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DESIGN AND ANALYSIS OF SHIPBOARD ELECTRICAL DISTRIBUTION

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(ABSTRACT)

This research is a preliminary design and feasibility analysis of a new type of shipboard electrical distribution system for Naval vessels. The design combines three traditionally separate disciplines: damage control, marine engineering, and electric power engineering to produce a hybrid system well suited for present and future surface warship environments.

The design structure is a combination of shore based power utility and shipboard distribution. The primary section is an interconnected bus feeder ring which resembles a shipboard vertical loop firemain. The bus feeder ring emulates the firemain's network structure because it is well suited for both normal and emergency operating conditions. The distribution ring is used to transfer power between fire zones to load centers which radially feed loads within each zone.

Electrical feasibility of the system was established through standard power system load flow contingency analysis, use of Navy design specifications, and direct comparison with an icebreaker radial electrical system.

The new system could best be applied to small ships where the effective use of zone distribution is difficult, or where automation is needed to implement reduced manning. For large ships, this system would provide additional design alternatives which could help to reduce intersystem design interference where the requirements for one system impinge on those of another. As a final point, this system provides a viable network for facilitating the application of shore based automatic switching technology to Naval vessels.

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CHAPTER I

INTRODUCTION

The purpose of this research is to examine the possibility of combining the techniques used in designing shore based power utility and naval shipboard electrical distribution systems. This was done through the design and evaluation of a new, hybrid type, electrical distribution system. To facilitate analysis, this new system was based on the design specifications of an existing ship, the U.S. Coast Guard Icebreaker Polar Star.

Shore based switched radial distribution systems are used to facilitate remote and automatic distribution reconfiguration to isolate damaged lines, restore power, and redistribute load to match changing system operating conditions and costumer demands. The basic switching components used in these types of systems are remotely operated switches. These devices contain no circuit protection equipment and as such are relatively simple and inexpensive.

Naval ships use zone distribution as a standard design method for making electrical systems survivable. Navy specifications define zone distribution as "A modification of the radial pattern, adaptable to large ships, wherein the ship is subdivided into zones using main subdivision bulkheads as boundaries. Each zone contains one or more load center switchboards for supplying power panels and individual loads within the zone. This method is a decentralization of the distribution-to-load function of the generator bus extending the bus via feeders to load center switchboards." [1].

A heavy emphasis was placed on the operability of the new system under emergency damaged conditions. This environment was made the focal operating condition for evaluating system feasibility as a means to address established ship electrical system survivability problems, and the undocumented operability problems experienced as a result of past assignment as a Naval Engineering Officer aboard the U.S. Coast Guard Icebreaker Mackinaw.

The Mackinaw is in an intermediate size group in regards to electrical distribution design. The ship is too small to effectively use zone distribution, and too large to reliably use a standard radial designs. This was a function of having good longitudinal compartmentation, but poor lateral separation. This means that redundant engineering system components in one engine room would have adequateseparation from damage to another engine room; but not, radial power cables which are difficult to adequately separate because they run the length of several main engineering spaces. This makes them more vulnerable than the the electrically powered motors and power panels which they serve.

Another problem which was experienced aboard the Mackinaw was difficulty in operating the distribution system to isolate compartments and maintain power to vital loads during damage control operations. The required doctrines, official operating instruction which dictate required actions, were long and complex. Adding to this is the fact that the Mackinaw is operated with a reduced crew. This made coordinating distribution operation with other required emergency operation actions very difficult.

Combining these two system types with a design emphasis on damage control operability provides several potential benefits:

1. Increases distribution system flexibility, allowing operators to improve allocation of remaining ship resources following sustained damage.
2. Simplifies damage operation by providing a structure that is easy to visualize and understand by shipboard personnel.
3. Reduces the number of remotely located switching devices, making the distribution system more amenable to centralized automated control.
4. Furthers efforts to integrate damage and casualty control operation of separate ship systems into one total ship automated damage control system by providing flexible and automatable network structure.

The goal of the design steps described in this paper was to explore the conceptual feasibility of a novel distribution design that appears to have the potential to significantly improve electrical system survivability. The individual components and network structure which make up this system are by no means unique, but the method by which they are combined combined is. To show this, the original design guidance drawings from an existing vessel, the U. S. Coast Guard Icebreaker Polar Star, were used to provide a reference platform. Design requirements included matching or reducing system weight, matching system capacity, and meeting feeder redundancy and voltage drop restrictions. (See Chapter IX for Coast Guard drawings and Navy design specification listing.)

A standard Gauss-Seidel load flow routine, commonly used in shore based power system analysis, was used to evaluate the voltage drop and line flow characteristics of the new system's nonstandard distribution ring sections. Navy design specifications and direct comparison with the Polar Star's actual system were used to validate the rest of the design.

Survivability is a function of both design and system operability. This means that a system must not only be resilient to damage, but must also be easy for shipboard personnel to operate in emergency conditions. Reliability is built into shipboard engineering systems primarily through the use of redundant components. This is the same method used in traditional radial distribution systems. Each vital motor controller and power panel has at least two power system feeds, one to a main switchboard and primary generator, and an alternate to an emergency switchboard and generator.

As the number and size of electrical loads have grown, so has the complexity of distribution systems. This presents a problem during emergency damage control operations where simplicity is the key to facilitating rapid effective action under severe conditions. As a result of increased system loads, radial systems like the Mackinaw's have become a maze of power feeders which is difficult to work with.

During a damage control evolution, personnel are required to isolate all electrical equipment in, and all power cables passing through a damaged compartment. They must also maintain electrical power to as many vital loads as possible outside the damaged compartment. For a large compartment, or group of compartments, operating all necessary circuit breakers at all of the diversely located main and emergency switchboards within allotted time constraints may be very difficult or even impossible.

The layout of the new system is similar to that of ship fire main systems. Fire mains are designed to be operated by zones which are defined by fire and flooding boundaries. They provide fire fighting water throughout the ship through several interconnected distribution mains. System isolation is provided for by cutoff valves located at watertight bulkheads. System restoration is provided for by the use of fire main risers and cross connects which can be used circumvent damaged areas. This type of system design is well suited for damage control operation because damage control strategies are structured according to fire zone arrangements.

Operated as a switched radial system, the new design would provide a flexible electrical distribution system capable of meeting both engineering and damage control requirements. For ships with standard radial systems, it could be used to extend the survivability of the main distribution system to match that of the vital loads it serves as a result of giving both feeders and loads similar exposure to possible damage. For large ships, most Navy combatants, this system could be used to provide additional design alternatives, including the possibility of developing a reliable automated electrical distribution system. Having a distribution system that is both automatable and reliable could provide a basic foundation for developing future total ship control systems capable of directly carrying out and coordinating emergency systems operation.

Chapter Summary

Chapter II reviews two related topics, standard naval ship design and shipboard damage control. The basic design of the new distribution system is simple, but the environment where it operates is not. The distribution system is a key part of a very complex, interdependent arrangement of systems that must be capable of operating under extreme conditions. The background presented in this section is relevant to the understanding of system operation requirements, design trade offs, and the intersystem impact considerations that go into distribution design. All of these considerations are a part of standard marine practice. Commonly used reference books which describe standard marine practice in detail have been listed in the Bibliography. The second section of this chapter discusses historical trends and operational experiences that add background information for understanding naval ship operating conditions and performance problems.

Chapter III describes the existing electrical system on the Coast Guard Icebreaker Polar Star. This system is typical of standard radial shipboard electrical design. This section is intended to be an explanation of both the operating characteristics of this particular system and standard marine electrical practice in general.

Chapter IV argues the need for conforming distribution design to damage control requirements. Damage control is the securing of damage in, and the stop of the spread of damage from, a compartment where a casualty has occurred.

Distribution systems are commonly considered to be engineering systems which are designed to be reliable under extreme conditions. Survivability is accomplished mainly through vital component redundancy and separation. Unlike other standard ship engineering systems, electrical distribution is not located in any one section but runs through most of the ship and is used to provide power and support through electrical auxiliaries to almost every system on the ship. As such, damage to nearly any section of the ship affects electrical distribution; conversely, electrical distribution affects the control of damage to nearly every part of the ship. Fire mains, which also cover multiple ship sections, are designed to effectively isolate damage, and then restore service around damaged areas through system interconnections. For this system, survivability is provided through the use of system flexibility. Since both the distribution and firemain systems have similar emergency operation requirements, a reasonable argument exists for giving them similar network structures.

Chapter V looks at topics covering future shipboard system development where the new distribution system could make a contribution. This includes the importance of distribution structure to possible development of a total ship damage control system.

Chapter VI is a detailed description of the new distribution system design. A preliminary design, using the Navy's general design specifications and design drawings for the Coast Guard Cutter Polar Star as guidance was completed. Navy design specifications provide general system requirements which specify operating configurations, characteristics, and acceptable use of components.

Design drawings give specific direction pertaining to the actual ship being constructed.

The purpose of using the Polar Star's system was to provide a reference for establishing the feasibility of the new system. In keeping the systems comparable, conservative estimates for both cable sizing and lengths were used. These and other design aspects left significant margin for future design refinement.

Chapter VII contains the electrical feasibility section of this design. A standard contingency analysis performed with a Gauss-Seidel load flow program, and a reliability comparison which was based on a manual feeder cable failure analysis for both systems, were used for system evaluation.

Standard load flow analysis output for line loading and node voltages was summarized and presented in this chapter. Detail listings of program output were included in Appendix B. A description of the Gauss-Seidel routine used for system analysis has not been included. The reason for this omission is that this type of numerical analysis routine is an accepted standard for performing power system analysis. Description of this method can easily be found in most power system text and reference books. Any future refinement of this type of design would best be done using routines better tailored to analyze radial systems. Feasibility aspects not directly analyzed were compared to original system characteristics and standard design specifications.

Chapter VIII is the conclusion section. Electrical feasibility and practical application of the new design are summarized. Recommendations include specific changes to the Polar Star's isolation instructions, as well as changes to the procedures that the Coast Guard uses to generate these instructions for other vessels. Suggestions for future work have also been included in this section.

Chapter IX contains the reference list, bibliography, list of Coast Guard drawings used for design guidance, and a glossary of the major ship terms used in this paper. The bibliography section was added to list the publications that were used as general guides. These documents describe standard marine practice, Navy design specifications, and emergency damage control procedures for engineering systems.

Appendix A contains a detailed list of the information used to determine individual cable weight estimates as well as gives lengths and sizes for the distribution cables used in both systems. Cable sizing and weight estimation were done in accordance with Navy Gen Spec and Design Data Sheet instructions. These documents provide step by step directions for performing this task.

Appendix B and C contains detailed listings of the load flow program output that was summarized in Chapter VII.

Appendix D contains the data taken from the Coast Guard design drawings and Navy design data sheets which was used to perform the load flow analysis. This information, as presented in the original drawings, was not readily usable for generating load data for individual loads. This information had to be removed piece by piece, and then reorganized into a form which could be used for load flow and damage reliability analysis. A significant contribution made by this research was the consolidation of this information, for this specific vessel into a form that could be analyzed and compared. Considerable effort went into identifying cable locations, interconnections, and specific modes of failure. This consolidated information is included here to make it accessible for future related research.

CHAPTER II

GENERAL BACKGROUND

2.1 Need For Electrical Distribution Design Change

Documentation for establishing the need to alter the basic design methods used in naval electrical distribution systems could not be found as part of the literature search.

2.2 Historical Background

Many papers have been written analyzing the performance of ship systems during the Falkland Island conflict. The following was taken from a summary included in a paper discussing the need for centralized control of ship fire main systems [2]. This list is also pertinent to electrical system development. Items shown in parentheses were added for explanation.

Common casualties which led to the sinking of Royal Navy vessels:

1. Loss of electrical power to forward or after ship sections.
2. Unexploded weapons damage to weapons system power feeders.
3. Lack of electrical system redundancy left RN ships helpless as a result of less than major damage.
4. Heavy black smoke greatly hindered firefighting effectiveness (Ventilation is electrically powered).

5. Loss of fire main capacity significantly reduced firefighting effectiveness (Fire pumps electrically driven).
6. Loss of a few key personnel significantly reduced damage control efforts on ships with low manning.

2.3 Operating Experience Background

Much of the damage control operation information used in this study came from personal experience while serving as the Damage Control Officer, Electrical Assistant, and Assistant Engineer aboard the United States Coast Guard Icebreaker Mackinaw. Coast Guard damage control procedures and equipment are very similar to those used on Navy combatants.

The USCGC Mackinaw WAGB(83) is a Great Lakes Icebreaker currently operated by the Coast Guard. The Mackinaw has similar electrical distribution characteristics to those of the Polar Star. In January and February of 1987, the Mackinaw conducted Naval Refresher Training with Naval Training Personnel in Cleveland Ohio.

This was a significant undertaking in that the Icebreaker Mackinaw had been operating with a reduced crew since the early nineteen eighties because of budget constraints and reduced commercial shipping on the Great Lakes. This training provided a unique opportunity to view the effectiveness of operating a large Coast Guard vessel with reduced manning to navy damage control standards.

The crew and vessel was able to meet all performance requirements for all required emergency drills with the exception of operation of electrical distribution during a main space fire. The primary reason for this was the presence of ship service generator control system wiring problems.

Despite control system isolation problems, an electrical isolation bill was prepared for each of the ship's three engine rooms. The bill established step by step instructions for electrically isolating each engine room during the occurrence of an engine room fire. The lists of required operations was long and involved It did not include power feeders that just passed through the engine rooms, only those that were physically connected to electrical equipment within each space. This left many of the cables that interconnected the three separate engine room compartments unidentified. Even with this omission, the isolation instructions appeared to be too long and complicated to be completed by the reduced crew within the standard four minute time limit set for training purposes. Having the control wiring problem kept ship's personnel from actually carrying out these instructions, so any apparent operational deficiencies were not documented.

During an actual fire, the incomplete isolation instructions could inflate shipboard expectations for electrical system capabilities. The ship has three engine rooms and three ship service generators. This makes maintaining ship power through the loss of one engine room seem easier than it would actually be. This false sense of security could leave ship's personnel unprepared for total electrical system loss during an actual fire. Use of incomplete isolation instructions would waste electrician time by making feeder cables with power sources located in separate compartments difficult to secure, and would expose firefighters to unnecessary electrical hazards by increasing the possibility of leaving electrical equipment and cables energized where firefighting water is going to be used.

The operation of almost every ship system depends on the reliable operation of the electrical distribution system. Despite this prominence, operation of this system is left almost entirely to junior electricians. This is acceptable for standard casualties, but not for occasions when changing mission and damage priorities require reallocation of diminishing electrical system resources following the loss of compartments containing ship service generators or vital power cables. The Damage Control Assistant (DCA) is responsible for coordinating the allocation of personnel and equipment during major ship casualties. Other officers are in charge of individual groups of systems such as engineering or weapons. As the main coordinator of efforts to save the ship, the DCA has the best overall ship status picture.

This makes the DCA an excellent person for coordinating damage and casualty control of the distribution system; but, unfortunately it is the system he is probably least familiar with. Familiarity with the location and operation of major electrical system components is common, but knowledge of the location of cable runs is not. A regular part of engineering qualification procedures on Coast Guard vessels is the requirement to trace out and memorize the operating procedures for most fixed engineering and damage control systems. The distribution system is generally not included in this because of its size and complexity. DCA's are given isometric diagrams of all pertinent fixed systems except the distribution system. Its complexity and component density make the practical use of such a diagram impractical.

The historical and operational information presented in this section does not in itself establish the need for altering standard distribution system design, but does show need for further study. Primary reasons for including this information was to show why distribution was singled out as an area for making ship survivability improvements, and to show the motivation behind the design decisions that were made, and to give background describing the unique engineering operating environment of a naval surface warship.

2.4 Reliability and Basic Naval Ship Design Theory

All United States Naval Vessels are designed to the same general specifications in regards to reliability, security, and survivability. These standards are set so that a naval vessel can sustain heavy damage to its structure and systems, yet still survive to carry out its primary missions.

This is true for both combat and support vessels that are operated by military personnel. Coast Guard vessels fit into both of these categories. The design philosophy for these vessels weights reliability and security much higher than most shore based engineering systems. This is because ship operation is a hazardous endeavor whether during time of war or peace. During peace time, military vessel perform dangerous training, rescue, and in the case of the Coast Guard, law enforcement missions in all types of weather.

Added to the inherent risks of military missions, are the hazards of operating ship equipment. Weapons system malfunction, high pressure fuel leaks in the presence of high temperature exhaust systems, and high voltage electrical equipment failure can all cause severe fires. These fire hazards are compounded by the large amounts of flammable materials stored aboard ships such as the hundreds of thousands, to even millions of gallons of fuel needed for normal operations.

2.5 Damage Control and Marine Engineering Design

Damage control is the containment and prevention of secondary damage. Secondary damage is damage that spreads from the compartment that originally caught fire or became flooded. Historically, most ship losses have resulted not from the initial effects of damage, but from its unchecked spread to other sections of the ship [3]. Design of ship systems must take into account both engineering and damage control operation requirements to produce a ship capable of performing its missions.

Damage Control Operation Criteria

General damage control procedures are specified in the Navy's Naval Ships Technical Manuals and the Coast Guard Naval Engineering Manual. Specific engine room engineering casualty and damage control procedures are specified for Coast Guard vessels in the Main Space Fire Doctrine M9555. The main design guidance for implementing these procedures is the Navy's General Specifications, or "Gen

Specs". The information in these publications has been proven and refined through many ship constructions, hours of operation, and damage incidences. This is also true for the electrical system, but increased electrical demands on modern warships may now be exceeding traditional designs.

2.6 Selection of the Polar Star

The ship used for this research is a currently active Coast Guard Polar Icebreaker, USCGC Polar Star WAGB(10), one of two ships of its class. The Polar Star, and its sister ship the Polar Sea, are the two largest vessels operated by the Coast Guard.

The Polar Star was selected for this study for several reasons:

1. Detailed drawings of the electrical system were available for use from Coast Guard Headquarters.
2. The ship has been operating since 1976 so standard engineering casualty control and damage control procedures have been long established.
3. The ship is a good size and type for illustrating operation and design limitations in current ship electrical distribution systems. It is large enough to have several engine rooms, which provides redundant system components such as multiple ship service and propulsion generator sets, but not large enough to utilize standard zone distribution, which is an effective way of making electrical systems survivable.

The Polar Star's main mission is to provide support to military and scientific operations in the polar regions. It is not a typical combat vessel, but was still built to naval standards the same as other military vessels. Characteristic to its main purpose of ice breaking, it has multiple engine rooms, effective longitudinal compartmentation, and good stability as a result of the large horse power and displacement requirements needed to break ice. The arrangement of the propulsion system, and the ship's large displacement, made it possible to build good vital system redundancy and diversity into the overall ship design. This means that for the loss of any one compartment, the system components within that compartment can be replaced by a backup system located elsewhere. This makes the Polar Star a good platform for examining distribution system damage susceptibility, and the affect that this damage would have on total ship mission capabilities.

Polar Star General Specifications

Length Between Perpendiculars	352' - 0"
Length Overall	399' - 0"
Breadth, Extreme	83' - 7"
Draft, To Bottom of Keel, Full Load Displacement	31.81'
Crew Accommodations	183
	[4]
Full Load Displacement	12087 Tons
Main Engines:	
6 Alco Diesels	18,000 shp
3 Pratt & Whitney Gas Turbines	60,000 shp
Icebreaking Capabilities	6 ft continuous at 3 knots
21 ft maximum	
Date Of Commission	19 January 1976
	[5]

CHAPTER III

SHIP SERVICE ELECTRICAL SYSTEM DESIGN AND OPERATION

This chapter describes the Polar Star's existing electrical system. Shipboard systems are made up of three subsystems: generation, distribution, and load. Figure 7, located in chapter VI, illustrates the electrical systems major component arrangement. The arrangement of individual feeders, loads, and circuit switching and protection devices were not included. Depiction of this information on anything smaller than a set of standard full sized design drawings is impractical. The Coast Guard drawings which fully illustrate these systems are listed in chapter IX. The major components of the Polar Star's system are as follows:

Generators:

Three main ship service generators

Rated Power: 750.0 KW at 0.8 pf

Rated Amperage: 1202.85/-36.87 amps

Operating Voltage: 450.0 volts

One emergency ship service generator

Rated 400.0 KW at 0.8 pf

Rated Amperage: 641.58/-36.87 amps

Operating Voltage : 450.0 volts

Distribution:

Vital loads: Primary feed - nearest ship service switchboard

Emergency feed - emergency switchboard

Non-vital loads: nearest ship service switchboard

Exceptions to using the nearest switchboard are made for the purpose of maintaining resilience to damage through cable run diversity.

3.1 Generation Description

The number and size of generators meets general requirements for naval vessels. Generators are sized using a standard electrical load analysis determined by electrical component requirements for specific operating conditions.

Prevention of generator overload following the return of voltage after a voltage failure is implemented through the use of automatic low voltage release and voltage protection for vital loads. Non vital loads are installed with manual restarts. Allocation of these devices coordinates total system restart to limit simultaneous starting currents.

The Polar Star's ship service generation system consists of three main generators. Each generator has its own switchboard and can be operated in parallel with any of the other generators through switchboard interconnections. Two generators are located in the first engine room, the third is in the second engine room. The ship also has an emergency standby generator located on the

O2 deck, away from the main engineering spaces. (See figures 5 and 7 for reference)

System Operation

General shipboard practice is to match on-line generation to the expected demand, including starting currents for deck machinery with large motors. Generators are usually equally sized and are operated, as necessary, in parallel to meet load requirements. During emergency situations, additional generators may be brought on line to insure continuity of power to vital systems. This is done in either parallel operation; or, for some ship designs, in split-plant operation where the electrical system is isolated into separate sections so that damage to one area will not affect others.

Propulsion Interconnections

The propulsion system for the Polar Star is electrical and is powered by gas turbine or diesel generator sets. The service system and propulsion system are not interconnected, but the propulsion system is dependent on service system powered auxiliaries.

3.2 Distribution Description

The Polar Star's ship service electrical system is of standard design, and consists of:

Primary Distribution: 450 volt, 3 phase, 60 Hz
Vital and Non-vital auxiliary loads

Emergency Distribution: 450 volt, 3 phase, 60 Hz
Vital auxiliary loads

Lighting Distribution: 120 volt, 1 phase 60 Hz
Emergency and normal lighting, 120 volt receptacles

Special Distribution: 120 volt, 3 phase, 400 Hz

The 450 volt distribution system is a standard radial that extends from the main ship service switchboards to power distribution panels and motor controllers located throughout the ship. Motor controllers feed individual large motors while power distribution panels feed individual mains to single loads which are organized by location and type. The 120 and 220 volt loads other than lighting and receptacles are fed through local transformers via the 450 volt system. Reliability and survivability are attained by the use of redundant emergency power feeders. This provides all vital loads with a second source of power.

3.3 System Protection

The type of electrical protection used on shipboard installations is mostly over current protection designed to isolate faults and over loads as far out in the radial network as possible. (See figure 1) Standard ship distribution has an ungrounded neutral which precludes circuit breakers from opening for single phase-to-ground faults. The primary reason for this is to limit the loss of vital auxiliaries to phase-to-phase faults.

To offset increased personnel hazards, systems are routinely checked for ground faults through the use of ground detector lights. Hourly checking limits the time that single phase-to-ground faults remain on the system. Once this type of fault is identified by the on-duty watch stander, an electrician is immediately notified. The fault will then be either repaired, or the damaged circuit will be taken out of service.

CHAPTER IV

PROBLEMS WITH SHIPBOARD ELECTRICAL DISTRIBUTION

4.1 Present System Survivability.

The Polar Star's electrical system is typical of current ship design. It meets continuity requirements by using an emergency generator and switchboard installed in a remote location from the main generators. Emergency feeders are run individually from vital loads to the emergency switchboard. The emergency generator has automatic start capabilities with automatic transfer switches connecting critical loads such as steering motors and fire pumps. Locally operated manual transfer switches are used for less critical loads. This provides two sources of power to vital loads. Main and emergency switchboards are also interconnected providing for multiple generator operation and flexible distribution. (See figure 7 in chapter VI)

Survivability is built into the primary feeders by separating the cableways both high and low, and, port and starboard. Cable runs and individual feeder arrangements are diversified so that vital systems are not dependent on any one switchboard or cableway. Cable separation on some vessels, those too narrow to utilize lateral subdivision, by use of reinforced structural bulkheads, is difficult when large numbers of vital loads are involved.

