Electric Ship: Historical Perspective

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U.S. Navy

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Naval Electric Power System Design

"The primary aim of the electric power system design will be for survivability and continuity of the electrical power supply. To insure continuity of service, consideration shall be given to the number, size and location of generators, switchboards, and to the type of electrical distribution systems to be installed and the suitability for segregating or isolating damaged sections of the system."

- *NAVSEA DESIGN PRACTICES and CRITERIA MANUAL, ELECTRICAL SYSTEMS for SURFACE SHIPS*, CHAPTER 300 NAVSEA T9300-AF-PRO-020

Properties of a Naval Power (and Energy) System

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

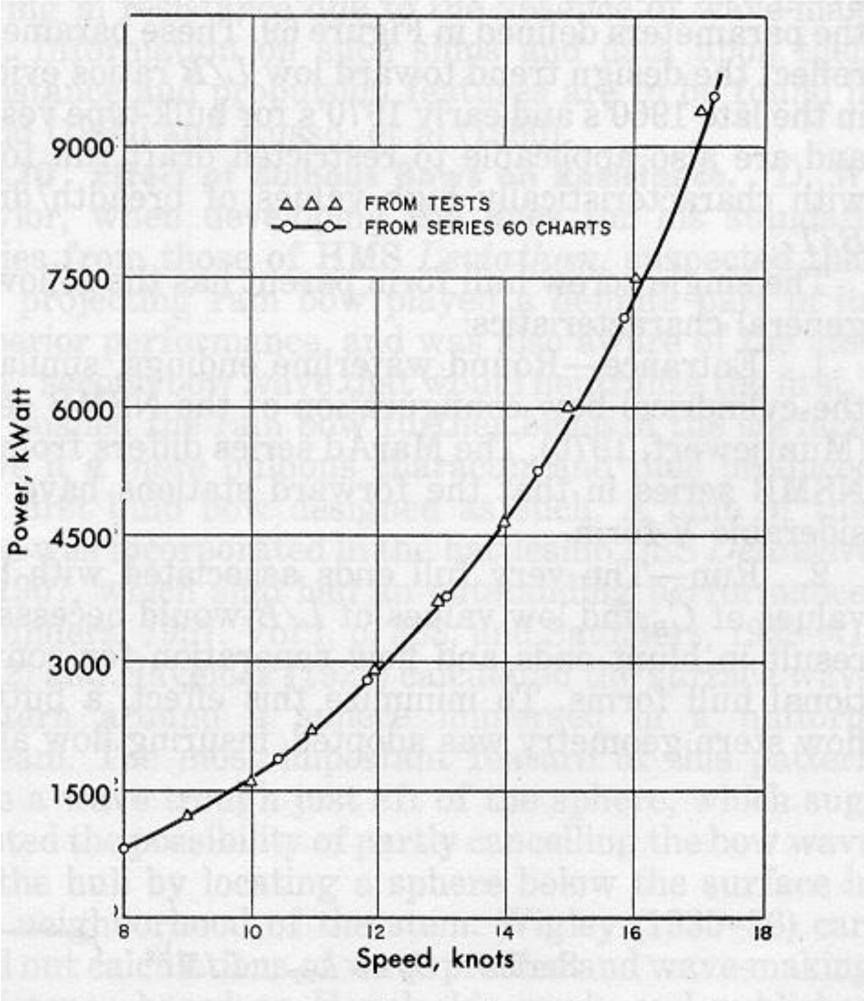
Electric Drive – Integrated Power System Design Opportunities

- Support High Power Mission Systems
- Reduce Number of Prime Movers
- Improve System Efficiency
- Provide General Arrangements Flexibility
- Improve Ship Producibility
- Support Zonal Survivability
- Improve Quality of Service

161208-N-MB306-079 USS Zumwalt DDG 1000 (US Navy Photo by Zachary Bell)

Speed – Power Curve

- How to calculate
  - Bare Hull Drag
    - Synthesis and specialized computer Tools
    - Standard Series
    - Scaling from existing ships
  - Propeller Characteristics
  - Power Margin Factor
  - Ship Propeller interaction
  - Bearing and Shafting Efficiencies
- Standard Assumptions
  - Clean Bottom
  - Calm Seas
  - Deep Water
  - Full Load Displacement



Comparison of P_E from model tests of a bulk carrier with estimate from Series 60 charts.

Motors: Basic Scaling Law

$$\mathbf{HP \propto D^2 \cdot L \cdot A \cdot B \cdot RPM}$$

HP **Power Rating**

D **Rotor Diameter**

L **Rotor Active Length**

A **Surface Current Density**
(Cooling Method)

B **Rotor Flux Density**
(Saturation of Magnetic Material)

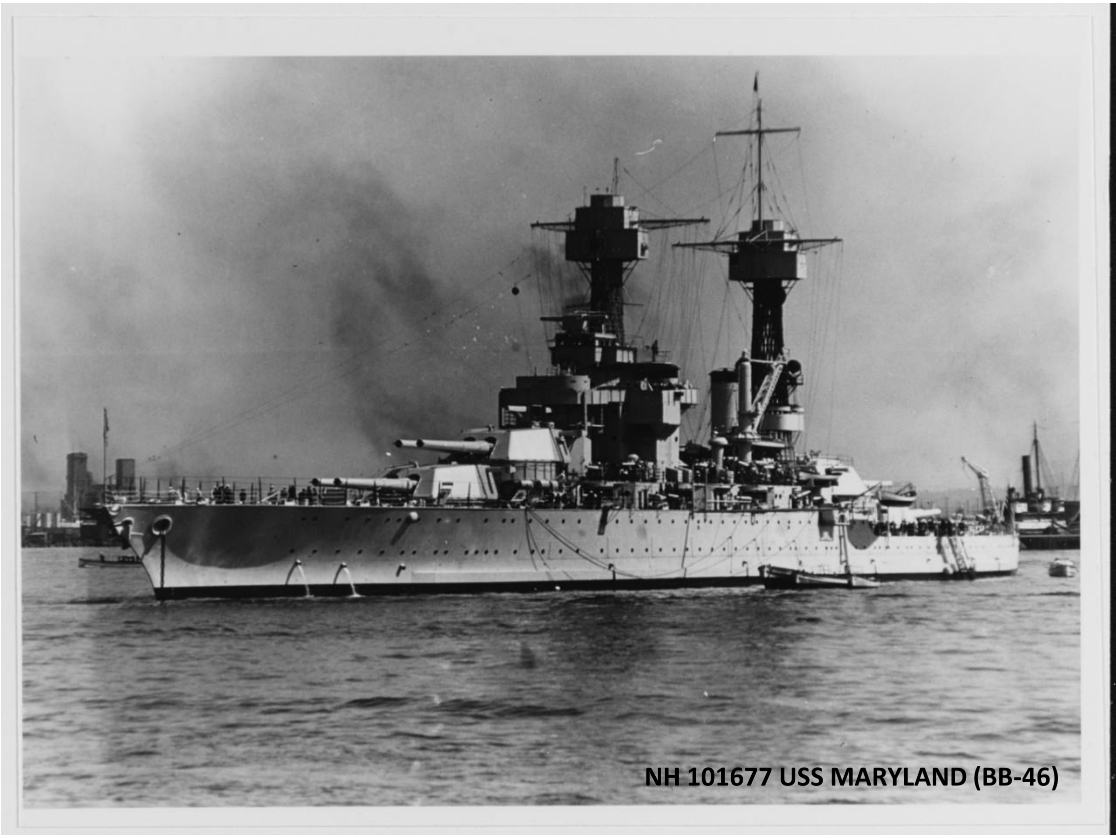
RPM **Shaft Speed**

Propulsion motor thumb rules

- For a given technology, cost is roughly proportional to Torque.
- As the rated speed of a motor increases, the peak efficiency occurs at a lower diameter.
- Higher rated speeds generally translate into smaller and more efficient motors.
- Maximum Rotor Diameter is limited by shaft rake considerations, manufacturability, and transportability.
- Motor efficiencies at design speed can typically fall in range of 90-98%.
- The efficiency of a conventional motor is relatively flat above about 25-35% rated speed. Below about 25-35% rated speed, the efficiency drops rapidly.

