibit a similar failure pattern over their lifetime. This pattern is known as the bathtub curve, and is made up of three distinct parts, as seen in Figure 6. The first portion of the bathtub is a period of decreasing failure rate known as the infant mortality or wear-in period. During this time, early failure of defective members of the item population is the dominant effect. This period is followed by a period (usually the longest) of low, often near-constant failure rate known as the useful life. During this period failures are primarily caused by external factors or extreme conditions and occur randomly with roughly constant frequency. The final period is one of increasing failure rate known as the aging or wear-out period. During this period failures due to cyclic loading and other time-dependent stresses dominate.

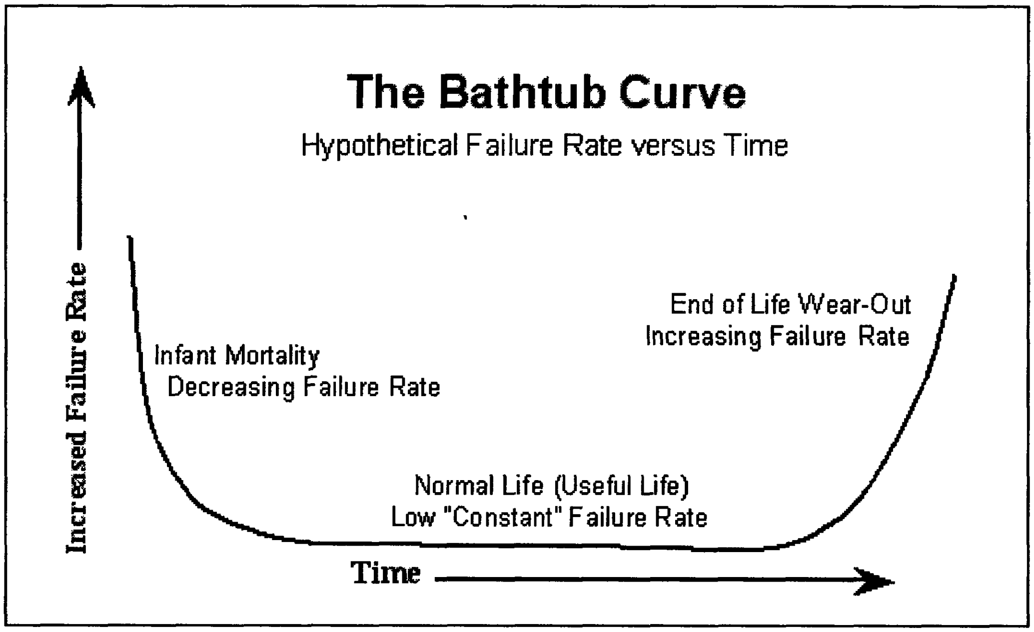


Figure 6 - The Bathtub Curve (Wilkins, 2002)

While most items display the bathtub pattern, the actual shape of the various bathtubs can differ dramatically. In the case of the electronic components being discussed here – and particularly so for the components normally employed in naval power systems-, the typical bathtub curve demonstrates very brief wear-in and wear-out periods separated by a long useful life, as seen in Figure 7. The brief wear-in is mostly attributable to using mature designs and good manufacturing practices, including burn-in, where defective components are revealed before shipment to end users. The eventual wear-out is due primarily to heat effects on the materials of surviving population members. The vast majority of failures for electronic items surviving wear-in occur during the useful life period. These failures may be caused by extreme loading or other external factors or they may be due to slight defects that manifest themselves over time. Regardless of the exact source, they tend to occur randomly throughout the period and at a constant rate (Lewis, 1996). This fact has important implications for the choice of distribution used to model IPS component failure behavior.

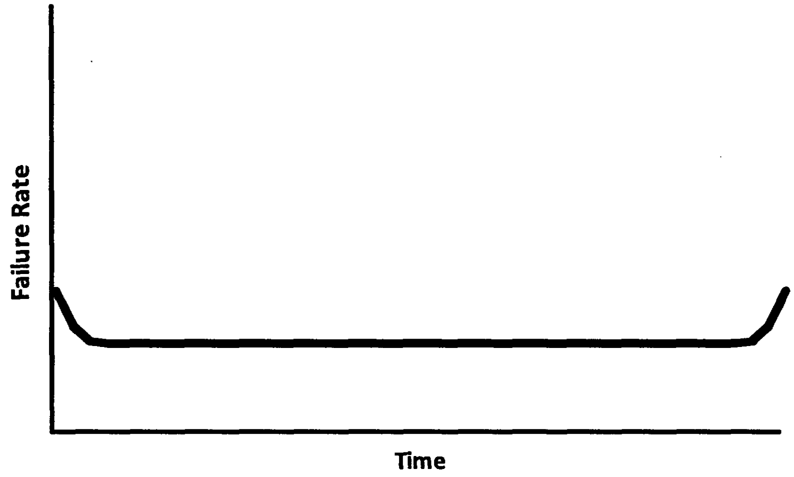


Figure 7 - Typical Bathtub Curve for Electronic Components

Probability Distributions

By assuming that system elements are only present in the IPS system after they have entered their useful life (i.e. inspection and burn-in have weeded out early wear-in failures) and also assuming that Navy maintenance practices will result in replacement before age effects dominate, we can thus reasonably assume a constant failure rate for all components considered within the power system. This implies that the components exhibit memoryless behavior, or in other words the likelihood of failure during some future time period is independent of the items age. Furthermore, since the ship requires the use of its power system at all times, it can be considered to be continuously in operation.

The standard continuous probability distribution used to model constant failure rate behavior is the single-parameter exponential distribution (hereafter simply the exponential distribution). The exponential distribution is characterized by the constant parameter λ, which is the failure rate. The probability density function (PDF) for the time to failure is given by

$$f(t) = \lambda e^{-\lambda t}.$$

The cumulative density function (CDF), which represents the probability that failure has occurred by time t, is then calculated

$$F(t) = \int_{-\infty}^{t} \lambda e^{-\lambda t} d\lambda = 1 - e^{-\lambda t}.$$

The reliability, or the probability that the item has not failed by time t, is then calculated

$$R(t) = 1 - F(t) = e^{-\lambda t}.$$

The expected value, commonly referred to as the mean time between failures (MTBF), or mean time to failure (MTTF) for non-repairable items, is calculated

$$MTBF = \int_{0}^{\infty} R(t)dt = \frac{1}{\lambda}.$$

The variance and standard deviation can then be calculated as $\frac{1}{\lambda^2}$ and $\frac{1}{\lambda}$ respectively. When plotted versus time, the PDF and reliability for the exponential distribution take on the forms shown in Figure 8, while the failure rate plots as a horizontal line.

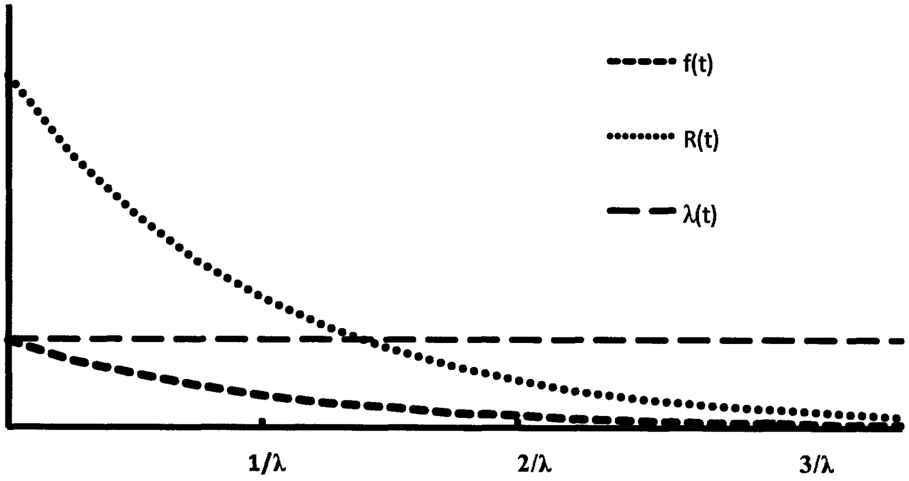


Figure 8 - Exponential Distribution: PDF, Reliability, and Failure Rate vs. Time

Another common distribution in reliability studies is the Weibull distribution. The Weibull distribution, in either its two or three-parameter forms, is widely used due to its versatility. By carefully choosing the parameters, the Weibull distribution can be used to model the failure rates seen during wear-in or wear-out, and can also produce the constant failure rate exponential distribution as a special case. It can also be used in situations where a threshold time exists during which failure cannot occur. While the Weibull distribution is more versatile, the exponential distribution is sufficient for this study, and so the more complicated Weibull will not be discussed further.

Availability

A companion concept to reliability is availability, the probability that an item will be available (i.e. able to operate) when required. Availability is normally applied only to repairable systems, and in addition to the failure rate involves a repair (or replacement) rate for the item as well. While generally a gross simplification, it is common to assume a constant repair rate, μ, which is also modeled using the exponential distribution. The expected value of μ is known as the mean time to repair (MTTR) and the two are inversely related, just as MTBF and λ. Instantaneous availability, the probability the item will be available at time t, can be calculated using the expression

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t},$$

which, as t becomes large, simplifies to the steady state availability

$$A(\infty) = \frac{\mu}{\lambda+\mu} = \frac{MTBF}{MTBF+MTTR}.$$

Since availability is generally a very high number or percentage, it is often most instructive to look at the unavailability, or downtime, of a system instead, which is simply 1-A. One common problem when modeling availability is the fact that maintenance can take many forms and is not as well studied or understood as failure. Attempting to model maintenance as other than a simple MTTR, or including preventative maintenance or training can greatly increase the complexity of the model. To avoid these complications, availability will only be examined in this study in its simplest form.

3

Chapter 3 – Modeling & Simulation

Approach

In order to model the quality of service characteristics of an integrated power system, the first step is naturally to select or create a power system to model. Due to the security issues involved with using a current naval power system, it was clearly infeasible to model an existing power system. The best and most expedient alternative was instead to develop a power system based on current naval IPS design work and preliminary concept designs available in the public domain. In addition to modeling the power system itself, a simulated "ship" with set equipment and electrical and propulsion loads dictated by a mission profile was also necessary. Once the required elements were created, a simulation model was developed, using a modular approach to simplify coding, testing, and debugging. This simulation model was then used to run Monte Carlo simulations of normal power system operations, using stochastic methods to examine behavior patterns over a large number of similar, but randomly arranged events. The key input variables to be examined through the model were component reliability levels. Even limiting the model's focus to high-level components still resulted in too many components to evaluate all combinations without excessive computing costs, and so Design of Experiments principles were used to develop an experimental plan to evaluate the effects of component reliability. Once the simulation runs were conducted for each individual trial of the experiment, the data could be collected and analyzed to determine the importance of the reliability of each of the various components on overall system QOS performance.

Model Ship Design

Worldwide the two primary IPS warship programs currently underway are the U.S. Navy's DDG-1000 *Zumwalt* class, which is currently undergoing detail design, and the Royal Navy's Type 45 *Daring* class, currently under construction and scheduled to commission in 2009. While the specifics of both ships' IPS systems are classified, sufficient publicly releasable information is available that a representative power system could be designed based on either of these vessels. The ready availability of DDG-1000 information and the author's status as a U.S. Navy Engineering Duty Officer led naturally to its selection as the primary model for designing the power system to be used within this study.

One excellent source of data was a software program developed by the U.S. Naval Sea Systems Command's (NAVSEA) Naval Surface Warfare Center, Carderock Division known as the Advanced Surface Ship and Submarine Evaluation Tool (ASSET). ASSET is the Navy's primary software tool for early stage ship concept design and alternatives analysis. In addition to facilitating parametric-based ship design from a blank slate, the program also contains data on current ships and ship concepts, including the DD(X), which was an earlier name used for the ship program that later became DDG-1000. While the available DD(X) data from ASSET was neither complete nor necessarily representative of the ultimate DDG-1000 design, it proved more than sufficient as a starting point for the simulated system design. An additional benefit to ASSET is the unclassified nature of the software and the ship database (in the form distributed to MIT).

The first step in designing the model ship was to design the power generation and propulsion motor modules, which have the largest impacts on other system elements. The PMM selection was simplified by the fact that the Navy had already chosen and announced the Converteam (formerly Alstom) Advanced Induction Motor (AIM), shown in Figure 9, as the propulsion motor for DDG-1000. Initially a more advanced permanent magnet motor solution had been envisioned, but technology risk led to the choice of the AIM, which is also being used on the *Daring* class destroyers. The DDG-1000 AIMs will be rated at 34.6MW each. The PGM design, which at the level of detail required by this study consisted mainly of selecting the prime movers to be used, was also relatively simple. Based both on the engines detailed within ASSET and also on the equipment in use at the IPS Land Based Engineering Site (LBES), the PGMs selected were two Rolls-Royce MT30 gas turbine engines as main turbine generators (MTGs) and two General Electric LM500G gas turbine engines as auxiliary turbine generators (ATGs) (Stauffer, 2003). The two MTGs are rated to provide 36MW each, while the ATGs are rated at 3.94MW each, for a total of 79.88MW of installed power generation.

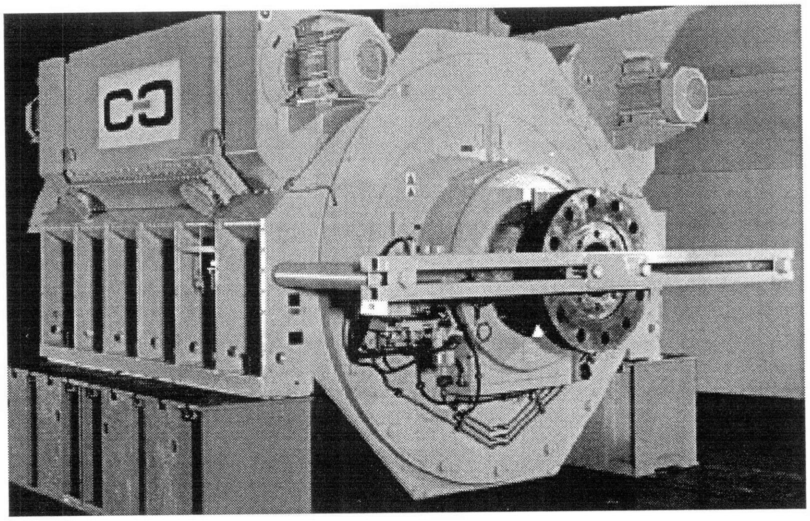


Figure 9 - Converteam Advanced Induction Motor (Converteam, 2006)

The next step in designing the model ship was to develop a set of ship service electrical loads. This area was where the ASSET data proved the most useful. Within the ASSET Machinery Module is a list of electric loads (pieces of equipment drawing electrical power), organized by their Expanded Ship Work Breakdown Structure (ESWBS) code, and providing the maximum load drawn by each piece of equipment under a range of ship operating and environmental conditions. The operating conditions used by ASSET include Cruise and Battle conditions, both of which involve underway steaming, with the Battle condition involving full operational readiness of all combat and engineering systems. These two conditions are further divided based on environmental conditions represented by Summer and Winter (high and low ambient air temperature, respectively). The division of environmental conditions into summer and winter represents a considerable oversimplification, especially for IPS ships. Due to the interaction between the effects of ambient temperature on both gas turbine efficiency and electrical loads (for heating and cooling), the difference between conditions is not as straightforward as standard mechanical transmission ships, which experience only engine efficiency effects due to ambient temperature (Fireman & Doerry, 2007). Despite the flaws in the ASSET conditions, the presence of detailed load data was too valuable to pass up. Creating new conditions and attempting to translate the load data between them would have added another dimension of complexity to the design process with little added value for the study. In addition to the four conditions already mentioned, ASSET provides load data for two further conditions, Anchor and Emergency. Anchor could stand either for a vessel literally at anchor or a vessel inport steaming, for instance when the shore-based power supply is incompatible or inadequate. Emergency represents a minimal power consumption condition, and could be considered to represent a damage situation (or damage drills during normal operations).

The load data from ASSET was transferred to a spreadsheet, where the various ESWBS load groups were evaluated for completeness. Additional loads were added within the groups to account for equipment not included in the ASSET report, such as electric fire pumps, or to divide systems into multiple components for placement within different electrical zones. Each load was also assigned to one of three power types: 450 VAC, 60Hz power, the most common type of power used in the U.S.; 450 VAC, 400Hz power, used in special applications such as radar, helicopter support, and missile systems; and 650 VDC power, which is only one of several DC voltages used aboard ships, but was chosen to represent all of them for simplicity. Various types of DC motors and resistive heating units use DC power, represented in this model by 650 VDC. Load values were based primarily on the ASSET data where possible, with other values based on engineering judgment and the author's experience onboard a U.S. Navy destroyer. The exact values and descriptions of the loads were not critical for this study. Instead it was desired to have a sufficiently large number of loads, requiring multiple types of power, and distributed evenly throughout the ship.

Once the load list was created, the loads were then placed into six zones within the ship. This number of zones was chosen both as representative of a likely IPS design and also based on conversion gear capacities, which will be discussed later. Originally a three zone configuration was considered for simplicity, but capacity issues, a desire for realism, and the minimal impact of zone quantity on simulation complexity and processing time led to the increase.

Consideration was given to logical zonal placement of equipment, based on likely location within the ship, collocation for related systems, and survivability for distributed systems.

In addition to zonally dividing the loads, further additions were necessary to the load list. The ASSET loads provided were the maximum load for each piece of equipment for each condition, and were intended to be used for power system design and component sizing. Toward this end, the maximum load for all conditions for each piece of equipment was determined and compiled for use in designing the power system. The resulting maximum margined ship service load was 13.76 MW. While the maximum loads are useful for design, these values are of limited use in modeling operations, where loads may only draw a fraction of their maximum load or may only operate a portion of the time. To address this, an operational load factor was assigned to each load. This factor was a value between 0 and 1 (the actual maximum was 0.99) and represented the portion of time that each load would draw its conditional load. While this factor does not completely represent a variable load over variable periods of time, it was adequate for the purpose of this study. Another crucial area not addressed by the ASSET data was QOS. Each load was assigned to one of the three QOS load categories (UI, STI, LTI), based primarily on engineering judgment and also the need to have a reasonable number and distribution of each of the categories throughout the ship. The final load list of 193 ship service loads, including the load nodes discussed later in this chapter, can be found in Appendix I – Ship Service Electrical Loads.

The final step in designing the ship was to create a simulated mission profile for the model. It was deemed undesirable to fix the duration of the mission at this stage in the model development, so the profile was developed using percentages of operating time. The profile consisted of two primary factors, the operating condition and the propulsion motor module loading, as derived from vessel speed. The operating conditions chosen were those used by ASSET, discussed above. Within the constraints of the ASSET operating conditions, the total time was allotted as shown in Table 1, with roughly two-thirds of underway time spent in the cruise condition, divided equally between summer and winter, while summer and winter battle conditions accounted for one-third of underway time. Time at anchor and inport was allotted one-tenth of the total mission time, which translates to 18 days for a typical six-month deployment. This was considered a reasonable amount for several portcalls as well as refueling and replenishment stops. This mission profile was meant to address a single continuous deployment, as opposed to a longer period of normal vessel operations including time spent in its homeport. This could be included in future versions the model, but was not done in this study to avoid the added complications of modeling shore power and the impacts on vessel operations of timing within the inter-deployment training cycle.

Operating Condition	Time Fraction
Summer Cruise	30%
Winter Cruise	30%
Summer Battle	14%
Winter Battle	14%
Anchor	10%
Emergency	2%

Table 1 - Operating Conditions

In addition to allotting time to each operating condition, the mission profile also includes PMM loads. These loads are dependent primarily on the ordered speed of the vessel, although other factors due come into play. The efficiency of the PMM varies based on loading. For the Converteam AIM, efficiency of roughly 97% is achievable above 80% loading, decreasing to as low as 80% efficiency at 20% loading and below (Hodge & Mattick, 2000). Additionally there is the option to use only a single shaft at lower speeds. This is commonly done on mechanical drive ships to conserve fuel, but this benefit does not translate directly to IPS. There are reasons for single shaft IPS operation, however, including running one PMM at a higher loading (and thus greater efficiency than two PMMs) or the need to conduct maintenance on one shaft.

To calculate the required PMM loads, it was first necessary to determine the speeds to be examined. The potential speeds of the vessel were grouped into seven bins based roughly on the concept of engine bells. Each bell group was then given a representative speed, which was compared to the DD(X) speed-power curve data generated by ASSET. Based on this data, a spreadsheet program was used to calculate the PMM loading necessary for each speed, accounting for variations in efficiency based on loading and number of shafts. The PMM loads calculated in this manner are given in Table 2.

Bell	No.	Speed [kt]	% of Max PMM Load	Both PMM PMM1 [KW]	PMM2 [KW]	Single PMM [KW]
Off	1	0	0%	0	0	0
All Stop	2	0	0%	0	0	0
1/3	3	5	2%	865	865	1903
2/3	4	10	3%	1298	1298	2855
Standard	5	15	7%	3028	3028	6661
Full	6	20	16%	6920	6920	13096
Flank	7	30	95%	33887	33887	N/A

Table 2 – Speed-Derived PMM Loads

Within the time allotted to each operating condition, it was also necessary to assign each of the speed-derived PMM loadings a percentage of time. Since the ship does not use propulsion loads at Anchor, and ambient temperature has no discernable effect on propulsor or PMM efficiency, only three different conditions, Cruise, Battle, and Emergency needed to be considered. Based to some extent on the work of Surko and Osborne (2005) as well as the author's destroyer experience and engineering judgment, the time factors for each speed were determined for each operating condition, and are given in Table 3.