4.2 Damage Control Operating Procedures

The distribution system must be reliable enough to maintain electrical power to vital loads during damage situations, but must also be simple enough to facilitate quick isolation and restoration actions. Standard electrical system operation procedure during a shipboard fire is to secure all electrical cables and equipment inside a damaged compartment. This electrical isolation must be completed to make it safe for emergency personnel to enter the damaged compartment and begin fighting the fire. It also protects the rest of the electrical system from possible short circuits and overloads.

Spaces with fixed fire fighting systems such as Halon, CO2, and AFFF bilge flooding eliminate the need for personnel to enter an engine room in order to initiate fire fighting procedures. (See Glossary for system definition) This does not eliminate the need for electrical isolation. Damaged cables and electrical equipment could reignite the once extinguished fire or effect the operation of electrical equipment in other areas of the ship.

Isolation must be completed quickly because a fire can rapidly expand beyond the containment capabilities of both the ship's damage control systems and personnel. Countering the requirement for speed is the need to minimize power loss to vital systems outside an effected space. Several of the ship's key damage control systems such as the fire main, fixed ventilation, and emergency lighting, depend on the availability of electrical power. Ships are equipped with portable pumps and blowers, but their capacities are much less than those of fixed systems.

During hazardous operations, such as combat or operation in heavy weather, other systems such as propulsion, navigation, communications, and combat are also necessary to insure ship survival. All of these systems are heavily dependent on the electrical distribution system.

4.3 Distribution Capacity Growth

Ship service electrical systems have remained basically the same since World War II. At that time most propulsion, navigation, and combat systems were manually controlled, and the number of vital interdependent auxiliaries were limited.

Since then, the offensive capabilities of naval vessels have been emphasized as the main method of insuring ship survivability. This has come at the expense of defensive capabilities [6]. As a result, the number and size of interdependent electrical loads have also increased, significantly increasing the number of primary and emergency cables used. This has made it made it more and more difficult to make distribution systems survivable through cable run diversity and operational simplicity.

Reduced manning levels, driven by budget constraints, has also become a factor. To meet these new requirements, centralized automatic control has been added at the generation level for supervising the operation of generators and main switchboards. Current systems can automatically start and place generation sets on the distribution bus. This primarily protects against loss of the prime mover and against system overloads. It monitors the electrical system voltage, frequency, and load, as well as takes corrective action for such problems as prime mover loss of cooling water or lube oil pressure. Loads can also be selectively shed automatically at the main switchboards to reduce overloads.

4.4 Distribution and Damage Control Compatibility.

Response To Primary Damage

Conventional electrical systems respond well to primary damage to individual components. Upon the loss of a generator, the system will automatically bring another generator on line. Faults are quickly isolated, and alternate feeds can be remotely or locally energized as needed.

Response To Secondary Damage

Secondary damage is the spread of damage from the original damaged compartment to other sections of the ship. Ship systems must be reliable enough to survive primary damage, and then be flexible enough to be effective in stopping the spread of secondary damage.

Survivability is designed into the distribution system through a combination of power system feeder redundancy and feeder layout diversity. Detailed procedures for damage control operation of this system is specified for each ship in specifically tailored main space fire doctrines and repair party manuals. The complexity of the distribution system, plus difficulties in providing sufficient subdivision through large engineering compartments can make these instructions ineffective for some vessels.

The Coast Guard Machinery Space Firefighting Doctrine For Bravo Fires states "Complete electrical isolation will be very difficult due to the number of cables within and transiting through any given space. To the extent possible, secure all electrical equipment from outside the affected space at the cutter's, [IC and emergency switchboard,] load center(s) or distribution panel(s)." [7]. Inability to carry out electrical damage isolation and system restoration slows firefighting efforts, endangers personnel, and leads to cascading casualties of systems not in the effected space.

Backup systems such as the casualty power system and portable fire pumps designed to be used during major loss to electrical distribution take time to set up and are of much smaller capacity than their fixed system counterparts.

CHAPTER V

FUTURE DEVELOPMENTS IN SHIPBOARD ELECTRICAL DISTRIBUTION

5.1 Future Distribution Design

Distributed Generation

In order to limit the effect that one damaged area can have on interdependent systems throughout the ship, one proposed future design philosophy is to locate entire systems and their required auxiliaries together in the same fire and flooding zone so that the loss of one zone means the loss of only the systems in that zone. Generation and distribution would be distributed in the same way. Each zone would have its own generator, switchboard, and distribution system. This would effectively limit cascading casualties in other zones and would allow electrical isolation to be quickly implemented [8].

Two drawbacks to this arrangement are:

1. Many systems are size and location sensitive due to system operating requirements, ship weight and balance limitations, and damage criteria. This is more prevalent on medium to smaller size vessels and multimission vessels where more equipment must be placed in less available space.

2. Possible equipment acquisition and operational savings from the use of common auxiliaries is reduced.

5.2 Damage Control System Development

Integrated System Control

Centralized automated control systems have been applied to propulsion, navigation, and combat systems to facilitate reduced manning requirements, and improve system monitoring and operation. This has been very effective for reducing personnel requirements for operation of these systems. Similar advancements have not been made with damage control systems. This is significant for reduced manning considerations because damage control is one of the more manpower intensive shipboard operations.

Distribution and Integrated System Control

In a paper entitled "Advanced Damage Control System" [3], David Geer, technical director for Navy damage control systems, described requirements for developing an integrated damage control system. The main discussion addressed the need, and proposed solutions, for accurately assimilating and analyzing all of the information necessary to carry out effective use of personnel and equipment during damage situations.

It also discussed the need for developing a total ship control system capable of coordinating the use of both personnel and equipment. A primary step towards realizing this goal would be to increase flexibility and speed of operation of the electrical system. An interconnected, switched distribution ring could provide a simple means for accomplishing this.

Automatic control of the distribution system would allow immediate electrical isolation of damaged compartments. Concurrent actions could provide power for setting optimal ventilation for smoke boundaries, as well as allocate remaining generation and distribution to vital loads according to current mission requirements and damage status. This would be especially beneficial to multimission vessels where load priorities could change rapidly with changes to mission priorities.

Possible Augmentation of Weapons System Power Management

The implementation of solid state circuit breakers and switches, such as those used on the Space Shuttle and the B1 Bomber, would provide remotely operable devices well suited for the implementation of supervisory control of distribution. The use of such devices is now being developed for supply and management of power to weapons systems [9]. Future distribution system architectures should be able to take advantage of these developments.

CHAPTER VI

NEW DESIGN DEVELOPMENT

6.1 General System Description

The primary goal of the design proposed in this thesis was to create a more flexible and survivable ship service electrical distribution system. The main difference between this and conventional radial designs is that the new distribution system was specifically tailored for operation according to damage control procedures while still maintaining conformity to engineering requirements.

This was physically accomplished by replacing the majority of the power system feeders with one distribution ring. The distribution ring consists of interconnected bus feeders which join load centers to the ship's standard generator arrangement. Load center placement coincided with fire and flooding boundaries. This was done to conform the distribution system to damage control procedures for the purpose of simplifying emergency electrical isolation and restoration.

Emergency feeders located within the same fire zone as their primary counterparts, serve little purpose. This is true because all feeders within any one zone would be identically effected by casualties which require space isolation. For this reason, loads for the new system were fed with single feeders from their prospective load centers. For distribution between zones, where redundant emergency feeders are effective, the bus feeder distribution ring was used to meet both primary and emergency system requirements.

Aircraft carriers use distribution rings combined with multiple generators in diverse locations and switchboard interconnections sized according to the larger of the normal loads at each switchboard. This type of system, figure 2, somewhat resembles a down scale version of a shore based transmission system.

The bus feeder ring design, shown in figure 3, more resembles a shore based distribution ring where power is injected from one or more points in the system. Supply circuits for this type of system are designed to maintain continuity of power through parallel feeds, each sized to supply their radially connected loads. Use of parallel feeds on ship systems would not be acceptable because of the increased probability of system security loss.

Shore based distribution systems with automatic switching, figure 4, have the ability be to reconfigured to restore service following component failures like line outages. The proposed bus feeder ring would be operated radially as a combination of shore based distribution ring, and automatic switching type systems.

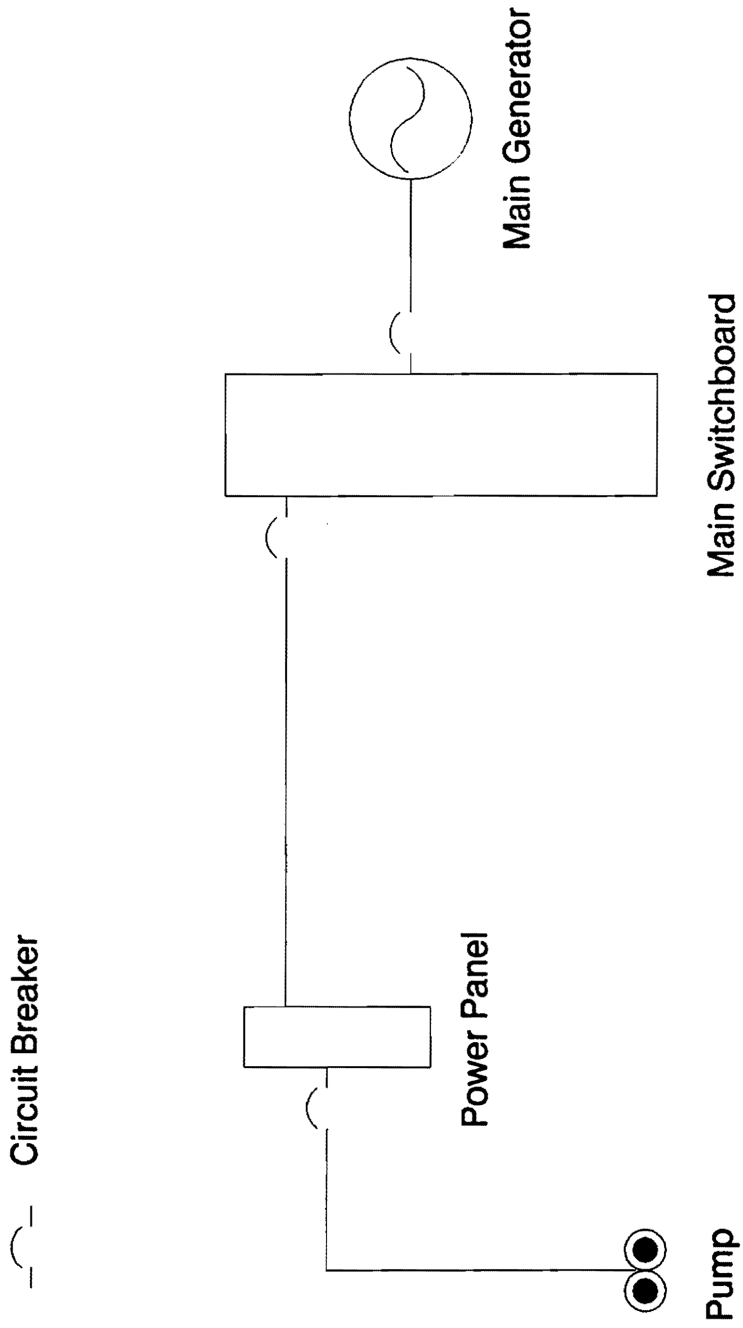


Figure 1. Radial Circuit Protection

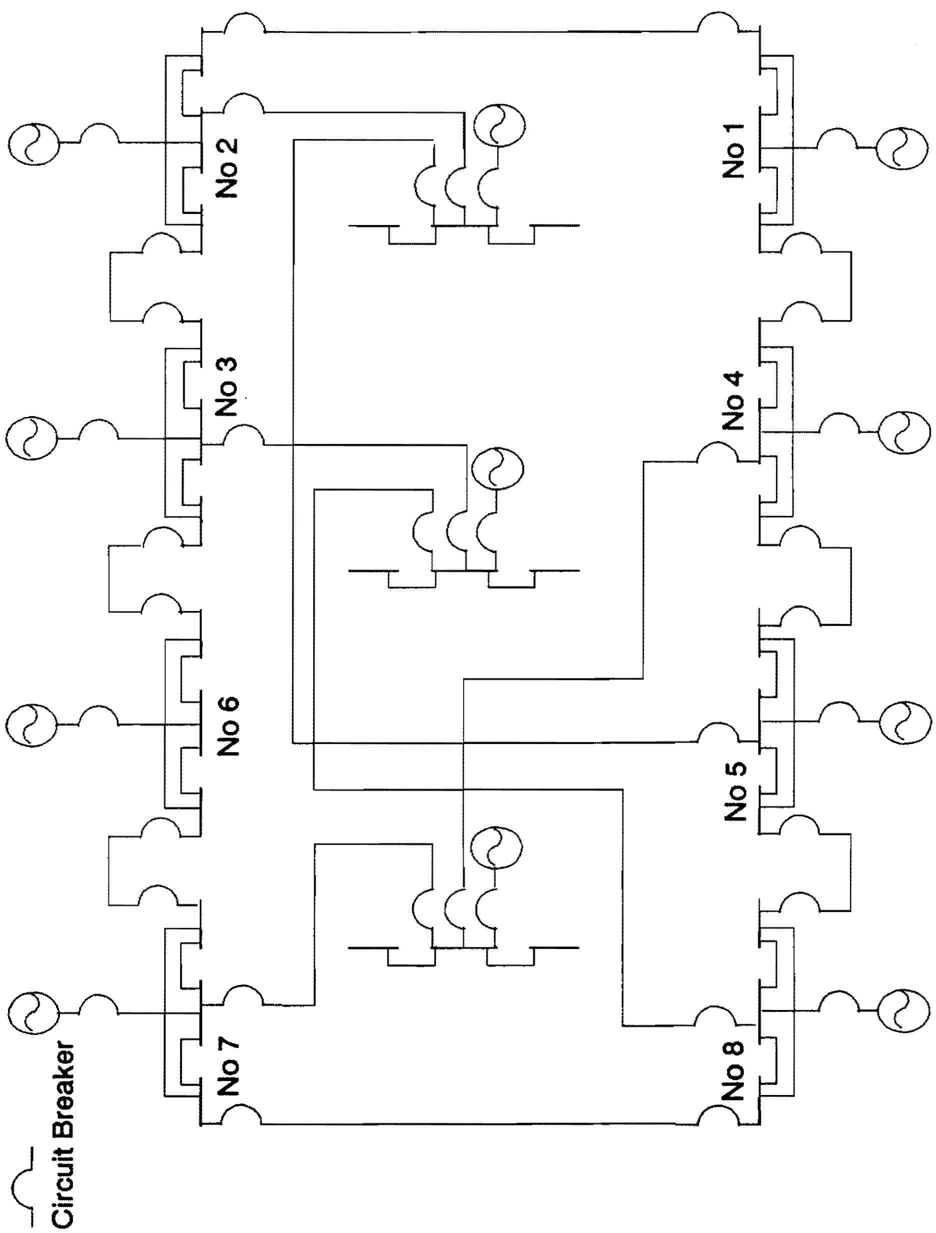


Figure 2. Aircraft Carrier System Arrangement [9]

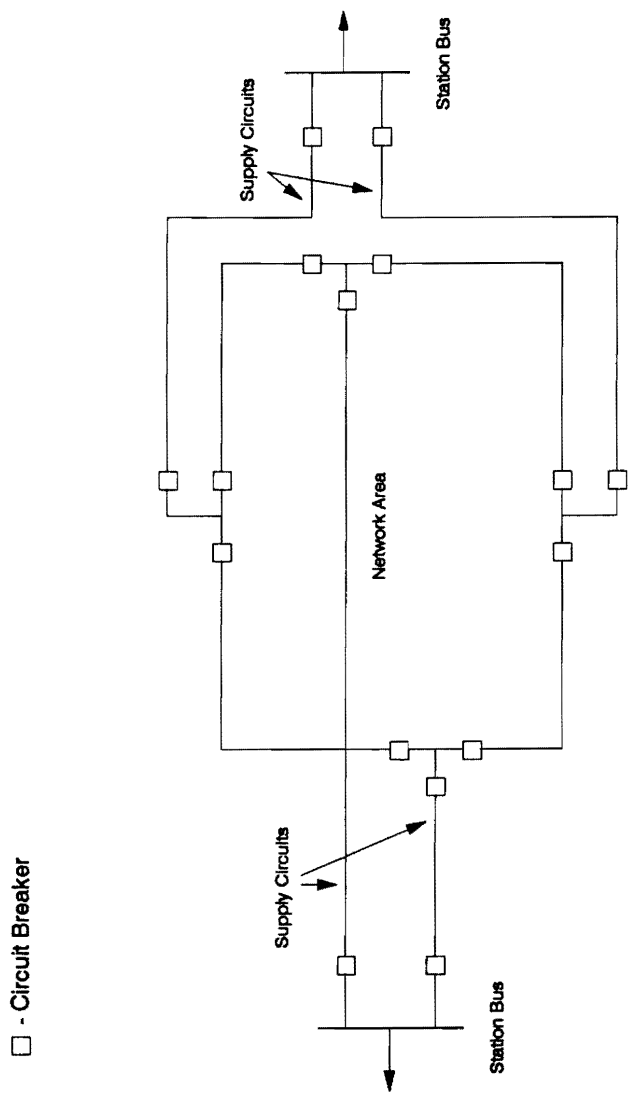


Figure 3. Shore Based Loop Circuit With Multiple Sources [10]

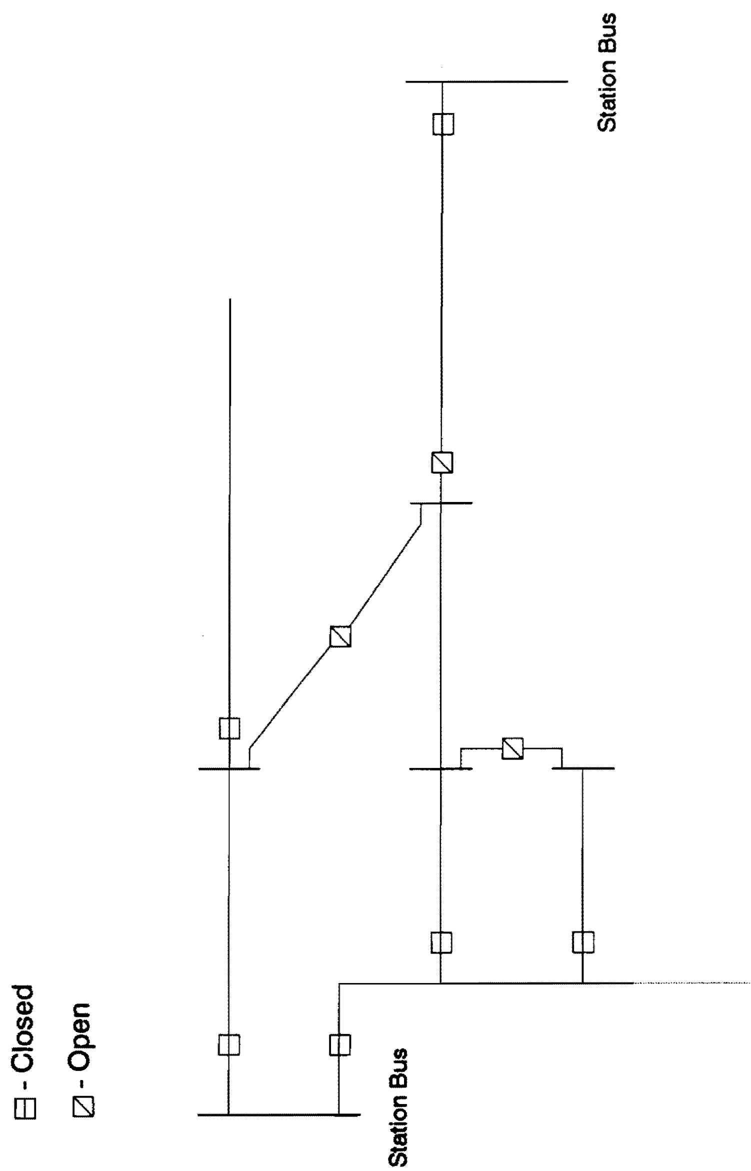


Figure 4. Shore Based Radial Switch System [11]

6.2 Design Procedure

The Naval Gen Specs were used as the regulatory guide for design requirements. The new design used the same engineering assumptions and load estimates used in sizing power system feeders for the Polar Star's original distribution system.

The predominant criteria addressed in this first design iteration were cable capacity, voltage drop, cable routing, and the required number of alternate sources to vital motor controllers and power distribution panels. Gen Spec regulations for these criteria were met specifically with the exception of bus feeder capacity and alternate source requirements. The new design meets functional requirements for these two areas but does not do it according to standard marine practice.

The power system, which constitutes all 450 volt, 60 Hz, three phase distribution, was the only part of the electrical system considered in this study. Out of this system, only the bus ties between switchboards and the feeders between the switchboards and the distribution power panels and motor controllers were altered. Lighting distribution, and power system distribution past the power panels were not included. These components were not needed to illustrate the feasibility of the proposed bus feeder ring.

6.3 New System Arrangement

The basic arrangement for the new distribution design is similar to a common layout for shipboard fire main systems. (See figure 6 for new system arrangement) This is an appropriate system to emulate because it is one of the primary systems used in shipboard damage control. Fire mains are configured as vertical loops, horizontal loops, or combined horizontal and vertical loops, depending on ship size and type. Vertical loops are used on ships large enough to have good vertical and longitudinal compartmentation, but not wide enough to have significant athwartship compartmentation. Combination systems are used on larger vessels where compartmentation is more complete.

Risers interconnect the horizontal sections between decks. Cut off valves and cross connects are located at watertight boundaries so that the system can be reconfigured to isolate damaged sections and restore service to vital areas. Placement of risers and cutoff valves conform to fire and flooding zones.