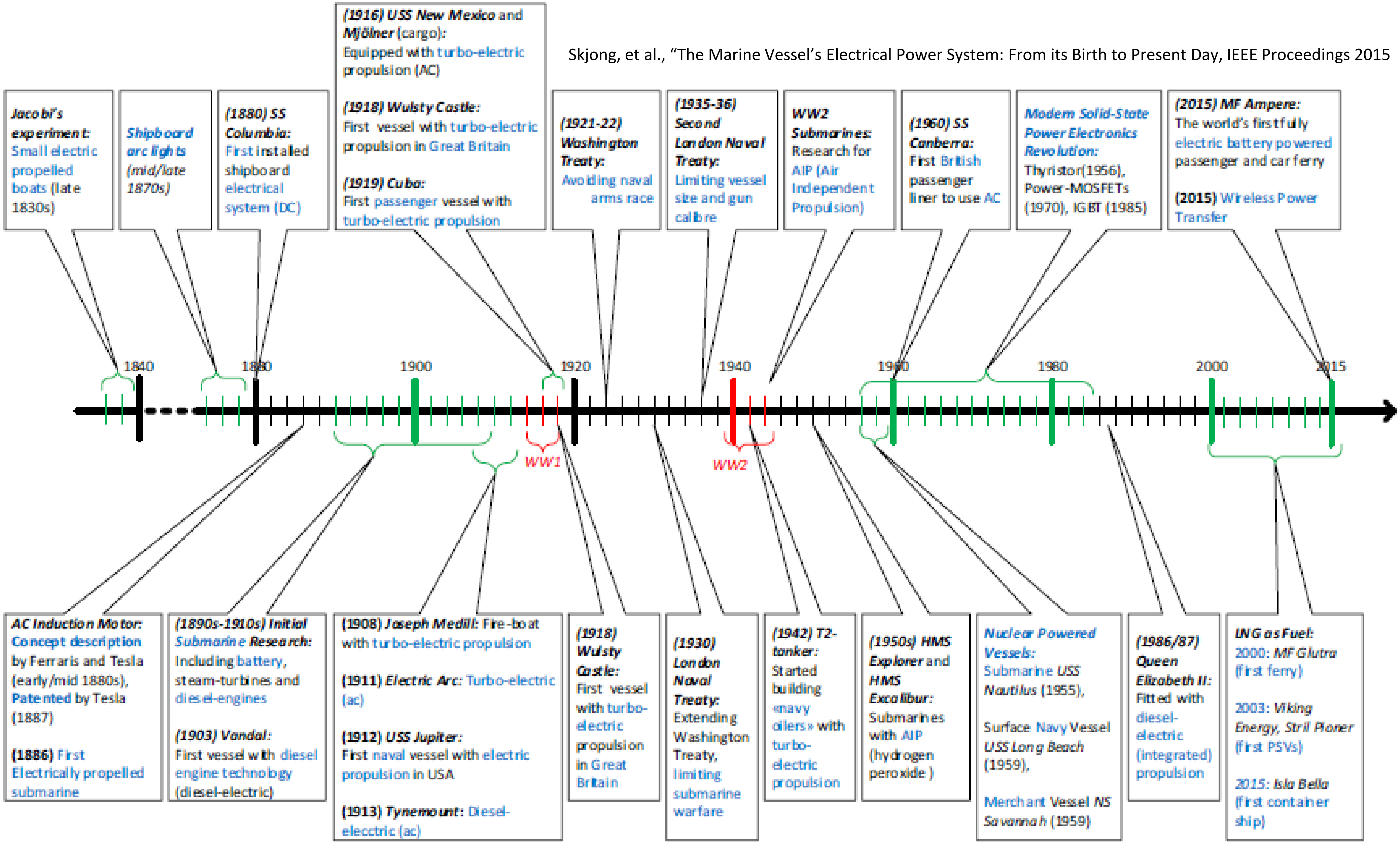
Electrical System on Ships

- Prior to ~1903: Special Purpose and Lighting only
- ~1903 to ~1945: Electric Propulsion = "Electric Reduction Gear"
  - Match prime mover (steam turbine / diesel) RPM to propeller RPM
  - DC Ship Service Distribution for most ships (between 100 and 240 volts)
  - AC Ship Service Distribution (440 VAC) for U.S. Navy since 1932
- ~1945 to 1988: Electric Propulsion used for special applications
  - A.C. Ship Service
  - DC drives (SCR based)
  - AC Cycloconverters, Load-Commutated Inverters
- Since 1988: Increased Commercial Application
  - IGBT based variable speed drives
- Since 1960's: U.S. Navy investment
  - Super Conducting Motors
  - Advanced Integrated Electric Propulsion Plant
  - Integrated Electric Drive
  - Integrated Power System (DDG 1000)
  - MVAC power distribution (LHD 8, DDG 51 flight III, CVN 68, CVN 78)
  - Hybrid Electric Drive (LHD 8, LHA 6, DDG 51 Flight IIA)
  - Next Generation Integrated Power System
  - Integrated Power and Energy Systems / Naval Power and Energy Systems



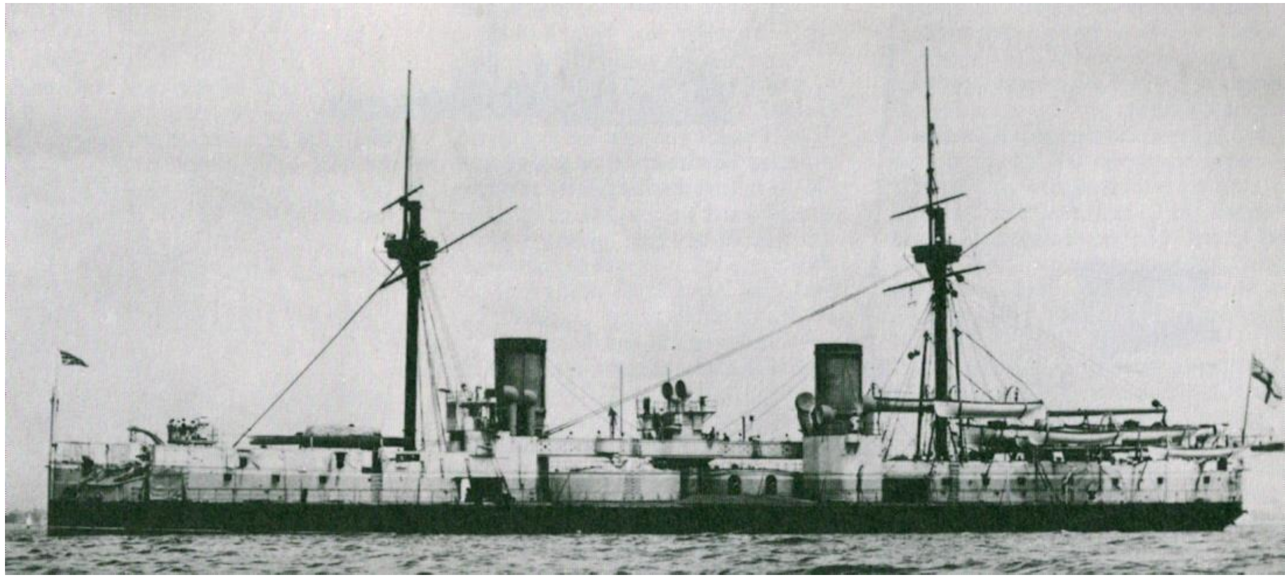
NH 101677 USS MARYLAND (BB-46)

Skjong, et al., “The Marine Vessel’s Electrical Power System: From its Birth to Present Day, IEEE Proceedings 2015



Early Shipboard Applications of Electricity

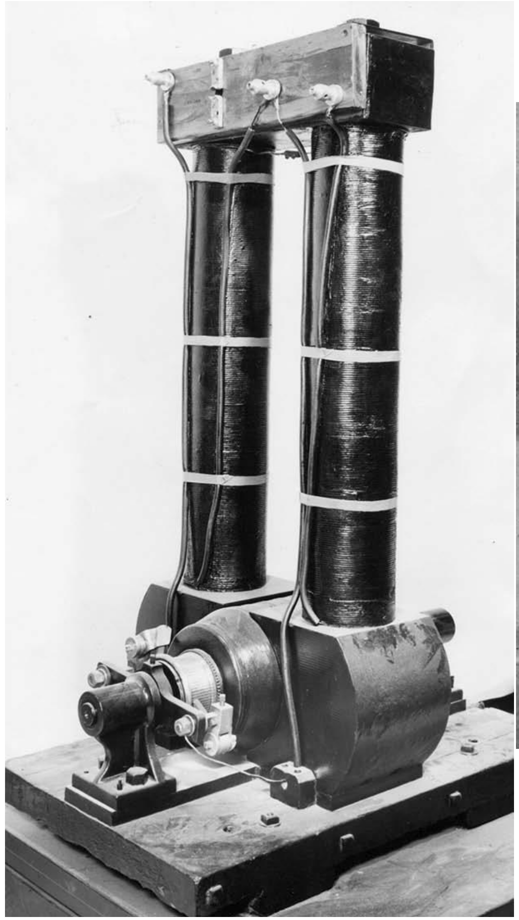
- First shipboard applications probably in the early 1870’s
- Batteries initially used as the supply, later dynamos
- Loads included
  - Arc lamps (later Edison lamps)
  - Gun-firing circuits
  - Call bells
  - Search Lights
    - First “killer app”
  - Motors (starting ~1890)
    - Ventilation
    - Auxiliaries



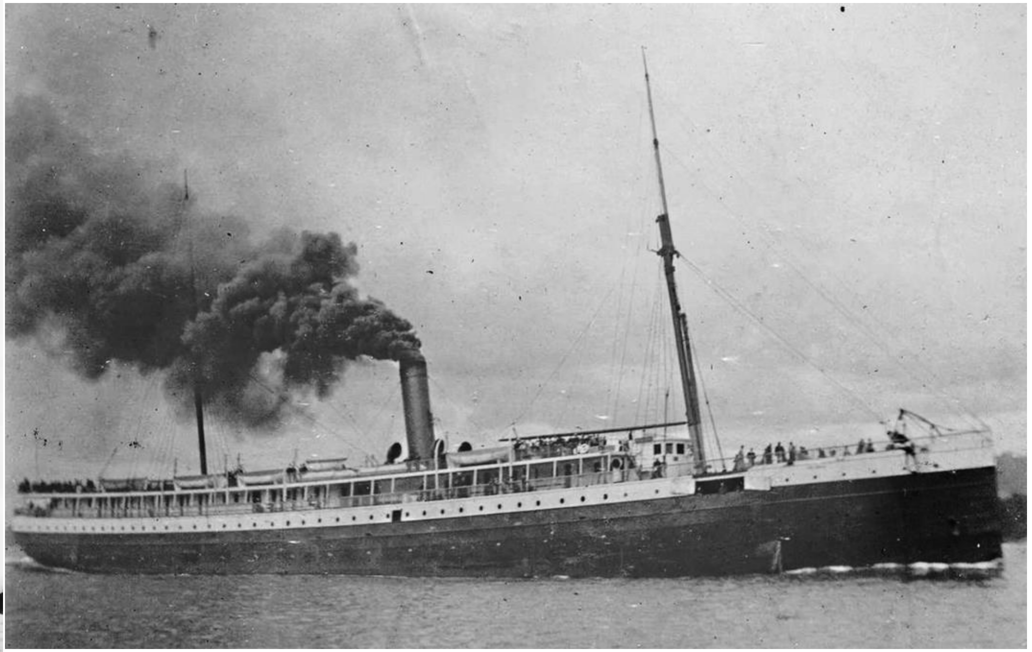
HMS Inflexible: Outfitted in 1881 with 80 volt dynamo to supply the searchlights

S.S. Columbia

- April 1880: First commercial installation of the Edison incandescent light bulb
  - Following demonstration at Menlo Park on 31 December 1879
- System
  - 4 6-kW dynamos
    - Each could supply 60 lamps
    - 1 used as exciter for other 3
    - Belt driven from 2 vertical steam engines
  - 120 incandescent lamps (16 candlepower)
    - 7 main circuits
    - Protected by fuses
  - Wire insulated with cotton fabric dipped in melted paraffin. Also used rubber tubing.