Condition	Bell No.	% of time	Total PMM Load [KW] 2 PMM	1 PMM
Cruise	2	5%	0	0
	3	40%	1730	1903
	4	20%	2595	2855
	5	25%	6055	6661
	6	10%	13840	13096
Battle	2	5%	0	
	3	25%	1730	
	4	20%	2595	
	5	20%	6055	
	6	15%	13840	
	7	15%	67773	
Emergency	1	20%	0	0
	2	15%	0	0
	3	30%	1730	1903
	4	15%	2595	2855
	5	5%	6055	6661
	6	15%	13840	13096

Table 3 - PMM Loads by Operating Condition

IPS System Design

With the other aspects of the ship model completed, the power system itself could be designed. The system architecture chosen was the current generation IFTP architecture discussed in Chapter 2. The shipwide architecture was straightforward in design, with the four PGMs feeding an MVAC bus. From this bus the PMMs were supplied with power as well as the PCM-4s. Two PCM-4s at a time would be online, each converting power from the MVAC bus voltage (the specific voltage is not a factor within the model) to feed the port or starboard 1000 VDC bus. Based on the maximum margined ship service load, each PCM-4 must be rated at 6.88MW (50% of the total). It is important to note that any PCM-4 can power either the port or starboard bus. This architecture is shown in Figure 10.

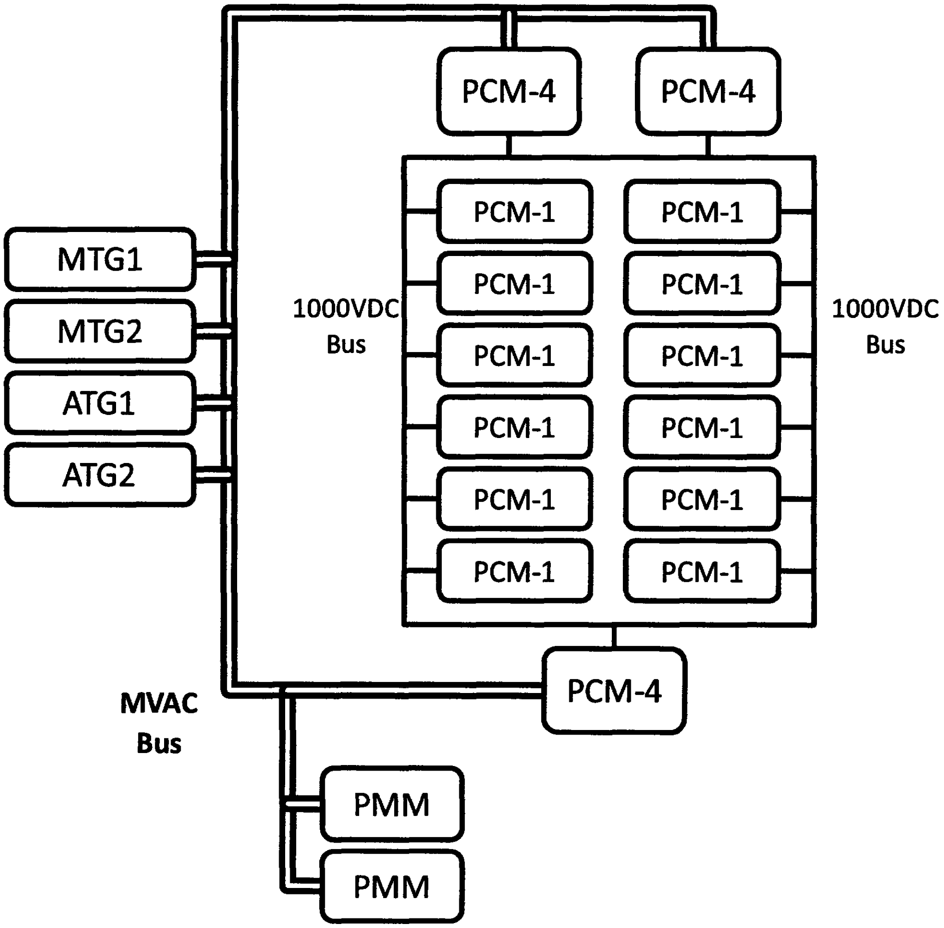


Figure 10 - Shipwide IPS Architectures

The in-zone architecture of the system is shown in Figure 11, and this is where most of the power system design work was required, as the number and type of converters required differed from zone to zone. Again following the IFTP architecture, with each zone there are two PCM-1s, one per 1000 VDC bus. The PCM-1s each contain a number of SSCMs, converting power to either 650 VDC (the generic DC voltage used by DC loads within the model) or 800 VDC. From the PCM-1, the 650 VDC power goes directly to its PDM, with a cross-connect (most likely auctioneering diodes) joining the SSCMs from the two PCM-1s. The 800 VDC power from each PCM-1 is then routed, again via auctioneering diodes to the single PCM-2 within the zone. The PCM-2 contains a number of SSIMs to convert the 800 VDC power to 450 VAC, at either 60Hz or 400Hz. The 400Hz and 60Hz AC power is then fed to its respective PDM, which represents the necessary switches and load centers required for distribution.

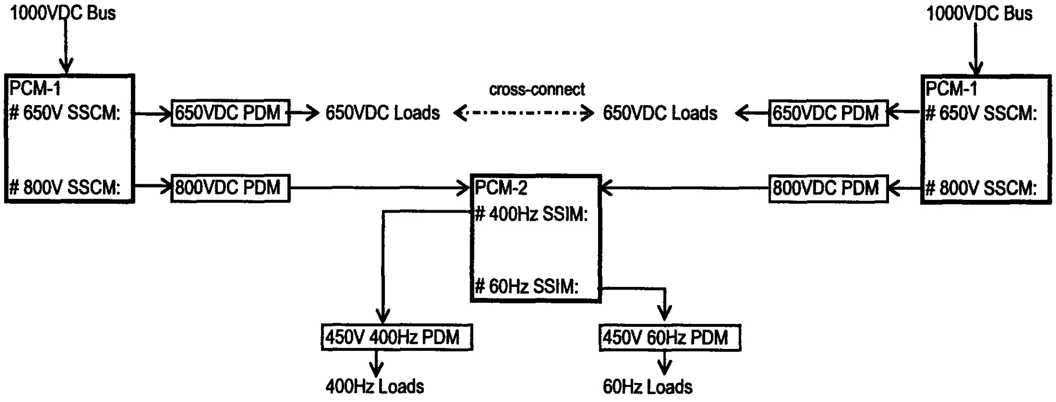


Figure 11 - Zonal IPS Architecture

Within each zone the number of conversion or inversion modules required was dictated by the quantity of each load type present in the zone. Each SSCM or SSIM was considered to have a capacity of 300KW, with a maximum of 10 modules per PCM-1 or PCM-2 (Hiller, 2003). The zonal loads were tabulated and sorted to determine the total load for each type of power and then for each QOS category within the types. These load totals were then increased by a 30% margin factor. To ensure adequate supply in the event of a SSCM/SSIM failure, an N+1 redundancy scheme was employed. Using this approach, the total capacity required for each power type and QOS category was divided by the 300KW module capacity to calculate the number of modules required, and then an additional module was added to the total. This process was repeated for each zone, yielding the zonal requirements shown in Table 4. At several points during this process it was necessary to go back and reapportion the loads between adjacent zones in order to reduce the total number of modules or stay within the PCM-2 capacity limit while still maintaining the requisite redundancy within each individual zone.

Zone	PCM-1	650V SSCM per PCM-1	800V SSCM per PCM-1	PCM-2	400Hz SSIM per PCM-2	60Hz SSIM per PCM-2
1	2	1	4	1	2	6
2	2	1	5	1	2	8
3	2	2	5	1	0	8
4	2	2	5	1	0	8
5	2	2	6	1	2	8
6	2	1	5	1	2	8

Table 4 - Zonal SSCM / SSIM Requirements

While the ship model and IPS design did not fully encompass the design considerations required for an actual IPS warship, they are a fairly representative model for a vessel similar in size and function to a DDG-1000. The model contains all the necessary information about the ship and its mission, as well as its IPS system architecture, to more than adequately simulate the normal operations of such a vessel.

Computer Simulation Model

In developing a computer model to simulate the ship operations and QOS characteristics, a needs-based approach was used. After reviewing the study goals, required inputs and outputs, and nature of the system being modeled, as well as evaluating the author's capabilities, it was determined that the model needed the following capabilities and qualities:

- Model a highly complex probabilistic system, including parallel and series components as well as redundancy

- Model multiple random failures with cascading system impacts
- Model the system behavior over small increments for very long periods of time
- Accept a large number of input variables
- Run in an accessible, user-friendly environment
- Facilitate early and frequent code testing and debugging

The first feature to be determined was the modeling technique to be applied. The first two needs presented a problem for most traditional analytic reliability modeling techniques. The complexity of the power system and random nature of the failures pointed to Monte Carlo Simulation as an obvious solution. Monte Carlo Simulation takes its name from the casino district in Monaco, and is characterized by repeated evaluation of a system model using random values of the system parameters according to a desired probability distribution. The primary benefit of Monte Carlo Simulation is that it avoids complex mathematical analysis of the system. Provided the model adequately simulates the system's behavior, Monte Carlo Simulation can, over a sufficiently large number of runs, reveal important behavioral trends that would be prohibitively difficult to determine through traditional analytic methods. The primary drawback to this technique is its costly use of computer processing time, due to the large number of runs required to effectively discern system trends (O'Connor, 1991, pp. 142-143).

The next feature to be addressed was the software environment. Based first on accessibility, three main options presented themselves, Microsoft Excel, MATLAB, and MathCAD. MathCAD was eliminated quickly due to unfamiliarity with its Monte Carlo capabilities and previous difficulties writing and debugging complex programs within the software. Excel was the most familiar program, with well documented Monte Carlo Simulation capabilities, but a spreadsheet approach was considered too tedious for modeling the extreme complexity of the potential system interactions. This left MATLAB, which was less familiar than Excel, but possessed the most documentation and was considered to be the simplest method for implementing the complex IPS system. In the end MATLAB was selected, but used in tandem with Excel. Any manipulation that could be accomplished outside of the MATLAB code helped to simplify the model, and Excel was used extensively for this purpose. This dual environment approach also facilitated the input of large numbers of variables.

The remaining needs had to be addressed by the architecture of the simulation model itself. In order to facilitate testing and debugging early and often, a modular approach was decided upon. The code would be built in pieces as separate m-files (MATLAB code files) that would be called as functions by a master module. Each piece would accomplish a specific function within the model and the information passed between modules would be minimized and standardized as much as possible. The standardization was accomplished together with the need for analysis of small increments over a large time period. By establishing the simulation timeframe and desired increment upfront, all information passed between modules could be set to a standard array size (the total number of increments), which would help to eliminate data mismatch issues and simplify validation of individual modules. It also ensured that the model was optimized to function over a large time period. If a module functioned poorly (i.e. slowly) for the desired number of increments, it could be evaluated and measures taken to enhance its performance. This ultimately proved to be a major factor in the time required to build the model, but at the same time was essential for its successful function.

Within the overall program, the code was broken into modules according to its function. Early in the program design, the need for certain functional modules became apparent. A module to generate randomly sequenced ship missions of a given duration and according to the mission profile was clearly needed, and would provide the basic inputs for most of the other modules. A module to generate the actual loads for each time increment was also needed. A module to generate and evaluate the impacts of power system failures was another necessity. As program development progressed, the need for additional functional modules arose. These included a new module for addressing only PGM loads and splitting the power system evaluation module into two, one to generate the failures and another to evaluate their impact on the power system. In addition to addressing the functional modules, it was necessary to minimize the impact of loading inputs and compiling the ultimate output data on the model's performance. This was accomplished through a master module, which called the submodules as functions within its routine, while taking care of loading a few large input arrays and compiling and saving the output data separately from the system evaluation performed by the submodules. The final program architecture for the functional modules is shown in Figure 12, and is followed by descriptions of the individual modules as well as the master module. Information passed between modules is indicated in brackets and located along the path it travels, while inputs and outputs sent to and from the master module are shown in braces. The software code for each of the program modules can be found in Appendix II – Simulation Model Code.

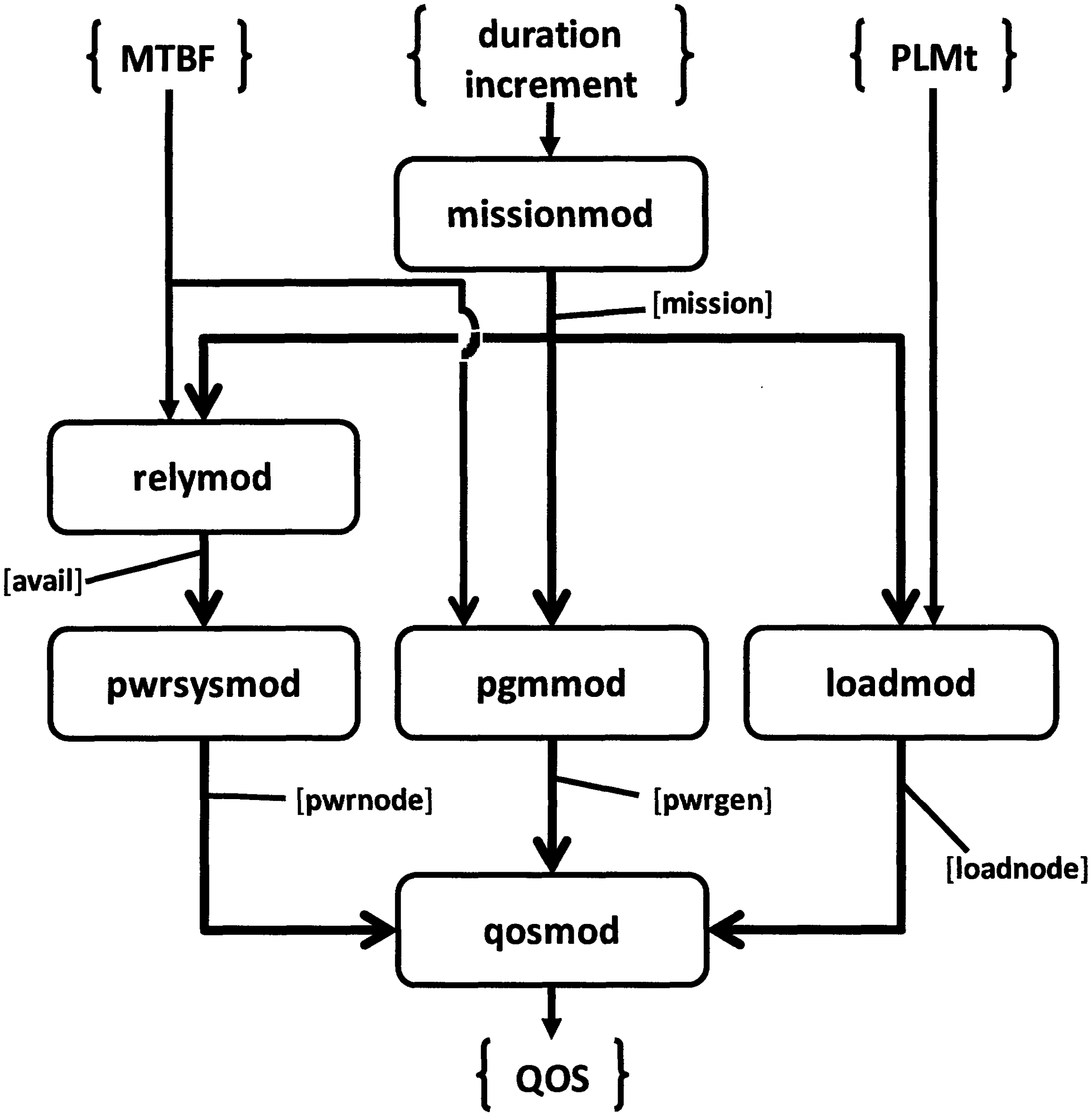


Figure 12 - Simulation Model Architecture

A. Mission Array Creation Module: missionmod

The first program module has the function of generating a random mission. The inputs to this module are the mission duration in hours, the time increment (similar to sample period) in seconds, and the anchor fraction, or total mission time spent in the Anchor condition. By default, the Anchor time is set to 10%, and the time increment is set to 300s (5 minutes). After reviewing the input variables and default values, the module generates a random sequence of operating conditions, each lasting for one hour of the mission duration. The conditions are numbered one through six, corresponding to the ASSET operating conditions as listed in Table 1, and are governed by the time fractions given in the table as well. However, condition five, representing Anchor, is not included at this point. This is addressed in the next program process, which randomly inserts full 24 hour blocks of time in the anchor condition (1 day is assumed to be the smallest unit of time the ship will spend in this condition), up to a maximum number of days governed by the anchor fraction described above. The next process enforces the constraint that the ship will not switch directly between summer or winter temperature conditions, although it can switch between cruise and battle conditions within the same temperature condition. Up to this point the function has been operating on loops or vectors of length = duration. The next process expands the existing operating condition vector to its full length and final form, a column vector of length = the total number of time increments in the mission, which is named *opcon.*

Once the operating conditions have been established, the second half of the mission module generates random PMM loads at each time increment according to the assigned operating condition and governed by the time fractions and loads given in Table 3 for each condition. The final process collects the incremental load data into a column vector named *pmm.* The *opcon* and *pmm* vectors are then merged into the module's single output variable, a two column array of length = total increments named *mission.* It is important to note that efforts were made to utilize only standard MATLAB built-n functions, such as **rand.m**, which generates a uniformly distributed random number. This applies to all modules of the simulation model. One notable exception is the use of the **randint.m** function in the anchor insertion process. This function resulted in a slight time savings per run which is then magnified by the large number of runs required for Monte Carlo Simulation.

B. Power Load Array Creation Module: loadmod

The second program module has the function of generating the individual PLM loads required for each increment of the mission. It takes as inputs the *mission* array from the previous module and a fixed input array called *PLMt*. The *PLMt* array is simply a reordered and transposed version of the load table in Appendix I, optimized for use within the program code. After evaluating its inputs, the first module process is to determine the individual equipment loads during each increment. This is accomplished by generating an array of random numbers, comparing them with the operational load factors from *PLMt*, and then outputting the appropriate conditional load for each load that is "on". The second major process within the module is generating a useful load output. It would be impractically slow to evaluate the system for each individual load, so instead the loads are grouped into load nodes by zone, power type, and QOS category. This classification resulted in the 37 nodes shown in Table 5, far more manageable than the 193 individual loads. The output array is named *loadnode*, and is created by summing the individual loads within each node for each increment. It consists of 37 column vectors, one for each node, and has length = total increments. This common length is part of the information standardization that is a key to the successful function of the simulation program.

Node	Zone	Pwr Type	QOS Cat
1	2	400Hz AC	UI
2	5	400Hz AC	UI
3	1	60Hz AC	UI
4	2	60Hz AC	UI
5	3	60Hz AC	UI
6	4	60Hz AC	UI
7	5	60Hz AC	UI
8	6	60Hz AC	UI
9	1	650 VDC	STI
10	2	650 VDC	STI
11	3	650 VDC	STI
12	4	650 VDC	STI
13	5	650 VDC	STI
14	6	650 VDC	STI
15	1	400Hz AC	STI
16	2	400Hz AC	STI
17	5	400Hz AC	STI
18	6	400Hz AC	STI
19	1	60Hz AC	STI
20	2	60Hz AC	STI
21	3	60Hz AC	STI
22	4	60Hz AC	STI
23	5	60Hz AC	STI
24	6	60Hz AC	STI
25	1	650 VDC	LTI
26	2	650 VDC	LTI
27	3	650 VDC	LTI
28	4	650 VDC	LTI
29	5	650 VDC	LTI
30	6	650 VDC	LTI
31	1	60Hz AC	LTI
32	2	60Hz AC	LTI
33	3	60Hz AC	LTI
34	4	60Hz AC	LTI
35	5	60Hz AC	LTI
36	6	60Hz AC	LTI
37	-	PMM	LTI, exempt

Table 5 - Load Nodes

C. Power Generation Capacity Array Creation Module: pgmmod

The next program module was given the function of creating the available power generation capacity from the PGMs for each time increment. This module takes as inputs the *mission* array from the first module and the array *MTBF*, generated by the master module. After evaluating its inputs, the first process is to set the PGM availability constants MTBF and MTTR. The MTBF is a variable from the input *MTBF*, while the MTTR was set within the module to a default value of 5 hours. The next process is to set an operating array for the PGMs. This array is based on the incremental condition, and consists of binary column vectors specifying whether each of the four prime movers is operating for each increment. A notable simplification at this step is the lack of distinction between the individual PGMs. While the code allocates a number of each type of engine based on the operating condition, it does not specify which specific engine is operating (MTG1 vs. MTG2, for instance). Given the complex issues involved with choosing which engine is online, addressing this decision would have involved considerable additional coding time and potential increases in processing time for little added value to the model.

Once the array of PGM operation has been created, the next process is to generate the random engine failure and repair times. This is done by generating arrays of random numbers, limited in length to a reasonable maximum number of failures per engine (10 in this case, which statistically should almost never occur within a six month duration). The failure and repair times are both exponentially distributed, using the means generated earlier, and are then combined to insert engine downtimes (binary zeros) into the PGM operation array. The next process involves detecting these random downtimes and bringing the appropriate standby PGMs online by the next increment (5 minutes is a reasonable timeframe to bring a standby turbine generator online). Once the standby generator operations have been inserted, the binary matrix is multiplied by the PGM ratings and then summed for each increment. This results in the output array *pwrgen*, which is a column vector of the standard length containing the total power generation capacity available for each increment.