Bus Feeder Layout

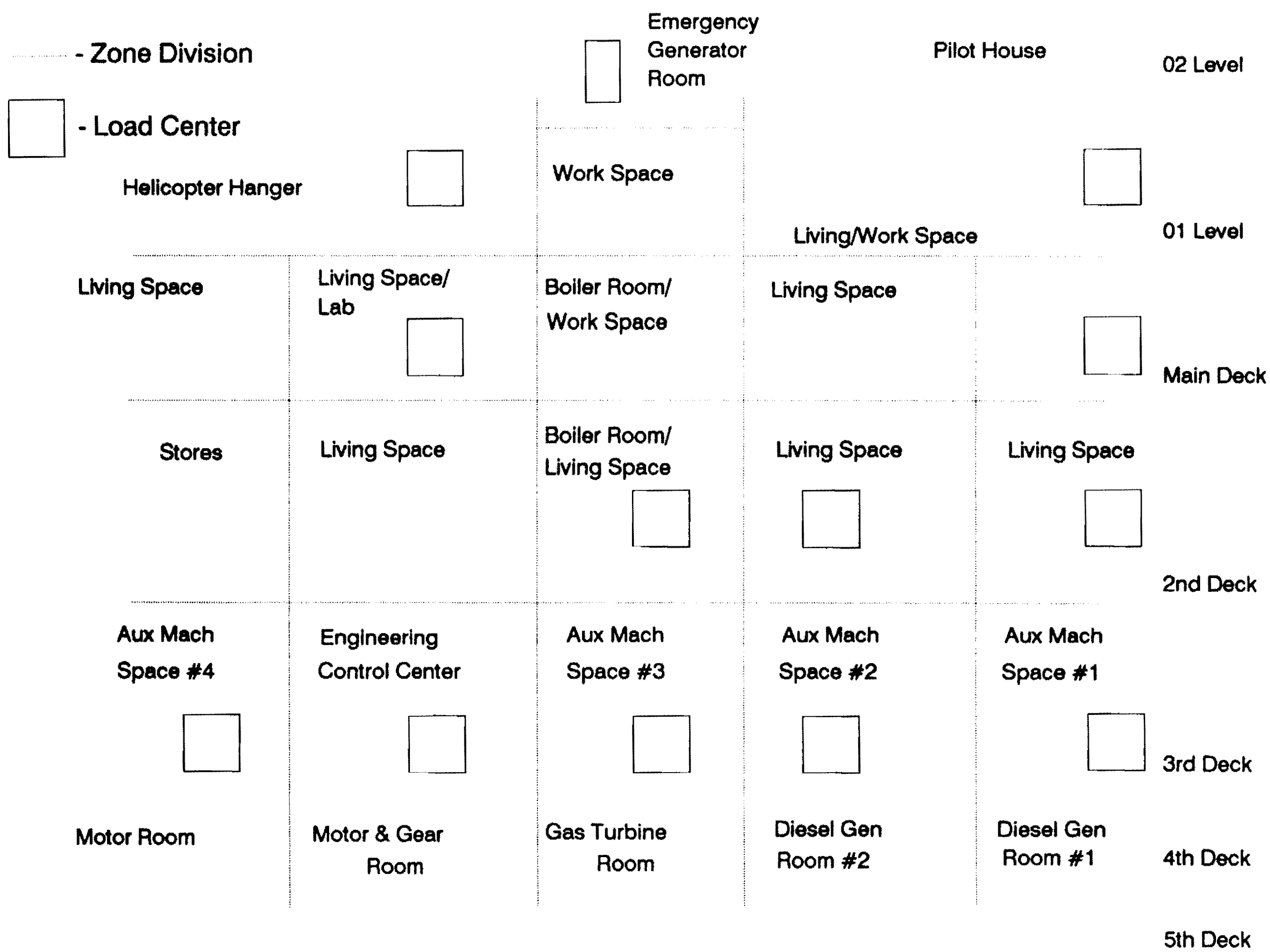
The bus feeder ring network layout emulated standard marine practice for vertical loop fire mains, guidance from the Polar Star's wireway diagram, and compartmentation arrangement. The new system routing was drawn out on a copy of the ship's general arrangement drawings which depict compartment arrangement to scale. The bottom horizontal main was placed at the forth deck on the starboard side, center main at the second deck port side, and the top main, starboard side, O2 level. (See figure 5 for general arrangement reference)

Vertical risers were placed on the ship's centerline. One was placed in each of the three engine rooms and two motor rooms to connect the bottom and center horizontal main sections. Two risers were used to connect the center and top horizontal section, one for each central fire zone division above the main deck. This layout provided each load center with two direct links to alternate power sources and took advantage of the protection provided by the vertical fire bulkheads located at the fire zones.

Switches were placed at strategic locations to allow remote compartment isolation and system reconfiguration. The bus feeders supply power to twelve load centers which were centrally located within each zone using the arrangement drawings. Power panels and motor controllers were radially fed from the load centers.

Figures 5, 6, and 7 illustrate central compartment arrangement, load center placement, and bus feeder and bus tie arrangements for the new and old systems. Illustration of other system components, such as power feeders, could not be included because of the size and complexity of the systems.

Figure 5. Inboard Profile, Center Section, General Arrangement



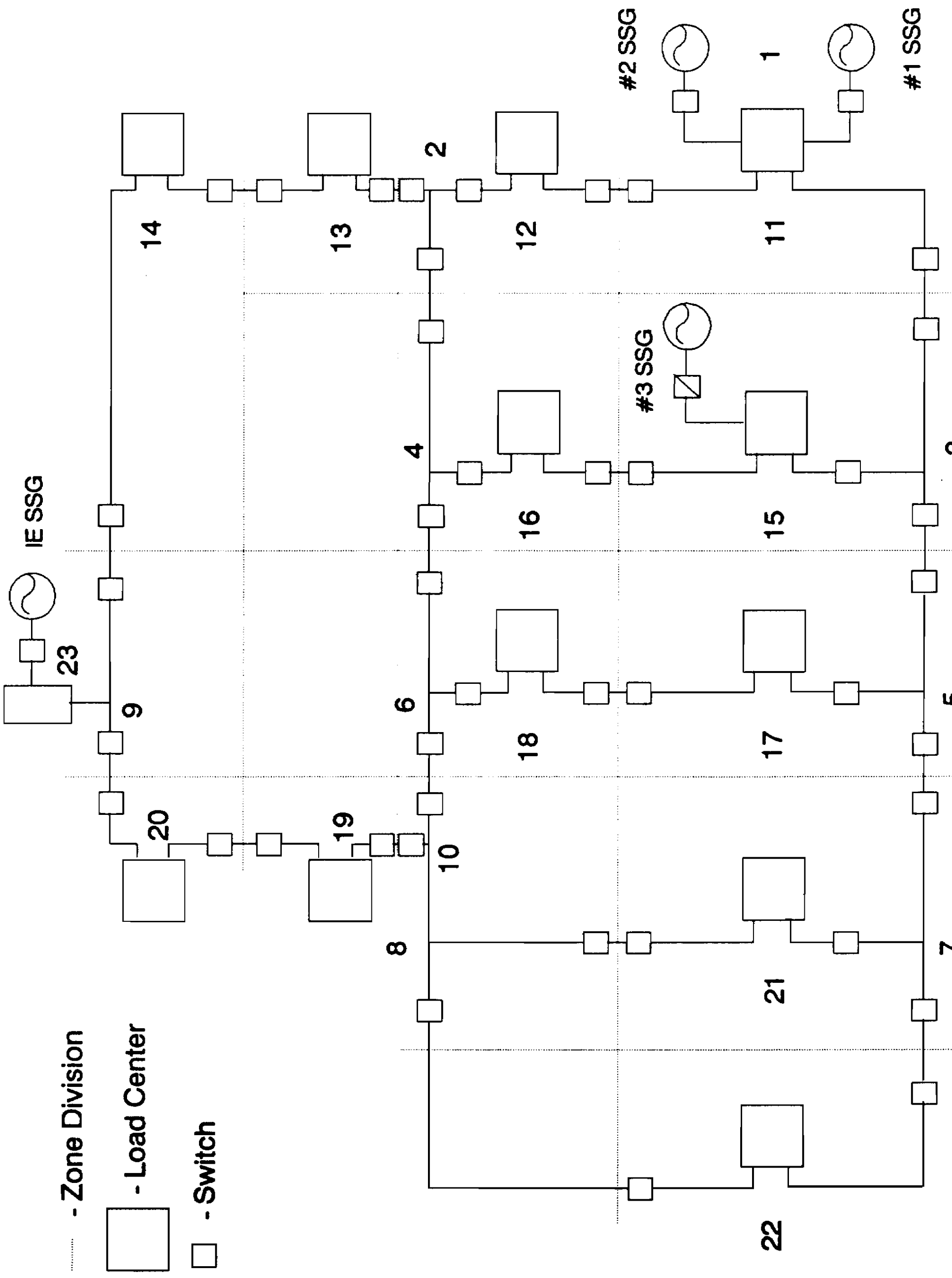


Figure 6. Ring System Arrangement

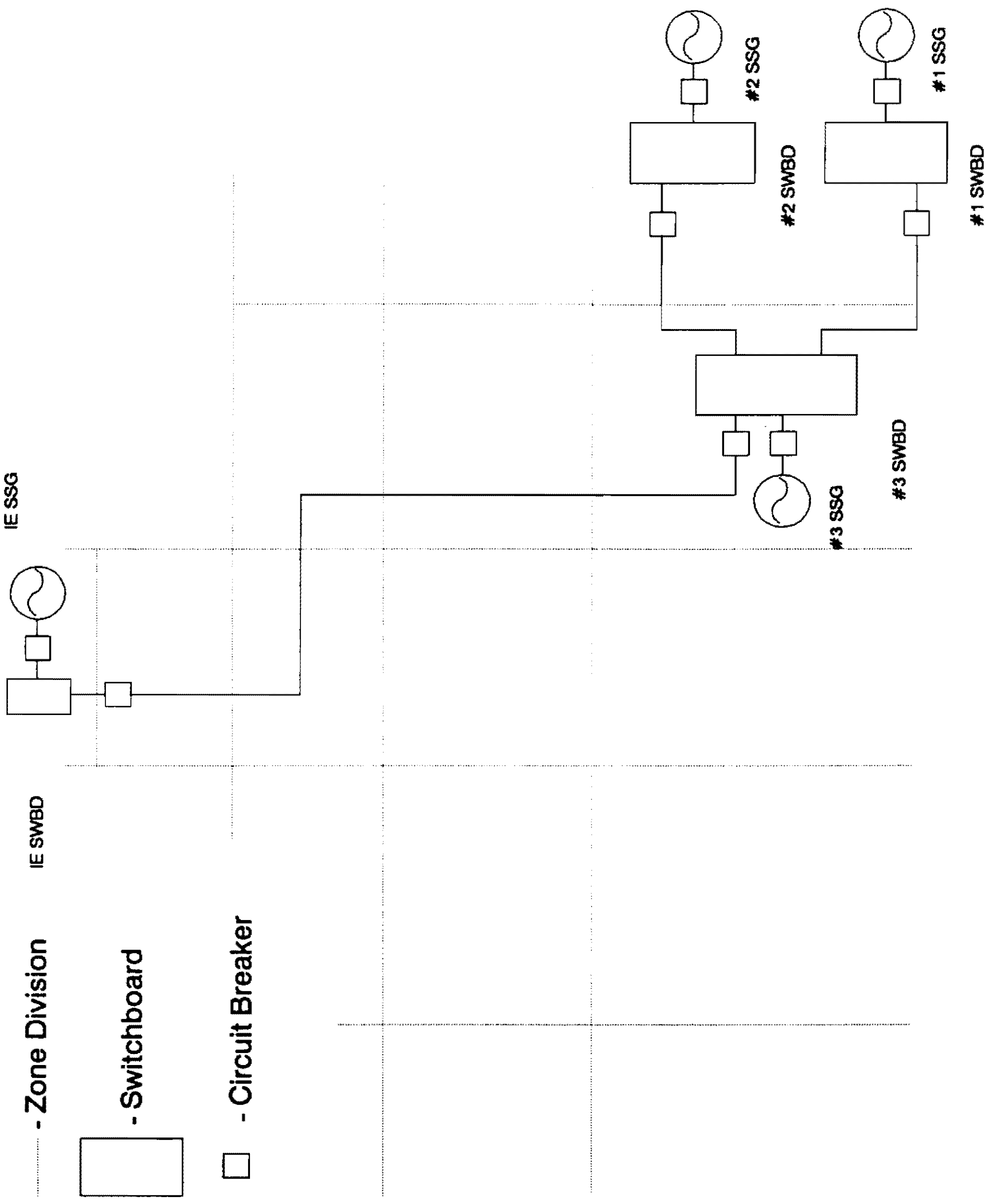


Figure 7. Radial System Arrangement

6.4 Distribution Feeder Arrangement

Load Center Location

Load centers were located centrally within each major fire zone. Each power panel and motor controller within each fire zone was fed from its corresponding fire zone load center. This strategy was used for all loads except those that extended past the for and aft ranges of the main engineering compartments. For these loads, power feeders were laid out similarly to the original system.

Load Feeder Layout

Routing for the power system feeders from the load centers followed standard guidances used for the Polar Star's original system. Some deviation was made from the wireways diagram for several sections to take advantage of the characteristics of the bus feeder ring which would allow shorter cable lengths to be utilized. Where these changes were made, standard marine practice was followed.

The third, fourth, and fifth decks of the engine rooms were combined into one zone for the purposes of power system distribution. A watertight boundary exists between the third and fourth decks, but most of the machinery located on the third level are electrically interconnected with the equipment located below. The probability of survival of ship service electrical equipment located directly above the main engines and ship service generators in this compartment during a main space fire would be low. System and mission wise, combining these zones is a good trade off. It reduces the number of remote switches required, and reduces system complexity.

This configuration provides the capability to narrow isolation down to the boundaries of each affected fire zone without loosing distribution to the undamaged zones. This zoned isolation and restoration could be maintained as long as damage doesn't extend vertically through all three horizontal main bus feeders, or vertically through all five main engineering compartments

6.5 Cable Capacity Determination

Bus Feeder Ring Cable Capacity Determination

Cable capacity selection for the bus feeder ring was done in a nonstandard manner. Overall power system feeder weight was used as the driving design factor for determining allowable cable selection alternatives for the bus feeder sections. This was done because many naval ships are weight critical. Combat requirements, plus the reduced cost of constructing and operating smaller multimission vessels has pushed many modern ship designs to their weight and balance limits. This means that for any new type of distribution design to be acceptable, it should not significantly exceed the total weight for the current system.

The total combined weight of all power system feeders from the original system was estimated to determine a reference weight for sizing the bus feeder cables for the new system. The weight of all primary and emergency power feeders which connect switchboards to distribution power panels and motor controllers, plus the switchboard bus ties were included.

Lengths for original power system cables were taken from the Polar Star's power system feeders list and power system isometric wiring diagram. These cable lengths, plus weight estimates from Navy Design Data Sheet DDS304-2, were used to estimate the total weight of all cables considered in the study. (See Appendix A for details)

6.6 Cable Selection

Load Feeder Cable Selection

The resultant current for each load was used for sizing load feeder cables. Load current magnitudes in polar form were used to size cables, while load currents in rectangular form were used to develop load flow program input. (See Appendix D for detailed current listings) The Gen Specs specify that for individual loads, the rated load current shall be used for determining cable current ratings. Power system cables are first selected by ampacity, and are then checked for voltage drop limits. If the voltage drop is too large, a larger sized cable must be selected. The standard for feeder cables is that the voltage drop at equipment terminals shall not exceed twelve percent under maximum resultant current conditions. Maximum resultant current is defined as "The vector sum of the starting current of the largest motor supplied and the rated load currents of all remaining motors and power appliances plus the allowance for spare switches." [13].

For cables less than 250 feet that have a demand factor greater than 0.8, voltage drop calculations are not required. For these cables, if ampacity requirements are met then voltage drop requirements are satisfied as a part of standard cable design. All of the load feeder cables in the new design had a capacity factor of 1.0 and a length of less than 250 feet. This length was measured from load center to load.

Because of the large capacity of the bus feeder ring, load center voltage drops should be small. If the load centers meet voltage drop criteria throughout the various possible distribution configurations, then standard feeder capacity requirements would be sufficient for sizing the new systems load feeders.

Calculating voltage drops for the bus feeder ring at maximum resultant current conditions is beyond the scope and means of this study. Determination of this information would involve an exhaustive contingency analysis using detailed equipment starting schedules based on possible mission and damage requirements. The availability of software specifically tailored to do radial system load flow and reliability analysis would greatly simplify this task.

Voltage transients due to switching, restoration and isolation of power to fire zones should be different from those encountered in the old system. This would result from the new system being operated by zones instead of by individual components. Transients resulting from total system loss and restoration should be the same.

Connected loads at power panels and motor controllers, as specified in the Coast Guard power system feeders list drawing, were used to select the cable size for each feeder from the load centers to the panels and controllers. The general arrangement drawings were used to lay out cable runs using standard marine practice.

Cable lengths for distribution feeders included an arbitrary four extra feet at terminal ends plus a ten percent cable length allowance for bends and slack. Cable lengths for the bus feeder sections were less generous. The slack factor was set at five percent, and no terminal allowance was added since cable runs for these sections were more direct.

Weights for the power system feeders were estimated using the same procedure as those used for the bus feeders. Cable ampacity ratings for TSGU/A cable at 60 Hz, 50° C ambient, were used.

Bus Feeder Cable Selection

The Total weight of the old system minus the combined weights of the new system's feeders from load centers to loads were used to determine an allowable weight per foot limit for bus feeder ring sections. This was used to guide initial cable combination selection.

Cable Selection Calculations

IE Load Center Bus Tie:

Generator Resultant Current 641.52 A PF 0.8

$641.52\underline{/-36.870}$ A

Cable Selection:

Length 16 ft	2-400	Ampacity at 50°C	2(400) = 800 A
	2-300		2(320) = 640 A

Selected 2-400

Weight 2(5.5)(16) = 176.0 lbs

R = 0.031 ohms/1000 ft (2)(16 ft) = 0.992 μΩ

X = 0.025 ohms/1000 ft (2)(16 ft) = 0.800 μΩ

Preliminary Cable Weight Totals:

New System:

Load Feeder Weight	4079.29
IE Bus Tie	+ 176.00
	4255.29

Old System:

Load Feeder Weight	27849.60
Bus Ties	+ 4184.50
	32034.10

Cable Weight Guideline For Bus Feeder Selection:

Break Even Weight:

Radial System Total	32034.10
New System Partial	- 4255.29
Lbs Available	27768.81

Main Feeder Total Length	915.0 ft
Slack Allowance	5.0 %
Total Length Plus Slack	960.8 ft

27768.81/960.8 = 28.91 lbs/ft

Cable Size and Configuration Selection:

TSGU/A-400:

Ampacity 400 amps Weight 5.5 lbs/ft

R 0.031 Ω/1000 ft

X 0.025 Ω/1000 ft

28.91/5.5 = 5.26

5-400:

Ampacity 5(400) = 2000 A

Main Feeder Weight (5)(5.5)(960.8) = 26422.0 lbs

Total Weight 26422.0 + 4255.3 = 30677.3

Comparison (100)(30677.3 - 32034.1)/(32034.1) = - 4.2 %

Total Cable Section Width (5)(2.20) = 11.00 in

R = (5)(0.031) = 0.153 Ω/1000 ft

X = (5)(0.025) = 0.125 Ω/1000 ft

6-400:

Ampacity 6(400) = 2400 A

Main Feeder Weight (6)(5.5)(960.8) = 31706.4 lbs

Total Weight 31706.4 + 4255.3 = 35961.7

Comparison (100)(35961.7 - 32034.1)/(32034.1) = + 12.3 %

Total Cable Section Width (6)(2.20) = 13.20 in

R = (6)(0.031) = 0.186 Ω/1000 ft

X = (6)(0.025) = 0.150 Ω/1000 ft

TSGU/A-300:

Ampacity 320 A Weight 4.1 lbs/ft

R - 0.043 Ω/1000 ft

X - 0.026 Ω/1000 ft

28.91/4.1 = 7.05

7-300:

Ampacity 7(320) = 2240 A

Main Feeder Weight (7)(4.1)(960.8) = 27575.0 lbs

Total Weight 27575.0 + 4255.3 = 31830.3

Comparison (100)(31830.3 - 32034.1)/(32034.1)
= - 0.6 %

Total Cable Section Width (7)(1.96) = 13.72 in

R = (7)(0.043) = 0.301 Ω/1000 ft

X = (7)(0.026) = 0.182 Ω/1000 ft

8-300:

Ampacity 8(320) = 2560 A

Main Feeder Weight (8)(4.1)(960.8) = 31514.2 lbs

Total Weight 31514.2 + 4255.3 = 35769.5

Comparison (100)(35769.5 - 32034.1)/(32034.1)
= + 11.7 %

Total Cable Section Width (5)(1.96) = 15.68 in

R = (8)(0.043) = 0.344 Ω/1000 ft

X = (8)(0.026) = 0.208 Ω/1000 ft

Summary Of Results

Cable Size	No. Parallel	Capacity amps	% Gen Capacity	Weight lbs	Added Sys. Weight	Added Sys. Weight(%)
400	5	2000	83.13	30677.3	-2287.7	-6.9
400	6	2400	99.76	35961.7	2996.7	9.1
300	7	2240	93.11	32034.1	-1134.7	-3.4
300	8	2560	106.41	35769.5	2804.5	8.5

Note:

1. Percent Generator Capacity is for normal operation with two main ship service generators in parallel.

2. All cables are standard shipboard three conductor cables, one conductor per phase, ungrounded neutral.

Final Cable Selection

Six T-400 cables in parallel were selected giving each bus feeder section a capacity of 2400 amps, or 1870 KVA, equal to parallel generator capacity of two main ship service generators. This configuration was selected because it matched bus feeder section capacity to normal available generation. Since actual capacity requirements would have to be determined as a part of possible future system analysis, this seemed to be a good preliminary standard.

The system weights for all four evaluated configurations would be acceptable for this particular ship. Weight and capacity results for other vessels would depend on the number and lengths of the individual power system feeders installed.

Actual Bus Feeder Capacity Requirements

The Gen Specs allow the use of demand factors for power system feeders supplying two or more loads, and maximum normal switchboard loads for interconnections between load centers and main switchboards. Classification for the bus feeder ring should fit somewhere between these two standards.

The reason that this system doesn't meet the definition for switchboard interconnections is that each cable section must be capable of carrying its share of the radial load for the entire system for every possible configuration. Cable loading would change significantly with system reconfiguration. Sizing the cables this way would provide flexibility that the standard definition would not.

System weight was used as a design starting point which resulted in a bus feeder section capacity of 1870 KVA. This exceeds the largest normal estimated load by approximately 500 KVA. Individual section loads should be significantly lower than this for distribution configurations where system loading could be evenly distributed. Further study would probably show this standard to be excessive. This would allow distribution weights to be decreased.

Cable capacity requirements for other vessel would be a function of ship's mission. The higher the percentage of vital loads, the greater the weight benefits should be from replacing redundant power system feeders.

6.7 Preliminary Feasibility Evaluation

As an initial measure of system feasibility, a comparison of the capacity of each bus feeder section to normal on-line generation capacity shows the two systems to be approximately equal. This is a worse case comparison where total system load could not be evenly distributed among the three major sections of the bus feeder ring.

The Polar Star has four ship service generators, but at most only two of them would normally be placed on line at any one time meet peak load requirements. This includes normal and emergency operations. The only reason more than two would ever be used is not due to exceeding generator capacity, but due to the loss of distribution interconnections which would isolate parts of the system.

Main ship service aggregate capacity is determined using standard marine practice. The generating plant must consist of at least two generator sets rated so that if one set is not in operation, the remaining sets are able to carry the largest normal estimated peak load. This requirement is exclusive of emergency generator requirements [14].

The Polar Star's main ship service generators were sized to meet this criteria. Normal procedure for this type of ship during peak load operation is to run two generators in parallel, each equally sharing the load.

Generator stability should not be a factor in operating the new system by zones since electrical generation and load control are designed to stabilize the system through total voltage loss and restoration and on-off operations of large deck machinery. Starting currents, following total system simultaneous start after loss of voltage, are limited by the strategic allocation of controllers with automatic and manual restart capabilities. These requirements would be identical to a worst case stability problem for the bus feeder ring system.

6.8 New System Protection

Protection of the electrical system would remain basically the same. System protection for the generators, and from the load centers to loads would be of the same type as used in the original system. Some method for preventing the closing of any loops in the bus feeder ring would be required to insure that system security is maintained. Some changes may also be necessary if there is a significant change in fault currents due to the ability to significantly reconfigure the system. No preliminary fault analysis was performed as a part of this study because no suitable software was available for doing a contingency fault analysis on the new system.

CHAPTER VII

LOAD FLOW ANALYSIS AND SYSTEM COMPARISON

Two types of analysis were performed to evaluate the feasibility of the new system and to locate possible problem areas:

1. Contingency analysis using a Gauss-Seidel load flow routine to examine line loading and system voltage profile.
2. Damage control operation reliability comparison with old system.

7.1 Contingency Analysis Description

Standard Power System Contingency Analysis

Conventional contingency analysis of transmission systems examine the affect of line and generator loss on total system operation. The loss of one line can cause the overloading and subsequent loss of other lines, resulting in cascading casualties which can bring down the whole system. Major changes in generation can bring on similar results. The goal of contingency analysis is to identify weak sections of the system, and to aid operators in carrying out defensive measures which keep the system secure during normal operations [15].

Because of reliability requirements, most shipboard systems consist of series components sized so that exceeding component capacities is seldom the cause of cascading casualties or insecure system operation. Cascading casualties of ship systems are usually the result of the loss of vital system auxiliaries or sections of interdependent systems. A good example of this is the loss of main propulsion due to the failure of an on line ship service generator which supplies propulsion generator excitation through a motor generator.