(photo courtesy of Hal Wallace, Smithsonian Institution, National Museum of American History, Behring Center, Washington, D.C.)

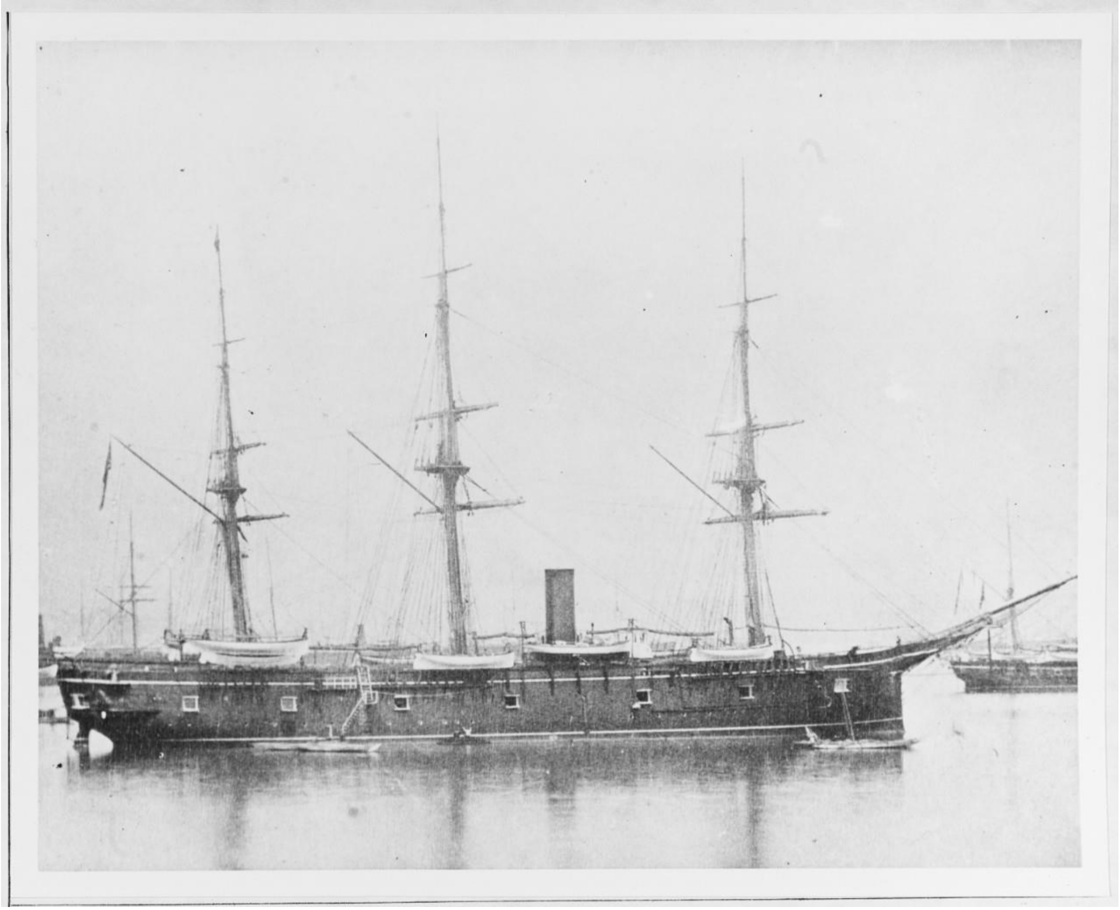


SS Columbia (photo in the public domain)

Sulzberger, Carl, “first Edison lights at sea, the SS Columbia story, 1880-1907,” IEEE power & energy magazine, January/February 2015, pp. 92-101

U.S.S. Trenton

- Commissioned 1877
- Wrecked 1889
- 1883: First installation of electric lights onboard U.S. Navy warship (Edison Company for Isolated Lighting)
  - One L dynamo (110 volts 120 amp)
  - One Armington-Sims engine
  - Electric Lights
    - 104 16-candle (201 lumens)
    - 130 10-candle (126 lumens)
    - 4 32-candle (402 lumens)
- Considered Success
- 1884 lighting added to
  - U.S.S. Atlanta
  - U.S.S. Boston
  - U.S.S. Omaha

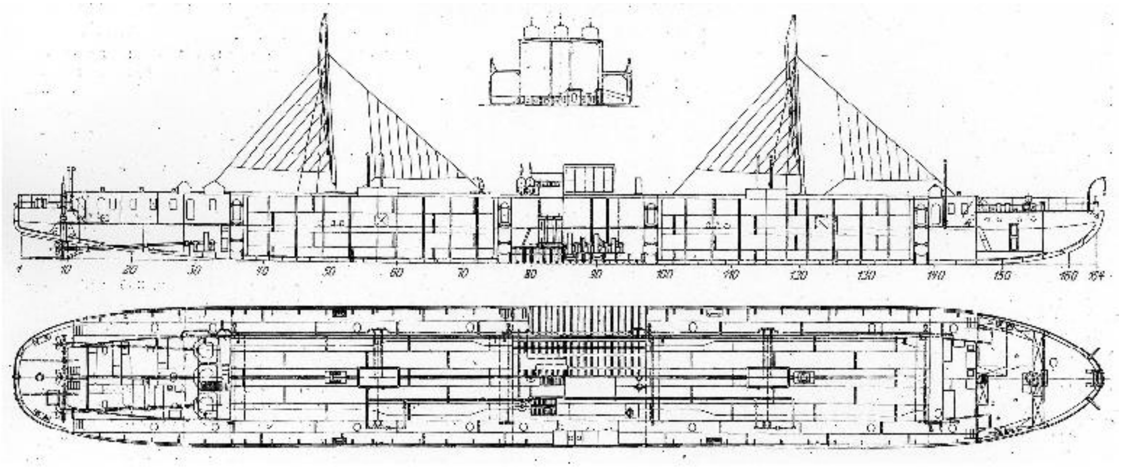


https://www.history.navy.mil NH 299 USS Trenton (1877-1889)

https://www.history.navy.mil/browse-by-topic/exploration-and-innovation/electricity-and-uss-trenton.html

River Tanker Vandal

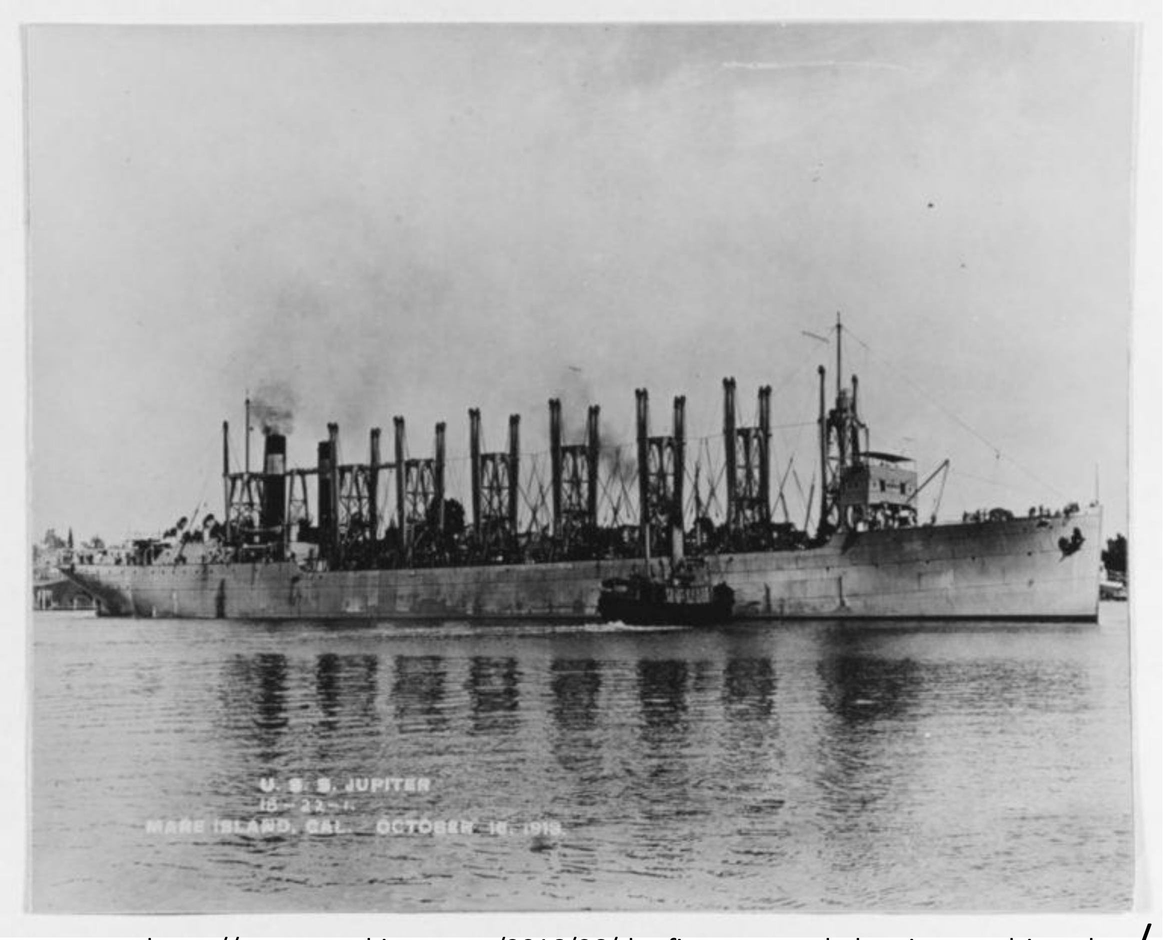
- Constructed in 1903 for transport of petroleum products in Russia.
- First Diesel Electric Drive
  - 3 diesel generators 90 kW, 500 V d.c., 250 rpm (constant speed)
  - 3 100 HP (300 rpm) motors
  - Ward-Leonard Drive
    - Speed controlled by varying voltage on generator field winding