D. Power System Availability Array Creation Module: relymod

This program module has the function of randomly generating the availability of each element of the power system for each time increment. It takes the inputs *mission* and *MTBF*. From *MTBF* it creates an array of failure times, one for each system element.

Two notable simplifications take place at this phase. First, each element has only one failure time during the mission. This was done to save processing time due to the low likelihood of multiple failures per element during the mission. While a certain number of elements would certainly fail multiple times during a mission, the element MTBFs being examined were all an order of magnitude greater than the mission duration, and it was determined that the added complexity was of limited value for this study. This does not hold true for the PGM failures (based on their considerably lower MTBF), and explains why separate modules were used to evaluate the PGMs and the remaining power system failures. The second simplification is a fixed repair time, set at 5 increments in this case. Again, this simplification was used to reduce processing time, by assuming all repairs take exactly the MTTR to conduct, instead of using the MTTR to model repairs probabilistically. Once the failure times are generated, they are combined with the fixed repair downtime and inserted into an binary array of ones having the standard length and containing a column for each system element (171 columns). This array is the module output *avail.*

E. Power System Operational Evaluation Module: pwrsysmod

This program module has the function of evaluating the effects of element failures on the available power delivered to the loads by the power system. The input to this module is the *avail* array from the previous module. After evaluating the input, the first process is to account for PCM-4 failures and their impact on the system (through the loss of the port or starboard bus). These bus failures are then inserted into a column vector which gives the total bus power available for each increment and is stored in the last column of the module output array *pwrnode.* This array has standard length and contains a column for each load node fed by the power system plus the bus power column mentioned above.

The remainder of the module evaluates the power system within each zone. First the available total capacity is determined for each type of SSCM within each of the zonal PCM-1s, based on SSCM and bus failures. From the available 800 VDC SSCM capacity, the available SSIM capacity is determined. The power available at each node within the zone is then determined by multiplying the availability of the respective node PDM with the appropriate available SSCM/SSIM capacity and storing this value for each increment in the appropriate nodal column of *pwrnode*. This process is then repeated for the remaining electrical zones. This module simplifies the power system by limiting the evaluation to high level components only and ignoring switching failures. The decision to ignore these elements was made again for complexity and processing time considerations, as this module already involves over 80% of the overall processing time required by the simulation model.

F. Quality of Service Failure Evaluation Module: qosmod

The final program module has the function of evaluating the performance of the power system and determining when and where QOS failures occurred during the simulated mission. The module takes the arrays *loadnode*, *pwrnode*, and *pwrgen* as inputs from the modules preceding it. The first process is to manipulate the input arrays to create two arrays for comparison. The nodal loads are summed for each increment and subtracted from the available PGM capacity to give the available power at the PMM node and inserted into the final column of *pwrnode*, while the QOS exempt portion of the PMM load in the final column of *loadnode* is removed. These actions result in two arrays of identical dimension which represent the power delivered to the nodes and the power required from the nodes, respectively. The module then simply compares these values to determine if a QOS failure has occurred. Due to the 5 min increment time, UI and STI nodes are considered QOS failures at any increment where power required is greater than power available, while LTI loads require 2 subsequent increments to cause a QOS failure. The output of this module is the array *QOS*, where the first column is the increment and the second the node for each QOS failure. Because the number of failures is not fixed, *QOS* has variable length.

G. Master Simulation Module: Monte_XX

The master module performs all operations required for a single Monte Carlo Simulation trial (the specific trial within an experimental set is indicated by the number XX). Its first process is to call the static input files *PLMt* and *MTBF*_XX, and store them in its workspace to act as inputs for the function modules. The number of simulation runs to be conducted is also determined at this point. The number of runs selected for Monte Carlo Simulation is a prime determinant of the simulation's accuracy, however this is a square relationship, and thus the return on more runs is diminishing. An experiment was conducted to evaluate the number of runs required by running the model for 10, 50, 100, 500, and 1000 runs and then evaluating the standard error of the results. While the results improved as runs increased, the improvement diminished considerably when compared to the great increase in run time. For this reason the number of runs was capped at 1000 to maintain a reasonable amount of processing time per trial while still gaining acceptable accuracy. The only remaining input necessary for the module was the mission duration. For this study the duration was selected as 4,380 hours, which equals six months, the length of a nominal overseas deployment. This duration also represented a reasonable timeframe to examine from the standpoint of failure data and processing time, resulting in 52,560 total increments to examine given a five minute increment length. While Doerry and Clayton (2005, p. 4) propose 30,000 hours (3.4 years) as a reasonable target QOS value (although they are referring to individual load QOS), due to the processing time required and the fact that this study does not examine shorepower or homeport conditions, a six month deployment was selected as the duration.

The central process of the master module is to call the functional modules in a loop for the desired number of simulation runs. In addition to calling these six functions, it also collects necessary data from each run within the loop. This includes collecting the *QOS* output array as well as calculating the increment of the first failure and the total number of failures for each run, and repeating these calculations while excluding QOS failures at the PMM node. Once the looped runs are complete, the module then computes the mean values of these failure characteristics for the entire trial. It also calculates the number of failures for each node and the percent of the total failures that occurred at that node during the entire trial. The final process is saving these trial output values in a file named *Data*_XX so that they can be compared between different experimental trials.

Design of Experiments

With the simulation model complete, the remaining item to address was the treatment of component reliability as a variable. In order to examine the effects of changes in individual component reliability on the overall system, the reliability (in the form of component MTBF) would have to be varied for each component and an individual Monte Carlo trial (1000 runs) conducted. In examining the power system, no fewer than 13 different types of components existed, and each should be considered over a range of MTBF values. Assuming simply a high and a low value were considered for each, 2^{13}, or 8,192 trials would need to be conducted. For three MTBF levels per component the number of trials increases to 1.6 million! At over 1 hour of processing time per trial, this sort of analysis was not possible. Clearly an experimentation plan was needed to reduce the number of trials while still capturing the effects of changes in reliability on QOS performance.

This sort of difficulty is common in engineering problems and is addressed by a concept called Design of Experiments (DOE). The basic purpose of DOE is to determine the relationship between the factors affecting a system or process and its output, while minimizing the number of experiments necessary to effectively determine these relationships. There are numerous techniques that fall within the realm of DOE, including fractional factorial design, response surface methodology, Taguchi methods, robust parameter design, and many others (Wu & Hamada, 2000). It was not the goal of this study to examine their individual merits, however, and so for the experimental design the JMP statistical software program was employed. Using the JMP DOE platform, the 13 component types were entered as factors and given three nominal levels of reliability. Based on the inputs given to the program an experimental trial plan was recommended. This plan was an array giving the level to be used for each of the 13 components in each trial. The final array selected was based on a Taguchi L27 orthogonal array, but with the addition of 2 extra trials to add a center point and opposite corner point to the experiment. The final experimental design consisted of 29 total trials (L27 is named for the number of trials) shown in Table 6. As the MTBF values were not known, all electrical components were given three basic levels, 10,000, 20,000, and 30,000 hours, while the PGMs were assumed to have much lower MTBFs with the levels 1,000, 3,000, and 5,000 hours. These values were chosen primarily to ensure a measureable number of failures occurred within the mission duration, and are not necessarily meant to reflect the performance of the actual components available for a real ship.

Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
PGM	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5	3
PCM-4	10	10	10	20	20	20	30	30	30	10	10	10	20	20	20	30	30	30	10	10	10	20	20	20	30	30	30	30	20
SSCM650	10	10	10	20	20	20	30	30	30	20	20	20	30	30	30	10	10	10	30	30	30	10	10	10	20	20	20	30	20
SSCM800	10	10	10	20	20	20	30	30	30	30	30	30	10	10	10	20	20	20	20	20	20	30	30	30	10	10	10	30	20
SSIM400	10	20	30	10	20	30	10	20	30	10	20	30	10	20	30	10	20	30	10	20	30	10	20	30	10	20	30	30	20
SSIM60	10	20	30	10	20	30	10	20	30	20	30	10	20	30	10	20	30	10	30	10	20	30	10	20	30	10	20	30	20
STI650	10	20	30	10	20	30	10	20	30	30	10	20	30	10	20	30	10	20	20	30	10	20	30	10	20	30	10	30	20
LTI650	10	20	30	20	30	10	30	10	20	10	20	30	20	30	10	30	10	20	10	20	30	20	30	10	30	10	20	30	20
UI400	10	20	30	20	30	10	30	10	20	20	30	10	30	10	20	10	20	30	30	10	20	10	20	30	20	30	10	30	20
STI400	10	20	30	20	30	10	30	10	20	30	10	20	10	20	30	20	30	10	20	30	10	30	10	20	10	20	30	30	20
UI60	10	20	30	30	10	20	20	30	10	10	20	30	30	10	20	20	30	10	10	20	30	30	10	20	20	30	10	30	20
STI60	10	20	30	30	10	20	20	30	10	20	30	10	10	20	30	30	10	20	30	10	20	20	30	10	10	20	30	30	20
LTI60	10	20	30	30	10	20	20	30	10	30	10	20	20	30	10	10	20	30	20	30	10	10	20	30	30	10	20	30	20

Table 6 - Experiment Design Array (MTBF in 10^3 hours)

To carry out the experimental plan, the input array *MTBF_XX* was modified to reflect each of the 29 individual component reliability trials shown in Table 6. For each new version of *MTBF_XX*, a corresponding version of the master module *Monte_XX* was modified to call the correct input and save the appropriate *Data_XX* output file. These trials were then allowed to run and the data collected and compiled for analysis, again using the JMP software program.

4

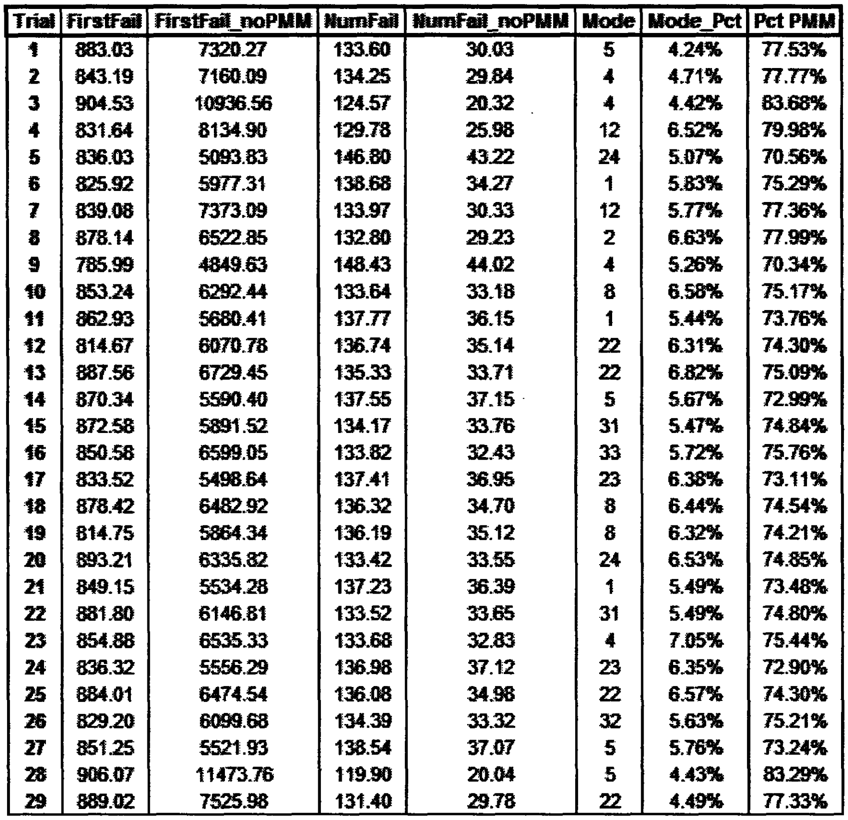
Chapter 4 – Results & Analysis

Experimental Results & Analysis

Once the experimental trials were complete, the output data from each individual output file was compiled into a spreadsheet for analysis. The response data was collected in Table 7, and included the following items for each trial [brackets indicate JMP response label], for the load nodes described in Chapter 3:

1. Mean increment of first failure [FirstFail]
2. Mean increment of non-PMM failure [FirstFail_noPMM]
3. Mean number of failures per mission [NumFail]
4. Mean number of non-PMM failures per mission [NumFail_noPMM]
5. Non-PMM node with highest number of failures [Mode]
6. Percent of the non-PMM failures occurring at the Mode [ModePct]
7. Percent of total failures occurring at the PMM node [PctPMM]

Because there were so many factors used and their values were set based on the experimental array, it is nearly impossible to discern any meaningful insight from Table 7 alone. The only item that potentially stands out is the repeated presence of several nodes as the most frequent failure site. This can be slightly misleading, however, as in these cases a closer look at the raw data shows that there were generally other nodes responsible for almost as many failures. This issue will be revisited later in the discussion. Complete simulation output data can be found in Appendix III – Simulation Output Data.



Trial	FirstFail	FirstFail_noPMM	NumFail	NumFail_noPMM	Mode	Mode_Pct	Pct PMM
1	883.03	7320.27	133.60	30.03	5	4.24%	77.53%
2	843.19	7160.09	134.25	29.84	4	4.71%	77.77%
3	904.53	10936.56	124.57	20.32	4	4.42%	83.68%
4	831.64	8134.90	129.78	25.98	12	6.52%	79.98%
5	836.03	5093.83	146.80	43.22	24	5.07%	70.56%
6	825.92	5977.31	138.68	34.27	1	5.83%	75.29%
7	839.08	7373.09	133.97	30.33	12	5.77%	77.36%
8	878.14	6522.85	132.80	29.23	2	6.63%	77.99%
9	785.99	4849.63	148.43	44.02	4	5.26%	70.34%
10	853.24	6292.44	133.64	33.18	8	6.58%	75.17%
11	862.93	5680.41	137.77	36.15	1	5.44%	73.76%
12	814.67	6070.78	136.74	35.14	22	6.31%	74.30%
13	887.56	6729.45	135.33	33.71	22	6.82%	75.09%
14	870.34	5590.40	137.55	37.15	5	5.67%	72.99%
15	872.58	5891.52	134.17	33.76	31	5.47%	74.84%
16	850.58	6599.05	133.82	32.43	33	5.72%	75.76%
17	833.52	5498.64	137.41	36.95	23	6.38%	73.11%
18	878.42	6482.92	136.32	34.70	8	6.44%	74.54%
19	814.75	5864.34	136.19	35.12	8	6.32%	74.21%
20	893.21	6335.82	133.42	33.55	24	6.53%	74.85%
21	849.15	5534.28	137.23	36.39	1	5.49%	73.48%
22	881.80	6146.81	133.52	33.65	31	5.49%	74.80%
23	854.88	6535.33	133.68	32.83	4	7.05%	75.44%
24	836.32	5556.29	136.98	37.12	23	6.35%	72.90%
25	884.01	6474.54	136.08	34.98	22	6.57%	74.30%
26	829.20	6099.68	134.39	33.32	32	5.63%	75.21%
27	851.25	5521.93	138.54	37.07	5	5.76%	73.24%
28	906.07	11473.76	119.90	20.04	5	4.43%	83.29%
29	889.02	7525.98	131.40	29.78	22	4.49%	77.33%

Table 7 - Collected Experimental Response Data

The most effective way to examine the experimental output was to use statistical software, for this study JMP was chosen again, to help separate the impacts of each component reliability factor on the system responses. After transferring the data into JMP, a model fit was conducted for all responses and all reliability factors. The most directly useful outputs from this operation are the JMP profiler diagrams, which are produced individually for each combination of factor and response. Each diagram displays the response on the vertical axis and the factor on the horizontal. The factors consist of the component types whose MTBF values were the input variables, while the responses are those given above. Within each diagram, the range of response values is represented by a vertical band located at each of the three factor levels (low, medium, and high, using the values given in Table 6). The means of each response range are then connected by a solid line to indicate roughly the effect (or lack thereof) on the response resulting from the progression from the low to middle to high levels of the factor. These diagrams for the experimental data are shown below, separated into groups for display purposes only. Figure 13 shows the output diagrams for the PGM and PCM component types as variables, while Figure 14 shows the diagrams for PDM component types.

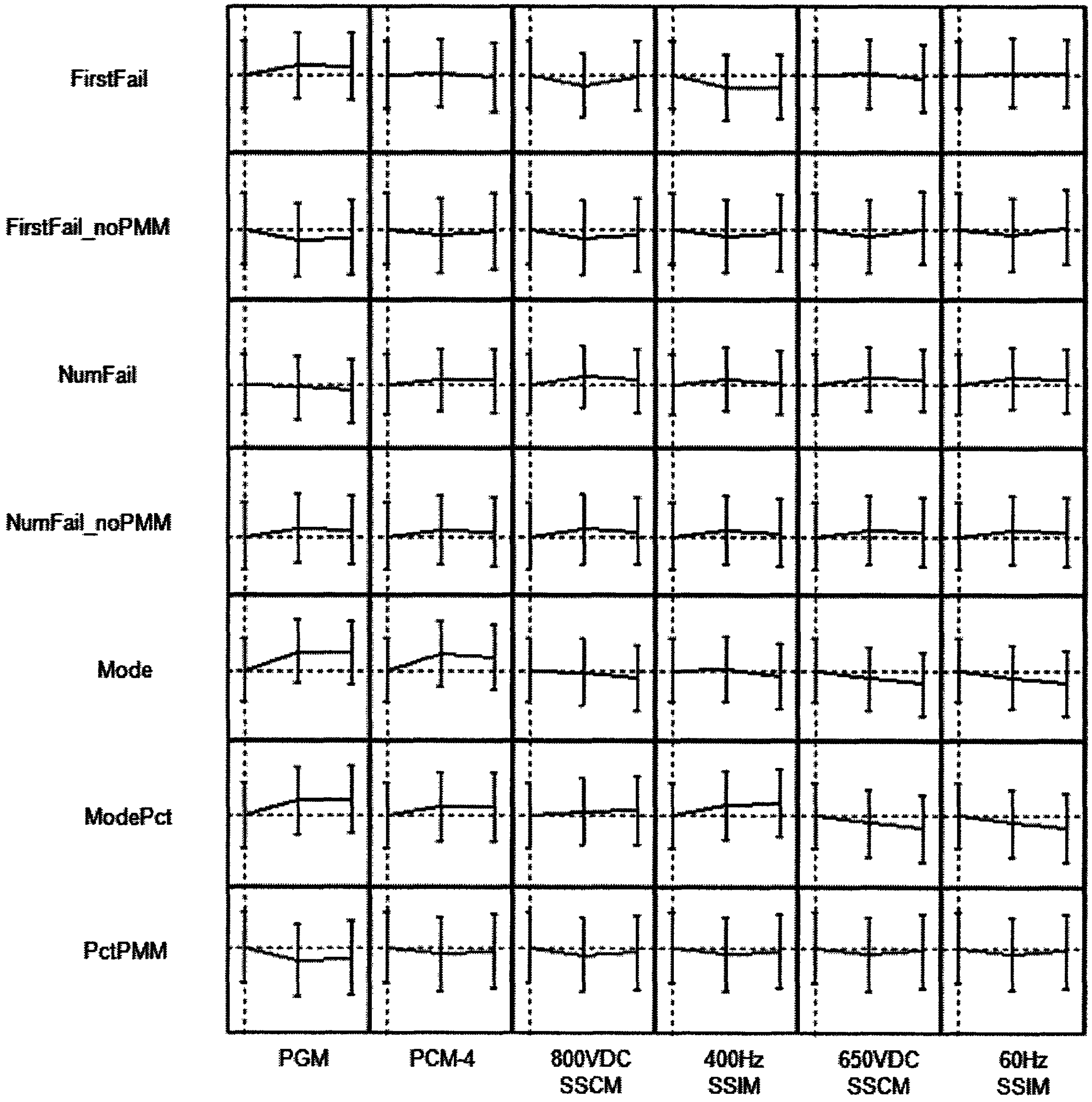


Figure 13 - JMP Profiler Output for PGM and Power Conversion Component Types as Variables