Contingency Analysis of Procedure

The contingency analysis was performed to examine the effects of system reconfiguration on line loading and system voltage profile. Both of these factors need to be within acceptable limits for every possible configuration for the new system design to be acceptable.

Normal Operation Analysis

Four likely operating configurations were selected and combined with three standard generator combinations to form twelve possible operating configurations. Load flows were run for each contingency. The loading condition used was the largest normal estimated load, which was icebreaking with the propulsion diesel generator sets on line. Typical problems with performing load flow studies on small radial systems were encountered. Two standard transmission analysis packages were tried unsuccessfully. Neither one would converge for either the old or new system. The program that was finally used was a simple Gauss-Seidel routine that was altered by making system variables double precision.

Allowed to run long enough, the program consistently converged to a viable solution. The average load flow problem analyzed had 90 buses and lines. Problem solution took an average of 1000 to 3000 iterations. On the IBM, Model 70, with math coprocessor; which was used to run the program, processor time ranged from one to three hours. Though cumbersome, the program served the purposes of this study. Detailed refinement of this type of design would require the use of analysis software particularly designed for radial distribution systems analysis.

Resulting node voltage drops and line flows were tabulated. (See Appendix B and C for detailed load flow output) The final tabulations presented in this chapter are summaries the load flow output produced for all twelve contingencies. The contingencies performed were not exhaustive, but were sufficient to illustrate the preliminary feasibility of the new design.

Power system feeder cables are sized primarily by load current requirements. By design, standard power system cables meet voltage drop requirements when ampacity requirements are met. This can be seen by comparing the cable sizes and lengths between the alternate and normal feeder cables used in the original system. (See Appendix A)

Cable sizing between the old and new system were different for several reasons:

1. Shorter new system cables allowed use of smaller cable sizes where voltage drop was a factor in the original design.
2. Data for all intermediate sizes used in the original design was not listed in the current navy design data sheets. This resulted in cable size increases.
3. Interconnected power distribution panels were spilt up and individually fed from load centers. This resulted cable size reductions.

Contingency Generator Configurations

Three generator combinations were chosen for the contingency analysis which follow standard operating procedures. The first two combinations represent normal operations. The third represents parallel operation with the emergency generator, which was included to simulate spinning reserve for possible generator loss.

Case A: #1 SSG // #2 SSG

Case B: #1 SSG // #3 SSG

Case C: #1 SSG // #2 SSG // IE SSG

For case C, the emergency generator bus was clamped at 300 KVAR because its capacity limits were exceeded when used as a voltage control bus.

Voltage drop and line flow results for the feeders connecting the load centers to the distribution panels and motor controllers was not included in the tabulation of contingency results. Line currents for these sections were identical to those of the original system. This part of the system was compared to the corresponding components of the original system for one normal and one damage condition in the system comparison section of this paper.

Bus Feeder Contingency Configurations

The configuration depicted by figure 8 provides uniform distribution. Two benefits to this are more even line loading, and reduced probability of equipment failure due to possible loss of any single feeder section. Staggering power distribution between the bottom, center, and top horizontal feeders would reduce the impact to the propulsion system resulting from the loss of any one of these main lines.

The configurations in figures 9, 10, and 11, were selected as possible variations of the normal operating configuration shown in figure 8. Each one uses one of the main horizontal feeds as its primary section.

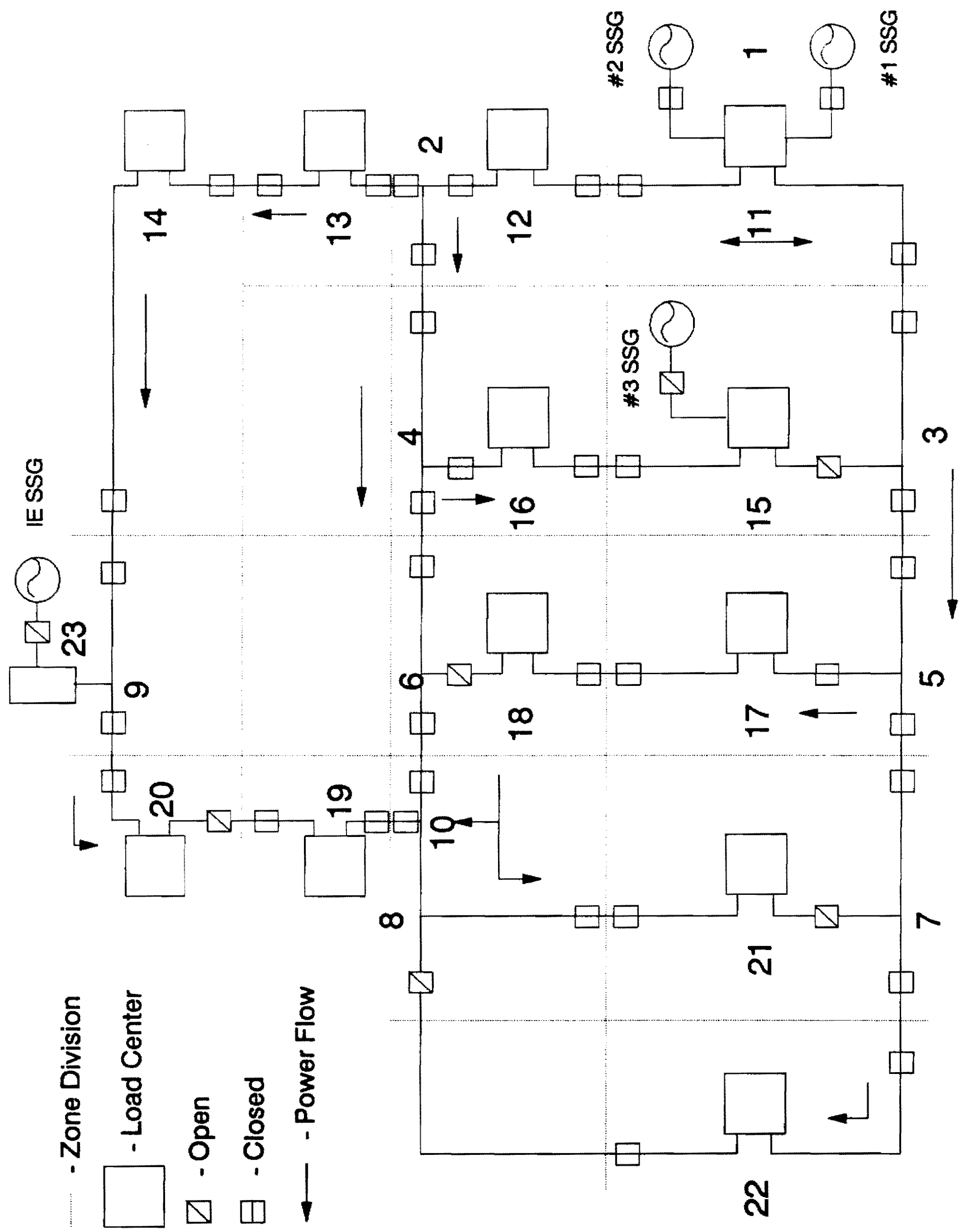


Figure 8. Normal Operation, Split Distribution

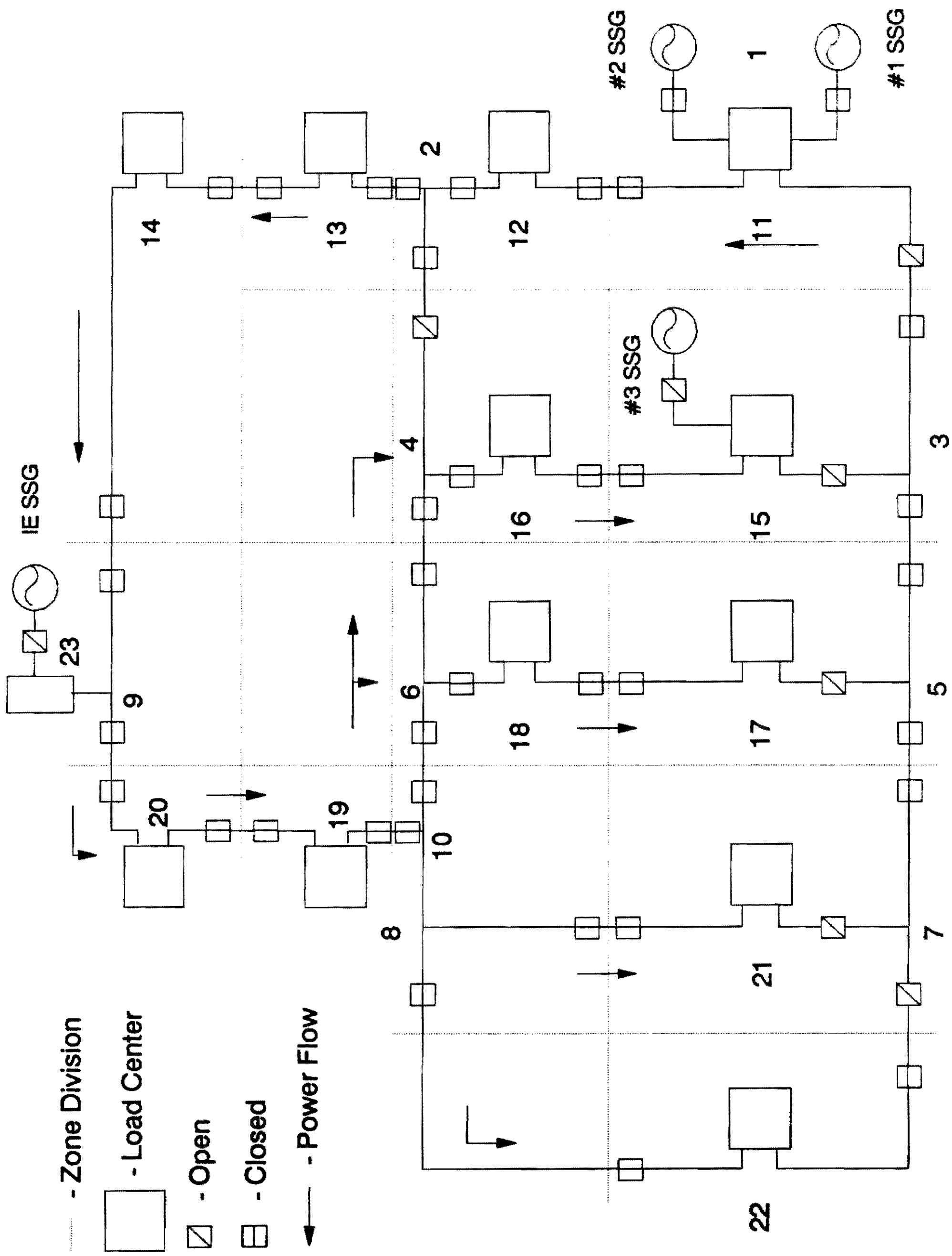


Figure 9. Normal Operation, Top Feeder Operation

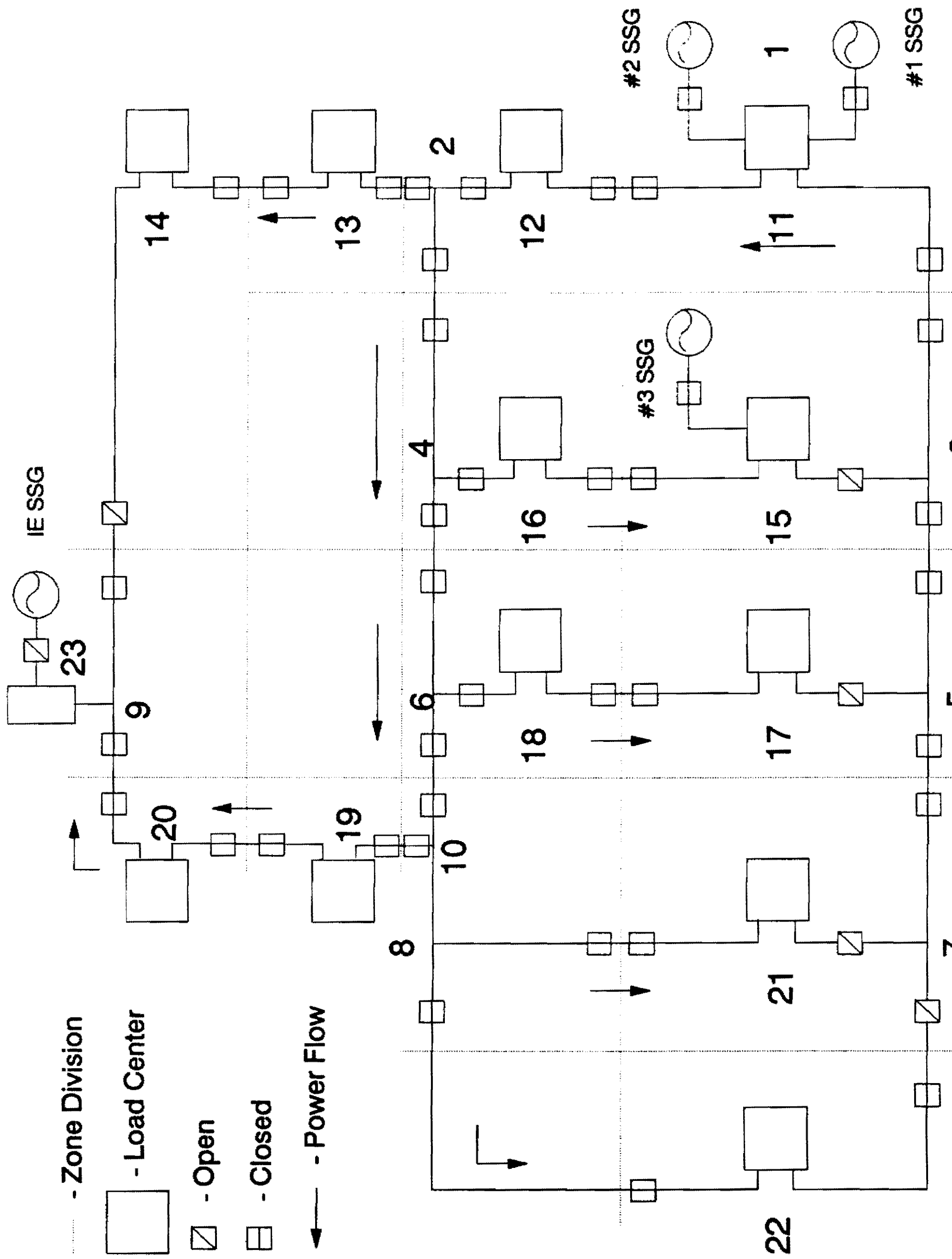


Figure10. Normal Operation, Center Feeder Distribution

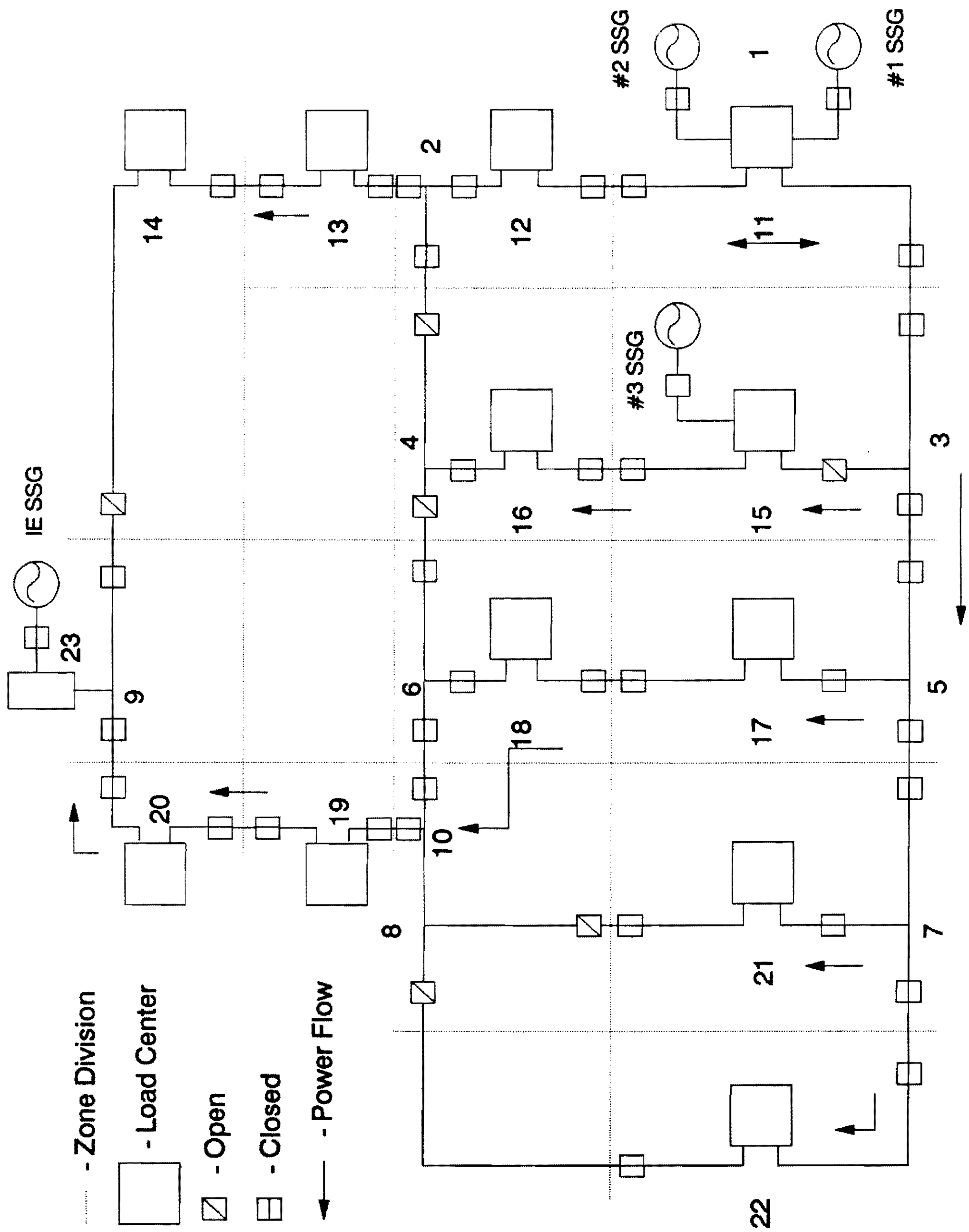


Figure11. Normal Operation, Bottom Feeder Operation

7.2 Contingency Analysis Results

Voltage drops for all contingencies were well within the 2.0 percent limit for load center bus feeders as set by Navy specifications. The generator configuration with the lowest average voltage drops, and most uniform voltage profile was case B. This case had generation divided evenly between the first and second engine rooms.

Line flow analysis showed the new design to be well suited for major reconfiguration. No individual line was loaded significantly higher than the majority of the other lines. Maximum line loading was well within the 1870.6 KVA cable operating limit. Many lines were consistently loaded at a much lower level, indicating the possibility of reducing the size of some cables.

Tables 2 and 3, and figure 12 were used to present summarized results of the load flow analysis. To be able to put some type of quantitative measure on system performance, the mean average and standard deviation for load center voltage drops and percentage of full load line flow were calculated. Full load for the bus feeder sections was taken to be feeder cable full load continuous current ratings for 50° C. The mean average was selected to give a rough measure for system loading. Standard deviation was used to show over all voltage regulation and line loading uniformity. The formulas for calculating these measures were :

N - Number of samples X - Sample value

$$\text{Mean} = \overline{X} = \frac{\sum_{i=1}^{N} X_i}{N} \qquad \text{Sdev} = \sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} (X-\overline{X})^2}$$

Detailed load flow program output listings for line flows, and load center voltages and voltage drops are given in Appendix B.

Line Loading

Table 2 shows system line flows to vary greatly from section to section as can be seen by the relative size of the line flow standard deviations and mean averages. Nonuniform line loading is a function of the systems isolation and reconfiguration capabilities. Section cables must be sized to meet any load which might be connected. This flexibility makes it difficult to uniformly load cable sections; but, for a vital system, this is an acceptable trade off.

Table 3 and figure 12 depict maximum line loading for each section through all twelve contingencies. These ranged from 8.7 to 72.0 percent. Since anything under 100.0 percent is acceptable, the sizing of distribution ring cables are well within specification limits.

Voltage Profile

Table 2 uses the same statistical calculations as the previous section to evaluate load center voltage drops. Unlike line loading, uniform voltage profile is an important characteristic for this system. The small relative size of standard deviations, as well as low voltage drop averages are indicative of uniform voltage performance which would serve to increase electrical system security and would reduce the need for use of voltage regulation equipment at the loads

Appendix B contains complete output listings for load center voltage drops. The largest estimated voltage drop was 1.322 percent. This was for case A, configuration 4. (See table 12) The maximum voltage drop allowed by Navy specifications is two percent. By fixed systems standards this shows distribution ring reconfiguration and cable sizing to be acceptable.

Meeting load center requirements also validates the method previously used in chapter VI to size load feeders. These cables are used to radially connect load centers to individual electrical loads. Navy Gen Specs allow cables of less than 250 feet in length to be sized by ampacity only. This length is measured from main switchboard to load. Having all load centers meet the two percent requirement allows the load centers to be used as the starting point for this measurement, eliminating the need to include distribution ring sections as part of the sizing procedure.

Further steady state and transient condition contingency analysis would need to be performed for the purpose of refining this design. The twelve contingencies performed were sufficient for showing load center voltage profile and bus feeder capacity feasibility.