http://www.branobelhistory.com/themes/innovations/ms-vandal-a-historical-ship/

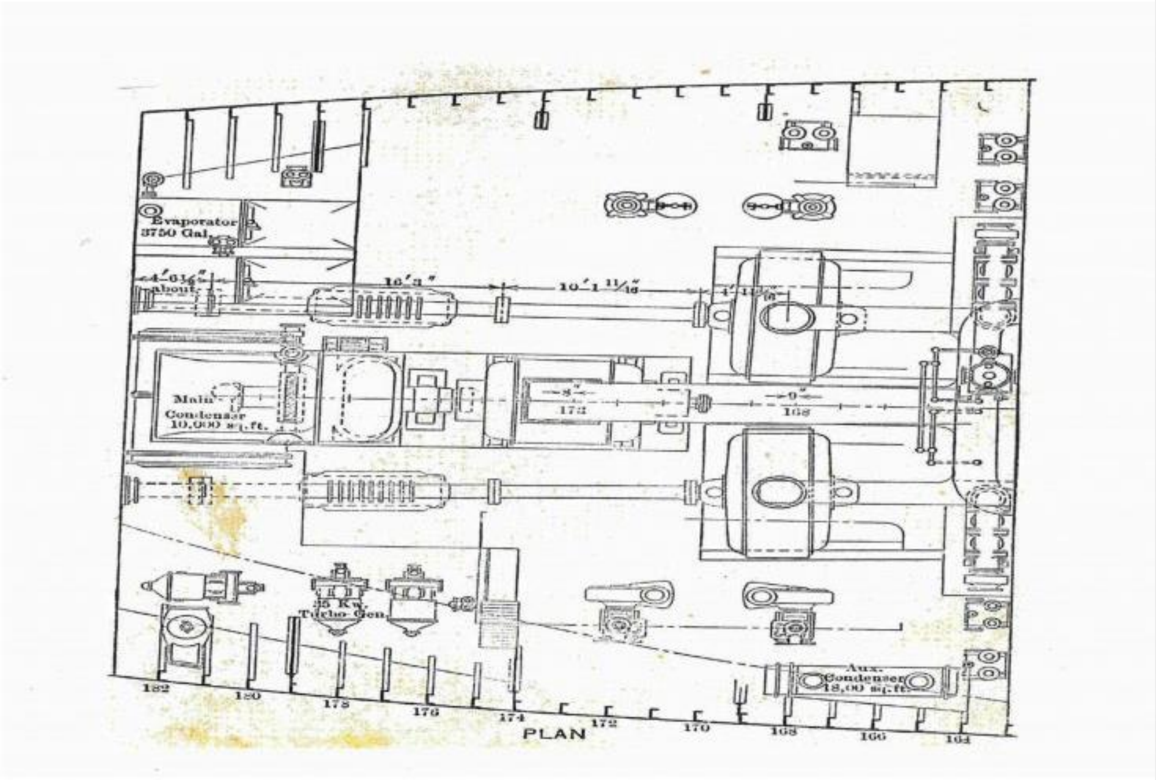
U.S.S. Jupiter (later CV 1 *U.S.S. Langley*)

- Commissioned 1912
- Converted 1920
- Scuttled 1942
- Length – 542’
- Beam – 65’
- Draft -27’8”
- Displacement 19,360 Tons
- Complement – 163 personnel
- Twin Screw
  - wound rotor induction motors (3500 HP)
  - 36 pole
- 6500 SHP (both shafts)
- 15.5 knots
- 5000 kW 2 pole a.c. main turbo-generator
- Ship Service: 3 x 35 kW turbine driven d.c. generators



https://www.navyhistory.org/2016/06/the-first-u-s-naval-electric-propulsion-plant/

U.S.S. Jupiter / U.S.S Langley



Approved for Release - Distribution is Unlimited

U.S.S. New Mexico (BB-40)

- Commissioned 1918
  - 20% less fuel consumption than sister ships
- Modernization 1931
  - Removed Electric Drive (replaced with gear)
  - Needed more power due to weight growth
  - Treaty limits worked against electric drive
- Decommissioned 1946
- Length – 624 ft
- Beam – 97 ft
- Draft – 30 ft
- Displacement – 32,000 lton
- 4 screws:
  - 7000 HP double squirrel cage Induction motors
- 21 Knots

https://www.history.navy.mil NH 63524 USS NEW MEXICO (BB-40)

US Navy WWII Turboelectric Propulsion

- BB-43 Tennessee
- BB-44 California
- BB-45 Colorado
- BB-46 Maryland
- BB-48 West Virginia
- AV-3 Langley
- CV-2 Lexington
- CV-3 Saratoga

NH 82117 USS Lexington (CV-2)

80-G-343630 USS West Virginia (BB-48)

US Navy WW II Turboelectric Propulsion

- Buckley Class (DE 51)
  - 102 produced
- Rudderow Class (DE 224)
  - 22 completed as DE
  - 50 completed as APD
- T2-SE-A1 / A2 / A3 Tankers
  - ~500 constructed
  - A1: 6,600 HP Synchronous Motor
  - A2 / A3: 10,000 HP Synchronous Motor
- AP (Personnel Transport)

80-G-269441 USS BUCKLEY (DE-51)

USS Schuylkill (AO-76) in Chesapeake Bay on 3 March 1943

WW II Diesel Electric Drive

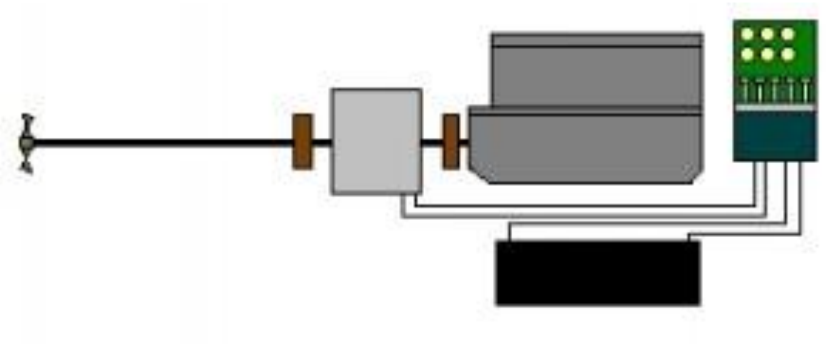
- Submarines
- Mine Sweepers
- Tugs / Salvage Vessels / ASR
- Tenders
- Destroyer Escorts
    - Evarts Class (DE-5)
        - 65 USN
        - 32 UK
    - Cannon Class (DE-99)
        - 66 USN
        - 6 Free French Forces

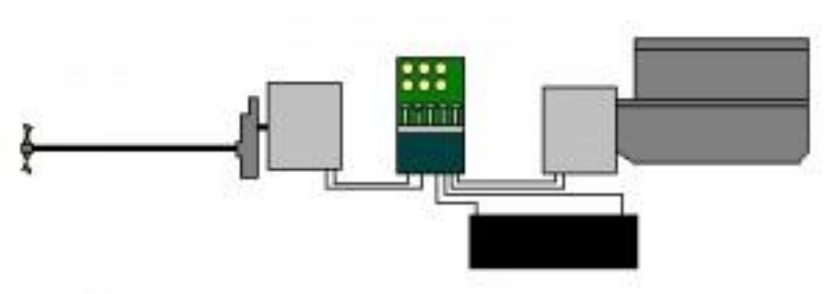
NH 107099 USS Evarts

UA 450.04 U.S.S. Balao (SS 285)