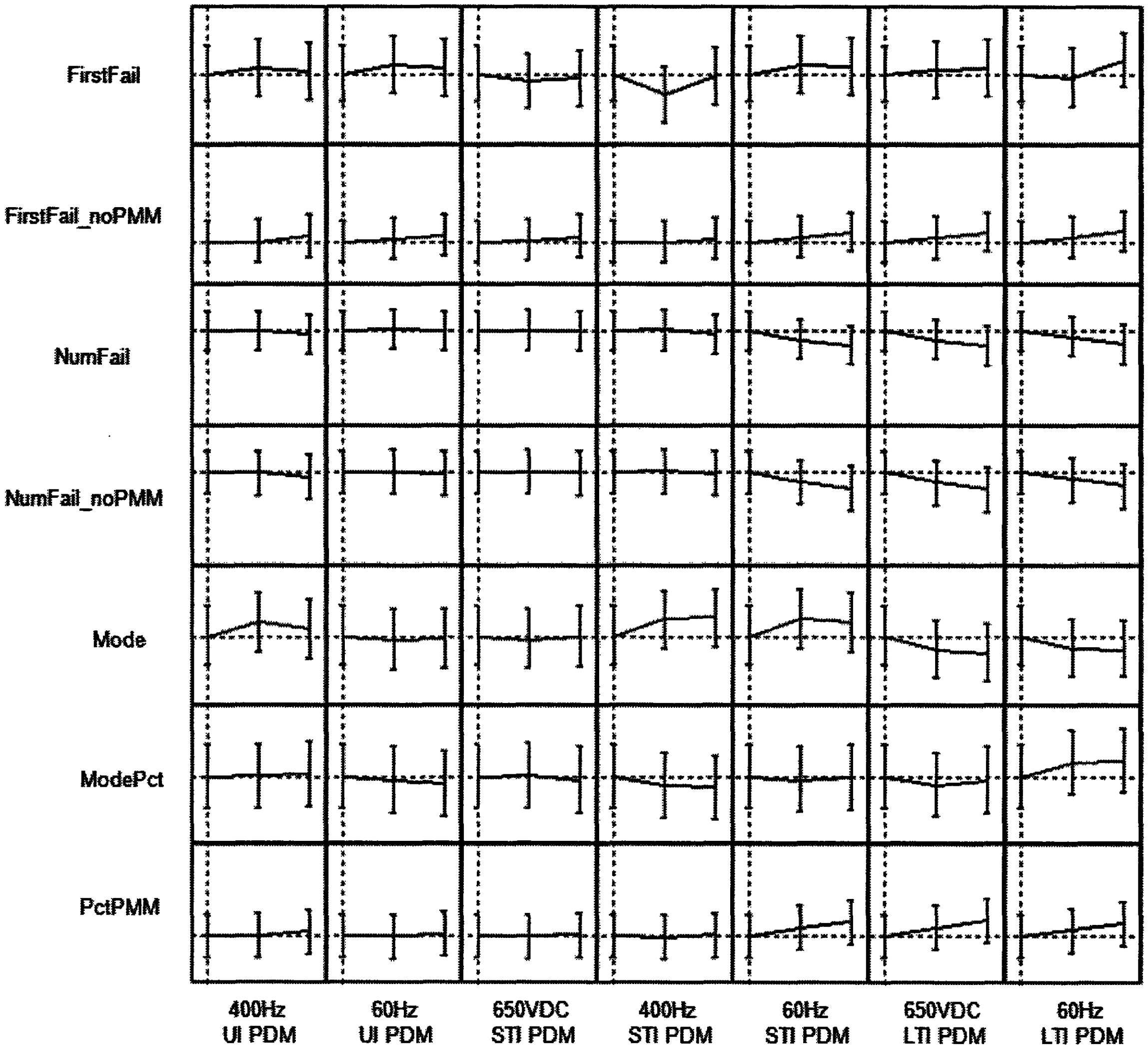


Figure 14 - JMP Profiler Output for PDM Component Types as Variables

Looking first at the initial failure responses FirstFail and FirstFail_noPMM, it is clearly impossible to discern any correlations from the former. While the PMM failures confound any relationships in the FirstFail diagrams, when these failures are removed, it is possible to see if any correlations are present. There do not appear to be any strong correlations with the SSCMs, SSIMs or PCM-4. This is unsurprising, given that the redundancy in these items makes them less likely to be direct failure sources. In looking at the PDM components' diagrams (Figure 14), however, a strong correlation is evident. A clear trend is shown by the consistently positive slope of the mean connecting lines for each component. This result could also be anticipated, given that these components as modeled by the simulation are single points of failure within each zone. Higher reliability should extend the average time before they fail, and since they are guaranteed to cause a failure, the first instance of PDM failure will frequently be the first non-PMM failure. The one slightly surprising result from within these first two rows of response diagrams is the lack of a clear correlation with PGM reliability. As these items possess significantly lower MTBFs than the electronic components, they fail much earlier and more frequently on average. This result is useful, however, in that it could indicate that the redundancy provided by the standby generators is adequate to prevent QOS failures arising solely from PGM failure.

In examining the next two rows of diagrams, for the total number of failures, there is much less of an issue with PMM failures concealing relationships. In fact the response profile for NumFail vs. PGM component reliability actually requires the PMM failures to display a correlation. In this case, the PGM reliability appears to have no clear impact on the total number of power system failures shown in PGM vs. NumFail_noPMM (Figure 13), but when PMM failures (which account for roughly 75% of failures on average according to the experimental data) are included in the diagram immediately above, there is a clear decline in total failures as PGM reliability improves. This indicates that most PGM failures result only in PMM QOS failures, and their impact on the electrical system QOS is less severe. Again no clear trend emerges from the diagrams for the power conversion components, owing most likely to redundancy. The most interesting area is once again the single point of failure PDMs. There is a very clear correlation between reliability and total failures, with and without PMM failures for three components, the 60Hz STI and LTI PDMs and the 650 VDC LTI PDM. This correlation is not surprising, as these PDMs serve the most loads, and are thus most likely to cause unmet demands (QOS failure) when they fail. Similar, though much less pronounced effects can be seen in the 400Hz UI and STI PDM component diagrams. What is intriguing is that there is not a lack of correlation for the remaining components, but instead a fairly clear zero correlation. This could indicate that these components result in such a small number of failures that improving their reliability has almost no effect on the total number of QOS failures in the overall system. Based on these results, if the goal is to reduce the total number of failures, clearly the 60Hz and 650 VDC PDMs should be targeted for reliability improvement.

In examining the Mode and Mode Percentage responses, there appear to be few, if any, correlations. This is not surprising, as numerically (as opposed to qualitatively) the most frequently occurring failure node has little significance aside from the QOS category of the node. The mode percentage considered numerically by itself can only offer a clue to the prominence of the most common failure node types (based on QOS and power type), since nearly all trials displayed a consistent behavior pattern wherein similar types of nodes accounted for similar percentages of the total QOS failures. There are two potential correlations, however, and both exist within the redundant power conversion components. The first is a negative correlation between the 60Hz SSIM and 650 VDC SSCM and the Mode Percentage. While this may be a false correlation, a possible explanation is that increasing reliability in these components causes the source of QOS failures to be more random and therefore less concentrated in nodes downstream from these components. The other possible correlation exists between the same two components and the mode. This result is even more difficult to interpret and may also be false, but a possible explanation could be that increasing reliability to these components, which serve all of the LTI and most of the STI loads could shift more failures to numerically lower nodes, which serve STI and UI loads. One fact that disputes this explanation is that these conversion modules also serve a majority of the UI and STI loads, indicating this relationship may not exist, or may require a more detailed examination.

Looking at the diagrams for the percentage of failures occurring at the PMM node, there are no apparent relationships with the reliability of the PGMs or any of the conversion module components. This is unsurprising for the redundant conversion modules which cause few failures, but slightly unexpected for the PGM. As discussed above, it appears as if most PGM failures lead to PMM QOS failures, so one would expect a lower percentage of total failures to be PMM failures if PGM reliability improves. Clear correlations do exist, however, between the percentage of failures occurring at the PMMs and the reliability of the PDMs. As before these relationships are less pronounced for the PDMs that are less prevalent (and therefore result in fewer total failures), while the improving reliability for the PDMs which cause the most failures greatly increases the percentage of total failures occurring at the PMMs. This result helps to confirm the earlier indications that improving the reliability of the highly loaded PDMs first would have a more significant positive effect on system QOS.

5

Chapter 5 – Evaluation & Conclusions

Model Evaluation

The results from this study demonstrate the potential benefits of this approach to modeling IPS systems and QOS. While certainly not conclusive, this analysis indicated or validated several key correlations between reliability and QOS performance that may not have been anticipated without the use of modeling. The model effectively performed its purpose of simulating the QOS performance of a given system architecture over the length of a mission. It allowed the examination of a key unknown, reliability, to be conducted for a range of components and displayed the influence of these variables on the overall system. Most importantly, the model accomplished these tasks in a straightforward and relatively expedient manner, a necessity for any early stage design tool.

While the simulation model generally fulfilled its objectives, it has several weaknesses and limitations. Many simplifications were required to reduce the complexity of the program code and minimize the processing time required. The current model only includes the highest-level elements of the power system, and even many of these were left out or assumed away. This resulted in a model that, while sufficient for a study of this narrow scope, would require considerable modification and improvement to be a truly useful IPS design tool. A more realistic model would need to include considerably more components and model their interdependencies in a much more sophisticated manner. It would also most likely be expected to model the individual PGMs and PMMs and their components, instead of treating them as identical, monolithic entities that function as "black boxes".. The manner in which component failures and repair are treated would also require considerable improvement. Instead of single failures and fixed repair times, the power system components should be modeled in a manner similar to the PGM availability module, where both failure and repair are modeled as random events that can occur multiple times. It would also be better to get away from the constant failure and repair rate assumptions, and instead model the failure and repair behaviors using more advanced probability techniques, such as the multi-parameter Weibull distribution. In the extreme, preventative maintenance and less-than-perfect repairs could also be modeled. A final area for improvement would be the experimental design and data analysis. These areas were not the main focus of this study, and were handled rather simplistically. To be of real benefit, the Design of Experiments would have to be conducted in a much more thorough manner. The data analysis also requires improvement, primarily in terms of the chosen response variables. While these responses seemed to be reasonable measures of system QOS performance, most were interconnected or difficult to evaluate numerically. These complications limit the confidence one can place in any conclusions drawn from the data analysis. Any of these changes would have a significant impact on the complexity and performance of the model, but most of them are necessary to make it a useful tool for examining future IPS designs.

Despite these limitations, the simulation model has many positive attributes that argue for its continued use in future applications. The most important of these is its modular architecture. This allows different facets of the program to be improved or expanded independently as the program is tailored to the specific needs of the user, and also facilitates testing and debugging. The standard inter-module array length is also a benefit for improvement and testing of the model. Another important asset is the ability to run within the MATLAB environment. This software is among the most commonly available numerical tools, and a significant proportion of design engineers possess at least a basic familiarity with its use and programming techniques. This feature represents considerable value, in that the module is essentially an open-source, open-architecture application, which can be used by nearly anyone and freely and readily adapted for each user's specific needs.

The capabilities of individual users or user groups also significantly impact the model's effectiveness. Access to more powerful computing resources would allow the number of runs to be increased sufficiently to realize noticeable benefits in the variance of the output data. This could greatly reduce the uncertainty involved in the data analysis and allow detection of smaller effects that might otherwise go unnoticed. Greater processing power would also allow more complex models to be examined, and possibly over longer periods of time, again increasing the model's usefulness. The level of access to system and component data is also a major determinant of the model's utility. If the system architecture and operating characteristics are known accurately, then many simplifying assumptions can be avoided; and likewise if the components are more thoroughly known. Any data that is known for certain allows the user to examine and evaluate the unknowns with much higher granularity. This can result in more valuable insights into the power system and its constituents.

Applications of the Model

The approach taken in this study is merely one application for this IPS simulation model. In this case, the ship characteristics and system architecture were created based on the best available information, experience, and engineering judgment. Even less was known about the components that made up the integrated power system. A model that is still useful under these conditions has great potential for use in applications involving less uncertainty.

One such application would be to conduct a more focused version of a reliability improvement study. For a known ship and system architecture, component reliability could again be treated as a variable. Assuming, however, that the current system components and their reliability characteristics were known, the study could be used to target areas for improvement. First the system in its current configuration would be modeled and repeatedly simulated to establish a solid baseline. Design of Experiments principles would then be used to develop a test plan for systematically evaluating improvements in individual components to determine which components or combinations of components produced the greatest improvement in QOS performance. These components could then be upgraded (if better components exist) or development work could be commenced to improve them. Conversely, a cost reduction study could be conducted along the same lines, but instead looking for the components that had the smallest influence on system QOS. These components could then be swapped for less reliable (and presumably less expensive) versions.

Another application for this type of model would be an analysis of alternative system architectures. Assuming a fixed set of available components with known reliability characteristics (although due to the model's flexibility the fixed requirement is not a necessity), the model could be used to simulate the performance of various modifications to the power system architecture and analyze their influence on QOS performance. Similarly, the effect and importance of component redundancy within a system architecture could be explored by evaluating QOS for different levels of redundancy or alternative redundancy schemes. These studies could again be targeted either at improving performance or maintaining a minimum performance threshold while reducing costs.

A third possible application could involve modifying the model to examine a different concept of Quality of Service. By modifying the node assignment scheme and changing aspects of the QOS evaluation module, the model could be used to simulate a ship's performance in terms of mission system QOS, where loads are grouped by their function within the overall ship mission (e.g. air defense mission loads) and QOS is defined not by the delivery of power to individual loads, but instead by the continued ability of the ship to complete its individual missions. Once again the objective could be either performance or cost-centric. This type of analysis could be especially useful in further developing the concept of a "high-low mix" of warships possessing varying levels of capability and survivability for similarly differing levels of cost. Other potential QOS concepts could include an increased focus on the traditional definition of power quality, which is essentially avoided in the current model. This type of approach would most likely require significant modification to most of the modules, or perhaps even the addition of one or more modules to account for the new factors involved.

A final application (although there are certainly others) for the model could be employment as a submodule within a larger IPS modeling continuum. Whether a self-contained piece of software or simply a series of interconnected steps, each handing off to the other, such a program could be very useful for IPS ship concept design studies and alternatives analysis. This QOS submodule could receive a power system architecture and list of components and their characteristics and then proceed to model system reliability and quality of service. As more refined information, such as mission profiles and equipment loads, is fed into it, the model would produce results with increasing confidence levels. It could be used either for the purpose of validating design work conducted in other sections of the main program, or alternatively for specifying requirements for components, redundancy, or system architecture to meet a stated QOS threshold. Whatever its purpose, the model would certainly add considerable value to any IPS design framework.

In Conclusion

The objectives of this study included the development of a basic simulation model for integrated power system Quality of Service, the evaluation of that model through a component reliability analysis, and the exploration of additional applications for the model. Each of these objectives was met, with the ultimate result being a flexible, open-architecture model that can be effectively employed in the examination of a multitude of different reliability and system architecture issues for IPS vessels. Quality of Service is a metric whose importance will continue to grow as warship design continues to evolve and incorporate new technologies. The model created in this study is a stepping stone toward the goal of fully understanding and predicting the factors that influence this metric and the successful operation of integrated power systems in warships.

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Appendix I – Ship Service Electrical Loads

Node	Zone	Name	Pwr Type	QOS Cat	Max Load	Max Marg Load	Summer Cruise	Winter Cruise	Summer Battle	Winter Battle	Anchor	Emerg ency	OF SC	OF WC	OF SB	OF WB	OF AN	OF EM
22	4	Gas Turbines - MTG1	450VAC	STI	18.0	23.4	3.0	3.0	3.0	3.0	18.0	3.0	0.50	0.55	0.99	0.99	0.10	0.30
23	5	Gas Turbines - MTG2	450VAC	STI	18.0	23.4	3.0	3.0	3.0	3.0	18.0	3.0	0.50	0.55	0.99	0.99	0.10	0.30
20	2	Gas Turbines - ATG1	450VAC	STI	2.0	2.6	0.3	0.3	0.3	0.3	2.0	0.3	0.50	0.30	0.99	0.99	0.55	0.60
21	3	Gas Turbines- ATG-2	450VAC	STI	2.0	2.6	0.3	0.3	0.3	0.3	2.0	0.3	0.50	0.30	0.99	0.99	0.55	0.60
24	6	Electric Propulsion - PMM1(non propulsive loads)	450VAC	STI	278.0	361.4	155.0	155.0	278.0	278.0	0.0	155.0	0.60	0.60	0.99	0.99	0.00	0.70
24	6	Electric Propulsion - PMM2(non propulsive loads)	450VAC	STI	278.0	361.4	155.0	155.0	278.0	278.0	0.0	155.0	0.60	0.60	0.99	0.99	0.00	0.70
36	6	Shafting - Shaft 1	450VAC	LTI	1.3	1.7	1.3	1.3	1.3	1.3	0.4	1.3	0.60	0.60	0.99	0.99	0.10	0.70
36	6	Shafting - Shaft 2	450VAC	LTI	1.3	1.7	1.3	1.3	1.3	1.3	0.4	1.3	0.60	0.60	0.99	0.99	0.10	0.70
22	4	Combustion Air System - MTG1	450VAC	STI	157.6	204.9	79.2	79.2	157.6	157.6	0.0	0.0	0.50	0.55	0.99	0.99	0.10	0.30
23	5	Combustion Air System - MTG2	450VAC	STI	157.6	204.9	79.2	79.2	157.6	157.6	0.0	0.0	0.50	0.55	0.99	0.99	0.10	0.30
20	2	Combustion Air System - ATG1	450VAC	STI	17.5	22.8	8.8	8.8	17.5	17.5	0.0	0.0	0.50	0.30	0.99	0.99	0.55	0.60
21	3	Combustion Air System - ATG2	450VAC	STI	17.5	22.8	8.8	8.8	17.5	17.5	0.0	0.0	0.50	0.30	0.99	0.99	0.55	0.60
8	6	Propulsion Control System	450VAC	UI	48.5	63.1	48.5	48.5	48.5	48.5	5.4	48.5	0.90	0.90	0.90	0.99	0.90	0.90
7	5	Secondary Propulsion Cntrl Sys	450VAC	UI	4.9	6.3	4.9	4.9	4.9	4.9	0.5	4.9	0.10	0.10	0.10	0.10	0.10	0.30
22	4	Circ + Cool Seawater - 1	450VAC	STI	140.9	183.2	133.8	133.8	140.9	140.9	133.8	140.9	0.67	0.67	0.75	0.75	0.50	0.25
23	5	Circ + Cool Seawater - 2	450VAC	STI	140.9	183.2	133.8	133.8	140.9	140.9	133.8	140.9	0.67	0.67	0.75	0.75	0.50	0.25
12	4	Circ + Cool Seawater Pump - 1	650VDC	STI	211.4	274.8	200.7	200.7	211.4	211.4	0.0	0.0	0.67	0.67	0.75	0.75	0.50	0.25
13	5	Circ + Cool Seawater Pump - 2	650VDC	STI	211.4	274.8	200.7	200.7	211.4	211.4	0.0	0.0	0.67	0.67	0.75	0.75	0.50	0.25
22	4	Main Propulsion lube oil - MTG1	450VAC	STI	48.8	63.5	48.8	48.8	48.8	48.8	48.8	48.8	0.50	0.55	0.99	0.99	0.10	0.30
23	5	Main Propulsion lube oil - MTG2	450VAC	STI	48.8	63.5	48.8	48.8	48.8	48.8	48.8	48.8	0.50	0.55	0.99	0.99	0.10	0.30
20	2	Main Propulsion lube oil - ATG1	450VAC	STI	5.4	7.1	5.4	5.4	5.4	5.4	5.4	5.4	0.50	0.30	0.99	0.99	0.55	0.60
21	3	Main Propulsion lube oil - ATG2	450VAC	STI	5.4	7.1	5.4	5.4	5.4	5.4	5.4	5.4	0.50	0.30	0.99	0.99	0.55	0.60
34	4	Lube oil handling - 1	450VAC	LTI	5.1	6.6	5.1	5.1	0.5	0.5	1.3	0.0	0.67	0.67	0.99	0.99	0.55	0.00
35	5	Lube oil handling - 2	450VAC	LTI	5.1	6.6	5.1	5.1	0.5	0.5	1.3	0.0	0.67	0.67	0.99	0.99	0.55	0.00
6	4	Ship Service Power Gen - MTG1	450VAC	UI	7.9	10.3	4.6	4.6	7.9	7.9	4.6	2.6	0.50	0.55	0.99	0.99	0.10	0.30
7	5	Ship Service Power Gen - MTG2	450VAC	UI	7.9	10.3	4.6	4.6	7.9	7.9	4.6	2.6	0.50	0.55	0.99	0.99	0.10	0.30
4	2	Ship Service Power Gen - ATG1	450VAC	UI	0.9	1.1	0.5	0.5	0.9	0.9	0.5	0.4	0.50	0.30	0.99	0.99	0.55	0.60
5	3	Ship Service Power Gen - ATG2	450VAC	UI	0.9	1.1	0.5	0.5	0.9	0.9	0.5	0.4	0.50	0.30	0.99	0.99	0.55	0.60
23	5	Batteries & Service Facil - 1	450VAC	STI	2.0	2.6	1.5	1.5	2.0	2.0	0.8	0.0	0.33	0.33	0.45	0.45	0.10	0.00
24	6	Batteries & Service Facil - 2	450VAC	STI	2.0	2.6	1.5	1.5	2.0	2.0	0.8	0.0	0.33	0.33	0.45	0.45	0.10	0.00
6	4	Power Conversion Equip - MTG1	450VAC	UI	6.0	7.8	6.0	6.0	6.0	6.0	2.2	3.0	0.50	0.55	0.99	0.99	0.10	0.30
7	5	Power Conversion Equip - MTG2	450VAC	UI	6.0	7.8	6.0	6.0	6.0	6.0	2.2	3.0	0.50	0.55	0.99	0.99	0.10	0.30
4	2	Power Conversion Equip - ATG1	450VAC	UI	0.7	0.9	0.7	0.7	0.7	0.7	0.2	0.3	0.50	0.30	0.99	0.99	0.55	0.60
5	3	Power Conversion Equip - ATG2	450VAC	UI	0.7	0.9	0.7	0.7	0.7	0.7	0.2	0.3	0.50	0.30	0.99	0.99	0.55	0.60
31	1	115V 60Hz misc loads - 1	450VAC	LTI	1.0	1.3	0.8	0.8	0.6	0.6	0.8	0.1	0.40	0.40	0.33	0.33	0.33	0.10
32	2	115V 60Hz misc loads - 2	450VAC	LTI	1.0	1.3	0.8	0.8	0.6	0.6	0.8	0.1	0.40	0.40	0.33	0.33	0.33	0.10
33	3	115V 60Hz misc loads - 3	450VAC	LTI	1.0	1.3	0.8	0.8	0.6	0.6	0.8	0.1	0.40	0.40	0.33	0.33	0.33	0.10
34	4	115V 60Hz misc loads - 4	450VAC	LTI	1.0	1.3	0.8	0.8	0.6	0.6	0.8	0.1	0.40	0.40	0.33	0.33	0.33	0.10
35	5	115V 60Hz misc loads - 5	450VAC	LTI	1.0	1.3	0.8	0.8	0.6	0.6	0.8	0.1	0.40	0.40	0.33	0.33	0.33	0.10
36	6	115V 60Hz misc loads - 6	450VAC	LTI	1.0	1.3	0.8	0.8	0.6	0.6	0.8	0.1	0.40	0.40	0.33	0.33	0.33	0.10
6	4	Switchgear & Panels - MTG1-1	450VAC	UI	213.3	277.3	213.3	213.3	213.3	213.3	0.0	0.0	0.50	0.55	0.99	0.99	0.10	0.30
6	4	Switchgear & Panels - MTG1-2	450VAC	UI	213.3	277.3	213.3	213.3	213.3	213.3	0.0	0.0	0.50	0.55	0.99	0.99	0.10	0.30
7	5	Switchgear & Panels - MTG2-1	450VAC	UI	213.3	277.3	213.3	213.3	213.3	213.3	0.0	0.0	0.50	0.55	0.99	0.99	0.10	0.30
7	5	Switchgear & Panels - MTG2-2	450VAC	UI	213.3	277.3	213.3	213.3	213.3	213.3	0.0	0.0	0.50	0.55	0.99	0.99	0.10	0.30
4	2	Switchgear & Panels - ATG1	450VAC	UI	47.4	61.6	47.4	47.4	47.4	47.4	0.0	0.0	0.50	0.30	0.99	0.99	0.55	0.60
5	3	Switchgear & Panels - ATG2	450VAC	UI	47.4	61.6	47.4	47.4	47.4	47.4	0.0	0.0	0.50	0.30	0.99	0.99	0.55	0.60
3	1	Switchgear & Panels - 1	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
3	1	Switchgear & Panels - 2	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
4	2	Switchgear & Panels - 3	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
4	2	Switchgear & Panels - 4	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
5	3	Switchgear & Panels - 5	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
5	3	Switchgear & Panels - 6	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
6	4	Switchgear & Panels - 7	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
6	4	Switchgear & Panels - 8	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
7	5	Switchgear & Panels - 9	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
7	5	Switchgear & Panels - 10	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
8	6	Switchgear & Panels - 11	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
8	6	Switchgear & Panels - 12	450VAC	UI	157.8	205.1	157.8	157.8	157.8	157.8	0.0	0.0	0.99	0.99	0.99	0.99	0.99	0.99
19	1	Zonal Lighting - 1	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
19	1	Zonal Lighting - 2	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
20	2	Zonal Lighting - 3	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
20	2	Zonal Lighting - 4	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
21	3	Zonal Lighting - 5	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
21	3	Zonal Lighting - 6	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
22	4	Zonal Lighting - 7	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
22	4	Zonal Lighting - 8	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
23	5	Zonal Lighting - 9	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
23	5	Zonal Lighting - 10	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
24	6	Zonal Lighting - 11	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
24	6	Zonal Lighting - 12	450VAC	STI	13.1	17.1	13.1	13.1	13.1	13.1	13.1	8.8	0.75	0.75	0.85	0.85	0.75	0.90
3	1	Data Processing Group - 1	450VAC	UI	217.9	283.2	217.9	217.9	217.9	217.9	43.6	0.0	0.75	0.75	0.90	0.90	0.33	0.00
4	2	Data Processing Group - 2	450VAC	UI	108.9	141.6	108.9	108.9	108.9	108.9	21.8	0.0	0.75	0.75	0.90	0.90	0.33	0.00
7	5	Data Processing Group - 3	450VAC	UI	108.9	141.6	108.9	108.9	108.9	108.9	21.8	0.0	0.75	0.75	0.90	0.90	0.33	0.00
5	3	Radio Systems Receive Group	450VAC	UI	45.6	59.3	45.6	45.6	45.6	45.6	27.3	22.8	0.99	0.99	0.99	0.99	0.99	0.99
4	2	Radio Systems Process Group	450VAC	UI	45.6	59.3	45.6	45.6	45.6	45.6	27.3	22.8	0.75	0.75	0.90	0.90	0.75	0.90
5	3	Radio Systems Transmit Group	450VAC	UI	136.9	178.0	136.7	136.7	136.9	136.9	82.0	68.5	0.15	0.15	0.33	0.33	0.10	0.25
5	3	Air Search Radar (2D)	450VAC	UI	2.7	3.5	2.7	2.7	2.4	2.4	0.0	2.0	0.90	0.90	0.99	0.99	0.00	0.50
5	3	Identification Systems	450VAC	UI	2.7	3.5	2.7	2.7	2.4	2.4	0.0	1.0	0.90	0.90	0.99	0.99	0.00	0.50
1	2	Multiple Mode Radar - 1	400Hz	UI	22.7	29.5	22.7	22.7	22.7	22.7	12.0	11.2	0.75	0.75	0.99	0.99	0.20	0.50
1	2	Multiple Mode Radar - 2	400Hz	UI	22.7	29.5	22.7	22.7	22.7	22.7	12.0	11.2	0.75	0.75	0.99	0.99	0.20	0.50
2	5	Multiple Mode Radar - 3	400Hz	UI	22.7	29.5	22.7	22.7	22.7	22.7	12.0	11.2	0.75	0.75	0.99	0.99	0.20	0.50
2	5	Multiple Mode Radar - 4	400Hz	UI	22.7	29.5	22.7	22.7	22.7	22.7	12.0	11.2	0.75	0.75	0.99	0.99	0.20	0.50