Table 2. Ring System Power Feeder Contingency Analysis Case Comparison

Case A: #1 SSG // #2 SSG
Case B: #1 SSG // #3 SSG
Case C: #1 SSG // #2 SSG // IE SSG

Load Center Voltage Drop (%)

Configuration:		1	2	3	4
Case A	Mean	0.297	0.473	0.525	1.004
	Sdev	0.119	0.209	0.224	0.378
Case B	Mean	0.180	0.208	0.208	0.223
	Sdev	0.106	0.138	0.170	0.137
Case C	Mean	0.161	0.233	0.299	0.630
	Sdev	0.196	0.123	0.126	0.249

Line Flows (% Maximum)

Configuration:		1	2	3	4
Case A	Mean	17.09	13.71	19.49	26.89
	Sdev	15.31	17.77	25.73	29.28
Case B	Mean	16.02	13.37	18.02	19.24
	Sdev	11.34	15.19	18.81	15.98
Case C	Mean	18.51	17.46	18.67	24.50
	Sdev	10.88	11.73	15.72	21.57

Note:

Power Feeder Maximum Section Capacity at 50 C 1870.61 KVA
Connected Load Case A, B, and C: 1257.00 KW 521.00 KVAR
Generator Capacity Case A and B: 1200 KW 900 KVAR
Generator Capacity Case C: 1600 KW 1200 KVAR

Table 3. Ring System Power Feeder Contingency Analysis Line Flow Summary

```
Case A: #1 SSG // #2 SSG
Case B: #1 SSG // #3 SSG
Case C: #1 SSG // #2 SSG // IE SSG
```

Contingency Line Flows (KVA/DEG)

Buses\Case:	A	B	C	Largest Case
2 4	1113.77/24.4	393.09/12.0	653.16/21.1	1113.77/24.4
2 12	-1301.54/23.2	-577.06/13.1	-819.72/14.8	-1301.54/23.2
2 13	1301.58/23.2	562.90/ 3.3	819.75/14.8	1301.58/23.2
3 5	1041.07/24.2	1041.44/24.2	546.18/12.9	1041.44/24.2
3 11	-1112.06/24.4	-446.72/29.0	-633.22/14.6	-1112.06/24.4
3 15	71.13/27.6	718.74/38.0	71.13/27.6	718.74/38.0
4 6	1041.44/24.2	1041.79/24.2	582.01/20.3	1041.79/24.2
4 16	71.13/27.6	-662.87/31.3	817.15/23.8	817.15/23.8
5 7	817.15/23.8	817.21/23.8	356.67/28.2	817.21/23.8
5 17	222.84/25.5	223.21/25.5	-372.22/42.5	-372.22/42.5
6 10	951.16/23.4	951.44/23.4	581.52/20.3	951.44/23.4
6 18	-133.89/21.0	-134.14/21.0	461.47/20.3	461.47/20.3
7 21	461.47/20.3	461.47/20.3	356.32/28.2	356.32/28.2
7 22	-815.98/23.7	-816.08/23.7	356.37/28.2	-816.08/23.7
8 10	-815.99/23.7	-816.09/23.7	815.99/32.7	-816.09/23.7
8 21	461.58/20.3	461.59/20.3	461.56/20.3	461.59/20.3
8 22	-1112.03/24.4	-384.06/-2.6	-372.28/42.5	-1112.03/24.4
9 14	1107.51/24.5	384.06/-2.6	-633.30/14.6	1107.51/24.5
9 20	10.64/41.2	10.64/41.2	1107.49/24.5	1107.49/24.5
9 23	-976.41/24.8	266.41/-14.2	495.77/37.2	-976.41/24.8
10 19	134.02/21.0	134.12/21.0	-976.41/24.8	-976.41/24.8
11 12	1348.21/22.4	624.46/12.1	867.19/14.1	1348.21/22.4
13 14	1180.19/23.2	714.70/31.3	700.09/13.4	1180.19/23.2
15 16	51.12/30.6	770.30/37.5	20.24/20.2	770.30/37.5
17 18	162.21/23.3	162.45/23.2	-61.05/31.6	162.45/23.2
19 20	-1095.62/24.3	14.78/28.3	1095.62/24.3	1095.62/24.3

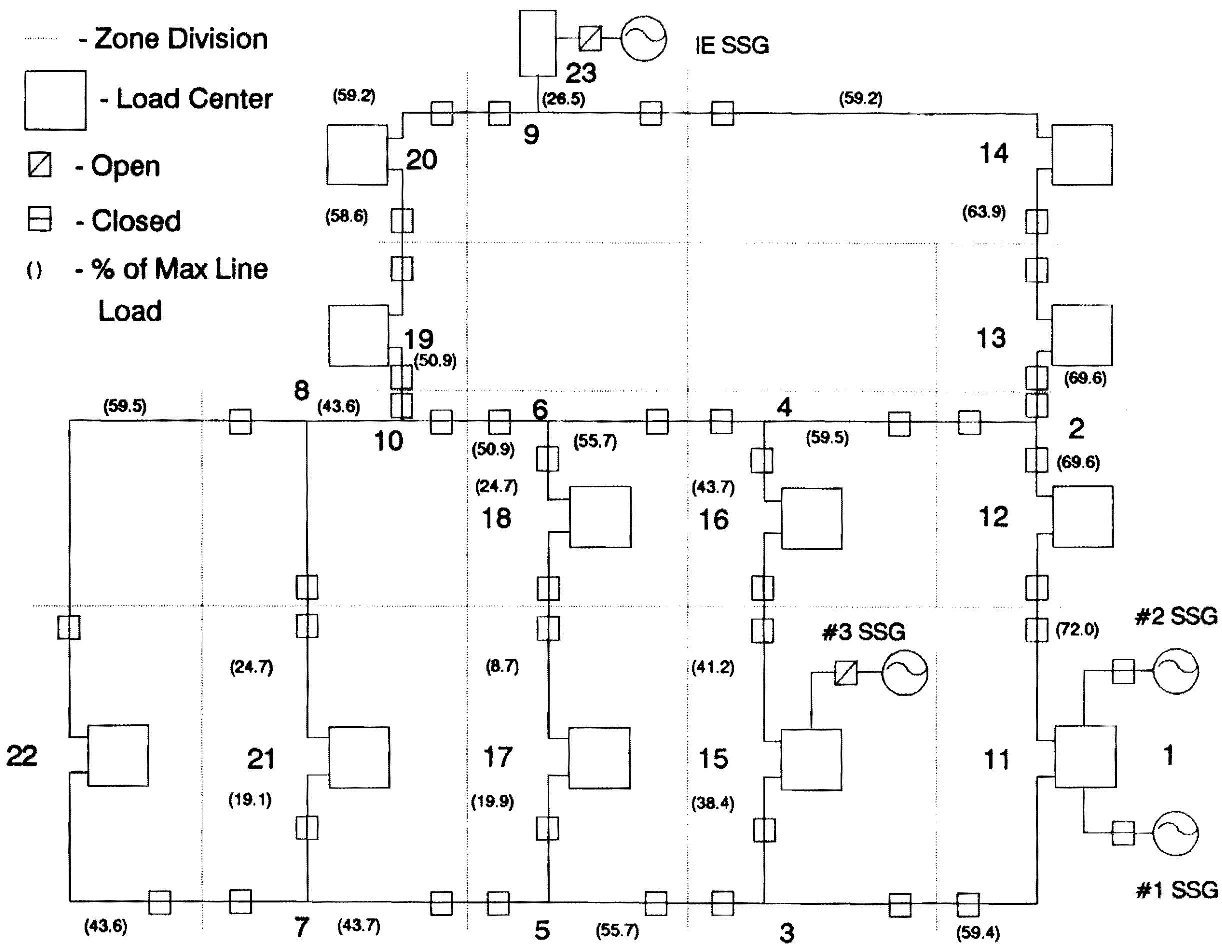


Figure12. Contingency Analysis Maximum Line Flow Summary

7.3 Radial and Ring System Comparison

Comparison of voltage profile and system operation was made between the two systems for one normal condition and one damaged condition.

Normal Operation Comparison

The normal operation condition consisted of normal distribution and generator configurations, icebreaking diesel, and the first and second ship service generators in parallel. Voltage drops at the loads and overall system losses were tabulated and compared using calculations identical to those used for load center voltage drop analysis. Table 4 compares load voltage drops between the old and new systems. The first two rows of this table shows average voltage drops from generator to load to be similar for each system. The third compares the differences between identical loads as fed by the different systems.

The smaller losses experienced in the new system is a function of the large relative size of the new system's bus feeder section cables and subsequent loading at only partial capacity.

Tables 5 and 6 are a line by line comparison of system load feeder cable performance for the selected damaged condition. From this comparison, load voltages, cable failure and resulting load loss, and generator operating requirement differences can be seen. Every cable located within the second engine room was considered to be failed. In an actual fire, this would be true either as the result of actual damage or as part of required electrical isolation.

Table 4. Normal Operation Voltage Profile Comparison Results

Voltage Drop (%)	Mean	Sdev
Radial System	0.443	0.313
Ring System	0.413	0.210
Individual Load Differences Between Systems	0.030	0.304
Total Connected Load	1257.000	521.000
Radial System Total Losses	7.755	
Ring System Total Losses	5.650	

Normal Operation Comparison Results

Voltage profiles and system operation were very similar for both systems for the normal operating condition selected.

Damage Condition Operation Comparison

The loading condition used for this load flow analysis was a combination of icebreaking diesel and emergency conditions. The major load additions for the emergency condition were the magazine sprinkler pump, and the number one fire pump. The first and second main generators, and the emergency generator were used to provide power. Damage was simulated by disconnecting all distribution feeders in the second engine room. Generation requirements for the emergency condition for the new system could have been met without using the emergency generator. It was included for the system comparison purposes.

Electrical isolation is depicted in figures 13 and 14 through the operation of bus tie breakers and bus feeder switches. Isolation of the original radial system would also require operation of numerous power feeder circuit breakers at each of the ship service switchboards. These components were not included in figure 13 because of their large numbers and complex layout. Detailed isolation circuit operating requirements are illustrated in table 7 of section 7.4.

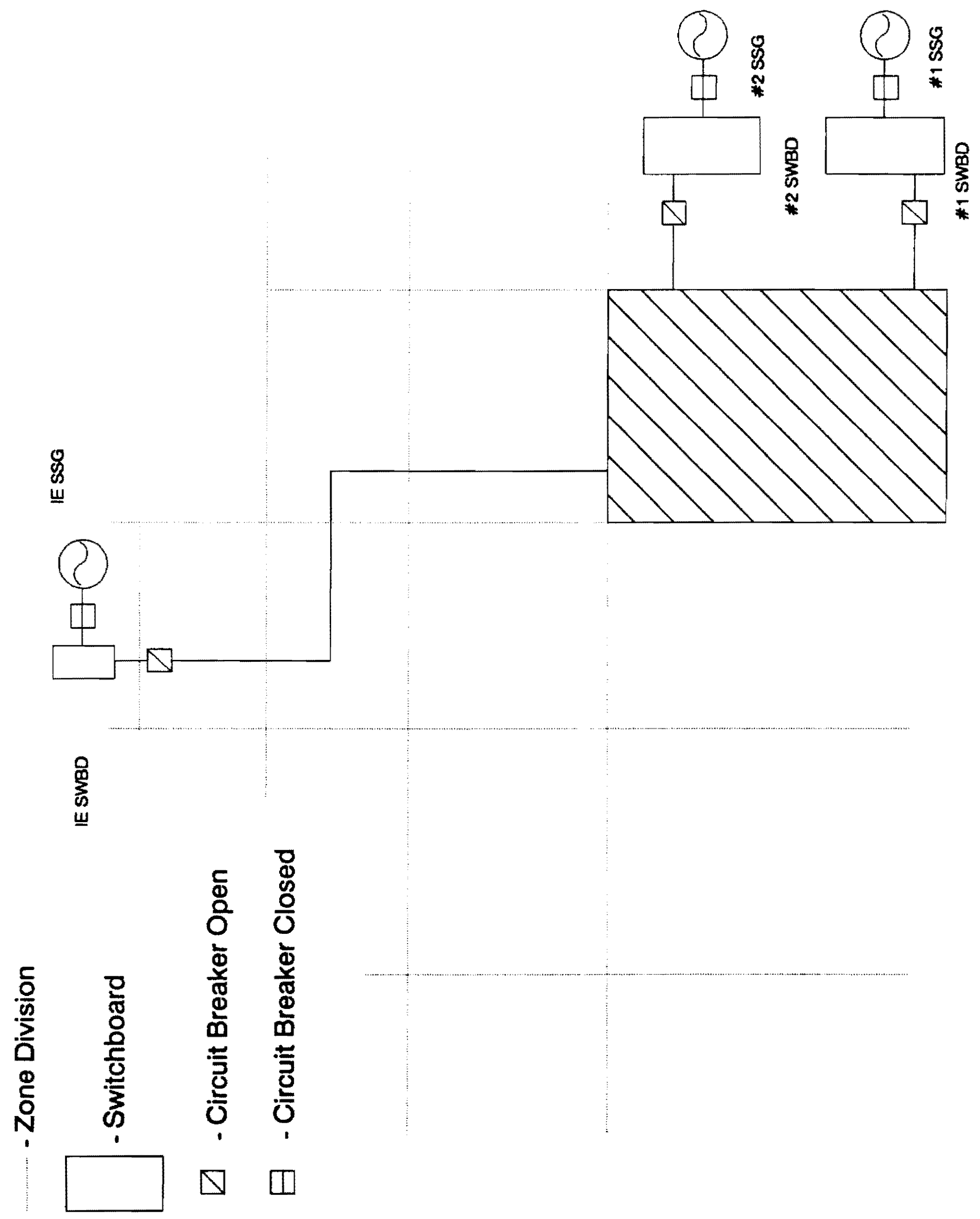


Figure13. Radial System, Damaged Operation

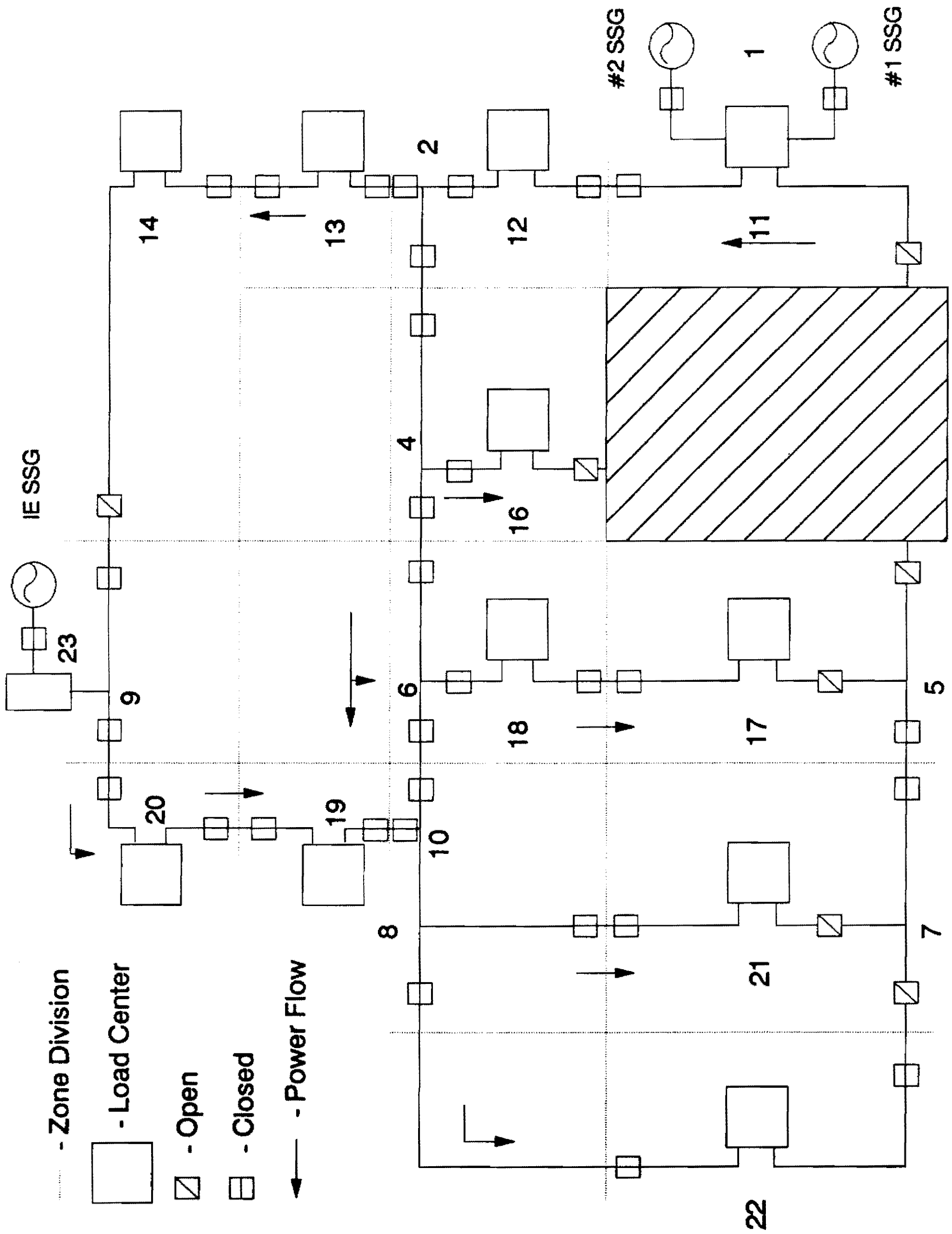


Figure14. Ring System, Damaged Operation

Damage Condition Operation Comparison Results

The damage operation comparison showed similar voltage drops and line flows for each system. The significant result from this comparison was in showing the difference between generator operation requirements. For the radial system, loss of the second engine room required split plant operation of the remaining three generators. This required isolation can be seen in figure 13. The majority of the vital loads were supported by the emergency generator which has a much smaller capacity than the number one and two ship service generators. This left no backup generation, exceeded emergency generator capacity, and required that some of the vital loads be dropped. To reduce the load to acceptable limits, vital auxiliaries to the number three shaft were secured, which left propulsion intact but at a reduced level.

The bus feeder ring system had adequate generator capacity to serve all applicable surviving loads because the number one and two ship service generators could be used in addition to the emergency generator. A significant addition to the loads that could be kept on-line was zebra ventilation which is commonly used to maintain smoke boundaries for the purpose of reducing the spread of toxic fumes and gases.

Damaged Condition, Fire in 2nd Engine Room

Radial System IE SWBD Loads			Ring System Loads		
Load	Voltage	V Drop (%)	Load	Voltage	V Drop (%)
2-105-1	448.850/ .028	0.256	2-105-1	448.446/-.085	0.345
3-126-4	448.996/ .022	0.223	3-126-4	448.048/-.103	0.434
3-133-5	446.863/-.132	0.697	3-133-5	448.059/-.104	0.431
4-142-1	449.391/ .012	0.135	4-142-1	448.078/-.105	0.427
3-164-2	449.889/-.002	0.025	3-164-2	447.028/-.149	0.661
3-164-4	449.889/-.002	0.025	3-164-4	446.835/-.155	0.703
3-166-2	449.889/-.002	0.025	3-166-2	446.870/-.154	0.695
3-170-1	446.598/-.014	0.756	3-170-1	447.141/-.143	0.635
3-170-3	446.598/-.014	0.756	3-170-3	447.063/-.143	0.653
3-170-5	446.992/-.012	0.668	3-170-5	447.221/-.142	0.617
IC	446.652/ .264	0.744	IC	446.589/-.084	0.758
3-175-1	Load Shed (#3 Shaft)		3-175-1	447.152/-.141	0.633
3-176-2	448.821/ .030	0.262	3-176-2	447.157/-.139	0.632
3-176-3	449.120/ .019	0.196	3-176-3	447.106/-.137	0.643
3-176-5	448.822/-.015	0.262	3-176-5	447.094/-.141	0.646
MAG PUMP	Load Shed		MAG PUMP	438.026/ .340	2.664
2-243-2	447.722/ .104	0.506	2-243-2	445.528/ .018	0.994
01-148-1	448.755/ .115	0.277	01-148-1	447.761/-.091	0.497
02-67-1	449.411/ .007	0.131	02-67-1	447.734/-.112	0.504
GEN HTR	Load Shed		GEN HTR	447.467/-.119	0.563
03-63-2	Load Shed (Window HTR)		3-63-2	447.207/-.079	0.621
SRCH LT	449.889/-.002	0.025	SRCH LT	448.158/ .009	0.409

Conn. Load = 367.000 KW 204.000 KVAR
Losses = 1.252 KW 0.632 KVAR

Damaged Condition, Fire in 2nd Engine Room

Radial System #1 SWBD Loads			Ring System Loads		
Load	Voltage	V Drop (%)	Load	Voltage	V Drop (%)
1-39-1	449.120/ .092	0.196	1-39-1	448.755/-.062	0.277
1-52-1	449.207/ .028	0.176	1-52-1	445.640/ .166	0.969
3-66-2	449.894/-.003	0.023	3-66-2	449.283/-.028	0.159
4-78-1	447.767/ .058	0.496	4-78-1	447.287/ .051	0.603
1-116-1	449.734/-.007	0.059	1-116-1	447.834/-.119	0.481
2-122-1	449.807/-.007	0.043	2-122-1	448.078/-.105	0.427
01-67-1	449.706/-.209	0.065	01-67-1	446.298/-.085	0.823

Conn. Load = 129.000 KW 47.000 KVAR
Losses = 0.475 KW 0.234 KVAR

Radial System #2 SWBD Loads			Zone System Loads		
Load	Voltage	V Drop (%)	Load	Voltage	V Drop (%)
1-67-1	446.275/ .282	0.828	1-67-1	448.623/-.052	0.306
1-70-1	447.244/ .220	0.613	1-70-1	448.731/-.060	0.282
2-66-1	446.844/-.045	0.701	2-66-1	448.048/-.061	0.434
3-66-4	449.908/-.003	0.021	3-64-4	449.292/-.029	0.157
2-122-2	448.706/ .071	0.288	2-122-2	447.701/-.078	0.511
1-143-2	449.772/-.004	0.051	1-143-2	447.941/-.119	0.458

Conn. Load = 120.000 51.000
Losses = 0.869 0.096

Table 6. Loads Not Supported By Radial System Under Damaged Condition

Radial System		Ring System		
1-65-1	O	1-65-1	448.635/-.069	0.303
1-68-2	O	1-68-2	448.750/-.066	0.278
3-73-1	+	3-73-1	449.338/-.035	0.147
3-73-3	\3-97-4	3-73-3	449.329/-.035	0.149
3-73-5	+	3-73-5	449.338/-.035	0.147
3-97-2	X	3-97-2	X	
3-97-4	X	3-97-4	X	
3-97-6	X	3-97-6	X	
3-104-2	X	3-104-2	X	
3-110-1	X	3-110-1	X	
3-110-3	X	3-110-3	X	
3-112-1	X	3-112-1	X	
4-85-1	X	4-85-1	X	
3-126-2	\3-110-2	3-126-2	448.057/-.104	0.432
3-126-6	\3-110-1	3-126-6	448.074/-.105	0.428
3-133-1	\3-97-2	3-133-1	448.071/-.105	0.429
3-133-3	\3-97-6	3-133-3	448.053/-.104	0.433
5-113-2	+	5-113-2	446.399/ .040	0.800
5-126-1	+	5-126-1	448.078/-.105	0.427
1-154-1	+	1-154-1	447.868/-.112	0.474
1-154-3	+	1-154-3	447.928/-.138	0.461
HYD A	+	HYD A	446.743/-.141	0.724
HYD B	O	HYD B	446.726/-.144	0.728
HYD C	+	HYD C	446.696/-.141	0.734
3-175-3	O	3-175-3	447.169/-.141	0.629
3-175-5	+	3-175-5	447.140/-.141	0.635
3-176-1	+	3-176-1	447.156/-.141	0.632
1-200-2	+	1-200-2	446.448/-.001	0.789
2-204-2	+	2-204-2	447.147/-.137	0.634
03-63-5	\1-68-2	03-63-5	445.940/-.081	0.902
02-119-2	O	02-119-	448.345/-.117	0.368

Load Summary (KW KVAR):

Radial System			Ring System		
Conn. Load =	616.000	302.000	Conn. LOAD =	1419.000	590.000
Losses =	2.600	1.000	Losses =	9.010	4.564

Legend:

O - Lost, feeder fed from switchboard in damaged Engine Room
\+ - Lost, feeder cable passes through damaged Engine Room
X - Lost, electrical load located in damaged compartment
\ - Lost, feeder cable fed from affected power panel
> - Switch to alternate feed, primary affected
IE - Normally fed from emergency switchboard

7.4 Damage Susceptibility Evaluation

The power system feeder isometric and one line wiring diagram[5] were used to conduct a manual cable failure analysis to evaluate the effects of engine room fires on distribution system capabilities. Restoration and isolation requirements, as well as component failure and interconnections were depicted in tabular form for three possible damage scenarios. Switchboard feeds, load priorities, and designation as to which components were covered in the Polar Star's Main Space Firefighting Doctrine, were included. All cables within the damaged compartment were considered to fail. This was done to include consideration for the effects of compartment isolation.

The purpose of this evaluation, shown in table 7, was to illustrate radial system damage control operation requirements and effectiveness. The physical locations and electrical interconnections of both electrical equipment and cables were used to generate this information.