WW II submarine propulsion

- Direct Drive
  - Diesel and motor / generator directly connected to propeller shaft
  - Engine on
    - Motor / generator recharges battery (generator)
  - Engine off
    - Battery supplies motor / generator (motor)
  - Used by Germany in WWII
- Diesel – Electric Drive
  - Allows 4 diesel d.c. generators
  - Batteries charged from generators
  - Motors
    - Single or tandem
    - Direct drive or geared drive
  - Most U.S. submarines in WWII

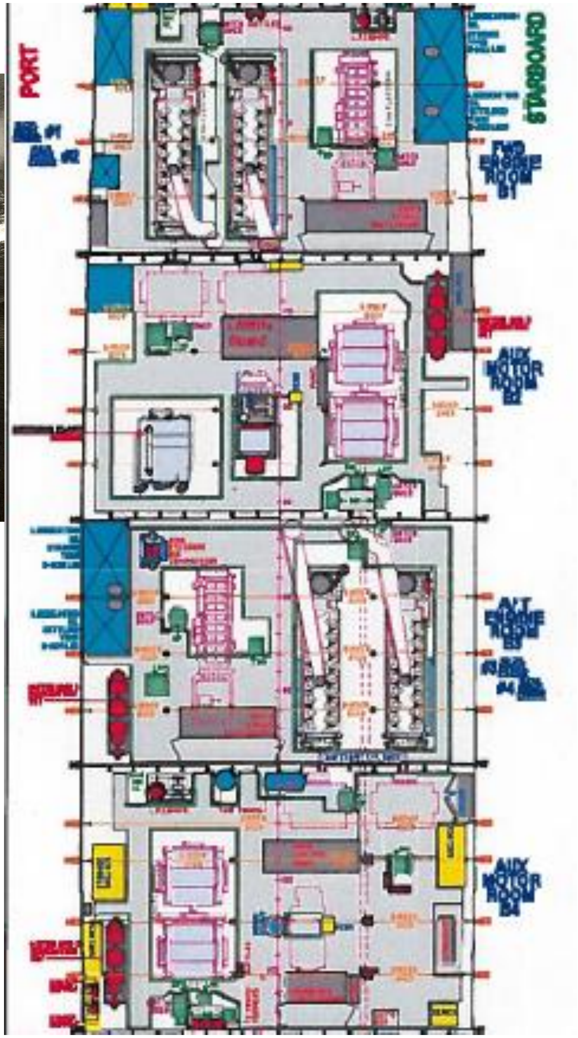


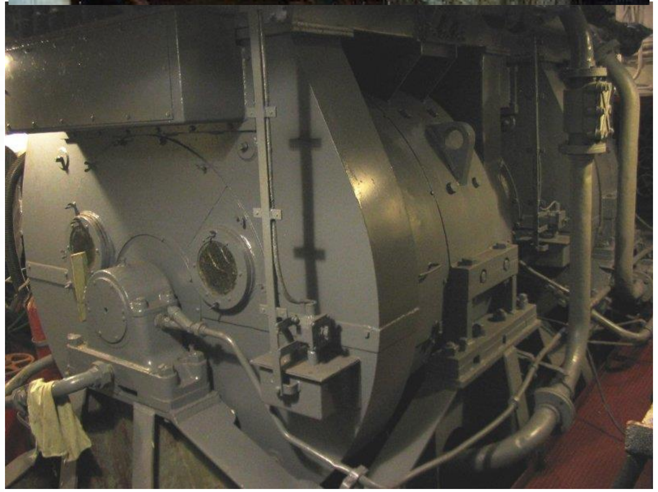


https://fleetsubmarine.com/propulsion.html

U.S.S. Slater (DE 766)

- *Cannon*-class destroyer escort
  - Commissioned 1944
  - Decommissioned 1947
  - Transferred to Greece 1951
  - Decommissioned 1991
- Displacement: 1240 lton
- Length: 306 ft
- Beam: 36 ft
- Draft 8 ft 9 in
- Propulsion
  - 4 GM Mod 16-278A 1700 HP diesel engines
  - 1200 kW 525 VDC 750 RPM d.c. generators
  - Tandem 1500 HP 525 VDC 600 RPM motors
  - 2 shafts
  - 21 knots
- Ship service
  - 200 / 300 kW 450 V a.c. generators
  - 40 kW 120 V d.c. generators
  - 8.5 kW motor generator sets

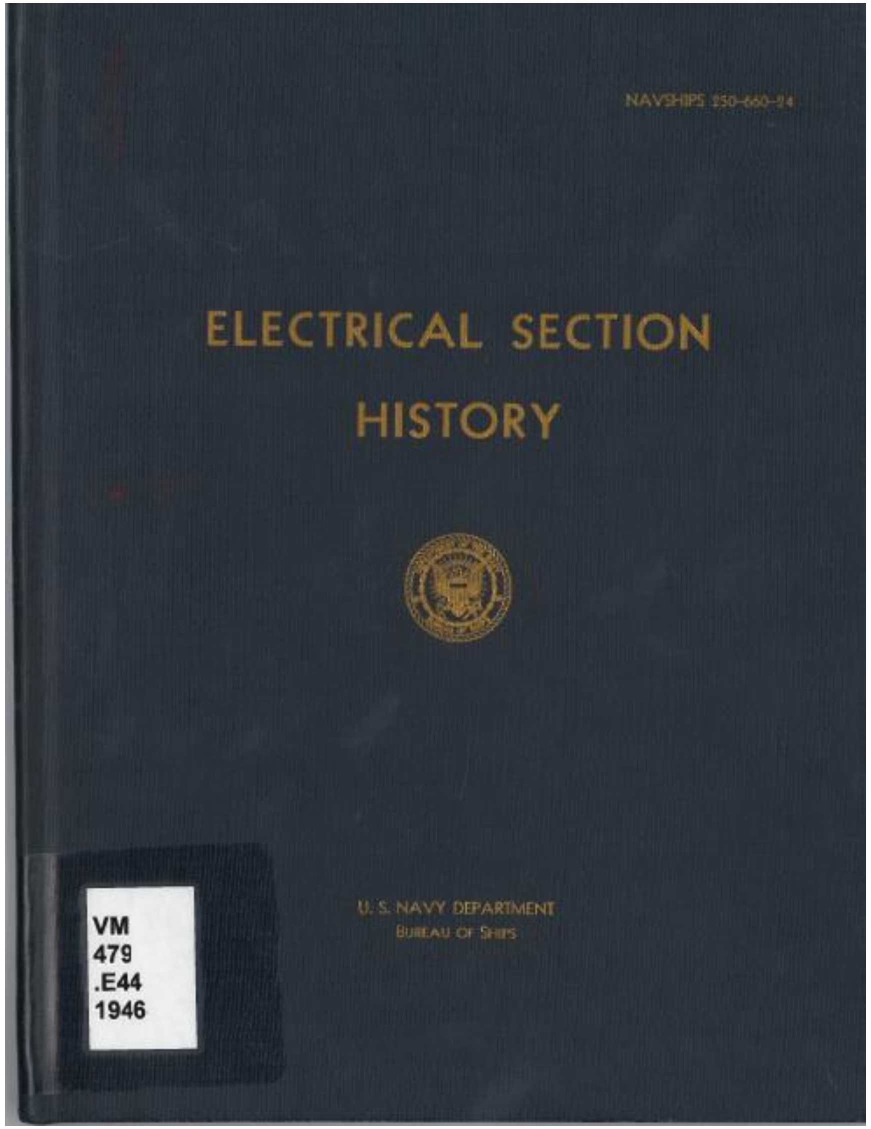




https://www.ussslater.org

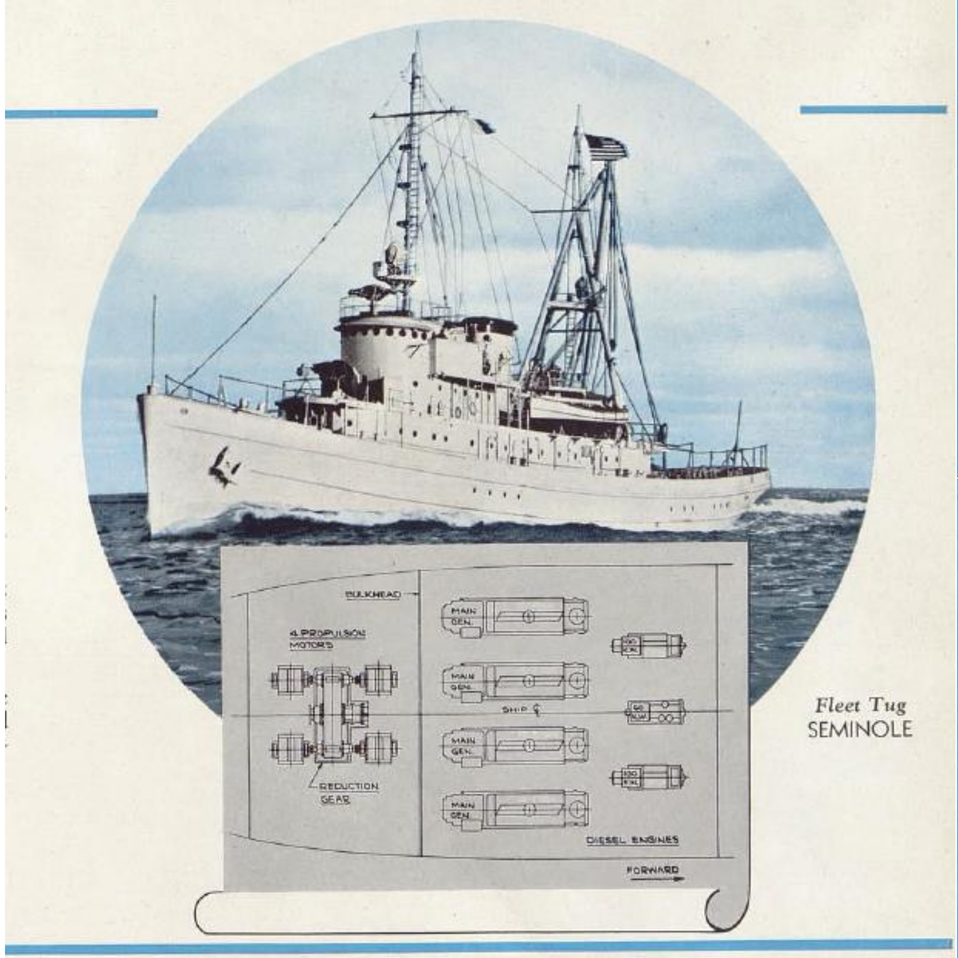
WW II Lessons Learned

- High Impact Shock
- Critical materials
- Fire Resistance
- Moisture Resistance
- Size and Weight
- Equipment Standardization
- General Performance and Reliability
    - Magnetic and Acoustic Characteristics
    - Carbon brushes
    - Automatic Bus Transfer (out-of-phase transfer)