32	2	Non-Combat Data Processing - 2	450VAC	LTI	3.0	3.9	3.0	3.0	3.0	3.0	3.0	0.0	0.67	0.67	0.33	0.33	0.67	0.00
35	5	Non-Combat Data Processing - 3	450VAC	LTI	3.7	4.8	3.7	3.7	3.7	3.7	3.7	0.0	0.67	0.67	0.33	0.33	0.67	0.00
25	1	Compartment Heating Sys - 1	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
25	1	Compartment Heating Sys - 2	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
26	2	Compartment Heating Sys - 3	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
26	2	Compartment Heating Sys - 4	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
27	3	Compartment Heating Sys - 5	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
27	3	Compartment Heating Sys - 6	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
28	4	Compartment Heating Sys - 7	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
28	4	Compartment Heating Sys - 8	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
29	5	Compartment Heating Sys - 9	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
29	5	Compartment Heating Sys - 10	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
30	6	Compartment Heating Sys - 11	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
30	6	Compartment Heating Sys - 12	650VDC	LTI	47.6	61.9	4.0	47.6	4.8	38.4	47.6	0.0	0.10	0.50	0.10	0.50	0.33	0.00
31	1	Ventilation System - 1	450VAC	LTI	41.1	53.5	1.0	41.1	41.1	41.1	41.1	8.2	0.99	0.99	0.99	0.99	0.99	0.75
32	2	Ventilation System - 2	450VAC	LTI	41.1	53.5	1.0	41.1	41.1	41.1	41.1	8.2	0.99	0.99	0.99	0.99	0.99	0.75
33	3	Ventilation System - 3	450VAC	LTI	41.1	53.5	1.0	41.1	41.1	41.1	41.1	8.2	0.99	0.99	0.99	0.99	0.99	0.75
34	4	Ventilation System - 4	450VAC	LTI	41.1	53.5	1.0	41.1	41.1	41.1	41.1	8.2	0.99	0.99	0.99	0.99	0.99	0.75
35	5	Ventilation System - 5	450VAC	LTI	41.1	53.5	1.0	41.1	41.1	41.1	41.1	8.2	0.99	0.99	0.99	0.99	0.99	0.75
36	6	Ventilation System - 6	450VAC	LTI	41.1	53.5	1.0	41.1	41.1	41.1	41.1	8.2	0.99	0.99	0.99	0.99	0.99	0.75
32	2	Air Conditioning Plant - 1	450VAC	LTI	267.0	347.1	193.9	212.9	190.7	267.0	170.3	95.4	0.50	0.10	0.60	0.20	0.33	0.20
32	2	Air Conditioning Plant - 2	450VAC	LTI	267.0	347.1	193.9	212.9	190.7	267.0	170.3	95.4	0.50	0.10	0.60	0.20	0.33	0.20
33	3	Air Conditioning Plant - 3	450VAC	LTI	267.0	347.1	193.9	212.9	190.7	267.0	170.3	95.4	0.50	0.10	0.60	0.20	0.33	0.20
33	3	Air Conditioning Plant - 4	450VAC	LTI	267.0	347.1	193.9	212.9	190.7	267.0	170.3	95.4	0.50	0.10	0.60	0.20	0.33	0.20
26	2	AC Chill Water Pump - 1	650VDC	LTI	105.0	136.5	105.0	105.0	105.0	105.0	105.0	105.0	0.50	0.10	0.60	0.20	0.33	0.20
27	3	AC Chill Water Pump - 2	650VDC	LTI	105.0	136.5	105.0	105.0	105.0	105.0	105.0	105.0	0.50	0.10	0.60	0.20	0.33	0.20
32	2	Refrigeration Sys - 1	450VAC	LTI	1.7	2.1	1.7	1.7	1.7	1.7	1.7	0.0	0.20	0.20	0.20	0.20	0.20	0.00
32	2	Refrigeration Sys - 2	450VAC	LTI	1.7	2.1	1.7	1.7	1.7	1.7	1.7	0.0	0.20	0.20	0.20	0.20	0.20	0.00
33	3	Aux Boilers + other heat - 1	450VAC	LTI	24.0	31.2	24.0	24.0	1.8	1.8	24.0	0.0	0.33	0.33	0.33	0.33	0.33	0.00
34	4	Aux Boilers + other heat - 2	450VAC	LTI	24.0	31.2	24.0	24.0	1.8	1.8	24.0	0.0	0.33	0.33	0.33	0.33	0.33	0.00
9	1	Fire Pump - 1	650VDC	STI	101.0	131.3	101.0	101.0	101.0	101.0	101.0	101.0	0.20	0.20	0.40	0.40	0.10	0.40
10	2	Fire Pump - 2	650VDC	STI	101.0	131.3	101.0	101.0	101.0	101.0	101.0	101.0	0.20	0.20	0.40	0.40	0.10	0.40
11	3	Fire Pump - 3	650VDC	STI	101.0	131.3	101.0	101.0	101.0	101.0	101.0	101.0	0.20	0.20	0.40	0.40	0.10	0.40
12	4	Fire Pump - 4	650VDC	STI	101.0	131.3	101.0	101.0	101.0	101.0	101.0	101.0	0.20	0.20	0.40	0.40	0.10	0.40
13	5	Fire Pump - 5	650VDC	STI	101.0	131.3	101.0	101.0	101.0	101.0	101.0	101.0	0.20	0.20	0.40	0.40	0.10	0.40
14	6	Fire Pump - 6	650VDC	STI	101.0	131.3	101.0	101.0	101.0	101.0	101.0	101.0	0.20	0.20	0.40	0.40	0.10	0.40
33	3	Washdown Sys	450VAC	LTI	91.0	118.3	0.0	0.0	91.0	91.0	0.0	0.0	0.00	0.00	0.05	0.05	0.00	0.00
34	4	Drainage & Ballasting Sys	450VAC	LTI	2.1	2.7	2.1	2.1	0.0	0.0	1.0	0.0	0.20	0.20	0.00	0.00	0.20	0.00
33	3	Distilling Plant - 1	450VAC	LTI	26.7	34.7	26.7	26.7	0.0	0.0	26.7	0.0	0.25	0.25	0.00	0.00	0.10	0.00
34	4	Distilling Plant - 2	450VAC	LTI	26.7	34.7	26.7	26.7	0.0	0.0	26.7	0.0	0.25	0.25	0.00	0.00	0.10	0.00
21	3	Cooling Water - 1	450VAC	STI	96.0	124.7	96.0	96.0	96.0	96.0	96.0	48.0	0.33	0.33	0.67	0.67	0.33	0.25
11	3	Cooling Water Pump - 1	650VDC	STI	100.0	130.0	100.0	100.0	100.0	100.0	100.0	50.0	0.60	0.60	0.75	0.75	0.55	0.50
22	4	Cooling Water - 2	450VAC	STI	96.0	124.7	96.0	96.0	96.0	96.0	96.0	48.0	0.33	0.33	0.67	0.67	0.33	0.25
12	4	Cooling Water Pump - 2	650VDC	STI	100.0	130.0	100.0	100.0	100.0	100.0	100.0	50.0	0.60	0.60	0.75	0.75	0.55	0.50
27	3	Potable Water Pump- 1	650VDC	LTI	76.2	99.0	76.2	76.2	46.6	46.6	76.2	0.0	0.15	0.15	0.10	0.10	0.15	0.00
28	4	Potable Water Pump- 2	650VDC	LTI	76.2	99.0	76.2	76.2	46.6	46.6	76.2	0.0	0.15	0.15	0.10	0.10	0.15	0.00
26	2	Ship Fuel & Compensating - 1	650VDC	LTI	27.6	35.8	4.0	27.6	4.0	27.6	5.5	0.0	0.10	0.10	0.10	0.10	0.10	0.00
29	5	Ship Fuel & Compensating - 2	650VDC	LTI	27.6	35.8	4.0	27.6	4.0	27.6	5.5	0.0	0.10	0.10	0.10	0.10	0.10	0.00
31	1	Compressed Air Systems - 1	450VAC	LTI	17.7	23.0	13.8	13.8	17.7	17.7	13.8	0.0	0.10	0.10	0.20	0.20	0.10	0.00
32	2	Compressed Air Systems - 2	450VAC	LTI	17.7	23.0	13.8	13.8	17.7	17.7	13.8	0.0	0.10	0.10	0.20	0.20	0.10	0.00
35	5	Compressed Air Systems - 3	450VAC	LTI	18.0	23.4	14.0	14.0	18.0	18.0	14.0	0.0	0.10	0.10	0.20	0.20	0.10	0.00
8	6	Steering Control System	450VAC	UI	300.0	390.0	300.0	300.0	300.0	300.0	0.0	300.0	0.99	0.99	0.99	0.99	0.00	0.90
7	5	Secondary Steering Control System	450VAC	UI	22.2	28.9	22.2	22.2	22.2	22.2	0.0	22.2	0.99	0.99	0.99	0.99	0.00	0.90
31	1	Replenishment at Sea Sys - 1	450VAC	LTI	6.1	8.0	6.1	6.1	6.1	6.1	0.0	0.0	0.01	0.01	0.01	0.01	0.00	0.00
32	2	Replenishment at Sea Sys - 2	450VAC	LTI	8.4	10.9	8.4	8.4	8.4	8.4	0.0	0.0	0.01	0.01	0.01	0.01	0.00	0.00
36	6	Replenishment at Sea Sys - 3	450VAC	LTI	6.1	8.0	6.1	6.1	6.1	6.1	0.0	0.0	0.01	0.01	0.01	0.01	0.00	0.00
36	6	Environmental Pollution System	450VAC	LTI	6.0	7.8	5.0	5.0	5.0	5.0	6.0	0.0	0.10	0.10	0.05	0.05	0.15	0.00
31	1	Airports, fixed portlights - 1	450VAC	LTI	5.1	6.6	1.8	5.1	1.5	4.5	1.4	0.0	0.25	0.33	0.25	0.33	0.30	0.00
32	2	Airports, fixed portlights - 2	450VAC	LTI	5.1	6.6	1.8	5.1	1.5	4.5	1.4	0.0	0.25	0.33	0.25	0.33	0.30	0.00
33	3	Airports, fixed portlights - 3	450VAC	LTI	5.1	6.6	1.8	5.1	1.5	4.5	1.4	0.0	0.25	0.33	0.25	0.33	0.30	0.00
34	4	Airports, fixed portlights - 4	450VAC	LTI	5.1	6.6	1.8	5.1	1.5	4.5	1.4	0.0	0.25	0.33	0.25	0.33	0.30	0.00
35	5	Airports, fixed portlights - 5	450VAC	LTI	5.1	6.6	1.8	5.1	1.5	4.5	1.4	0.0	0.25	0.33	0.25	0.33	0.30	0.00
36	6	Airports, fixed portlights - 6	450VAC	LTI	5.1	6.6	1.8	5.1	1.5	4.5	1.4	0.0	0.25	0.33	0.25	0.33	0.30	0.00
35	5	Cathodic Protection - 1	450VAC	LTI	3.7	4.8	3.7	3.7	3.7	3.7	3.7	0.0	0.95	0.95	0.95	0.95	0.95	0.00
36	6	Cathodic Protection - 2	450VAC	LTI	3.7	4.8	3.7	3.7	3.7	3.7	3.7	0.0	0.95	0.95	0.95	0.95	0.95	0.00
31	1	Commissary Spaces - 1	450VAC	LTI	44.9	58.4	44.9	44.9	38.0	38.0	44.9	0.0	0.40	0.40	0.20	0.20	0.40	0.00
35	5	Commissary Spaces - 2	450VAC	LTI	44.9	58.4	44.9	44.9	38.0	38.0	44.9	0.0	0.40	0.40	0.20	0.20	0.40	0.00
36	6	Commissary Spaces - 3	450VAC	LTI	44.9	58.4	44.9	44.9	38.0	38.0	44.9	0.0	0.40	0.40	0.20	0.20	0.40	0.00
19	1	Medical Spaces - 1	450VAC	STI	2.0	2.6	0.0	0.0	2.0	2.0	0.0	2.0	0.00	0.00	0.50	0.50	0.00	0.67
24	6	Medical Spaces - 2	450VAC	STI	2.0	2.6	0.0	0.0	2.0	2.0	0.0	2.0	0.00	0.00	0.50	0.50	0.00	0.67
36	6	Laundry Spaces - 1	450VAC	LTI	30.0	39.0	30.0	30.0	0.0	0.0	30.0	0.0	0.20	0.20	0.00	0.00	0.20	0.00
36	6	Laundry Spaces - 2	450VAC	LTI	21.7	28.2	21.7	21.7	0.0	0.0	21.7	0.0	0.20	0.20	0.00	0.00	0.20	0.00
35	5	Trash Disposal Spaces	450VAC	LTI	0.9	1.2	0.9	0.9	0.0	0.0	0.9	0.0	0.05	0.05	0.00	0.00	0.05	0.00
31	1	Workshops, labs, test areas - 1	450VAC	LTI	1.6	2.0	1.6	1.6	0.0	0.0	1.6	0.0	0.25	0.25	0.00	0.00	0.25	0.00
32	2	Workshops, labs, test areas - 2	450VAC	LTI	1.6	2.0	1.6	1.6	0.0	0.0	1.6	0.0	0.25	0.25	0.00	0.00	0.25	0.00
36	6	Workshops, labs, test areas - 3	450VAC	LTI	1.6	2.0	1.6	1.6	0.0	0.0	1.6	0.0	0.25	0.25	0.00	0.00	0.25	0.00
19	1	Guns - AGS1	450VAC	STI	200.0	260.0	50.0	50.0	200.0	200.0	10.0	200.0	0.05	0.05	0.99	0.99	0.01	0.50
31	1	Ammo Hdlg - AGS1	450VAC	LTI	60.0	78.0	0.0	0.0	60.0	60.0	0.0	60.0	0.00	0.00	0.20	0.20	0.00	0.10
3	1	GFCS - AGS1	450VAC	UI	25.0	32.5	20.8	20.8	25.0	25.0	20.8	25.0	0.20	0.20	0.99	0.99	0.10	0.50
20	2	Guns - AGS2	450VAC	STI	200.0	260.0	50.0	50.0	200.0	200.0	10.0	200.0	0.05	0.05	0.99	0.99	0.01	0.50
32	2	Ammo Hdlg - AGS2	450VAC	LTI	60.0	78.0	0.0	0.0	60.0	60.0	0.0	60.0	0.00	0.00	0.20	0.20	0.00	0.10
4	2	GFCS - AGS2	450VAC	UI	25.0	32.5	20.0	20.0	25.0	25.0	20.0	25.0	0.20	0.20	0.99	0.99	0.10	0.50
22	4	Guns - 57mm - 1	450VAC	STI	5.0	6.5	5.0	5.0	5.0	5.0	5.0	5.0	0.20	0.20	0.99	0.99	0.75	0.50
23	5	Guns - 57mm - 2	450VAC	STI	5.0	6.5	5.0	5.0	5.0	5.0	5.0	5.0	0.20	0.20	0.99	0.99	0.75	0.50