Table 7. Radial System Isolation, Restoration, and Sustained Damage Evaluation

Case A: 1st Engine Room Out Fr. 57 - 85
Case B: 2nd Engine Room Out Fr. 85 - 113
Case C: 1st & 2nd Engine Room Out Fr. 57 - 113

SWBD	Status	Load	Case: A	B	C
1S		1-39-1	O		O
1S		1-52-1	O		O
3S		1-65-1	+	O	O
2S		1-67-2	O	O	
3S		1-68-2	* +\3-4P-2S	O	O
2S		1-70-1	O	O	
2S		2-66-1	O	O	
1S/IE	V	3-66-2	* X	X	X
2S/IE	V	3-66-4	* X	* X	X
1S		3-73-1	X	* +	X
3-97-4		3-73-3	X	\3-97-4	X
2S		3-73-5	X	* +	X
1S/IE	V	4-78-1	* X		X
3S/IE	V	2-105-1	\3S-4P-1S>IE	O>IE	O>IE
3-73-1		3-97-2	\3-73-1	* X	X
3S		3-97-4	* \3S-4P-2S	X	X
3-73-5		3-97-6	\3-75-5	* X	X
3S		3-104-2		X	X
3-66-4	V	3-110-1	\3-66-4	* X	X
3-66-2	V	3-110-3	\3-66-2	X	X
3S/IE	V	3-112-1	* \3S-4P-1S>IE	* X	X
3S/IE	V	4-85-1	\3S-4P-2S>IE	* X	X
2-122-1		1-116-1	\2-122-1		\2-122-1
1S		2-122-1	O		O
2S		2-122-2	O		O
3-110-3		3-126-2	* \3-110-3	\3-100-3	\3-100-3
			\3-66-2	\3-66-2	\3-66-2
3-176-3	V	3-126-4	\3S-4P-1S	3-176-3>IE	3-176-3>IE
			\3-176-3		
			\3S-4P-1S>IE		
3-110-1	V	3-126-6	\3-110-1	\3-110-1	\3-110-1
			\3-66-4	\3-66-4	\3-66-4
3-97-2		3-133-1	\3-97-2	\3-97-2	\3-97-2
			\3-73-1		
3-97-6		3-133-3	\3-97-6	\3-97-6	\3-97-6
		\3-73-5			
3S/IE	V	3-133-5	*	* O>IE	O>IE
2S/IE	V	4-142-2		* O>IE	O>IE

Table 7. (Continued)

SWBD	Status	Load	Case:	A		B	C
2S		5-113-2		O		+	O
1S		5-126-1		O		+	O
2S		1-143-2		O	*		O
2S		1-154-1		O		+	O
2S		1-154-3		O		+	O
1S/IE	V	3-164-2		O>IE		+>IE	O>IE
3S/IE	V	3-164-4	*	\3S-4P-IE>IE		O>IE	O>IE
2S/IE	V	3-166-2		O>IE		+>IE	O>IE
2S/IE	V	3-170-1		O>IE		+>IE	O>IE
3S/IE	V	3-170-3				O>IE	O>IE
1S/IE	V	3-170-5		O>IE		+>IE	O>IE
3S/IE	V	IC				O>IE	O>IE
2S		HYD A		O		+	O
3S		HYD B				O	O
1S		HYD C		O		+	O
2S/IE	V	3-175-1		O>IE		O>IE	O>IE
3S		3-175-3	*	\3S-4P-2S		O	O
1S		3-175-5		O		+	O
2S		3-176-1		O		+	O
3S/IE	V	3-176-2	*	\3S-4P-2S>IE		O>IE	O>IE
3S/IE	V	3-176-3	*	\3S-4P-1S>IE		O>IE	O>IE
1S/IE	V	3-176-5		O>IE		+>IE	O>IE
IE	V	MAG PUMP		IE		IE	IE
2S		1-200-2		O		+	O
2S		2-204-2		O		+	O
2S/IE	V	2-243-2		O>IE		+>IE	O>IE
1S		01-67-1		O			O
IE	V	01-148-1		IE		IE	IE
3S/IE	V	02-67-1		+>IE		O>IE	O>IE
IE	V	GEN HTR		IE		IE	IE
1S		03-63-2		O			O
1-68-2		03-63-5		\1-68-2		\1-68-2	\1-68-2
IE	V	SRCH LT		IE		IE	IE
3S		02-119-2		+		O	O

Table 7. (Continued)

Bus Ties

SWBD	Status	Bus Tie	Case: A		B		C
3S-1S		3S-4P-1S	*	O	*	O	O
3S-2S		3S-4P-2S	*	O	*	O	O
3S-IE		3S-4P-IE			*	O	O

Legend:

O - Lost, feeder fed from switchboard in damaged Engine Room
+ - Lost, feeder cable passes through damaged Engine Room
X - Lost, electrical load located in damaged compartment
\ - Lost, feeder cable fed from affected power panel
> - Switch to alternate feed, primary affected
IE - Normally fed from emergency switchboard
* - Covered by Polar Star's Main Space Fire Doctrine Isolation Instructions

Damage Susceptibility Evaluation Results

The damage evaluation table is difficult to follow because of the amount of information that it attempts to depict. It is effective in illustrating the capabilities of the system through loss of one of the forward engine rooms, and the number of operations that must be performed in carrying out isolation and restoration procedures.

The susceptibility of the main distribution system to failure as a result of engine room fires is evident through evaluating illustrated losses of power distribution panels and motor controllers. The number of components lost within the affected spaces was small compared to the number lost outside of the damaged areas.

The majority of the loads that survived in each of the three conditions were those that were connected to emergency generation. This shows that primary distribution is very susceptible to failure during an engine room fire for this ship.

The combined loss of both forward engine rooms produced about the same level of electrical system losses as losing just one of the engine rooms. This shows the distribution system to be more likely to cause system degradation during a major casualty than damage to individual electrical loads and generating equipment. Improving the survivability of this one subsystem could improve the mission reliability of every electrically powered system on the ship.

Comparison of the Polar Star's isolation instructions, prepared by standard shipboard methods, and the analysis performed using the ship's power system isometric and one line wiring diagrams showed this section of the ship's Main Space Fire Doctrine to be incomplete. Coast Guard Main Space Firefighting Doctrines are issued to ships as a standardized Commandant Instruction. This instruction is then altered to meet specific ship characteristics by ship's personnel. For a large Coast Guard vessel, such as the Polar Star, this is a long and complicated process.

Examination of the Polar Star's isolation doctrine showed the instruction to closely follow the system information illustrated in the electrical system one line diagram. This diagram identifies generator, switchboard, distribution panel, and motor controller interconnections.

The evaluation performed in this study included cable run information taken from the power system feeder isometric wiring diagram as well as the one line diagram. Manually tracing out individual power feeders from this diagram is an arduous task, but it does expand isolation and restoration instructions to more accurately depict actual ship conditions and damage control requirements.

Radial Distribution Effectiveness

From an engineering perspective, this comparison does not show any serious distribution reliability deficiencies. The emergency distribution system has adequate redundancy and capacity for maintaining minimum powering requirements through a main space fire. From an operational perspective, operating all of the circuit breakers necessary to utilize emergency distribution effectively has been shown to be an involved task which is difficult for ship personnel to accurately identify. Taking feeder routing into consideration shows normal distribution and ship service generation to be rendered almost completely unusable while the emergency generator must be loaded to maximum capacity to maintain minimum requirements.

Because primary generators and vital loads have a much better chance of surviving than do the distribution feeders that interconnect them, increasing normal distribution feeder reliability would significantly increase usable generation capacity during damage conditions. On vessels with large combat systems, the number of vital loads greatly increases, this should make the potential for improvement of distribution survivability on these vessels even greater.

The capacity of emergency generation and distribution is very much a function of weight and balance criteria. Numerous emergency feeders increase system weight, and the capacity of remotely located emergency generators is restricted by stability limitations. As an example, the Polar Star, which has good stability which is a function of its relatively large displacement, beam, and low center of gravity, was able to have its emergency generator installed on the O2 level. (See figure 5 for arrangement reference) This provides good versatile separation for emergency distribution. A more weight critical vessel may not be able to utilize this type of arrangement.

7.5 Worst Case Contingency Analysis

Three contingencies were examined to provide worse case evaluation. The first two were longest possible distribution paths. The third was the result of closing all paths in the bus feeder ring, making it a loop system. Each of these contingencies used the first and second ship service generators operating in parallel to supply the load. This generator combination provides the most centralized generation and distant distribution path possible. The network configurations for the selected worst case configurations are shown in figures 15, 16, and 17.

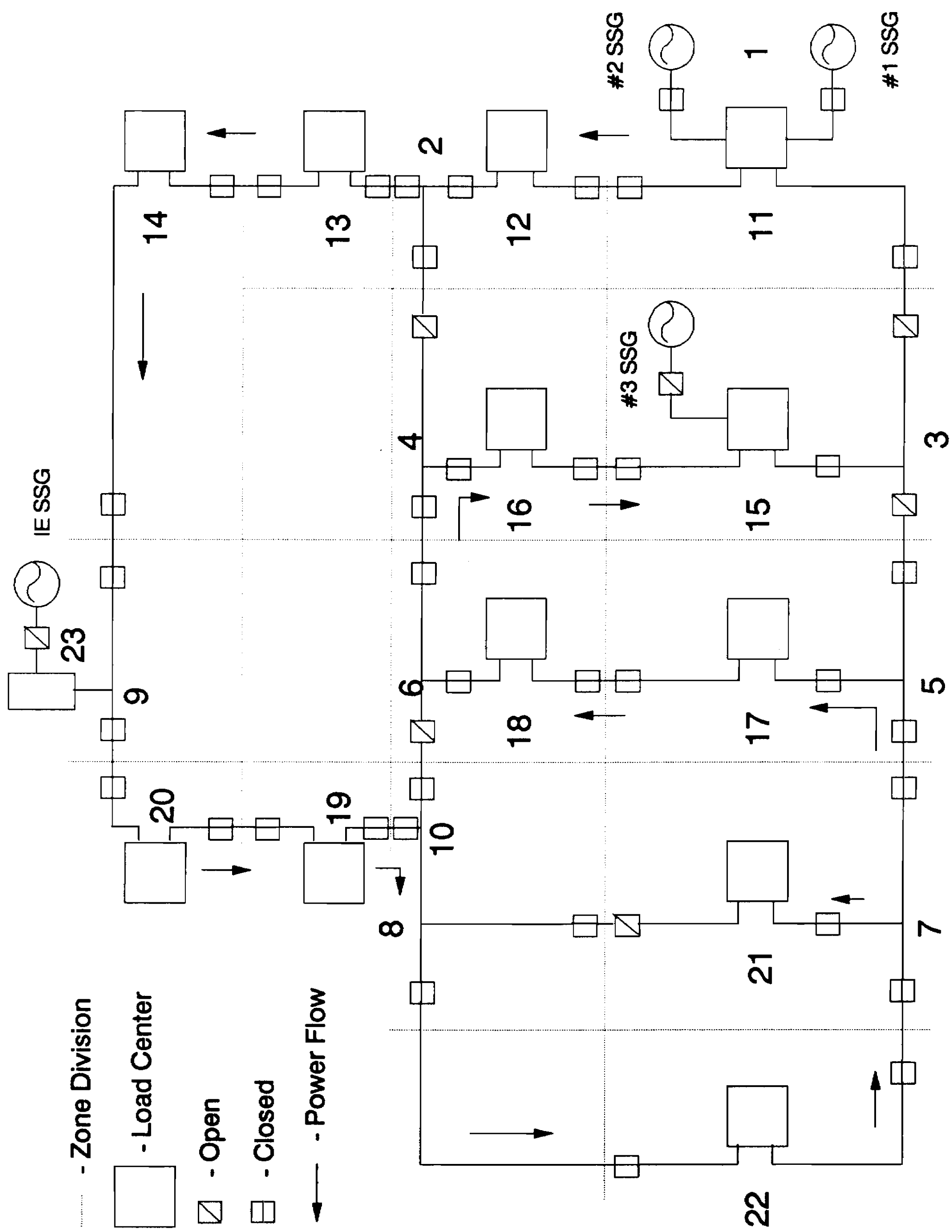


Figure15. Abnormal Operation, Longest Path, Top First

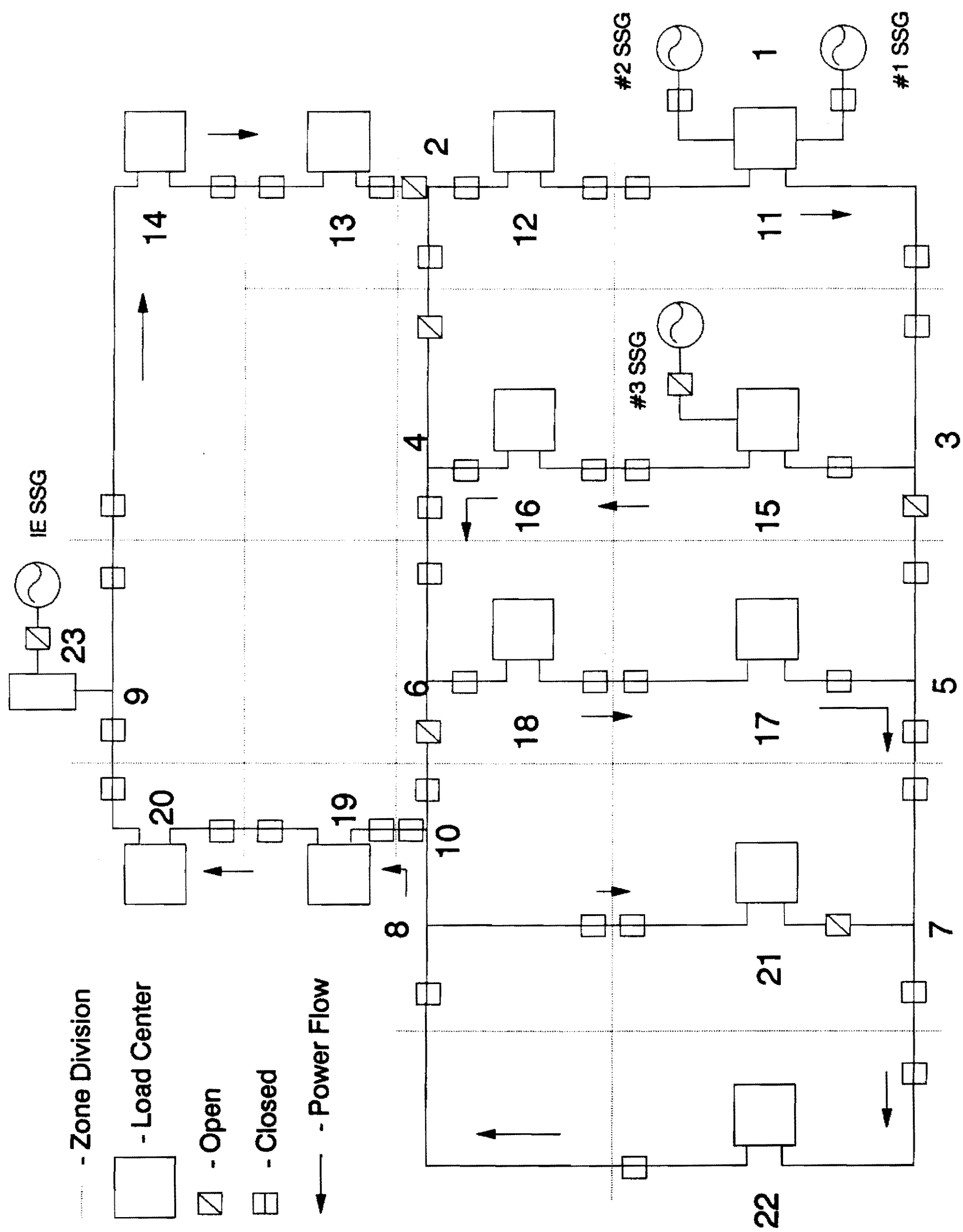


Figure16. Abnormal Operation, Longest Path, Bottom First

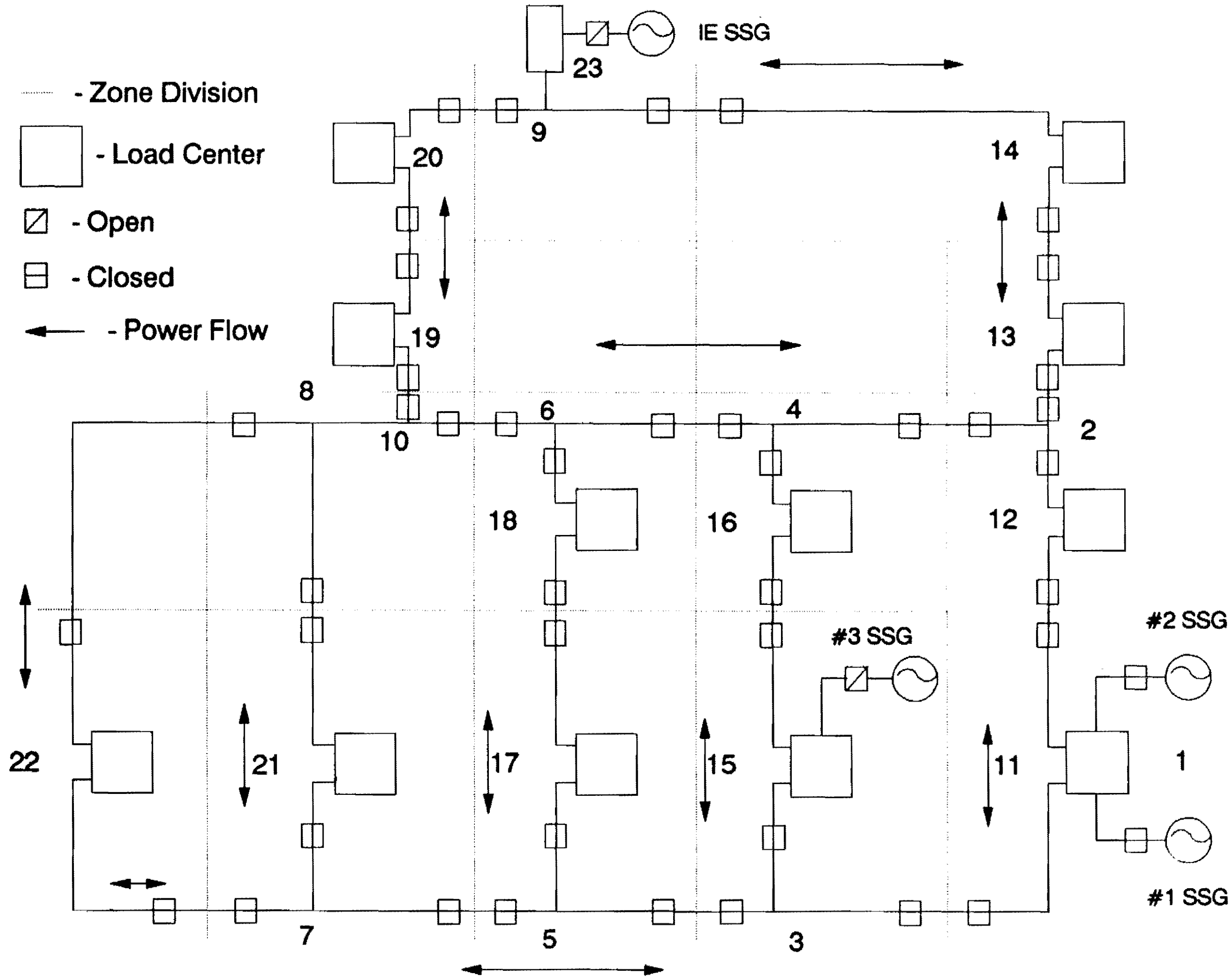


Figure17. Abnormal Operation, Closed Loop

Worst Case Contingency Results

All of the estimated bus feeder line flows and load center voltage drops for each of the three cases evaluated were within the prescribed limits. These results are shown in tables 8, 9, and 10.

Table 8. Worst Case Contingency Analysis Bus Feeder Ring Voltage Profile

Case 1: Longest Path, Top First
Case 2: Longest Path, Bottom First
Case 3: Closed Loop

Non-Normal Operation, Ice Breaking, Diesel, #1 and #2 SSG in Parallel

Case:	1		2		3	
Bus	Voltage	Voltage Drop (%)	Voltage	Voltage Drop (%)	Voltage	Voltage Drop (%)
2	448.33/-.06	0.371	449.11/-.03	0.198	448.69/-.05	0.291
3	442.62/-.25	1.640	447.85/-.08	0.477	448.57/-.05	0.318
4	442.66/-.25	1.632	446.33/-.13	0.816	448.51/-.06	0.331
5	442.84/-.24	1.591	444.22/-.21	1.285	448.33/-.06	0.372
6	442.70/-.25	1.623	445.63/-.16	0.972	448.30/-.06	0.380
7	442.98/-.24	1.559	443.26/-.25	1.498	447.97/-.07	0.451
8	444.32/-.19	1.263	442.80/-.27	1.600	448.00/-.07	0.445
9	445.43/-.16	1.015	442.55/-.28	1.655	448.24/-.07	0.391
10	444.67/-.18	1.184	442.69/-.27	1.625	448.14/-.07	0.413
11	449.12/-.03	0.196	449.12/-.03	0.196	449.13/-.03	0.194
12	448.85/-.04	0.256	449.11/-.03	0.198	448.98/-.04	0.228
13	448.24/-.06	0.392	442.14/-.30	1.748	448.67/-.05	0.296
14	447.75/-.08	0.501	442.19/-.30	1.736	448.58/-.06	0.316
15	442.62/-.25	1.640	447.17/-.10	0.630	448.53/-.05	0.327
16	442.63/-.25	1.639	446.82/-.12	0.707	448.51/-.06	0.331
17	442.75/-.25	1.611	444.85/-.19	1.144	448.29/-.06	0.381
18	442.73/-.25	1.615	445.06/-.18	1.097	448.28/-.06	0.381
19	444.74/-.18	1.168	442.67/-.28	1.630	448.14/-.07	0.413
20	444.91/-.18	1.132	442.64/-.28	1.636	448.16/-.07	0.408
21	442.73/-.25	1.615	442.92/-.26	1.575	447.85/-.08	0.478
22	443.39/-.23	1.468	442.93/-.26	1.572	447.84/-.08	0.479
23	445.43/-.16	1.015	442.55/-.28	1.655	448.24/-.07	0.391

Table 9. Worst Case Contingency Analysis Bus Feeder Ring Line Flows

Case:		1		2		3	
Buses		Line Flow (KVA/DEG)	% Load	Line Flow (KVA/DEG)	% Load	Line Flow (KVA/DEG)	% Load
2	4					371.93/24.3	19.9
2	12	-1304.14/23.2	69.7	0.00/00.0	0.0	-716.75/22.8	38.3
2	13	1304.17/23.2	69.7			345.65/20.1	18.5
3	5					496.37/23.8	26.5
3	11			-1305.30/23.2	69.8	-576.10/23.5	30.8
3	15	0.02/03.2	0.0	1305.30/23.2	69.8	79.79/22.0	4.3
4	6	-71.06/27.7	3.8	1230.05/22.9	65.8	380.46/24.1	20.3
4	16	71.06/27.7	3.8	-1230.05/22.9	65.8	-11.44/-16.1	0.6
5	7	-160.82/30.3	8.6	1135.76/22.1	60.7	421.96/23.3	22.6
5	17	160.84/30.2	8.6	-1135.76/22.1	60.7	74.25/26.4	4.0
6	10					365.64/22.6	19.5
6	18	-71.05/27.7	3.8	1231.65/23.3	65.8	17.72/57.5	0.9
7	21	461.48/20.3	24.7	636.16/20.6	34.0	230.87/19.3	12.3
7	22	-620.54/22.9	33.2	497.64/24.0	26.6	192.01/28.1	10.3
8	10	-978.27/24.8	52.3	318.13/17.2	17.0	-394.04/24.2	21.1
8	21			-174.41/21.3	9.3	230.56/21.4	12.3
8	22	978.30/24.9	52.3	-144.42/13.6	7.7	164.20/28.3	8.8
9	14	-1114.60/24.3	59.6	184.36/15.5	9.9	-162.57/25.3	8.7
9	20	1110.08/24.5	59.3	-189.16/15.1	10.1	158.10/26.1	8.5
9	23	5.01/00.0	0.3	5.01/00.0	0.3	5.01/00.0	0.3
10	19	-978.97/24.9	52.3	318.12/17.8	17.0	-30.62/44.6	1.6
11	12	1350.80/22.5	72.2	48.12/00.0	2.6	762.06/21.4	40.7
13	14	1182.78/23.2	63.2	-121.12/23.3	6.5	224.82/18.3	12.0
15	16	-20.20/20.3	1.1	1283.08/23.3	68.6	59.57/22.5	3.2
17	18	99.82/29.4	5.3	-1197.65/22.6	64.0	14.54/ 4.2	0.8
19	20	-1098.18/24.3	58.7	198.81/16.4	10.6	-147.82/25.1	7.9

Table 10. Worst Case Contingency Analysis Bus Feeder Ring Load Flow Results

Largest Voltage Drop	1.655 %
Maximum Line Loading	69.8 %

Power Feeder Maximum Capacity at 50° C 1870.61 KVA

Generator Output	Case 1	#1 SSG	636.213	KW	266.530	KVAR
		#2 SSG	636.213	KW	266.530	KVAR
	Case 2	#1 SSG	637.275	KW	267.266	KVAR
		#2 SSG	637.275	KW	267.266	KVAR
	Case 3	#1 SSG	631.241	KW	262.551	KVAR
		#2 SSG	631.241	KW	262.551	KVAR

Connected Load 1257.000 KW 521.000 KVAR

Total Losses	Case 1	15.424	KW	12.059	KVAR
	Case 2	17.550	KW	13.531	KVAR
	Case 3	5.481	KW	4.102	KVAR

CHAPTER VIII

VIII. CONCLUSIONS

The new type of distribution system was shown to be a viable alternative to Navy standard design. Combining ship and shore distribution with damage control philosophy has produced a system which is electrically feasible, fits well with damage control operations, and which provides a structure suitable for the application of established shore automation technology.