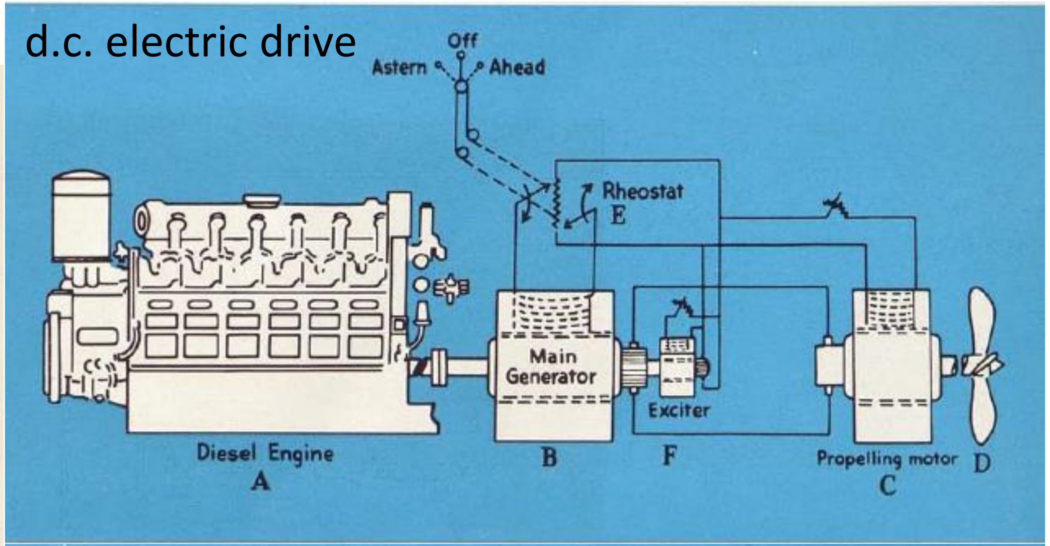


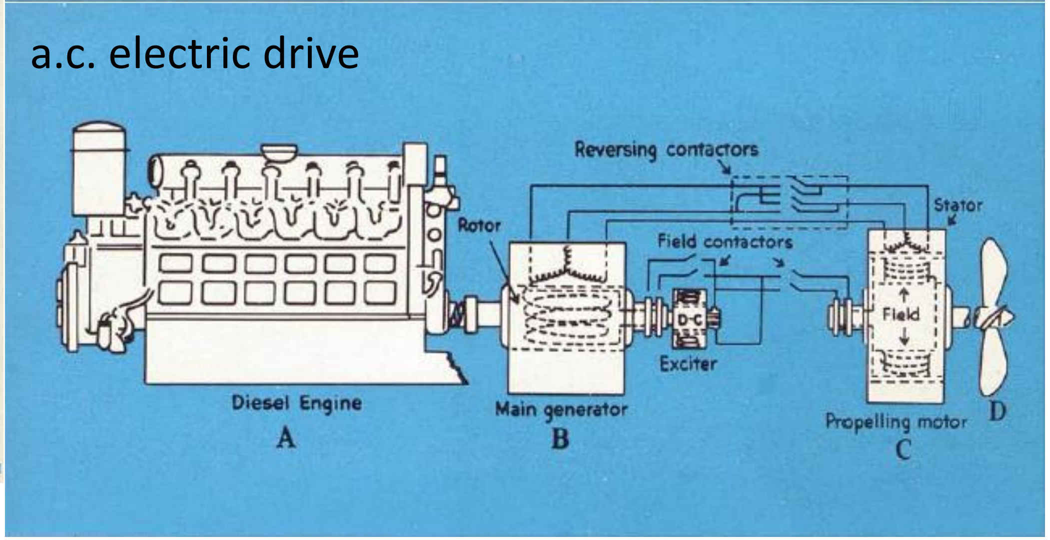
Early Diesel Electric Drives

- Yachts (1922)
- Tugboats (1924)
- Ferries (1926)
- Fireboat (1926)



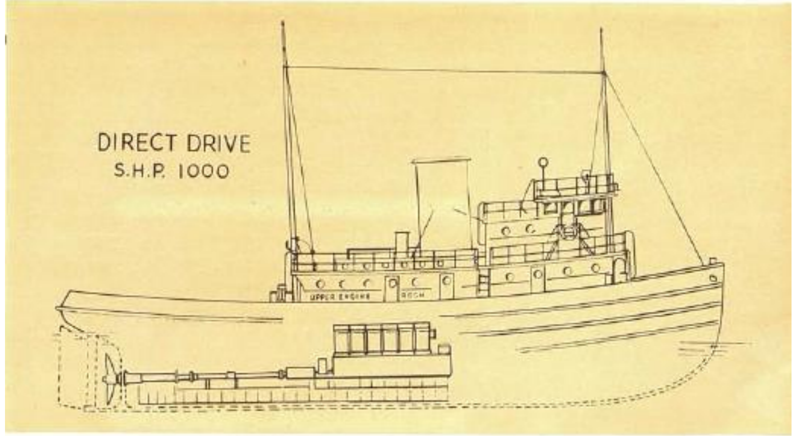
General Motors Diesel Electric Drive for Marine Service (circa 1945)



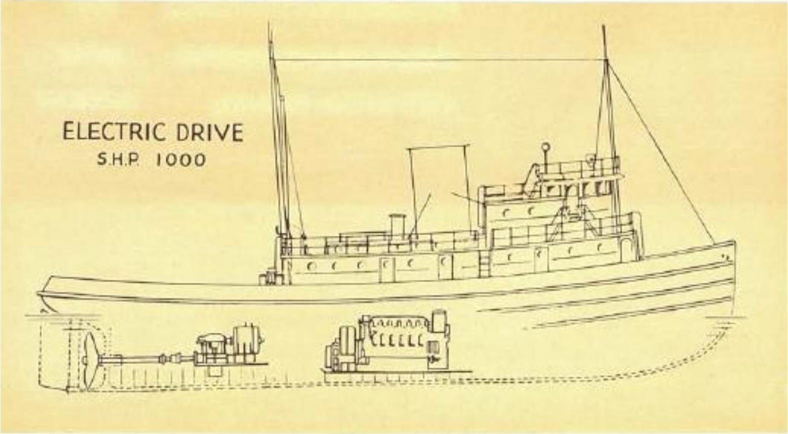


Commercial Experience (prior to 1945)

- “Electrical Reduction Gears”
  - Propulsion and Ship Service generally not integrated
- Diesel engines displacing steam on smaller vessels
- Electric Drive (mostly d.c. with smaller vessels) competed with
  - Direct Drive
  - Geared Drive
- Geared motor drives used as well.
- d.c. motors limited to 1000 V due to commutator limitations
- Steam-turbine drives used on some larger vessels
  - a.c. motors used for higher power levels



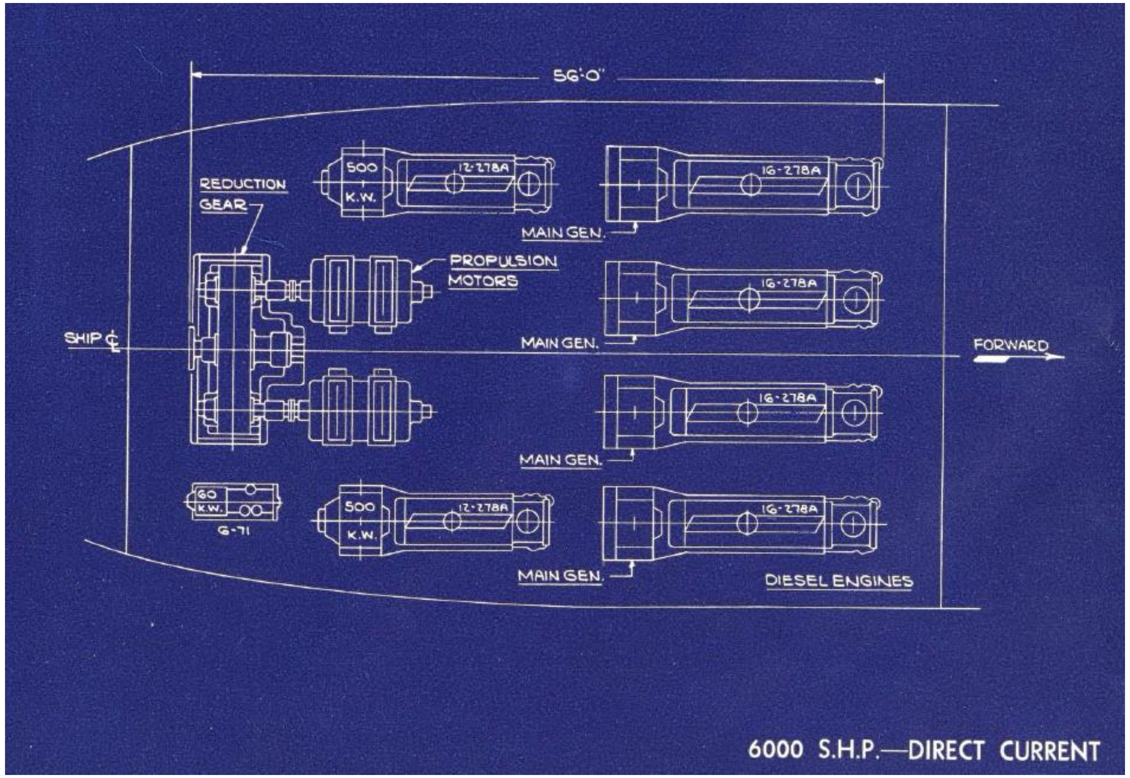
Typical direct-drive profile—note engine extending into second deck. Overall height of direct-drive engine installation, 15 or more feet.