Appendix II – Simulation Model Code

Mission Array Creation Module: missionmod

```
function mission = missionmod(duration,increment,anchor_fraction)
%MISSIONMODULE Mission creation module
%MISSIONMODULE(duration,increment) Generates a random mission lasting
%duration  hours, in time steps of  increment  seconds.  Outputs a 2
%column array of [Operating Condition; PMM Load] for each increment.
%MISSIONMODULE(duration,increment,anchor_fraction) specifies the maximum
%fraction of duration that will be spent at anchor.
%Default  increment = 300 sec;  anchor_fraction = 0.10

if nargin==1;    increment=300; anchor_fraction=.10;
elseif nargin==2;    anchor_fraction=.10;
end
inc=3600/increment; %creates a conversion factor with units 1/hr.

%Initial random sequence of Op Conditions generated
j= rand(duration,1);
A=j>=0;
B=j>.32;
C=j>.64;
D=j>.81;
E=j>.98;
op=A+B+C+D+2*E;%E is doubled to give op condition = 6

%Inserts # days at anchor as determined above - may be less if randint
%results in duplicated anchor day(s)
anchor=round(duration*anchor_fraction/24); %Max number of days at anchor
day=floor(duration/24);
inport=randint(anchor,1,[1,day]);
iphr=inport*24;
for p=1:length(iphr)
    op(iphr(p)-23:iphr(p))=5;
end

%Prevents switching directly between summer & winter Op Con's
op(duration+1)=0;
for k=1:duration
    if op(k)==1
        if op(k+1)==2;            op(k+1)=1;
        elseif op(k+1)==4;        op(k+1)=3;
        end
    elseif op(k)==3
        if op(k+1)==2;            op(k+1)=1;
        elseif op(k+1)==4;        op(k+1)=3;
        end
    elseif op(k)==2
        if op(k+1)==1;            op(k+1)=2;
        elseif op(k+1)==3;        op(k+1)=4;
        end
    elseif op(k)==4
        if op(k+1)==1;            op(k+1)=2;
        elseif op(k+1)==3;        op(k+1)=4;
```

```
        end
    end
end
op=op(1:duration);

%Expands op from hours to chosen increment, now called "opcon"
op=op';
opcon=op(ones(1,inc),:);%replaces function: opcon=repmat(op,inc,1);
opcon=opcon(:);

%Randomly generates propulsion loads at each increment
y=rand(length(opcon),1);
F=opcon<3; %cruise conditions
G=(opcon>2 & opcon <5); %battle conditions
H=opcon>5; %emergency condition
I=(F==1 & y>=.05 & y<.25); I=I*1730;
J=(F==1 & y>=.25 & y<.45); J=J*1903;
K=(F==1 & y>=.45 & y<.55); K=K*2595;
L=(F==1 & y>=.55 & y<.65); L=L*2855;
M=(F==1 & y>=.65 & y<.775); M=M*6055;
N=(F==1 & y>=.775 & y<.9); N=N*6667;
P=(F==1 & y>=.9 & y<.95); P=P*13840;
Q=(F==1 & y>=.95); Q=Q*13096;
R=(G==1 & y>=.05 & y<.3); R=R*1730;
S=(G==1 & y>=.3 & y<.7); S=S*6055;
T=(G==1 & y>=.7 & y<.85); T=T*13840;
U=(G==1 & y>=.85); U=U*67773;
V=(H==1 & y>=.35 & y<.5); V=V*1730;
W=(H==1 & y>=.5 & y<.65); W=W*1903;
X=(H==1 & y>=.65 & y<.725); X=X*2595;
Y=(H==1 & y>=.725 & y<.8); Y=Y*2855;
Z=(H==1 & y>=.8 & y<.825); Z=Z*6055;
AA=(H==1 & y>=.825 & y<.85); AA=AA*6667;
BB=(H==1 & y>=.85 & y<.925); BB=BB*13840;
CC=(H==1 & y>=.925); CC=CC*13096;
%sum above to get pmm load vector
pmm = I+J+K+L+M+N+P+Q+R+S+T+U+V+W+X+Y+Z+AA+BB+CC;

%output operating condition and pmm load at each increment
mission=[opcon pmm];
```

Power Load Array Creation Module: loadmod

```
function loadnode = loadmod(mission,PLMt)
%LOADMOD Load generator module
%LOADMOD(mission) takes the inputs from mission [opcon pmm] and outputs the
%load required at each load node for each increment as the
%(increments x nodes) array loadnode containing the node and required load
%for each increment.

opcon = mission(:,1);
pmm=mission(:,2);
inc=length(opcon);
A=rand(inc,193);%random array to compare with OFs to see if loads on or off
%Run loop to get individual loads by increment
```

```
B=zeros(inc,193);C=zeros(inc,193);%preallocate for loop speed!
for i=1:inc;
    if opcon(i)==1
        B(i,:)=(A(i,:)<PLMt(8,:));
        C(i,:)=B(i,:).*PLMt(2,:);
    elseif opcon(i)==2
        B(i,:)=(A(i,:)<PLMt(9,:));
        C(i,:)=B(i,:).*PLMt(3,:);
    elseif opcon(i)==3
        B(i,:)=(A(i,:)<PLMt(10,:));
        C(i,:)=B(i,:).*PLMt(4,:);
    elseif opcon(i)==4
        B(i,:)=(A(i,:)<PLMt(11,:));
        C(i,:)=B(i,:).*PLMt(5,:);
    elseif opcon(i)==5
        B(i,:)=(A(i,:)<PLMt(12,:));
        C(i,:)=B(i,:).*PLMt(6,:);
    elseif opcon(i)==6
        B(i,:)=(A(i,:)<PLMt(13,:));
        C(i,:)=B(i,:).*PLMt(7,:);
    end
end
%consolidate C into loads at each node by increment (node is column)
loadnode=zeros(inc,37);%preallocation
loadnode(:,1)=C(:,1)+C(:,2);
loadnode(:,2)=C(:,3)+C(:,4);
loadnode(:,3)=C(:,5)+C(:,6)+C(:,7)+C(:,8)+C(:,9)+C(:,10)+C(:,11);
loadnode(:,4)=C(:,12)+C(:,13)+C(:,14)+C(:,15)+C(:,16)+C(:,17)+C(:,18)+C(:,19)
;
loadnode(:,5)=C(:,20)+C(:,21)+C(:,22)+C(:,23)+C(:,24)+C(:,25)+C(:,26)+C(:,27)
+C(:,28);
loadnode(:,6)=C(:,29)+C(:,30)+C(:,31)+C(:,32)+C(:,33)+C(:,34);
loadnode(:,7)=C(:,35)+C(:,36)+C(:,37)+C(:,38)+C(:,39)+C(:,40)+C(:,41)+C(:,42)
+C(:,43);
loadnode(:,8)=C(:,44)+C(:,45)+C(:,46)+C(:,47)+C(:,48);
loadnode(:,9)=C(:,49);
loadnode(:,10)=C(:,50);
loadnode(:,11)=C(:,51)+C(:,52);
loadnode(:,12)=C(:,53)+C(:,54)+C(:,55);
loadnode(:,13)=C(:,56)+C(:,57);
loadnode(:,14)=C(:,58);
loadnode(:,15)=C(:,59)+C(:,60)+C(:,61)+C(:,62);
loadnode(:,16)=C(:,63)+C(:,64);
loadnode(:,17)=C(:,65)+C(:,66);
loadnode(:,18)=C(:,67)+C(:,68);
loadnode(:,19)=C(:,69)+C(:,70)+C(:,71)+C(:,72)+C(:,73)+C(:,74);
loadnode(:,20)=C(:,75)+C(:,76)+C(:,77)+C(:,78)+C(:,79)+C(:,80)+C(:,81);
loadnode(:,21)=C(:,82)+C(:,83)+C(:,84)+C(:,85)+C(:,86)+C(:,87)+C(:,88);
loadnode(:,22)=C(:,89)+C(:,90)+C(:,91)+C(:,92)+C(:,93)+C(:,94)+C(:,95)+C(:,96
);
loadnode(:,23)=C(:,97)+C(:,98)+C(:,99)+C(:,100)+C(:,101)+C(:,102)+C(:,103)+C(
:,104);
loadnode(:,24)=C(:,105)+C(:,106)+C(:,107)+C(:,108)+C(:,109)+C(:,110)+C(:,111)
;
loadnode(:,25)=C(:,112)+C(:,113);
loadnode(:,26)=C(:,114)+C(:,115)+C(:,116)+C(:,117);
loadnode(:,27)=C(:,118)+C(:,119)+C(:,120)+C(:,121);
```

```
loadnode(:,28)=C(:,122)+C(:,123)+C(:,124);
loadnode(:,29)=C(:,125)+C(:,126)+C(:,127);
loadnode(:,30)=C(:,128)+C(:,129);
loadnode(:,31)=C(:,130)+C(:,131)+C(:,132)+C(:,133)+C(:,134)+C(:,135)+C(:,136)
+C(:,137)+C(:,138)+C(:,139)+C(:,140);
loadnode(:,32)=C(:,141)+C(:,142)+C(:,143)+C(:,144)+C(:,145)+C(:,146)+C(:,147)
+C(:,148)+C(:,149)+C(:,150)+C(:,151)+C(:,152)+C(:,153)+C(:,154);
loadnode(:,33)=C(:,155)+C(:,156)+C(:,157)+C(:,158)+C(:,159)+C(:,160)+C(:,161)
+C(:,162)+C(:,163);
loadnode(:,34)=C(:,164)+C(:,165)+C(:,166)+C(:,167)+C(:,168)+C(:,169)+C(:,170)
;
loadnode(:,35)=C(:,171)+C(:,172)+C(:,173)+C(:,174)+C(:,175)+C(:,176)+C(:,177)
+C(:,178)+C(:,179);
loadnode(:,36)=C(:,180)+C(:,181)+C(:,182)+C(:,183)+C(:,184)+C(:,185)+C(:,186)
+C(:,187)+C(:,188)+C(:,189)+C(:,190)+C(:,191)+C(:,192)+C(:,193);
loadnode(:,37)=pmm;
```

Power Generation Capacity Array Creation Module: pgmmod

```
function pwrgen = pgmmod(mission,MTBF)
%PGMMOD Power generation simulation module
%PGMMOD(mission) takes the inputs from mission [opcon pmm] and outputs the
%available power produced by the pgm for each increment as the column
%vector pwrgen.  Module includes PGM availability based on ship operating
%condition, PGM faults, repairs, and standby PGM.

opcon = mission(:,1);
inc=length(opcon);
%Set PGM Reliability and Maintenance means
mtbf=MTBF(1)*12*ones(10,4);%Default  MTBF  per  PGM  is  1000  hrs,  5  min
increments
mttr=5*12*ones(10,4);%Default MTTR per PGM is 5 hrs

%Set engines ON array pgm: 1 MTG for Cruise, 2 MTG for Battle, 2 ATG for
%Anchor, 1 ATG for Emergency
pgm=zeros(inc,4); %preallocate 4 columns for engines [MTG MTG ATG ATG]
for i=1:inc;
    if opcon(i)==1 || opcon(i)== 2
        pgm(i,1)= (1);
    elseif opcon(i)==3 || opcon(i)== 4
        pgm(i,1:2)= (1);
    elseif opcon(i)== 5
        pgm(i,3:4)= (1);
    elseif opcon(i)== 6
        pgm(i,3)= (1);
    end
end

%Create Random Engine Failures & Repairs (exponential distribution)
lambda=1./mtbf;
mu=1./mttr;
u=rand(10,4);
TF=ceil(-log(u)./lambda);
u=rand(10,4);
TR=ceil(-log(u)./mu);TA=TR;
```

```
TR(1,:)=TF(1,:)+TR(1,:);
for j=2:10
    TF(j,:)=TR(j-1,:)+TF(j,:);
    TR(j,:)=TF(j,:)+TR(j,:);
end
TA=TF+TA;%increment available following repair

%Insert Failures into array pgm
for i=1:10
    for j=1:4
        pgm(TF(i,j):TA(i,j),j)=(0);
    end
end
pgm=(pgm(1:inc,:));

%Bring standby pgm online 5 min after failure
for i=1:inc
    if opcon(i)==1 || opcon(i)== 2
        if pgm(i,1)==0
            pgm(i+1,2)=(1);
        end
    elseif opcon(i)==3 || opcon(i)== 4
        if pgm(i,1)==0 || pgm(i,2)==0
            pgm(i+1,3:4)=(1);
        end
    elseif opcon(i)== 5
        if pgm(i,3)==0 || pgm(i,4)==0
            pgm(i+1,1)=(1);
        end
    elseif opcon(i)== 6
        if pgm(i,3)==0
            pgm(i+1,4)=(1);
        end
    end
end

%create output, column vector pwrgen of available power from PGMs
pgm(:,1:2)=36000*pgm(:,1:2);
pgm(:,3:4)=3940*pgm(:,3:4);
pwrgen=cumsum(pgm,2);
pwrgen=pwrgen(:,4);
pwrgen=pwrgen(1:inc);
```

Power System Availability Array Creation Module: relymod

```
function avail = relymod(mission,MTBF)
%RELYMOD Component Reliability generation module
%RELYMOD(mission,MTBF) takes the opcon input from mission and the input
%array MTBF of components and failure rates and generates a random set of
%component failures during the mission duration.  The component repair time
%is a constant, set within RELYMOD.  The output is the array avail of
%component availability status (1 or 0) for each increment.

opcon = mission(:,1);
inc=length(opcon);
```

```
MTBF=MTBF(2:172);
RT=5;%number of increments to repair component (total downtime is RT+1)

%Generate random time to failure for each component using exponential dist
lambda=1./(MTBF*12);%12 expands to 5 min increments
u=rand(length(MTBF),1);
TF=ceil(-log(u)./lambda);
TF=min(TF,inc+1);%makes inc+1 the upper bound for TF, will cut off later

%Insert failures into
avail=ones(inc+1,171);
avail(TF(1),1)=0;
avail(TF(2),2)=0;
avail(TF(3),3)=0;
for i=4:171
    avail(TF(i):TF(i)+RT,i)=0;
end
avail(inc+1:inc+1+RT,:)=[];
```

Power System Operational Evaluation Module: pwrsysmod

```
function pwrnode = pwrsysmod(avail)
%PWRSYSMOD Power System Evaluation Module
%PWRSYSMOD(avail) evaluates the power system
%for the supplied component availability, and outputs the array pwrnode
%containing the available power at each node for each increment.

opcon = avail(:,1);
inc=length(opcon);
pwrnode=zeros(inc,37);%for output column 37 is for total bus power below
                      %but will be changed to pmm pwr available in qosmod

%PCM-4 failures accounted for and impact on Port/Stbd busses
port=ones(inc,1);
stbd=ones(inc,1);
for i=1:inc
    if avail(i,1)==1 && avail(i,2)==1 && avail(i,3)==1
    elseif avail(i,1)==0 || avail(i,3)==0
    port(i)=0;
    elseif avail(i,2)==0
    stbd(i)=0;
    end
end
pwrnode(:,37)=6880*(port+stbd);%6880KW capacity per PCM-4, 1 PCM-4 per bus
cap=300*avail;%300KW capacity per SSCM/SSIM

%Zone 1
%available sscm capacity per increment
sscm650p_1=port.*sum(cap(:,4),2);%can remove sum if only 1 column
sscm650s_1=stbd.*sum(cap(:,9),2);
sscm800p_1=port.*sum(cap(:,5:8),2);
sscm800s_1=stbd.*sum(cap(:,10:13),2);
%available ssim capacity per increment
ssim400_1=sum(cap(:,14:15),2);
ssim60_1=min(sum(cap(:,16:21),2),sscm800p_1+sscm800s_1-ssim400_1);
```

```
%max available power at nodes per increment
pwrnode(:,3)=avail(:,25).*ssim60_1;%60UI
pwrnode(:,9)=avail(:,22).*(sscm650p_1+sscm650s_1);%650STI
pwrnode(:,15)=avail(:,24).*ssim400_1;%400STI
pwrnode(:,19)=avail(:,26).*ssim60_1;%60STI
pwrnode(:,25)=avail(:,23).*(sscm650p_1+sscm650s_1);%650LTI
pwrnode(:,31)=avail(:,27).*ssim60_1;%60LTI

%Zone 2
%available sscm capacity per increment
sscm650p_2=port.*sum(cap(:,28),2);%can remove sum if only 1 column
sscm650s_2=stbd.*sum(cap(:,34),2);
sscm800p_2=port.*sum(cap(:,29:33),2);
sscm800s_2=stbd.*sum(cap(:,35:39),2);
%available ssim capacity per increment
ssim400_2=sum(cap(:,40:41),2);
ssim60_2=min(sum(cap(:,42:49),2),sscm800p_2+sscm800s_2-ssim400_2);
%max available power at nodes per increment
pwrnode(:,1)=avail(:,52).*ssim400_2;%400UI
pwrnode(:,4)=avail(:,54).*ssim60_2;%60UI
pwrnode(:,10)=avail(:,50).*(sscm650p_2+sscm650s_2);%650STI
pwrnode(:,16)=avail(:,53).*ssim400_2;%400STI
pwrnode(:,20)=avail(:,55).*ssim60_2;%60STI
pwrnode(:,26)=avail(:,51).*(sscm650p_2+sscm650s_2);%650LTI
pwrnode(:,32)=avail(:,56).*ssim60_2;%60LTI

%Zone 3
%available sscm capacity per increment
sscm650p_3=port.*sum(cap(:,57:58),2);%can remove sum if only 1 column
sscm650s_3=stbd.*sum(cap(:,64:65),2);
sscm800p_3=port.*sum(cap(:,59:63),2);
sscm800s_3=stbd.*sum(cap(:,66:70),2);
%available ssim capacity per increment
ssim60_3=min(sum(cap(:,71:78),2),sscm800p_3+sscm800s_3);
%max available power at nodes per increment
pwrnode(:,5)=avail(:,81).*ssim60_3;%60UI
pwrnode(:,11)=avail(:,79).*(sscm650p_3+sscm650s_3);%650STI
pwrnode(:,21)=avail(:,82).*ssim60_3;%60STI
pwrnode(:,27)=avail(:,80).*(sscm650p_3+sscm650s_3);%650LTI
pwrnode(:,33)=avail(:,83).*ssim60_3;%60LTI

%Zone 4
%available sscm capacity per increment
sscm650p_4=port.*sum(cap(:,84:85),2);%can remove sum if only 1 column
sscm650s_4=stbd.*sum(cap(:,91:92),2);
sscm800p_4=port.*sum(cap(:,86:90),2);
sscm800s_4=stbd.*sum(cap(:,93:97),2);
%available ssim capacity per increment
ssim60_4=min(sum(cap(:,98:105),2),sscm800p_4+sscm800s_4);
%max available power at nodes per increment
pwrnode(:,6)=avail(:,108).*ssim60_4;%60UI
pwrnode(:,12)=avail(:,106).*(sscm650p_4+sscm650s_4);%650STI
pwrnode(:,22)=avail(:,109).*ssim60_4;%60STI
pwrnode(:,28)=avail(:,107).*(sscm650p_4+sscm650s_4);%650LTI
pwrnode(:,34)=avail(:,110).*ssim60_4;%60LTI

%Zone 5
```

```
%available sscm capacity per increment
sscm650p_5=port.*sum(cap(:,111:112),2);%can remove sum if only 1 column
sscm650s_5=stbd.*sum(cap(:,119:120),2);
sscm800p_5=port.*sum(cap(:,113:118),2);
sscm800s_5=stbd.*sum(cap(:,121:126),2);
%available ssim capacity per increment
ssim400_5=sum(cap(:,127:128),2);
ssim60_5=min(sum(cap(:,129:136),2),sscm800p_5+sscm800s_5-ssim400_5);
%max available power at nodes per increment
pwrnode(:,2)=avail(:,139).*ssim400_5;%400UI
pwrnode(:,7)=avail(:,141).*ssim60_5;%60UI
pwrnode(:,13)=avail(:,137).*(sscm650p_5+sscm650s_5);%650STI
pwrnode(:,17)=avail(:,140).*ssim400_5;%400STI
pwrnode(:,23)=avail(:,142).*ssim60_5;%60STI
pwrnode(:,29)=avail(:,138).*(sscm650p_5+sscm650s_5);%650LTI
pwrnode(:,35)=avail(:,143).*ssim60_5;%60LTI

%Zone 6
%available sscm capacity per increment
sscm650p_6=port.*sum(cap(:,144),2);%can remove sum if only 1 column
sscm650s_6=stbd.*sum(cap(:,150),2);
sscm800p_6=port.*sum(cap(:,145:149),2);
sscm800s_6=stbd.*sum(cap(:,151:155),2);
%available ssim capacity per increment
ssim400_6=sum(cap(:,156:157),2);
ssim60_6=min(sum(cap(:,158:165),2),sscm800p_6+sscm800s_6-ssim400_6);
%max available power at nodes per increment
pwrnode(:,8)=avail(:,169).*ssim60_6;%60UI
pwrnode(:,14)=avail(:,166).*(sscm650p_6+sscm650s_6);%650STI
pwrnode(:,18)=avail(:,168).*ssim400_6;%400STI
pwrnode(:,24)=avail(:,170).*ssim60_6;%60STI
pwrnode(:,30)=avail(:,167).*(sscm650p_6+sscm650s_6);%650LTI
pwrnode(:,36)=avail(:,171).*ssim60_6;%60LTI
```

Quality of Service Failure Evaluation Module: qosmod

```
function QOS = qosmod(loadnode,pwrnode,pwrgen)
%QOSMOD Quality of Service Evaluation module
%QOSMOD(loadnode,pwrnode) Compares the input arrays and determines (1)if a
%QOS failure has occurred, (2)when it occurred, and (3)at which node.
%Outputs an array of nodes and increments that experience a QOS failure.

inc=length(pwrgen);
%bustotal=pwrnode(:,37);%total pwr from port & stbd busses
ssreq=sum(loadnode(:,1:36),2);%total pwr req for ship service use
pwrnode(:,37)=pwrgen-ssreq;%pwr available for pmm use
%busfail=max(ssreq-bustotal,0);%amount to shed due to bus loss (PCM-4 fail)
loadnode(:,37)=min(loadnode(:,37),43880);%cut off qos "exempt" pmm load

A=loadnode > pwrnode;%
B=A(2:inc,25:37);B(inc,1:13)=zeros(1,13);
A(:,25:37)=(A(:,25:37) & B);
[I,J]=find(A);

QOS=[I J];
```