The radial distribution system currently used aboard the Polar Star was shown to meet engineering reliability requirements, but not damage control operational ones. Effective damage control operation of this system was shown to be difficult to define and to require a large number of manual circuit switching and securing operations. Primary distribution was shown to be unreliable, and emergency distribution was shown to be difficult to operate, during engine room fires.

On ships with similar compartmentation to that of the Polar Star's, good longitudinal and poor athwartship, improving main distribution reliability, and emergency distribution operability, could greatly improve overall ship survivability. The new bus feeder distribution ring design presented in this paper does both, and does it without significantly increasing system weight or complexity. In addition to these improvements, development of this type of system would enhance current efforts to develop automated total ship damage control systems.

8.1 Engineering and Operational Analysis Results

The contingency analysis showed the bus feeder ring cable capacities for the configurations tested to be electrically acceptable. Aspects not analyzed with the load flow program were shown to be feasible through comparison with the Polar Star's old established system, this includes system weight.

Primary evaluation of the new system may make it appear to be over designed. Any cable size reductions and subsequent weight savings that could be derived by optimizing the new design would depend on the actual ampacity requirements of the feeder main cables. A complete transient and steady state contingency analysis, keeping reliability and survivability requirements in mind, would have to be performed in order to optimize the size of these cables. This study used system weight for sizing these feeders since no standard guidelines were available for this type of system, and to make the system comparable to the Polar Star's original distribution system.

8.2 Possible Benefits and System Applications

Possible benefits to using this system are:

1. The ability to limit electrical system isolation to fire zone boundaries for major damage.

2. The ability to eliminate distribution system losses due to space isolation outside of fire zone boundaries.
3. The ability to effectively augment emergency generation capacity with main ship service generation under major damage conditions.
4. Simplified system feeder lay out which conforms to damage control operation procedures.

These benefits represent significant possible improvements in ship survivability following engine room fires, or battle damage to multiple compartments, both of which have frequently resulted in major to total electrical system loss in the past. These benefits would increase system survivability and improve damage control operation effectiveness.

Technical advances in warship offensive capabilities, and moves to reduce manning requirements because of budget constraints, have resulted in the use and development of shipboard automated control systems. The area of least advancement in these developments has been in application to damage control. One possible reason is the unreliability of ship service electrical systems during major damage. Without electrical power, there is little left to control.

A distribution system that could be quickly reconfigured to restore power to undamaged compartments would further the effort to use fixed systems to their fullest capabilities. Increased distribution survivability could allow remote and automatic control of such systems as ventilation, fire main, and even electrical distribution itself. Fixed systems far exceed the capabilities of portable emergency equipment like portable fire and dewatering pumps, or casualty power cables.

The papers encountered during the literature search conducted for this study which discussed automated control of the electrical system did not take distribution cable arrangement into consideration. This is an area where changing standard design guidelines could greatly enhance the application of modern electrical control system technology to shipboard use.

One major drawback to using automatic control for damage situations is that when the control system fails, operators are left with a complicated system that no one has the knowledge nor physical ability to operate manually. Use of a common bus feeder ring would greatly decrease the manpower needed to identify and operate the appropriate distribution components over those currently required for manual operation of the old system. This would be true because only the disconnect switches used to feed the load centers would have to be operated. Isolation and restoration operation of the old system requires the circuit breakers serving each individual load feeder to be separately operated.

8.3 Implementation of New System

The bus feeder ring system could be installed to be operated manually but would need an automated control system to be used to its fullest potential. An ideal platform for prototyping such a system would be the Coast Guard Icebreaker Mackinaw, which was mentioned at the start of this paper. This vessel has a reduced manning environment, multiple engine rooms, redundant ship service generation, and currently has electrical system isolation problems.

8.4 Recommended Procedural Changes for Polar Star System

Results of the damage susceptibility comparison showed the Polar Star's Main Space Electrical Isolation Doctrine to not adequately depict isolation requirements and restoration procedures. Isolation procedures should be reevaluated in respect to achieving compartment isolation in minimum time in conjunction with including all cables passing through the engine rooms. For a fire in either one of the two forward engine rooms, normal feed to all loads at the surviving main switchboards should be secured. Using limited time to optimize distribution by the use of a few main distribution feeders is a poor trade off. Vital loads outside the affected compartment should first be fed from the emergency bus. Allocation of electrical resources between normal and emergency distribution should be kept until after the initial action phase of the damage control process is completed.

This strategy provides simple and complete isolation instructions, and also creates realistic system capacity expectations. Isolation instructions should be expanded to include specific load schedules, listed by damage contingency, for guiding load shedding operations at the emergency switchboard since the vital feeders of the normal system will not be reliable.

Similar inflated expectations for electrical system damage capabilities were experienced aboard the Mackinaw. This situation shows the need for better engineering evaluation of damage control operation procedures for large Coast Guard vessels. Development of detailed isolation and restoration instructions might best be performed during the design stage of ship construction as part of reliability and survivability evaluations.

8.5 Suggestions for Future Work

Much additional study could be done in the area of damage and casualty control operation and design of ship service electrical systems. Here are several topics that could follow the investigation conducted in this study:

1. Application of interconnected zone distribution design to a Navy Fast Frigate or similar sized vessel.
2. Use of voltage control during damage situations to reduce peak loads.
3. Application of network optimizing techniques to improve distribution design.
4. Use of reliability analysis software to develop ship specific damage control isolation and restoration instructions.
5. Transient analysis to optimize bus feeder ring cable sizing.
6. Development of automated systems capable of performing electrical system damage control analysis for both design purposes and on line system operation.
7. Inclusion of electrical system development into automated ship damage control system.

CHAPTER IX

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LIST OF DRAWINGS

Machinery Arrangement, USCG Drawing No. 400 WAGB-0101-156, Rev. A.

Booklet of General Plans, USCG Drawing No. 400 WAGB-0103-3, Rev. J.

Electrical Distribution System One Line Diagram, USCG Drawing No. 400 WAGB-6000-1, Rev. AB.

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Wireways-Master Plan, USCG Drawing No. 400 WAGB-6202-13, Rev. G.

Power System List of Feeders and Mains, USCG Drawing No. 400 WAGB-6202-36, Rev. P.

Power System Feeders Isometric Wiring Diagram, USCG Drawing No. 400 WAGB-6202-37, Rev. T.

GLOSSARY OF SHIP TERMS

AFFF - Aqueous Film Forming Foam, a surfactant produced by mixing water with AFFF concentrate. Used to vapor secure fires and prevent large scale reflash [8].

Athwartship - Across the ship, at right angles to the fore-and-aft centerline [16].

Bravo Fire - A fire fueled primarily by a flammable liquid.

Casualty - General term referring to the failure of equipment, component to system; or personnel, incapacitating injury to death.

Damage Control - The isolation, securing, and temporary repair of damage to ship's structure and systems for the purpose of ensuring ship survival under emergency conditions.

Engineering Casualty Control - The isolation, securing, and temporary repair of damage to engineering systems and equipment under emergency conditions.

Fire Zone - Area designated for isolating damage such as fire or flooding. Usually corresponds with the location of reinforced bulkheads.

Halon - Gaseous agent used for extinguishing oil spray and oil spill fires. Used in fixed and portable systems [8].

Main Space - A machinery space with internal combustion engines, gas turbines, or boilers used for propulsion [8].

Prime Mover - Torque producing device such as a diesel engine or gas turbine.

Secure - To shut down, turn off, or put away.

Shp - Shaft Horse Power.

APPENDIX A

CABLE WEIGHT ESTIMATION DATA

Table 11. Load Feeder Cable Weight Estimations

	Ring System				Radial System			
Load	Cable Size	lb/ft	Length (ft)	Weight (lbs)	Cable Size	lb/ft	Length (ft)	Weight (lbs)
1-39-1	100	1.50	95	142.50	14	0.32	125	40.00
1-52-1	9	0.22	69	15.180	100	1.50	120	180.00
1-65-1	100	1.50	74	111.00	125	1.90	105	199.50
1-67-2	14	0.32	6	1.92	14	0.32	120	38.40
1-68-2	23	0.45	4	1.80	50	0.82	125	102.50
1-70-1	50	0.82	81	66.42	40	0.70	120	84.00
2-66-1	50	0.82	10	8.20	50	0.82	110	90.20
3-66-2	23	0.45	23	10.35	250	3.50	260	910.00
					250	3.50	50	175.00
3-66-4	14	0.32	25	8.00	250	3.50	255	892.50
					250	3.50	50	175.00
3-73-1	100	1.50	14	21.00	2-200	5.80	40	232.00
3-73-3	100	1.50	16	24.00	200	2.90	70	203.00
3-73-5	300	4.10	18	73.80	400	5.50	60	330.00
4-78-1	50	0.82	41	33.62	100	1.50	180	270.00
					100	1.50	90	135.00
2-105-1	75	1.20	83	99.60	150	2.30	120	276.00
					150	2.30	25	57.50
3-97-2	14	0.32	26	8.32	2-200	5.80	105	609.00
3-97-4	50	0.82	29	23.78	200	2.90	70	203.00
3-97-6	9	0.22	29	6.38	400	5.50	135	742.50
3-104-2	14	0.32	20	6.40	14	0.32	40	12.80
3-110-1	23	0.45	50	22.50	250	3.50	135	472.50
3-110-3	4	0.13	55	7.15	250	3.50	60	210.00
3-112-1	9	0.22	55	12.10	23	0.45	140	63.00
					23	0.45	30	13.50
4-85-1	75	1.20	61	73.20	100	1.50	175	262.50
					100	1.50	105	157.50
1-116-1	23	0.45	120	54.00	23	0.45	30	13.50
2-122-1	75	1.20	48	57.60	100	1.50	120	180.00
2-122-2	50	0.82	4	3.28	75	1.20	125	150.00
3-126-2	150	2.30	23	52.90	250	3.50	60	210.00
3-126-4	50	0.82	27	22.14	2-200	5.80	135	783.00
3-126-6	150	2.30	31	71.30	250	3.50	110	385.00
3-133-1	300	4.10	30	123.00	2-200	5.80	135	783.00
3-133-3	75	1.20	36	43.20	400	5.50	150	825.00
3-133-5	150	2.30	36	82.80	150	2.30	200	460.00
.					150	2.30	95	218.00
4-142-1	75	1.20	41	49.20	100	1.50	210	315.00
.					100	1.50	145	217.00

Table 11. (Continued)

		Ring System				Radial System		
Load	Cable Size	lb/ft	Length (ft)	Weight (lbs)	Cable Size	lb/ft	Length (ft)	Weight (lbs)
5-113-2	9	0.22	66	14.52	14	0.32	120	38.40
5-126-1	9	0.32	56	17.92	14	0.32	120	38.40
1-143-2	150	2.30	4	9.20	150	2.30	185	425.50
1-154-1	23	0.45	46	20.70	30	0.60	205	123.00
1-154-3	50	0.82	54	44.28	50	0.82	200	164.00
3-164-2	100	1.50	32	48.00	125	1.90	196	372.40
.					125	1.90	210	399.00
3-164-4	100	1.50	35	52.50	200	2.90	195	565.50
.					200	2.90	150	435.00
3-166-2	100	1.50	39	58.50	125	1.90	180	342.00
					125	1.90	205	389.50
3-170-1	4	0.13	19	2.47	9	0.22	175	38.50
					9	0.22	175	38.50
3-170-3	4	0.13	22	2.86	9	0.22	175	38.50
					9	0.22	160	35.20
3-170-5	9	0.22	25	5.50	9	0.22	185	40.70
					9	0.22	180	39.60
IC	14	0.32	34	10.88	14	0.32	235	75.20
					14	0.32	125	40.00
HYD A	300	4.10	61	250.10	300	4.10	165	676.50
HYD B	300	4.10	64	262.40	300	4.10	90	369.00
HYD C	300	4.10	67	274.70	300	4.10	145	594.50
3-175-1	400	5.50	20	110.00	400	5.50	235	1292.50
					400	5.50	180	990.00
3-175-3	400	5.50	25	137.50	400	5.50	145	797.50
3-175-5	150	2.30	33	75.90	125	1.90	180	342.00
3-176-1	200	2.90	17	49.30	200	2.90	170	493.00
3-176-2	100	1.50	36	54.00	100	1.50	240	360.00
					100	1.50	170	255.00
3-176-3	2-150	4.60	26	119.60	2-200	5.80	200	1160.00
					2-200	5.80	115	667.00
3-176-5	400	5.50	34	187.00	400	5.50	220	1210.00
					400	5.50	175	962.50
MAG PUMP	75	1.20	103	123.60	100	1.50	210	315.00
1-200-2	23	0.45	101	45.45	30	0.60	265	159.00
2-204-2	75	1.20	70	84.00	75	1.20	75	90.00
2-243-1-A	50	0.82	204	167.28	75	1.20	285	342.00
2-243-1-B	50	0.82	143	117.26	75	1.20	280	336.00
2-243-2-A	50	0.82	186	152.52	75	1.20	275	330.00
2-243-2-B	50	0.82	150	123.00	75	1.20	290	348.00

	Ring System				Radial System			
Load	Cable Size	lb/ft	Length (ft)	Weight (lbs)	Cable Size	lb/ft	Length (ft)	Weight (lbs)
01-67-1	23	0.45	20	9.00	60	1.00	105	105.00
01-148-1	9	0.22	44	9.68	14	0.32	70	22.40
02-67-1	150	2.30	10	23.00	200	2.90	160	464.00
					200	2.90	185	536.50
GEN HTR	4	0.13	35	4.55	14	0.32	35	11.20
03-63-2	23	0.45	41	18.45	30	0.60	125	75.00
03-63-5	14	0.32	60	19.20	14	0.32	60	19.20
SRCH LT	4	0.13	45	5.85	9	0.22	170	37.40
02-119-2	50	0.82	39	31.98	40	0.70	150	105.00
Total Weight				4079.29				28780.50

Bus Ties:

3S-4P-IE	2-400	11.0	140	1540.00
3S-4P-1S	3-300	12.3	100	1230.00
3S-4P-2S	3-300	12.3	115	1414.50

Bus Tie Total Weight 4184.50

28780.50
+ 4184.50

Load Feeders
Plus Bus Tie Weight 32965.00

APPENDIX B

CONTINGENCY ANALYSIS DATA

Normal Operation, Ice Breaking, Diesel, #1 and #2 SSG in Parallel

	Base Voltage (V)	Contingency Voltage Drop (%)			
Bus\Case:	Case 1	1	2	3	4
2	449.040/-.040	0.213	0.000	0.369	0.370
3	449.121/-.025	0.195	0.219	0.195	1.214
4	448.665/-.055	0.297	0.435	0.490	1.206
5	448.856/-.031	0.254	0.447	0.195	1.209
6	448.274/-.072	0.384	0.548	0.622	1.197
7	448.488/-.040	0.336	0.596	0.195	1.314
8	447.794/-.093	0.490	0.702	0.775	1.247
9	448.952/-.045	0.233	0.608	0.713	1.013
10	447.989/-.085	0.447	0.611	0.710	1.181
11	449.651/-.013	0.078	0.608	0.195	0.195
12	449.441/-.023	0.124	0.194	0.254	0.255
13	449.024/-.041	0.217	0.204	0.372	0.391
14	448.990/-.044	0.225	0.222	0.377	0.500
15	448.624/-.057	0.306	0.227	0.497	1.214
16	448.630/-.056	0.304	0.443	0.496	1.213
17	448.794/-.032	0.268	0.447	0.634	1.209
18	448.788/-.032	0.269	0.576	0.632	1.206
19	447.979/-.085	0.449	0.582	0.712	1.166
20	448.946/-.045	0.234	0.610	0.713	1.130
21	447.435/-.109	0.570	0.610	0.842	1.314
22	448.201/-.047	0.400	0.756	0.850	1.322
23	448.952/-.045	0.233	0.755	0.713	1.013

Contingency Line Flows (KVA/DEG)

Buses\Case:	1	2	3	4
2 4	653.15/21.1		1113.77/24.4	
2 12	-851.17/20.0	-184.17/15.4	1295.96/23.1	-1301.54/23.2
2 13	198.60/16.4	184.20/15.4	184.19/15.4	1301.58/23.2
3 5	446.66/29.0	1041.07/24.2	-0.002/00.0	
3 11	-446.65/29.0	-1112.06/24.4	0.009/00.0	0.02/3.8
3 15		71.13/27.6		71.08/27.7
4 6	582.00/20.3		1041.4/24.2	71.11/27.7
4 16	71.13/27.6	0.01/05.7	71.13/27.6	0.01/04.1
5 7	356.65/28.2	817.15/23.8	0.00/00.0	-160.81/30.2
5 17	89.94/32.3	222.84/25.5		89.89/32.3
6 10	581.51/20.3	133.92/21.0	951.16/23.4	
6 18		-133.89/21.0	89.91/32.3	0.01/04.1
7 21		461.47/20.3		
7 22	356.36/28.2	356.31/28.2		-815.98/23.7
8 10	-461.56/20.3	0.02/05.7	815.99/23.7	461.17/20.4
8 21	461.58/20.3		461.53/20.3	356.37/28.2
8 22			356.37/28.2	-1112.03/24.4
9 14	-14.75/28.3			1107.51/24.5
9 20	10.64/41.2	-4.96/0.0	-4.96/00.0	5.01/00.0
9 23	5.01/00.0	5.01/0.0	5.01/00.0	-976.41/24.8
10 19	119.46/20.1	134.02/21.0	122.79/23.0	
11 12	897.70/19.0	230.96/12.3	1342.63/22.4	1348.21/22.4
13 14	79.74/05.8	66.36/0.9	66.36/00.9	1180.19/23.2
15 16	-20.24/20.2	51.12/30.6	20.23/20.2	-20.21/20.3
17 18	8.87/33.7	162.21/23.3	61.04/31.6	61.02/31.6
19 20		14.73/28.4	14.74/28.4	-1095.62/24.3

Load Flow Summary

Bus Feeder Ring Maximum Capacity at 50° C 1870.61 KVA

Connected Load 1257.000 KW 521.000 KVAR

Generator Output	Case 1	#1 SSG	631.325	KW	262.508	KVAR
		#2 SSG	631.325	KW	262.508	KVAR
	Case 2	#1 SSG	632.401	KW	263.401	KVAR
		#2 SSG	632.401	KW	263.401	KVAR
	Case 3	#1 SSG	632.876	KW	263.845	KVAR
		#2 SSG	632.876	KW	263.845	KVAR
	Case 4	#1 SSG	635.160	KW	265.669	KVAR
		#2 SSG	635.160	KW	265.669	KVAR

Total Losses	Case 1	5.650	KW	4.015	KVAR
	Case 2	7.802	KW	5.802	KVAR
	Case 3	8.752	KW	6.689	KVAR
	Case 4	13.319	KW	10.338	KVAR

Table 13. Bus Feeder Ring Contingency Analysis Case B

Normal Operation, Ice Breaking, Diesel, #1 and #3 SSG in Parallel

	Base Voltage (V)	Contingency Voltage Drop (%)			
Bus\Case:	Case 1	1	2	3	4
2	449.553/0.008	0.099	0.061	0.000	0.096
3	449.256/-.012	0.165	0.119	0.108	0.047
4	449.483/0.022	0.115	0.045	0.035	0.160
5	448.991/-.018	0.224	0.231	0.147	0.266
6	449.092/0.005	0.202	0.279	0.035	0.254
7	448.623/-.027	0.306	0.384	0.279	0.445
8	448.613/-.016	0.308	0.291	0.035	0.379
9	449.465/0.004	0.119	0.294	0.432	0.272
10	448.808/-.007	0.265	0.291	0.370	0.314
11	449.786/0.000	0.048	0.036	0.367	0.031
12	449.702/0.002	0.066	0.045	0.035	0.054
13	449.537/0.008	0.103	0.064	0.060	0.103
14	449.503/0.005	0.111	0.069	0.111	0.136
15	449.863/0.061	0.031	0.042	0.116	0.047
16	449.699/0.045	0.067	0.045	0.043	0.094
17	448.929/-.019	0.238	0.259	0.087	0.266
18	448.923/-.019	0.239	0.265	0.291	0.264
19	448.798/-.008	0.267	0.293	0.289	0.312
20	449.459/0.004	0.120	0.294	0.369	0.303
21	448.255/-.031	0.388	0.439	0.369	0.445
22	448.337/-.034	0.370	0.437	0.498	0.454
23	449.465/0.004	0.119	0.294	0.507	0.272

Table 13. (Continued)

Contingency Line Flows (KVA/DEG)

Buses\Case:	1	2	3	4
2 4	211.82/95.5		393.09/12.0	
2 12	-316.54/57.5	-184.20/15.4	-577.06/13.1	-562.90/03.3
2 13	198.64/16.4	184.20/15.4	184.20/15.4	562.90/03.3
3 5	446.72/29.0	1041.44/24.2	0.00/00.0	
3 11	-446.72/29.0	-401.12/16.9	0.00/00.0	0.00/00.0
3 15		-645.58/28.7		718.74/38.0
4 6	582.14/20.3		1041.79/24.2	-718.74/38.0
4 16	-566.36/-0.9	0.00/00.0	-662.87/31.3	0.00/00.0
5 7	356.68/28.2	817.21/23.8	0.00/00.0	628.62/38.9
5 17	89.96/32.3	223.21/25.5		89.96/32.3
6 10	581.63/20.3	134.14/21.0	951.44/23.4	
6 18		-134.14/21.0	89.96/32.3	0.00/00.0
7 21		461.47/20.3		
7 22	356.39/28.2	356.35/28.1		-816.08/23.7
8 10	461.59/20.3	0.00/00.0	-816.09/23.7	461.52/20.3
8 21	461.59/20.3		433.06/02.2	356.43/28.2
8 22			356.43/28.2	-384.06/-2.6
9 14	-14.78/28.3			384.06/-2.6
9 20	10.64/41.2	-5.01/00.0	-5.01/00.0	5.01/00.0
9 23	5.01/00.0	5.01/00.0	5.00/00.0	266.41/-14.2
10 19	119.48/20.1	134.12/21.0	134.12/21.0	
11 12	344.99/50.7	230.99/12.3	624.46/12.1	611.32/03.1
13 14	79.77/05.8	66.36/00.9	714.70/31.3	450.98/-2.0
15 16	611.07/01.8	51.13/30.6	-61.09/31.6	770.30/37.5
17 18	28.87/33.7	162.45/23.2	14.74/28.3	-61.09/31.6
19 20		14.78/28.3	14.74/28.3	14.74/28.4

Load Flow Summary

Bus Feeder Ring Contingency Analysis Operation Summary Case B

Bus Feeder Ring Maximum Capacity at 50° C 1870.61 KVA

Connected Load 1257.000 KW 521.000 KVAR

Generator Output	Case 1	#1 SSG	631.922	KW	499.112	KVAR
		#3 SSG	630.00	KW	24.967	KVAR
	Case 2	#1 SSG	632.078	KW	180.798	KVAR
		#3 SSG	630.00	KW	343.405	KVAR
	Case 3	#1 SSG	632.723	KW	146.329	KVAR
		#3 SSG	630.00	KW	378.402	KVAR
	Case 4	#1 SSG	632.626	KW	47.950	KVAR
		#3 SSG	630.00	KW	476.700	KVAR