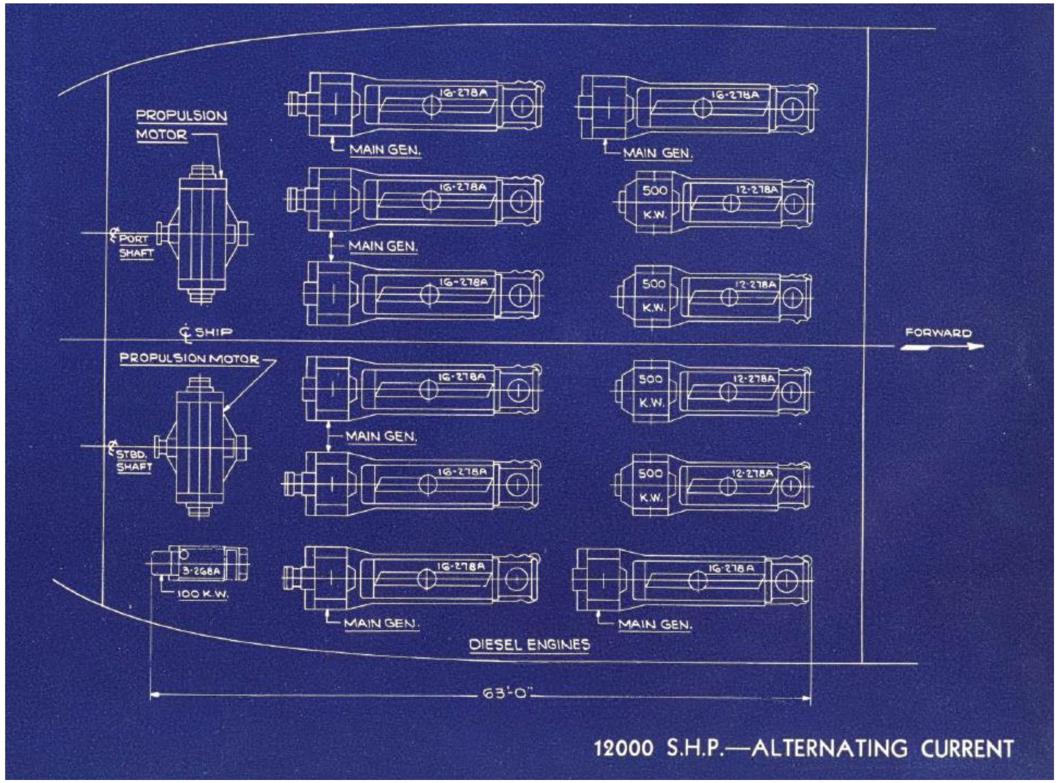


Typical electric-drive profile—engine contained within one deck space and placed where desired. Overall height of large model electric-drive engine, 9′ 7$\frac{7}{16}$″.

General Motors Diesel Electric Drive for Marine Service (circa 1945)

Diesel Electric Plants (circa 1945)





General Motors Diesel Electric Drive for Marine Service (circa 1945)

Commercial Turbine-Electric Drive

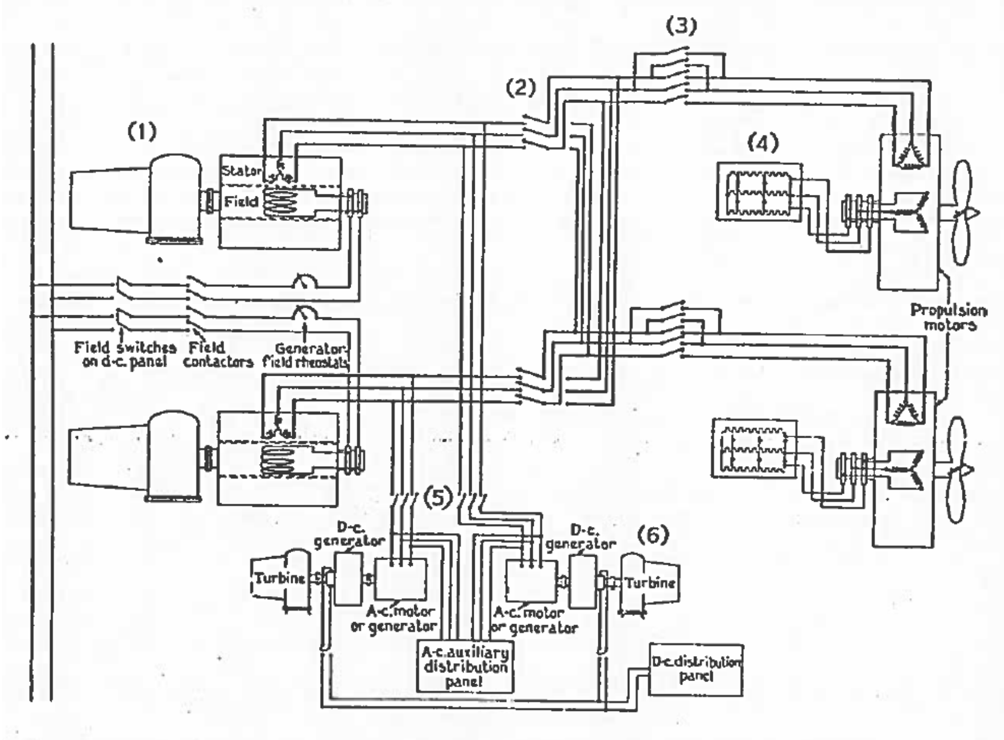


Fig. 14
Simplified connection diagram of main and field circuits of twin-screw, turbine-electric-drive ship with induction-type propulsion motors. The main units also furnish auxiliary power

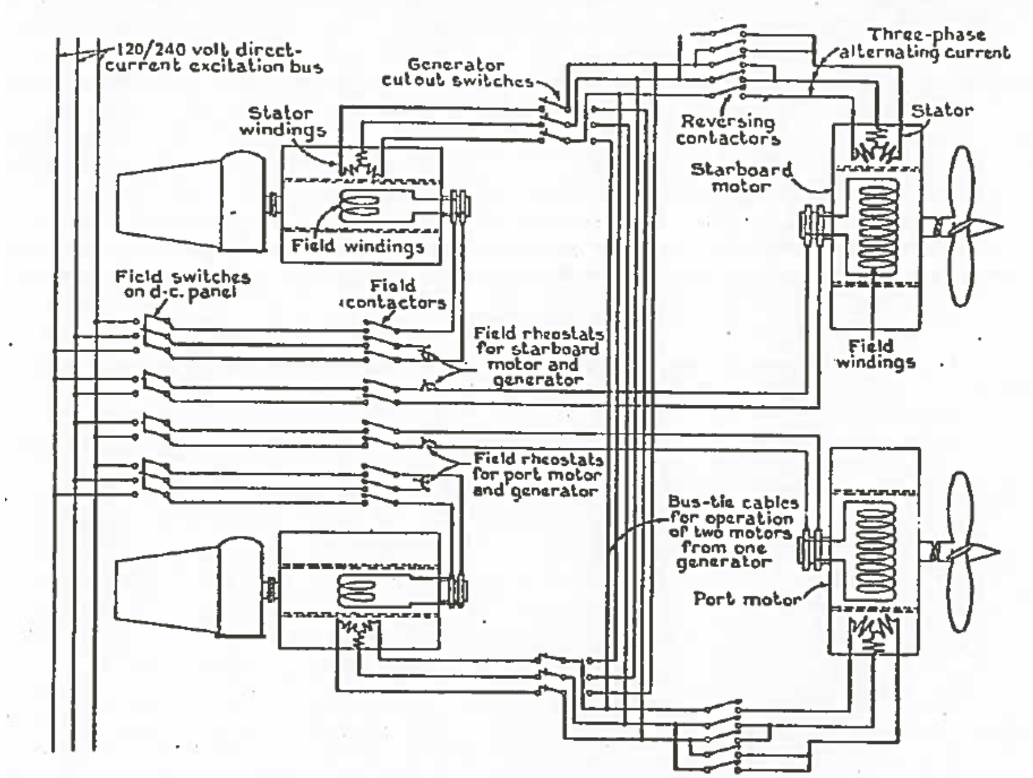


Fig. 15
Simplified connection diagram of main and field circuits of twin-screw, turbine-electric-drive ship with synchronous-propulsion type motors