Master Simulation Module: Monte_XX

```
%Monte_XX
%Performs the Monte Carlo Simulation and gathers relevant statistical data
%for the MCS for experiment number XX.  **Must change input MAT-file
%MTBF_XX below and also SAVE filename Monte_XX at bottom for each trial XX.
%Note:uses function randint.m from Communications Toolbox

clear all; clc
load PLMt;
load MTBF_XX;
runs=1000;%# of simulation runs

%loop to conduct desired number of runs through IPS sim model
incfail=zeros(500,runs);%preallocate
nodefail=zeros(500,runs);
numfail=zeros(1,runs);
firstfail=zeros(1,runs);
pmnumfail=zeros(1,runs);
pmfirstfail=zeros(1,runs);
for i=1:runs
    mission = missionmod(4380);

    pwrgen=pgmmod(mission,MTBF);

    loadnode=loadmod(mission,PLMt);

    avail = relymod(mission,MTBF);

    pwrnode = pwrsysmod(avail);

    QOS=qosmod(loadnode,pwrnode,pwrgen);

    incfail(1:length(QOS),i)=QOS(:,1);%increments of failure for run
    nodefail(1:length(QOS),i)=QOS(:,2);%nodes of failure for run
    numfail(i)=length(QOS);%number of failures for run
    firstfail(i)=min(QOS(:,1));%increment of first failure for run
    %now exclude pmm failures
    pmcanx=(QOS(:,2)~=37);
    pmqos=QOS(:,1).*pmcanx;
    pmqos(pmqos==0)=[];
    pmnumfail(i)=length(pmqos);
    if ~isempty(pmqos)
        pmfirstfail(i)=(min(pmqos));
    else
        pmfirstfail(i)=length(pwrgen);
    end
end

%compile data for all QOS failures
ifail=incfail(:);
ifail(ifail==0)=[];
nfail=nodefail(:);
nfail(nfail==0)=[];
fail(:,1)=ifail(:);
fail(:,2)=nfail(:);
%compile data excluding pmm QOS failures
```

```
pmcanx=(nfail~=37);
ifail=ifail.*pmcanx;
ifail(ifail==0)=[];
nfail=nfail.*pmcanx;
nfail(nfail==0)=[];
pmfail(:,1)=ifail(:);
pmfail(:,2)=nfail(:);

%Calculate and save relevant statistical data
%mean first failure
FirstFail=mean(firstfail);
%mean first failure excluding PMM failures
FirstFail_noPMM=mean(pmfirstfail);
%mean # failures
NumFail=mean(numfail);
%mean # failures excluding PMM failures
NumFail_noPMM=mean(pmnumfail);
%percent of failures at each node
n=histc(fail(:,2),1:37);
NodePct=100*n/length(fail);
NodeMaxModePct=[find(n==max(n)) max(n) max(NodePct)];
%percent of failures at each node excluding PMM failures
npm=histc(pmfail(:,2),1:36);
NodePct_noPMM=100*npm/length(pmfail);
NodeMaxModePct_noPMM=[find(npm==max(npm)) max(npm) max(NodePct_noPMM)];

%Save a MAT-file of the simulation statistical results (* includes _noPMM)
save('Data_XX',  'FirstFail*',  'NumFail*',  'n',  'npm',  'Node*',  'fail',
'pmfail');
```

Appendix III – Simulation Output Data

Trial 1			Trial 2			Trial 3		
FirstFail	883.027		FirstFail	843.189		FirstFail	904.532	
FirstFail_noPM	7320.271		FirstFail_noPM	7160.093		FirstFail_noPM	10936.555	
NumFail	133.599		NumFail	134.253		NumFail	124.567	
NumFail_noPM	30.025		NumFail_noPM	29.841		NumFail_noPM	20.324	
	NodeMaxModePct			NodeMaxModePct			NodeMaxModePct	
37	103574	77.52602939	37	104412	77.77256374	37	104243	83.68428235
	NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM	
5	1272	4.236469609	4	1407	4.714989444	4	898	4.418421571
n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM
973.00	0.73	3.24	1102.00	0.82	3.69	729.00	0.59	3.59
1048.00	0.78	3.49	967.00	0.72	3.24	637.00	0.51	3.13
1152.00	0.86	3.84	1113.00	0.83	3.73	760.00	0.61	3.74
1153.00	0.86	3.84	1407.00	1.05	4.71	898.00	0.72	4.42
1272.00	0.95	4.24	1222.00	0.91	4.10	828.00	0.66	4.07
972.00	0.73	3.24	1207.00	0.90	4.04	835.00	0.67	4.11
1167.00	0.87	3.89	1148.00	0.86	3.85	739.00	0.59	3.64
1219.00	0.91	4.06	1249.00	0.93	4.19	853.00	0.68	4.20
264.00	0.20	0.88	293.00	0.22	0.98	212.00	0.17	1.04
364.00	0.27	1.21	275.00	0.20	0.92	199.00	0.16	0.98
888.00	0.66	2.96	874.00	0.65	2.93	500.00	0.40	2.46
1022.00	0.76	3.40	976.00	0.73	3.27	723.00	0.58	3.56
835.00	0.63	2.78	790.00	0.59	2.65	620.00	0.50	3.05
329.00	0.25	1.10	311.00	0.23	1.04	202.00	0.16	0.99
615.00	0.46	2.05	532.00	0.40	1.78	420.00	0.34	2.07
554.00	0.41	1.85	464.00	0.35	1.55	356.00	0.29	1.75
528.00	0.40	1.76	435.00	0.32	1.46	348.00	0.28	1.71
456.00	0.34	1.52	526.00	0.39	1.76	391.00	0.31	1.92
1028.00	0.77	3.42	1146.00	0.85	3.84	777.00	0.62	3.82
1155.00	0.86	3.85	1189.00	0.89	3.98	807.00	0.65	3.97
1216.00	0.91	4.05	1106.00	0.82	3.71	743.00	0.60	3.66
1079.00	0.81	3.59	1128.00	0.84	3.78	798.00	0.64	3.93
1256.00	0.94	4.18	1199.00	0.89	4.02	762.00	0.61	3.75
1235.00	0.92	4.11	1164.00	0.87	3.90	760.00	0.61	3.74
275.00	0.21	0.92	245.00	0.18	0.82	186.00	0.15	0.92
541.00	0.40	1.80	476.00	0.35	1.60	287.00	0.23	1.41
522.00	0.39	1.74	573.00	0.43	1.92	370.00	0.30	1.82
359.00	0.27	1.20	303.00	0.23	1.02	204.00	0.16	1.00
308.00	0.23	1.03	325.00	0.24	1.09	224.00	0.18	1.10
337.00	0.25	1.12	304.00	0.23	1.02	148.00	0.12	0.73
936.00	0.70	3.12	873.00	0.65	2.93	618.00	0.50	3.04
906.00	0.68	3.02	900.00	0.67	3.02	653.00	0.52	3.21
1048.00	0.78	3.49	1007.00	0.75	3.37	665.00	0.53	3.27
977.00	0.73	3.25	1031.00	0.77	3.45	647.00	0.52	3.18
1041.00	0.78	3.47	1036.00	0.77	3.47	710.00	0.57	3.49
995.00	0.74	3.31	945.00	0.70	3.17	715.00	0.57	3.52
103574.00	77.53		104412.00	77.77		104243.00	83.68	

Trial 4			Trial 5			Trial 6		
FirstFail	831.639		FirstFail	836.032		FirstFail	825.921	
FirstFail_noPMM	8134.903		FirstFail_noPMM	5093.827		FirstFail_noPMM	5977.307	
NumFail	129.775		NumFail	146.797		NumFail	138.683	
NumFail_noPM	25.979		NumFail_noPM	43.223		NumFail_noPM	34.271	
NodeMaxModePct			NodeMaxModePct			NodeMaxModePct		
37	103796	79.98150645	37	103574	70.55593779	37	104412	75.2882473
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
12	1693	6.516802032	24	2192	5.071374037	1	1997	5.827084124
n	NodePct	NodePct_noPMM	n	NodePct	NodePct_noPMM	n	NodePct	NodePct_noPMM
1098.00	0.85	4.23	629.00	0.43	1.46	1997.00	1.44	5.83
1028.00	0.79	3.96	717.00	0.49	1.66	1895.00	1.37	5.53
686.00	0.53	2.64	2040.00	1.39	4.72	1113.00	0.80	3.25
778.00	0.60	2.99	2023.00	1.38	4.68	1407.00	1.01	4.11
882.00	0.68	3.40	2112.00	1.44	4.89	1222.00	0.88	3.57
823.00	0.63	3.17	1813.00	1.24	4.19	1207.00	0.87	3.52
720.00	0.55	2.77	2001.00	1.36	4.63	1148.00	0.83	3.35
851.00	0.66	3.28	2088.00	1.42	4.83	1248.00	0.90	3.64
530.00	0.41	2.04	264.00	0.18	0.61	197.00	0.14	0.57
508.00	0.39	1.96	364.00	0.25	0.84	186.00	0.13	0.54
1456.00	1.12	5.60	888.00	0.60	2.05	522.00	0.38	1.52
1693.00	1.30	6.52	1022.00	0.70	2.36	682.00	0.49	1.99
1551.00	1.20	5.97	835.00	0.57	1.93	594.00	0.43	1.73
566.00	0.44	2.18	329.00	0.22	0.76	210.00	0.15	0.61
612.00	0.47	2.36	407.00	0.28	0.94	1125.00	0.81	3.28
491.00	0.38	1.89	346.00	0.24	0.80	1005.00	0.72	2.93
495.00	0.38	1.91	318.00	0.22	0.74	896.00	0.65	2.61
492.00	0.38	1.89	307.00	0.21	0.71	907.00	0.65	2.65
796.00	0.61	3.06	2087.00	1.42	4.83	1146.00	0.83	3.34
712.00	0.55	2.74	1982.00	1.35	4.59	1189.00	0.86	3.47
849.00	0.65	3.27	2185.00	1.49	5.06	1106.00	0.80	3.23
774.00	0.60	2.98	1997.00	1.36	4.62	1128.00	0.81	3.29
852.00	0.66	3.28	2132.00	1.45	4.93	1199.00	0.86	3.50
786.00	0.61	3.03	2192.00	1.49	5.07	1164.00	0.84	3.40
251.00	0.19	0.97	162.00	0.11	0.37	553.00	0.40	1.61
487.00	0.38	1.87	327.00	0.22	0.76	893.00	0.64	2.61
443.00	0.34	1.71	350.00	0.24	0.81	999.00	0.72	2.92
391.00	0.30	1.51	230.00	0.16	0.53	550.00	0.40	1.60
354.00	0.27	1.36	229.00	0.16	0.53	518.00	0.37	1.51
284.00	0.22	1.09	213.00	0.15	0.49	473.00	0.34	1.38
620.00	0.48	2.39	1848.00	1.26	4.28	873.00	0.63	2.55
539.00	0.42	2.07	1756.00	1.20	4.06	900.00	0.65	2.63
595.00	0.46	2.29	1713.00	1.17	3.96	1007.00	0.73	2.94
595.00	0.46	2.29	1735.00	1.18	4.01	1031.00	0.74	3.01
681.00	0.52	2.62	1786.00	1.22	4.13	1036.00	0.75	3.02
710.00	0.55	2.73	1796.00	1.22	4.16	945.00	0.68	2.76
103796.00	79.98		103574.00	70.56		104412.00	75.29	

Trial 7			**Trial 8**			**Trial 9**		
FirstFail	839.075		FirstFail	878.144		FirstFail	785.987	
FirstFail_noPM	7373.092		FirstFail_noPM	6522.853		FirstFail_noPM	4849.625	
NumFail	133.969		NumFail	132.8		NumFail	148.43	
NumFail_noPM	30.329		NumFail_noPM	29.226		NumFail_noPM	44.018	
NodeMaxModePct			NodeMaxModePct			NodeMaxModePct		
37	103640	77.36118057	37	103574	77.99246988	37	104412	70.34427003
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
12	1751	5.773352237	2	1939	6.634503524	4	2314	5.256940343
n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM
793.00	0.59	2.61	1829.00	1.38	6.26	1102.00	0.74	2.50
769.00	0.57	2.54	1939.00	1.46	6.63	967.00	0.65	2.20
1023.00	0.76	3.37	714.00	0.54	2.44	1992.00	1.34	4.53
1100.00	0.82	3.63	800.00	0.60	2.74	2314.00	1.56	5.26
1254.00	0.94	4.13	924.00	0.70	3.16	2124.00	1.43	4.83
1182.00	0.88	3.90	689.00	0.52	2.36	2058.00	1.39	4.68
1106.00	0.83	3.65	884.00	0.67	3.02	2056.00	1.39	4.67
1246.00	0.93	4.11	861.00	0.65	2.95	2090.00	1.41	4.75
532.00	0.40	1.75	264.00	0.20	0.90	197.00	0.13	0.45
501.00	0.37	1.65	364.00	0.27	1.25	186.00	0.13	0.42
1416.00	1.06	4.67	888.00	0.67	3.04	522.00	0.35	1.19
1751.00	1.31	5.77	1022.00	0.77	3.50	682.00	0.46	1.55
1614.00	1.20	5.32	835.00	0.63	2.86	594.00	0.40	1.35
552.00	0.41	1.82	329.00	0.25	1.13	210.00	0.14	0.48
403.00	0.30	1.33	1107.00	0.83	3.79	532.00	0.36	1.21
312.00	0.23	1.03	871.00	0.66	2.98	464.00	0.31	1.05
321.00	0.24	1.06	834.00	0.63	2.85	435.00	0.29	0.99
333.00	0.25	1.10	969.00	0.73	3.32	526.00	0.35	1.19
1167.00	0.87	3.85	696.00	0.52	2.38	1960.00	1.32	4.45
1055.00	0.79	3.48	844.00	0.64	2.89	2010.00	1.35	4.57
1212.00	0.90	4.00	838.00	0.63	2.87	2089.00	1.41	4.75
1098.00	0.82	3.62	683.00	0.51	2.34	2008.00	1.35	4.56
1278.00	0.95	4.21	875.00	0.66	2.99	2108.00	1.42	4.79
1130.00	0.84	3.73	859.00	0.65	2.94	2038.00	1.37	4.63
185.00	0.14	0.61	547.00	0.41	1.87	245.00	0.17	0.56
309.00	0.23	1.02	909.00	0.68	3.11	476.00	0.32	1.08
306.00	0.23	1.01	955.00	0.72	3.27	573.00	0.39	1.30
254.00	0.19	0.84	656.00	0.49	2.24	303.00	0.20	0.69
250.00	0.19	0.82	562.00	0.42	1.92	325.00	0.22	0.74
172.00	0.13	0.57	569.00	0.43	1.95	303.00	0.20	0.69
999.00	0.75	3.29	652.00	0.49	2.23	1650.00	1.11	3.75
889.00	0.66	2.93	595.00	0.45	2.04	1674.00	1.13	3.80
869.00	0.65	2.87	686.00	0.52	2.35	1854.00	1.25	4.21
966.00	0.72	3.19	750.00	0.56	2.57	1842.00	1.24	4.18
934.00	0.70	3.08	727.00	0.55	2.49	1781.00	1.20	4.05
1048.00	0.78	3.46	700.00	0.53	2.40	1728.00	1.16	3.93
103640.00	77.36		103574.00	77.99		104412.00	70.34	

Trial 10			Trial 11			Trial 12		
FirstFail	853.243		FirstFail	862.933		FirstFail	814.667	
FirstFail_noPM	6292.441		FirstFail_noPM	5680.406		FirstFail_noPM	6070.783	
NumFail	133.637		NumFail	137.766		NumFail	136.736	
NumFail_noPM	33.178		NumFail_noPM	36.149		NumFail_noPM	35.14	
NodeMaxModePct			NodeMaxModePct			NodeMaxModePct		
37	100459	75.17304339	37	101617	73.76057953	37	101596	74.3008425
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
8	2183	6.579661221	1	1968	5.444134001	22	2219	6.314741036
n	NodePct	odePct_noPM	n	NodePct	odePct_noPM	n	NodePct	odePct_noPM
793.00	0.59	2.39	1968.00	1.43	5.44	1209.00	0.88	3.44
769.00	0.58	2.32	1893.00	1.37	5.24	1082.00	0.79	3.08
1965.00	1.47	5.92	1108.00	0.80	3.07	877.00	0.64	2.50
1977.00	1.48	5.96	1166.00	0.85	3.23	809.00	0.59	2.30
2153.00	1.61	6.49	1056.00	0.77	2.92	822.00	0.60	2.34
1980.00	1.48	5.97	1141.00	0.83	3.16	750.00	0.55	2.13
2011.00	1.50	6.06	1052.00	0.76	2.91	780.00	0.57	2.22
2183.00	1.63	6.58	1266.00	0.92	3.50	840.00	0.61	2.39
224.00	0.17	0.68	516.00	0.37	1.43	238.00	0.17	0.68
224.00	0.17	0.68	540.00	0.39	1.49	310.00	0.23	0.88
494.00	0.37	1.49	1596.00	1.16	4.42	912.00	0.67	2.60
729.00	0.55	2.20	1842.00	1.34	5.10	1042.00	0.76	2.97
672.00	0.50	2.03	1404.00	1.02	3.88	849.00	0.62	2.42
206.00	0.15	0.62	569.00	0.41	1.57	306.00	0.22	0.87
590.00	0.44	1.78	374.00	0.27	1.03	1146.00	0.84	3.26
483.00	0.36	1.46	369.00	0.27	1.02	917.00	0.67	2.61
506.00	0.38	1.53	413.00	0.30	1.14	948.00	0.69	2.70
505.00	0.38	1.52	413.00	0.30	1.14	901.00	0.66	2.56
1167.00	0.87	3.52	717.00	0.52	1.98	2131.00	1.56	6.06
1055.00	0.79	3.18	823.00	0.60	2.28	2129.00	1.56	6.06
1212.00	0.91	3.65	945.00	0.69	2.61	2142.00	1.57	6.10
1098.00	0.82	3.31	876.00	0.64	2.42	2219.00	1.62	6.31
1278.00	0.96	3.85	773.00	0.56	2.14	1934.00	1.41	5.50
1130.00	0.85	3.41	745.00	0.54	2.06	2153.00	1.57	6.13
501.00	0.37	1.51	339.00	0.25	0.94	186.00	0.14	0.53
955.00	0.71	2.88	462.00	0.34	1.28	378.00	0.28	1.08
836.00	0.63	2.52	579.00	0.42	1.60	348.00	0.25	0.99
614.00	0.46	1.85	317.00	0.23	0.88	218.00	0.16	0.62
574.00	0.43	1.73	299.00	0.22	0.83	217.00	0.16	0.62
544.00	0.41	1.64	299.00	0.22	0.83	180.00	0.13	0.51
639.00	0.48	1.93	1713.00	1.24	4.74	1062.00	0.78	3.02
544.00	0.41	1.64	1750.00	1.27	4.84	998.00	0.73	2.84
590.00	0.44	1.78	1629.00	1.18	4.51	1081.00	0.79	3.08
595.00	0.45	1.79	1719.00	1.25	4.76	996.00	0.73	2.83
647.00	0.48	1.95	1718.00	1.25	4.75	1042.00	0.76	2.97
735.00	0.55	2.22	1760.00	1.28	4.87	988.00	0.72	2.81
100459.00	75.17		101617.00	73.76		101596.00	74.30	