Total Losses	Case 1	4.921	KW	-21.888	KVAR
	Case 2	5.077	KW	-340.202	KVAR
	Case 3	5.723	KW	-374.671	KVAR
	Case 4	5.626	KW	-473.050	KVAR

Table 14. Bus Feeder Ring Contingency Analysis Case C

Normal Operation, Ice Breaking, Diesel, #1, #2,& IE SSG in Parallel

	Base Voltage (V)	Contingency Voltage Drop (%)			
Bus\Case:	Case 1	1	2	3	4
2	449.545/-.038	0.101	0.145	0.225	0.225
3	449.254/-.024	0.166	0.249	0.120	0.772
4	449.170/-.053	0.184	0.260	0.289	0.764
5	448.989/-.030	0.225	0.306	0.120	0.767
6	448.780/-.070	0.271	0.216	0.356	0.755
7	448.621/-.039	0.306	0.459	0.120	0.871
8	448.300/-.091	0.378	0.181	0.460	0.805
9	451.028/-.035	-.229	0.105	0.319	0.572
10	448.495/-.082	0.334	0.181	0.396	0.740
11	449.784/-.012	0.048	0.120	0.120	0.120
12	449.698/-.022	0.067	0.130	0.156	0.157
13	449.572/-.038	0.095	0.148	0.227	0.238
14	449.794/-.040	0.046	0.153	0.232	0.298
15	449.129/-.054	0.194	0.257	0.297	0.772
16	449.136/-.054	0.192	0.260	0.296	0.771
17	448.927/-.031	0.238	0.269	0.368	0.767
18	448.921/-.031	0.240	0.256	0.365	0.765
19	448.486/-.083	0.337	0.175	0.389	0.724
20	451.022/-.035	-.227	0.159	0.373	0.688
21	447.942/-.106	0.457	0.513	0.527	0.871
22	448.334/-.046	0.370	0.512	0.535	0.880
23	451.142/-.035	-.254	0.080	0.294	0.546

Contingency Line Flows (KVA/DEG)

Buses\Case:	1	2	3	4
2 4	653.16/21.1		632.92/14.6	
2 12	-401.09/-1.0	-184.17/15.4	-817.03/14.8	-819.72/14.8
2 13	-319.78/49.4	184.17/15.4	184.19/15.4	819.75/14.8
3 5	446.67/29.0	546.18/12.9	0.00/00.0	
3 11	446.67/29.0	-633.22/14.6	0.00/00.0	
3 15		71.13/27.6		0.02/-3.8
4 6	582.01/20.3	0.01/-11.3	563.48/12.9	71.08/27.7
4 16	71.14/27.6	817.15/23.8	71.13/27.6	71.11/27.7
5 7	356.67/28.2	-320.19/51.7	0.00/00.0	0.01/-4.1
5 17	89.94/32.3	-372.22/42.5		-160.82/30.3
6 10	581.52/20.3	372.22/42.5	479.26/09.3	89.89/32.2
6 18		461.47/20.3	89.91/39.3	
7 21		356.32/28.2		0.01/-4.1
7 22	356.37/28.2	0.02/-11.3		
8 10	-461.56/20.3	495.80/37.2	815.99/32.7	815.98/23.7
8 21	461.56/20.3	-495.77/37.2	461.52/20.3	461.51/20.3
8 22		-372.28/42.5	356.37/28.2	356.37/28.2
9 14	485.17/37.1	230.96/12.3		-633.30/14.6
9 20	10.64/41.2	66.36/00.9	495.81/37.2	1107.49/24.5
9 23	-495.75/37.2	51.12/30.6	-495.77/37.2	495.77/37.2
10 19	119.47/20.1	-343.55/43.2	-372.28/42.5	-976.41/24.8
11 12	449.42/-0.1	-484.85/37.1	864.52/14.0	867.19/14.1
13 14	-431.90/42.3		66.36/00.9	700.09/13.4
15 16	20.24/20.2		-20.23/20.2	-20.21/20.3
17 18	28.87/33.7		-61.05/31.6	-61.02/31.6
19 20			-484.85/37.1	1095.62/24.3

Load Flow Summary

Bus Feeder Ring Maximum Capacity at 50° C 1870.61 KVA

Connected Load 1257.000 KW 521.000 KVAR

Generator Output	Case 1	#1&2 SSG	862.789	KW	225.224	KVAR
		IE SSG	400.000	KW	300.000	KVAR
	Case 2	#1&2 SSG	862.118	KW	224.792	KVAR
		IE SSG	400.000	KW	300.000	KVAR
	Case 3	#1&2 SSG	861.801	KW	224.599	KVAR
		IE SSG	400.000	KW	300.000	KVAR
	Case 4	#1&2 SSG	864.123	KW	226.422	KVAR
		IE SSG	400.000	KW	300.000	KVAR

Total Losses	Case 1	5.789	KW	4.224	KVAR
	Case 2	5.118	KW	3.792	KVAR
	Case 3	4.801	KW	3.596	KVAR
	Case 4	7.123	KW	5.422	KVAR

APPENDIX C

VOLTAGE PROFILE COMPARISON DATA

Table 15. Normal Operation Load Voltage Profile Comparison

Load	Radial System Voltage	Radial System Volt Drop (%)	Ring System Voltage	Ring System Volt Drop (%)
1-39-1	448.831/0.069	0.260	448.975/-.037	0.228
1-52-1	448.918/0.006	0.240	445.861/0.191	0.920
1-65-1	444.141/-.349	1.302	448.855/-.044	0.254
1-67-2	445.858/0.102	0.920	448.843/-.027	0.257
1-68-2	446.509/-.146	0.776	448.970/-.041	0.229
1-70-1	446.828/0.040	0.705	448.951/-.035	0.233
2-66-1	446.428/-.226	0.794	448.327/-.038	0.372
3-66-2	449.546/-.025	0.101	449.589/-.006	0.091
3-66-4	449.457/-.183	0.121	449.598/-.007	0.089
3-73-1	449.559/-.025	0.098	449.645/-.013	0.079
3-73-3	448.313/-.123	0.375	449.636/-.012	0.081
3-73-5	449.399/-.186	0.134	449.645/-.013	0.079
4-78-1	449.623/-.026	0.084	449.651/-.013	0.078
2-105-1	448.390/-.110	0.358	448.448/-.047	0.345
3-97-2	449.456/-.019	0.121	448.624/-.057	0.306
3-97-4	448.447/-.119	0.345	448.457/-.059	0.343
3-97-6	449.251/-.189	0.166	448.505/-.057	0.332
3-104-2	448.467/-.107	0.341	448.544/-.052	0.324
3-110-1	449.357/-.182	0.143	448.604/-.055	0.310
3-110-3	449.474/-.024	0.117	448.571/-.050	0.317
3-112-1	448.510/-.103	0.331	448.566/-.050	0.319
4-85-1	448.626/-.117	0.305	448.624/-.057	0.306
1-116-1	449.446/-.029	0.123	447.869/-.086	0.474
2-122-1	449.519/-.029	0.107	448.778/-.032	0.272
2-122-2	448.292/-.109	0.380	448.401/-.005	0.355
3-126-2	449.413/-.024	0.130	448.773/-.031	0.273
3-126-4	447.668/-.090	0.518	448.764/-.030	0.275
3-126-6	449.338/-.181	0.147	448.791/-.031	0.269
3-133-1	449.300/-.015	0.156	448.787/-.032	0.270
3-133-3	449.098/-.192	0.200	448.769/-.030	0.274
3-133-5	448.405/-.111	0.354	448.775/-.031	0.272
4-142-1	448.626/-.117	0.305	448.794/-.032	0.268
5-113-2	447.808/-.041	0.487	447.118/ .113	0.641
5-126-1	449.623/-.026	0.084	448.794/-.032	0.268
1-143-2	449.359/-.185	0.143	447.976/-.085	0.450
1-154-1	446.529/0.055	0.771	447.903/-.079	0.466
1-154-3	444.354/-.254	1.255	447.963/-.105	0.453
3-164-2	448.077/-.080	0.427	447.166/-.116	0.630
3-164-4	447.318/-.185	0.596	446.974/-.121	0.673

Table 15. (Continued)

Load	Radial System		Ring System	
	Voltage	Volt Drop (%)	Voltage	Volt Drop (%)
3-166-2	445.005/-.326	1.110	447.009/-.120	0.665
3-170-1	446.208/-.195	0.843	447.279/-.109	0.605
3-170-3	445.610/-.127	0.975	447.201/-.109	0.622
3-170-5	447.935/-.032	0.459	447.360/-.109	0.587
IC	446.095/0.092	0.868	446.728/-.050	0.727
HYD A	447.679/-.178	0.516	446.881/-.107	0.693
HYD B	447.641/-.121	0.524	446.864/-.111	0.697
HYD C	448.017/-.024	0.441	446.835/-.108	0.703
3-175-1	448.321/-.198	0.373	448.175/-.047	0.406
3-175-3	448.400/-.136	0.356	448.192/-.047	0.402
3-175-5	448.588/-.045	0.314	448.164/-.048	0.408
3-176-1	448.897/-.215	0.245	448.180/-.048	0.404
3-176-2	447.734/-.075	0.503	448.180/-.046	0.404
3-176-3	447.705/-.091	0.510	448.129/-.043	0.416
3-176-5	448.149/-.043	0.411	448.117/-.047	0.418
MAG PUMP	448.346/-.128	0.367	448.201/-.047	0.400
1-200-2	446.006/0.082	0.888	446.483/0.032	0.782
2-204-2	449.396/-.174	0.134	448.171/-.044	0.407
2-243-2	447.215/-.071	0.619	445.564/ .052	0.986
01-67-1	449.418/-.232	0.129	446.508/-.061	0.776
01-148-1	447.208/-.010	0.620	448.691/-.018	0.291
02-67-1	447.853/-.118	0.477	447.769/-.079	0.496
GEN HTR	448.071/-.130	0.429	448.045/-.046	0.434
03-63-2	446.510/-.145	0.776	447.416/-.055	0.574
03-63-5	444.370/-.156	1.254	446.149/-.057	0.856
SRCH LT	447.801/-.062	0.489	448.366/0.034	0.363
02-119-2	448.520/-.118	0.329	448.923/-.045	0.239

APPENDIX D

GENERAL DESIGN DATA

(1) 750 KW Generator Connected

Type Of Load	Connected	Anchor	Cruising Diesel	Icebreaking Diesel	Icebreaking Turbine
Non-Transferable Loads:					
Lighting	244.906	92.282	76.902	76.902	76.902
Power	787.025	174.470	150.560	195.430	222.61
A: Total	1031.931	266.752	227.462	272.332	229.512
Normal Transferable Loads To Emerg SWBD					
Lighting	0.000	0.000	0.000	0.000	0.000
Power	624.910	16.860	106.380	151.030	79.84
B: Total	624.910	16.860	106.380	151.030	79.84
Normal SWBD Load (Conn & Oper A+B)					
Total	1656.841	283.612	333.842	423.362	379.352

Table 17. No. 2 Ship Service Switchboard Load Summary (KW)

(1) 750 KW Generator Connected

Type Of Load	Connected	Anchor	Cruising Diesel	Icebreaking Diesel	Icebreaking Turbine
Non-Transferable Loads:					
Lighting	111.900	67.140	53.069	53.070	53.070
Power	997.340	282.020	243.680	299.280	300.750
A: Total	1109.240	349.220	296.749	352.350	353.820
Normal Transferable Loads To Emerg SWBD					
Lighting	0.000	0.000	0.000	0.000	0.000
Power	571.430	11.510	102.160	147.930	59.760
B: Total	571.430	11.510	102.160	147.930	59.760
Normal SWBD Load (Conn & Oper A+B)					
Total	1680.670	360.730	398.909	500.280	421.090

Table 18. No. 3 Ship Service Switchboard Load Summary (KW)

(1) 750 KW Generator Connected

Type Of Load	Connected	Anchor	Cruising Diesel	Icebreaking Diesel	Icebreaking Turbine
Non-Transferable Loads:					
Lighting	136.023	75.150	62.630	62.630	62.630
Power	725.780	209.950	170.950	190.160	229.780
A: Total	851.803	285.100	233.580	252.790	292.410
Normal Transferable Loads To Emerg SWBD					
Lighting	11.320	0.090	0.470	0.470	0.470
Power	816.050	102.460	287.606	249.082	200.503
B: Total	827.370	102.550	288.076	249.082	200.973
Normal SWBD Load (Conn & Oper A+B)					
Total	1679.173	387.650	521.656	501.872	493.383

Table 19. Emergency Ship Service Switchboard Load Summary (KW)

(1) 400 KW Generator Connected

Type Of Load	Connected	Anchor	Cruising Diesel	Icebreaking Diesel	Icebreaking Turbine
Non-Transferable	146.380	44.260	45.560	45.560	45.560
Auto-Transfer	161.160	14.840	42.470	42.470	44.210
Sub Total	307.540	59.100	88.030	88.030	90.370
Manual Transfer	1918.520	127.398	483.526	542.425	326.143
Total	2224.02	187.748	572.316	631.215	417.273

Table 20. Total Load Normal Ship Service Switchboard Load Summary (KW)

Switchboard	Connected	Anchor	Cruising Diesel	Icebreaking Diesel	Icebreaking Turbine
No. 1 SWBD	1656.840	283.610	331.840	423.360	379.350
No. 2 SWBD	1680.670	360.730	398.910	500.280	421.090
No. 3 SWBD	1681.930	388.200	522.750	509.440	494.470
Total	5019.440	1032.540	1253.500	1433.080	1294.910

Table 21. Power Cable Electrical Ratings and Physical Characteristics

Type & Size	Area of each Conductor	Overall Diameter	Weight per ft.	Rated Voltage	Ampacity 60 Hz,50° C	Ohms/1000 ft. R	X
TSGU/A-3	2.83	0.41	0.10	1000	10	4.7	0.041
4	4.50	0.45	0.13	1000	17	2.9	0.039
9	9.02	0.58	0.22	1000	36	1.4	0.037
14	14.34	0.72	0.32	1000	47	0.88	0.032
23	22.80	0.81	0.45	1000	64	0.55	0.030
30						0.41	0.029
40						0.32	0.029
50	49.08	0.97	0.82	1000	101	0.26	0.028
60						0.21	0.028
75	75.78	1.13	1.20	1000	136	0.17	0.027
100	99.06	1.27	1.50	1000	160	0.13	0.027
125						0.10	0.027
150	157.60	1.52	2.30	1000	216	0.081	0.026
200	198.70	1.67	2.90	1000	250	0.064	0.026
250						0.051	0.026
300	296.40	1.96	4.10	1000	320	0.043	0.026
350						0.037	0.025
400	413.60	2.20	5.50	1000	400	0.031	0.025

Note:

1. Resistances are per conductor at 65° C
2. Reactances based on full coverage aluminum armored cables
3. Data taken from Table 1 of DDS 304-2, Electrical Cables Ratings and Characteristics, 1 June 1974, and Table 1 of DDS 304-1, Electric Cable Voltage Drop Calculations, 1 November 1963, Navy Design Data Sheets.

Table 22. Power System Design Currents

Load\Current:	Connected		Resultant		Max Resultant	
1-39-1	19.876	-15.426	21.358	-16.575	40.539	-51.610
1-52-1	118.600	-55.036	125.560	-56.980	196.405	-212.574
1-65-1	150.769	-6.748	152.250	-7.897	171.769	-44.330
1-67-2	31.053	-21.675	33.965	-23.333	96.730	-96.831
1-68-2	96.700	0.000	96.700	0.000	96.700	0.000
1-70-1	67.121	-48.943	71.135	-52.007	124.451	-144.050
2-66-1	87.630	0.000	87.630	0.000	87.630	0.000
3-66-2	54.111	-32.108	59.683	-35.692	69.072	-74.259
3-66-4	10.197	-7.326	10.824	-7.862	18.760	-25.702
3-73-1	145.668	-34.237	149.987	-36.498	188.643	-130.974
3-73-3	102.340	-63.425	118.915	-73.697	186.353	-261.250
3-73-5	238.858	-87.232	243.177	-89.493	290.333	-189.237
4-78-1	107.380	-48.924	107.380	-48.924	105.686	-302.319
2-105-1	160.141	-90.656	165.645	-94.167	214.378	-215.039
3-97-2	37.012	-3.005	37.012	-3.005	37.012	-3.005
3-97-4	89.978	0.000	89.978	0.000	89.978	0.000
3-97-6	33.870	-2.576	34.793	-3.220	48.870	-28.556
3-104-2	30.974	-22.425	33.844	-24.428	66.787	-84.512
3-110-1	48.750	-22.470	54.405	-25.675	114.879	-149.094
3-110-3	13.430	-7.330	14.057	-7.866	21.993	-25.706
3-112-1	23.647	-14.031	26.155	-16.176	32.679	-32.129
4-85-1	107.380	-48.924	107.380	-48.924	105.686	-302.319
5-113-2	22.681	-15.832	24.920	-17.249	78.558	-75.814
1-116-1	53.848	-1.524	53.848	-1.524	53.848	-1.524
1-143-2	170.191	-72.501	175.846	-75.706	227.328	-195.323
2-122-1	83.132	-46.492	86.002	-48.495	128.570	-135.825
2-122-2	69.670	-46.819	79.039	-53.114	112.908	-137.392
3-126-2	142.966	-84.831	170.026	-99.437	253.827	-378.415
3-126-4	48.948	-32.894	54.513	-36.488	108.761	-167.047
3-126-6	155.815	-92.455	182.875	-107.060	263.517	-384.135
3-133-1	225.185	-123.983	236.235	-130.831	318.642	-403.005
3-133-3	84.830	-52.573	95.880	-59.421	184.663	-335.546
3-133-5	147.818	-85.353	153.238	-88.204	205.926	-200.508
4-142-1	107.380	-48.924	107.380	-48.924	105.686	-302.319
5-126-1	22.712	-16.443	24.912	-18.093	46.937	-64.103
1-154-1	47.477	-30.667	48.929	-31.551	62.177	-58.423
1-154-3	85.670	0.000	85.670	0.000	85.670	0.000
3-164-2	143.830	0.000	143.830	0.000	143.830	0.000
3-164-4	143.830	0.000	143.830	0.000	143.830	0.000
3-166-2	143.830	0.000	143.830	0.000	143.830	0.000
3-170-1	15.930	0.000	15.930	0.000	15.930	0.000
3-170-3	16.360	0.000	16.360	0.000	16.360	0.000
3-170-5	17.960	0.000	17.960	0.000	17.960	0.000
MAIN SWBD	30.484	-20.976	32.484	-22.472	63.484	-71.087
PWR SYS A	212.940	-134.761	212.940	-134.761	204.154	-604.433
PWR SYS B	212.940	-134.761	212.940	-134.761	204.154	-604.433
PWR SYS C	212.940	-134.761	212.940	-134.761	204.154	-604.433
3-175-1	311.258	-209.167	331.471	-223.013	544.646	-713.339
3-175-3	102.340	-63.425	118.915	-73.697	186.353	-261.250
3-175-5	161.816	-46.121	170.486	-51.494	178.847	-90.398
3-176-1	243.720	-26.177	245.887	-27.520	288.047	-53.649

Table 22. (Continued)

Load\Current:	Connected		Resultant		Max Resultant	
3-176-2	126.449	-62.744	131.921	-65.205	258.972	-121.265
3-176-3	317.735	-214.069	337.947	-227.915	543.685	-713.632
3-176-5	308.735	-207.471	328.825	-221.494	538.935	-709.668
MAG PUMP	107.380	-48.924	107.380	-48.924	105.686	-302.319
1-200-2	44.041	-28.448	46.722	-29.902	95.511	-106.803
2-204-2	100.372	-42.758	103.242	-44.762	132.247	-103.321
2-243-1	80.840	-47.968	80.840	-47.968	98.651	-207.127
2-243-2	80.840	-47.968	80.840	-47.968	98.651	-207.127
01-67-1	63.970	0.000	63.970	0.000	63.970	0.000
01-148-1	21.224	-15.918	22.704	-17.028	47.062	-48.331
01-149-1	**NEGLECTED** - *Not in Power System Feeders List*					
02-67-1	168.904	-104.677	168.904	-104.677	168.904	-104.677
EM GEN HT	4.110	0.000	14.110	0.000	14.110	0.000
03-63-2	62.300	0.000	62.300	0.000	62.300	0.000
03-63-5	40.920	0.000	40.920	0.000	40.920	0.000
SRCH LT	11.050	6.848	11.050	6.848	15.000	-25.981
02-119-2	68.263	-34.972	72.513	-37.606	117.876	-129.496

Table 23. Ring System Cable Section Characteristics

Buses		Length (ft)	R (pu)	X (pu)
1	11	30	0.00115	0.00093
11	3	68	0.00173	0.00140
15	16	19	0.00048	0.00039
4	16	28	0.00071	0.00058
4	2	34	0.00087	0.00070
4	6	40	0.00102	0.00082
17	18	12	0.00031	0.00025
5	17	39	0.00100	0.00080
3	5	34	0.00087	0.00070
5	7	59	0.00151	0.00121
8	21	46	0.00117	0.00095
8	10	25	0.00064	0.00051
8	22	65	0.00166	0.00134
6	10	29	0.00074	0.00060
6	18	32	0.00082	0.00066
7	21	38	0.00097	0.00078
7	22	46	0.00117	0.00095
11	12	14	0.00036	0.00029
2	12	28	0.00071	0.00058
2	13	5	0.00013	0.00010
13	14	29	0.00074	0.00060
9	14	144	0.00367	0.00296
9	23	13	0.00040	0.00032
9	20	33	0.00084	0.00068
10	19	5	0.00013	0.00010
19	20	10	0.00026	0.00021

Note: Base MVA = 1.0
Base Volts = 0.45 KV
Lengths do not include 5% margin for bends and slack.

VITA

Kevin J. Russell is an active duty Lieutenant in the U. S. Coast Guard presently assigned to Virginia Polytechnic Institute and State University under DUINS. He is currently completing a masters degree program in electric power engineering.

Academic History: B. S., Marine Engineering, U. S. Coast Guard Academy, May 1984.

Shipboard Experience:

USCGC Storis: July 1984 - January 1986. Completed Coast Guard Student Engineering Program. Primary Duties consisted of Student Engineer, Auxiliary Officer, and Engineering Watch Officer. Qualified as inport and underway Engineering Watch Officer and underway Deck Watch Officer. Completed Navy Damage Control School, Newport, RI, November 1985. Completed advanced Fire Fighting School, San Diego, CA, December 1985.

USCGC Yocona: January 1986 - May 1986. Primary duties consisted of Assistant Engineering Officer, Damage Control Officer, and Engineering Watch Officer. Qualified as inport and underway Engineering Watch Officer. Primary activities consisted of preparing for and going through Navy Refresher Training at Pearl Harbor. Preparations included directing damage control training and updating shipboard damage control organization. Upon completion of training, Yocona received the Navy E for Damage Control.

USCGC Mackinaw: July 1986 - May 1988. Primary Duties consisted of Assistant Engineering Officer, Damage Control Officer, Electrical Officer, Auxiliary Officer, Engineering Watch Officer, and inport Deck Watch Officer. Qualified as inport Deck Watch Officer, and inport and underway Engineering Watch Officer. Primary activities consisted of preparing ship and crew for Navy Refresher Training, and assisting engineering officer in overseeing major yard period and dockside availability. Preparations for refresher training were significant in that the Mackinaw had never been through refresher training in its 40 year history and was a large vessel which had recently been changed to operating with reduced manning. Besides normal training, equipment, and organization preparations, major alterations to the ships main space fire fighting doctrine and repair party organization and procedures had to be completed. This aided Mackinaw to not only successfully complete refresher training, but to receive the Navy E for Damage Control. Insight gained from this experience lead to the development of this study.