Trial 13			**Trial 14**			**Trial 15**		
FirstFail	887.556		FirstFail	870.336		FirstFail	872.58	
FirstFail_noPM	6729.449		FirstFail_noPM	5590.4		FirstFail_noPM	5891.521	
NumFail	135.329		NumFail	137.552		NumFail	134.174	
NumFail_noPM	33.712		NumFail_noPM	37.149		NumFail_noPM	33.761	
	NodeMaxModePct			NodeMaxModePct			NodeMaxModePct	
37	101617	75.08885752	37	100403	72.9927591	37	100413	74.83789706
	NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM	
22	2298	6.816563835	5	2106	5.669062424	31	1848	5.473771512
n	NodePct	odePct_noPM	n	NodePct	odePct_noPM	n	NodePct	odePct_noPM
1968.00	1.45	5.84	973.00	0.71	2.62	629.00	0.47	1.86
1894.00	1.40	5.62	1043.00	0.76	2.81	717.00	0.53	2.12
809.00	0.60	2.40	2031.00	1.48	5.47	1152.00	0.86	3.41
782.00	0.58	2.32	2011.00	1.46	5.41	1153.00	0.86	3.42
762.00	0.56	2.26	2106.00	1.53	5.67	1272.00	0.95	3.77
798.00	0.59	2.37	1817.00	1.32	4.89	972.00	0.72	2.88
773.00	0.57	2.29	2013.00	1.46	5.42	1167.00	0.87	3.46
894.00	0.66	2.65	2075.00	1.51	5.59	1217.00	0.91	3.60
216.00	0.16	0.64	542.00	0.39	1.46	264.00	0.20	0.78
201.00	0.15	0.60	608.00	0.44	1.64	364.00	0.27	1.08
602.00	0.44	1.79	1510.00	1.10	4.06	888.00	0.66	2.63
753.00	0.56	2.23	1902.00	1.38	5.12	1022.00	0.76	3.03
590.00	0.44	1.75	1553.00	1.13	4.18	835.00	0.62	2.47
199.00	0.15	0.59	593.00	0.43	1.60	329.00	0.25	0.97
374.00	0.28	1.11	1104.00	0.80	2.97	615.00	0.46	1.82
369.00	0.27	1.09	876.00	0.64	2.36	554.00	0.41	1.64
413.00	0.31	1.23	832.00	0.60	2.24	528.00	0.39	1.56
413.00	0.31	1.23	969.00	0.70	2.61	456.00	0.34	1.35
1967.00	1.45	5.83	1034.00	0.75	2.78	696.00	0.52	2.06
2183.00	1.61	6.48	1155.00	0.84	3.11	844.00	0.63	2.50
2253.00	1.66	6.68	1204.00	0.88	3.24	838.00	0.62	2.48
2298.00	1.70	6.82	1085.00	0.79	2.92	683.00	0.51	2.02
2102.00	1.55	6.24	1256.00	0.91	3.38	875.00	0.65	2.59
2064.00	1.53	6.12	1241.00	0.90	3.34	859.00	0.64	2.54
339.00	0.25	1.01	167.00	0.12	0.45	547.00	0.41	1.62
462.00	0.34	1.37	324.00	0.24	0.87	909.00	0.68	2.69
579.00	0.43	1.72	341.00	0.25	0.92	955.00	0.71	2.83
317.00	0.23	0.94	228.00	0.17	0.61	656.00	0.49	1.94
299.00	0.22	0.89	228.00	0.17	0.61	562.00	0.42	1.66
299.00	0.22	0.89	213.00	0.15	0.57	569.00	0.42	1.69
942.00	0.70	2.79	657.00	0.48	1.77	1848.00	1.38	5.47
958.00	0.71	2.84	595.00	0.43	1.60	1756.00	1.31	5.20
930.00	0.69	2.76	686.00	0.50	1.85	1713.00	1.28	5.07
997.00	0.74	2.96	745.00	0.54	2.01	1735.00	1.29	5.14
969.00	0.72	2.87	722.00	0.52	1.94	1786.00	1.33	5.29
944.00	0.70	2.80	710.00	0.52	1.91	1796.00	1.34	5.32
101617.00	75.09		100403.00	72.99		100413.00	74.84	

Trial 16			Trial 17			Trial 18		
FirstFail	850.576		FirstFail	833.52		FirstFail	878.424	
FirstFail_noPM	6599.046		FirstFail_noPM	5498.642		FirstFail_noPM	6482.922	
NumFail	133.817		NumFail	137.41		NumFail	136.32	
NumFail_noPM	32.431		NumFail_noPM	36.951		NumFail_noPM	34.703	
NodeMaxModePct			NodeMaxModePct			NodeMaxModePct		
37	101386	75.76466368	37	100459	73.10894404	37	101617	74.54298709
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
33	1854	5.71675249	23	2356	6.376011475	8	2236	6.443246982
n	NodePct	odePct_noPM	n	NodePct	odePct_noPM	n	NodePct	odePct_noPM
1102.00	0.82	3.40	793.00	0.58	2.15	1968.00	1.44	5.67
967.00	0.72	2.98	769.00	0.56	2.08	1893.00	1.39	5.45
1113.00	0.83	3.43	640.00	0.47	1.73	1962.00	1.44	5.65
1407.00	1.05	4.34	718.00	0.52	1.94	2186.00	1.60	6.30
1222.00	0.91	3.77	888.00	0.65	2.40	2070.00	1.52	5.96
1207.00	0.90	3.72	840.00	0.61	2.27	1994.00	1.46	5.75
1148.00	0.86	3.54	752.00	0.55	2.04	2000.00	1.47	5.76
1248.00	0.93	3.85	803.00	0.58	2.17	2236.00	1.64	6.44
197.00	0.15	0.61	532.00	0.39	1.44	268.00	0.20	0.77
186.00	0.14	0.57	501.00	0.36	1.36	308.00	0.23	0.89
522.00	0.39	1.61	1416.00	1.03	3.83	856.00	0.63	2.47
682.00	0.51	2.10	1751.00	1.27	4.74	1110.00	0.81	3.20
594.00	0.44	1.83	1614.00	1.17	4.37	794.00	0.58	2.29
210.00	0.16	0.65	552.00	0.40	1.49	306.00	0.22	0.88
1125.00	0.84	3.47	590.00	0.43	1.60	374.00	0.27	1.08
1005.00	0.75	3.10	483.00	0.35	1.31	369.00	0.27	1.06
896.00	0.67	2.76	506.00	0.37	1.37	413.00	0.30	1.19
907.00	0.68	2.80	505.00	0.37	1.37	413.00	0.30	1.19
765.00	0.57	2.36	2060.00	1.50	5.58	955.00	0.70	2.75
879.00	0.66	2.71	1962.00	1.43	5.31	1190.00	0.87	3.43
755.00	0.56	2.33	2012.00	1.46	5.45	1314.00	0.96	3.79
792.00	0.59	2.44	2033.00	1.48	5.50	1337.00	0.98	3.85
762.00	0.57	2.35	2356.00	1.71	6.38	1127.00	0.83	3.25
748.00	0.56	2.31	2146.00	1.56	5.81	1014.00	0.74	2.92
199.00	0.15	0.61	501.00	0.36	1.36	339.00	0.25	0.98
299.00	0.22	0.92	955.00	0.70	2.58	462.00	0.34	1.33
367.00	0.27	1.13	836.00	0.61	2.26	579.00	0.42	1.67
220.00	0.16	0.68	614.00	0.45	1.66	317.00	0.23	0.91
226.00	0.17	0.70	574.00	0.42	1.55	299.00	0.22	0.86
152.00	0.11	0.47	544.00	0.40	1.47	299.00	0.22	0.86
1650.00	1.23	5.09	999.00	0.73	2.70	695.00	0.51	2.00
1674.00	1.25	5.16	889.00	0.65	2.41	649.00	0.48	1.87
1854.00	1.39	5.72	869.00	0.63	2.35	608.00	0.45	1.75
1842.00	1.38	5.68	966.00	0.70	2.61	721.00	0.53	2.08
1781.00	1.33	5.49	934.00	0.68	2.53	658.00	0.48	1.90
1728.00	1.29	5.33	1048.00	0.76	2.84	620.00	0.45	1.79
101386.00	75.77		100459.00	73.11		101617.00	74.54	

Trial 19			Trial 20			Trial 21		
FirstFail	814.745		FirstFail	893.207		FirstFail	849.146	
FirstFail_noPM	5864.344		FirstFail_noPM	6335.822		FirstFail_noPM	5534.283	
NumFail	136.187		NumFail	133.423		NumFail	137.234	
NumFail_noPM	35.118		NumFail_noPM	33.553		NumFail_noPM	36.388	
NodeMaxModePct			NodeMaxModePct			NodeMaxModePct		
37	101069	74.21339775	37	99870	74.85216192	37	100846	73.48470496
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
8	2218	6.315849422	24	2192	6.532947874	1	1997	5.488072991
n	NodePct	odePct_noPM	n	NodePct	odePct_noPM	n	NodePct	odePct_noPM
1209.00	0.89	3.44	629.00	0.47	1.87	1997.00	1.46	5.49
1082.00	0.79	3.08	717.00	0.54	2.14	1895.00	1.38	5.21
2113.00	1.55	6.02	1152.00	0.86	3.43	801.00	0.58	2.20
1978.00	1.45	5.63	1153.00	0.86	3.44	977.00	0.71	2.69
2118.00	1.56	6.03	1272.00	0.95	3.79	810.00	0.59	2.23
1947.00	1.43	5.54	972.00	0.73	2.90	851.00	0.62	2.34
2006.00	1.47	5.71	1167.00	0.87	3.48	744.00	0.54	2.04
2218.00	1.63	6.32	1217.00	0.91	3.63	894.00	0.65	2.46
238.00	0.17	0.68	201.00	0.15	0.60	536.00	0.39	1.47
310.00	0.23	0.88	239.00	0.18	0.71	574.00	0.42	1.58
912.00	0.67	2.60	572.00	0.43	1.70	1488.00	1.08	4.09
1042.00	0.77	2.97	684.00	0.51	2.04	1805.00	1.32	4.96
849.00	0.62	2.42	584.00	0.44	1.74	1584.00	1.15	4.35
306.00	0.22	0.87	186.00	0.14	0.55	552.00	0.40	1.52
475.00	0.35	1.35	1107.00	0.83	3.30	532.00	0.39	1.46
346.00	0.25	0.99	871.00	0.65	2.60	464.00	0.34	1.28
454.00	0.33	1.29	834.00	0.63	2.49	435.00	0.32	1.20
379.00	0.28	1.08	969.00	0.73	2.89	526.00	0.38	1.45
743.00	0.55	2.12	2087.00	1.56	6.22	1146.00	0.84	3.15
818.00	0.60	2.33	1982.00	1.49	5.91	1189.00	0.87	3.27
944.00	0.69	2.69	2185.00	1.64	6.51	1106.00	0.81	3.04
922.00	0.68	2.63	1997.00	1.50	5.95	1128.00	0.82	3.10
682.00	0.50	1.94	2132.00	1.60	6.35	1199.00	0.87	3.30
870.00	0.64	2.48	2192.00	1.64	6.53	1164.00	0.85	3.20
564.00	0.41	1.61	275.00	0.21	0.82	199.00	0.15	0.55
865.00	0.64	2.46	541.00	0.41	1.61	299.00	0.22	0.82
1011.00	0.74	2.88	522.00	0.39	1.56	367.00	0.27	1.01
522.00	0.38	1.49	359.00	0.27	1.07	220.00	0.16	0.60
575.00	0.42	1.64	308.00	0.23	0.92	226.00	0.16	0.62
453.00	0.33	1.29	337.00	0.25	1.00	151.00	0.11	0.41
1062.00	0.78	3.02	652.00	0.49	1.94	1650.00	1.20	4.53
998.00	0.73	2.84	595.00	0.45	1.77	1674.00	1.22	4.60
1081.00	0.79	3.08	686.00	0.51	2.04	1854.00	1.35	5.10
996.00	0.73	2.84	750.00	0.56	2.24	1842.00	1.34	5.06
1042.00	0.77	2.97	727.00	0.54	2.17	1781.00	1.30	4.89
988.00	0.73	2.81	700.00	0.52	2.09	1728.00	1.26	4.75
101069.00	74.21		99870.00	74.85		100846.00	73.49	

Trial 22			**Trial 23**			**Trial 24**		
FirstFail	881.804		FirstFail	854.883		FirstFail	836.323	
FirstFail_noPM	6146.805		FirstFail_noPM	6535.33		FirstFail_noPM	5556.292	
NumFail	133.516		NumFail	133.677		NumFail	136.98	
NumFail_noPM	33.646		NumFail_noPM	32.831		NumFail_noPM	37.124	
NodeMaxModePct			NodeMaxModePct			NodeMaxModePct		
37	99870	74.80002397	37	100846	75.44005326	37	99856	72.89823332
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
31	1848	5.492480533	4	2314	7.048216625	23	2356	6.34629889
n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM
629.00	0.47	1.87	1997.00	1.49	6.08	1077.00	0.79	2.90
717.00	0.54	2.13	1895.00	1.42	5.77	1059.00	0.77	2.85
714.00	0.53	2.12	1992.00	1.49	6.07	1023.00	0.75	2.76
800.00	0.60	2.38	2314.00	1.73	7.05	1100.00	0.80	2.96
924.00	0.69	2.75	2124.00	1.59	6.47	1253.00	0.91	3.38
689.00	0.52	2.05	2058.00	1.54	6.27	1182.00	0.86	3.18
884.00	0.66	2.63	2056.00	1.54	6.26	1106.00	0.81	2.98
861.00	0.64	2.56	2090.00	1.56	6.37	1246.00	0.91	3.36
264.00	0.20	0.78	198.00	0.15	0.60	532.00	0.39	1.43
364.00	0.27	1.08	186.00	0.14	0.57	501.00	0.37	1.35
888.00	0.67	2.64	522.00	0.39	1.59	1416.00	1.03	3.81
1022.00	0.77	3.04	682.00	0.51	2.08	1751.00	1.28	4.72
835.00	0.63	2.48	594.00	0.44	1.81	1614.00	1.18	4.35
329.00	0.25	0.98	210.00	0.16	0.64	552.00	0.40	1.49
1107.00	0.83	3.29	532.00	0.40	1.62	403.00	0.29	1.09
871.00	0.65	2.59	464.00	0.35	1.41	312.00	0.23	0.84
834.00	0.62	2.48	435.00	0.33	1.33	321.00	0.23	0.86
969.00	0.73	2.88	526.00	0.39	1.60	333.00	0.24	0.90
1028.00	0.77	3.06	765.00	0.57	2.33	2060.00	1.50	5.55
1155.00	0.87	3.43	879.00	0.66	2.68	1962.00	1.43	5.29
1216.00	0.91	3.61	755.00	0.56	2.30	2012.00	1.47	5.42
1079.00	0.81	3.21	792.00	0.59	2.41	2033.00	1.48	5.48
1256.00	0.94	3.73	762.00	0.57	2.32	2356.00	1.72	6.35
1235.00	0.92	3.67	748.00	0.56	2.28	2146.00	1.57	5.78
275.00	0.21	0.82	199.00	0.15	0.61	501.00	0.37	1.35
541.00	0.41	1.61	299.00	0.22	0.91	955.00	0.70	2.57
522.00	0.39	1.55	367.00	0.27	1.12	836.00	0.61	2.25
359.00	0.27	1.07	220.00	0.16	0.67	614.00	0.45	1.65
308.00	0.23	0.92	226.00	0.17	0.69	574.00	0.42	1.55
337.00	0.25	1.00	152.00	0.11	0.46	544.00	0.40	1.47
1848.00	1.38	5.49	873.00	0.65	2.66	639.00	0.47	1.72
1756.00	1.32	5.22	900.00	0.67	2.74	544.00	0.40	1.47
1713.00	1.28	5.09	1007.00	0.75	3.07	590.00	0.43	1.59
1735.00	1.30	5.16	1031.00	0.77	3.14	595.00	0.43	1.60
1786.00	1.34	5.31	1036.00	0.78	3.16	647.00	0.47	1.74
1796.00	1.35	5.34	945.00	0.71	2.88	735.00	0.54	1.98
99870.00	74.80		100846.00	75.44		99856.00	72.90	

Trial 25			Trial 26			Trial 27		
FirstFail	884.009		FirstFail	829.203		FirstFail	851.253	
FirstFail_noPM	6474.539		FirstFail_noPM	6099.675		FirstFail_noPM	5521.926	
NumFail	136.079		NumFail	134.386		NumFail	138.541	
NumFail_noPM	34.978		NumFail_noPM	33.317		NumFail_noPM	37.073	
	NodeMaxModePct			NodeMaxModePct			NodeMaxModePct	
37	101101	74.29581346	37	101069	75.20798297	37	101468	73.24041259
	NodeMaxModePct_noPMM			NodeMaxModePct_noPMM			NodeMaxModePct_noPMM	
22	2298	6.569843902	32	1876	5.630759072	5	2135	5.7589081
n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM	n	NodePct	NodePct_noPM
1968.00	1.45	5.63	1209.00	0.90	3.63	718.00	0.52	1.94
1893.00	1.39	5.41	1082.00	0.81	3.25	869.00	0.63	2.34
1108.00	0.81	3.17	877.00	0.65	2.63	1988.00	1.44	5.36
1166.00	0.86	3.33	809.00	0.60	2.43	2091.00	1.51	5.64
1056.00	0.78	3.02	822.00	0.61	2.47	2135.00	1.54	5.76
1141.00	0.84	3.26	750.00	0.56	2.25	1990.00	1.44	5.37
1052.00	0.77	3.01	780.00	0.58	2.34	2012.00	1.45	5.43
1266.00	0.93	3.62	840.00	0.63	2.52	2056.00	1.48	5.55
268.00	0.20	0.77	182.00	0.14	0.55	559.00	0.40	1.51
308.00	0.23	0.88	193.00	0.14	0.58	608.00	0.44	1.64
856.00	0.63	2.45	605.00	0.45	1.82	1612.00	1.16	4.35
1110.00	0.82	3.17	721.00	0.54	2.16	1782.00	1.29	4.81
794.00	0.58	2.27	625.00	0.47	1.88	1623.00	1.17	4.38
306.00	0.22	0.87	217.00	0.16	0.65	521.00	0.38	1.41
571.00	0.42	1.63	475.00	0.35	1.43	1144.00	0.83	3.09
484.00	0.36	1.38	346.00	0.26	1.04	873.00	0.63	2.35
536.00	0.39	1.53	454.00	0.34	1.36	968.00	0.70	2.61
635.00	0.47	1.82	379.00	0.28	1.14	941.00	0.68	2.54
1967.00	1.45	5.62	1140.00	0.85	3.42	757.00	0.55	2.04
2183.00	1.60	6.24	1195.00	0.89	3.59	770.00	0.56	2.08
2253.00	1.66	6.44	1275.00	0.95	3.83	797.00	0.58	2.15
2298.00	1.69	6.57	1235.00	0.92	3.71	707.00	0.51	1.91
2102.00	1.54	6.01	1005.00	0.75	3.02	773.00	0.56	2.09
2064.00	1.52	5.90	1267.00	0.94	3.80	834.00	0.60	2.25
234.00	0.17	0.67	564.00	0.42	1.69	308.00	0.22	0.83
350.00	0.26	1.00	865.00	0.64	2.60	504.00	0.36	1.36
385.00	0.28	1.10	1011.00	0.75	3.03	523.00	0.38	1.41
262.00	0.19	0.75	522.00	0.39	1.57	306.00	0.22	0.83
214.00	0.16	0.61	575.00	0.43	1.73	302.00	0.22	0.81
197.00	0.14	0.56	453.00	0.34	1.36	275.00	0.20	0.74
695.00	0.51	1.99	1844.00	1.37	5.53	967.00	0.70	2.61
649.00	0.48	1.86	1876.00	1.40	5.63	1128.00	0.81	3.04
608.00	0.45	1.74	1758.00	1.31	5.28	910.00	0.66	2.45
721.00	0.53	2.06	1867.00	1.39	5.60	843.00	0.61	2.27
658.00	0.48	1.88	1740.00	1.29	5.22	969.00	0.70	2.61
620.00	0.46	1.77	1759.00	1.31	5.28	910.00	0.66	2.45
101101.00	74.30		101069.00	75.21		101468.00	73.24	

Trial 28			Trial 29		
FirstFail	906.069		FirstFail	889.02	
FirstFail_noPM	11473.761		FirstFail_noPM	7525.982	
NumFail	119.895		NumFail	131.399	
NumFail_noPM	20.039		NumFail_noPM	29.782	
NodeMaxModePct			NodeMaxModePct		
37	99856	83.28620877	37	101617	77.33468291
NodeMaxModePct_noPMM			NodeMaxModePct_noPMM		
5	888	4.43135885	22	1337	4.489288832
n	NodePct	odePct_noPM	n	NodePct	odePct_noPM
793.00	0.66	3.96	1128.00	0.86	3.79
769.00	0.64	3.84	1025.00	0.78	3.44
640.00	0.53	3.19	1108.00	0.84	3.72
718.00	0.60	3.58	1166.00	0.89	3.92
888.00	0.74	4.43	1056.00	0.80	3.55
840.00	0.70	4.19	1141.00	0.87	3.83
752.00	0.63	3.75	1052.00	0.80	3.53
803.00	0.67	4.01	1266.00	0.96	4.25
224.00	0.19	1.12	268.00	0.20	0.90
224.00	0.19	1.12	308.00	0.23	1.03
494.00	0.41	2.47	856.00	0.65	2.87
729.00	0.61	3.64	1110.00	0.84	3.73
672.00	0.56	3.35	794.00	0.60	2.67
206.00	0.17	1.03	306.00	0.23	1.03
403.00	0.34	2.01	571.00	0.43	1.92
312.00	0.26	1.56	484.00	0.37	1.63
321.00	0.27	1.60	536.00	0.41	1.80
333.00	0.28	1.66	635.00	0.48	2.13
813.00	0.68	4.06	955.00	0.73	3.21
671.00	0.56	3.35	1190.00	0.91	4.00
801.00	0.67	4.00	1314.00	1.00	4.41
774.00	0.65	3.86	1337.00	1.02	4.49
834.00	0.70	4.16	1127.00	0.86	3.78
799.00	0.67	3.99	1014.00	0.77	3.40
185.00	0.15	0.92	339.00	0.26	1.14
309.00	0.26	1.54	462.00	0.35	1.55
306.00	0.26	1.53	579.00	0.44	1.94
254.00	0.21	1.27	317.00	0.24	1.06
250.00	0.21	1.25	299.00	0.23	1.00
172.00	0.14	0.86	299.00	0.23	1.00
639.00	0.53	3.19	942.00	0.72	3.16
544.00	0.45	2.71	958.00	0.73	3.22
590.00	0.49	2.94	930.00	0.71	3.12
595.00	0.50	2.97	997.00	0.76	3.35
647.00	0.54	3.23	969.00	0.74	3.25
735.00	0.61	3.67	944.00	0.72	3.17
99856.00	83.29		101617.00	77.34	