Turbine-Electric Drive For Modern Merchant Ships

Post World War II (1945-1975) U.S. Navy Electric Propulsion / Electric Innovation

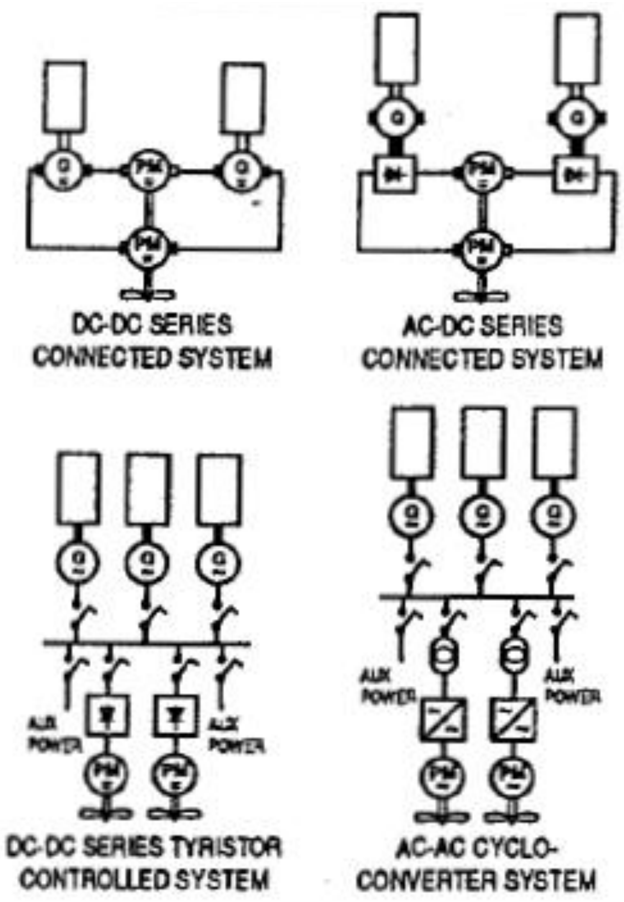
- EDD 828 *U.S.S. Timmerman* (modified *Gearing* class)
  - Operational Test Ship commissioned in 1952
  - 1000 VAC 400 hz system based on 600 kW turbo-generators
- Diesel Electric Submarines
  - 555 563 – 569 576 – 577 580 – 582
- SSN 587 *U.S.S. Tullibee* commissioned in 1960
  - 2500 SHP Turbo-electric DC Drive (reduce self noise)
- SSN 685 *U.S.S. Libscomb* commissioned in 1974
  - Turbo-electric DC Direct Drive
- AS-31 class (1962-1963)
  - 10 Fairbanks-Morse Diesels: 15,000 BHP
- AGB-4 *U.S.S. Glacier* (1955) Ice Breaker
  - Diesel Electric (10 diesel generators – 1340 kW, 837 V, 1600 A, 720 rpm)
  - 2 x 8,450 BHP DC motors
- T-AGM 19 class (1947 / 1966)
  - Turbo-electric 10,000 SHP
- T-AGOR-3 class (1962-1969)
  - Diesel Electric 10,000 SHP
  - 620 HP Gas Turbine generator for quiet operations
- T-AGOR 8 and 11 / T-AK 270 class (1957 - 1958)
  - Diesel Electric 3,200 BHP
- T-AGOR 14 class (1969-1970)
  - Diesel Electric (4 diesel generators) 3,000 SHP
  - 3 azimuth propellers (1 forward retractable, 2 aft)
- T-AOG 81 (1957) class
  - Diesel Electric 3,200 (or 4,000) BHP
- T-AGS -26 class (1965-1971)
  - Diesel-Electric 3,600 BHP
- T-ARC 3 (1945 / 1955)
  - Turbo-electric 6,000 SHP

Late Cold War (1975-1990) U.S. Navy Electric Propulsion

- T-ARC 2 (1946/1953) T-ARC 6 (1946/1963)
  - Originally reciprocating Steam Engines
  - Converted to steam-turbine electric drive in 1982 / 1980
  - 2 x 2000 HP DC (AC-SCR-DC)
- T-ARC 7 (1984)
  - 2 x 5000 HP DC (AC-SCR-DC)
- T-AGOS 1 class (1984-1990)
  - 2 x 800 HP DC (AC-SCR-DC)

Commercial Ice Breakers (1933 – 1993)

- 1933: *Ymer*, 4,300 tonnes, 6 diesel-generators, 3 motors each 2.1 MW
- 1939: *Sisu*, 2.9 MW, 3 motors, series connected DC-DC system
- 1960: *Moskva*, 16.2 MW, arctic
- 1974: *Yermak,* 26.5 MW, arctic
- 1976: *Kapitan Ismaylov*, AC-DC drive 2.5 MW
- 1977: *Kapitan Sorokin,* AC-DC Drive 16.2 MW, arctic
- 1986: *Otso class*, AC-AC Drive,
- 1988: *Taymyr* Class, nuclear AC-AC Drive
- 1990: *Seili* converted to incorporate first Azipod

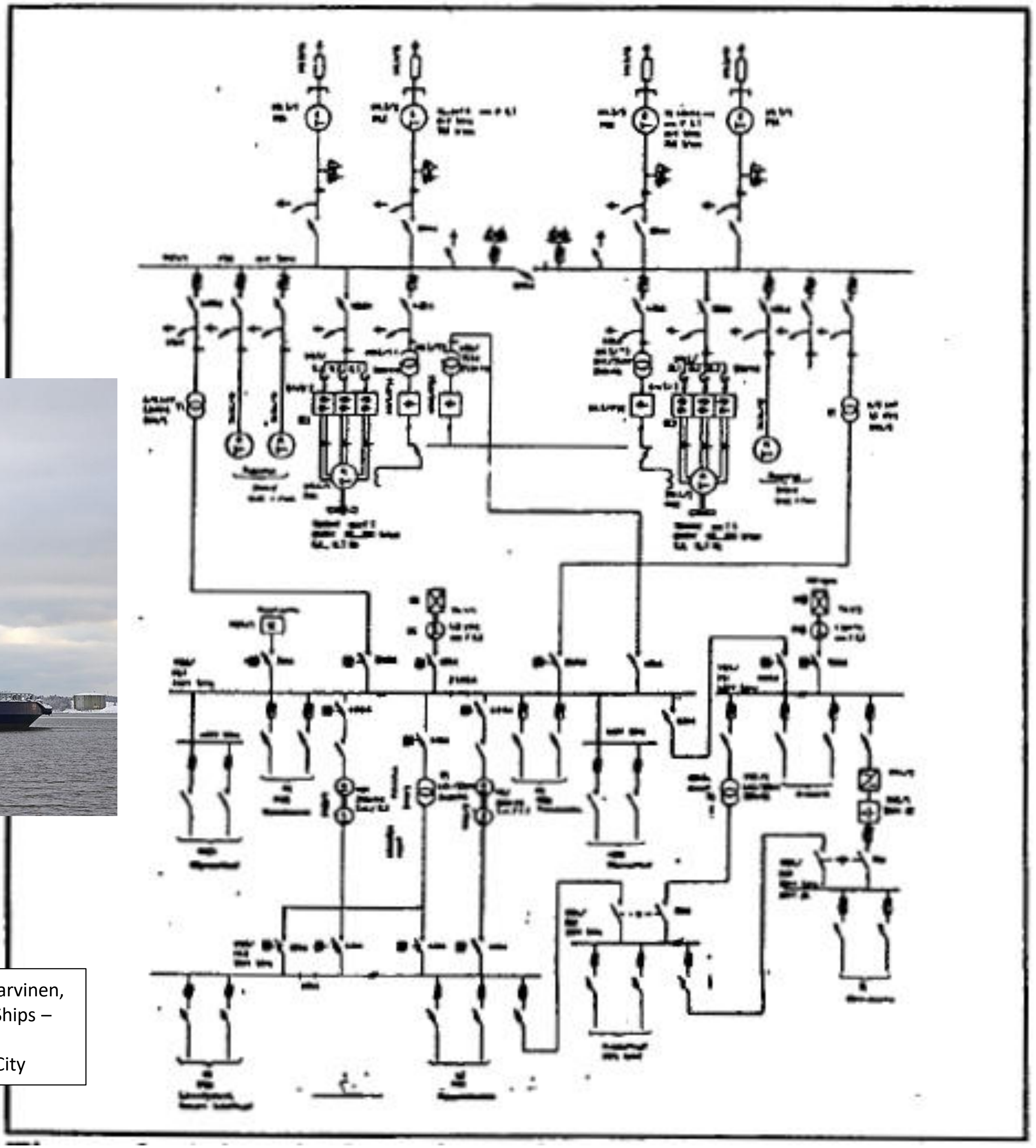


Apriainen, M., K Juurmaa, K. Laukia, M. Niini, K. Jarvinen, and Peter Noble, "Naval Architecture of Electric Ships – Past, Present, and Future," presented at SNAME Centennial Meeting, Sep 14-19, 1993, New York City

Otso Icebreaker

- Delivered 1986
- Displacement 9,130 tons
- Length: 99 m
- Beam: 24.2 m
- Draft: 8 m
- Propulsion: 15 MW
  - First icebreaker with cycloconverters
- Generation
  - 4 x 5.46 MW Diesel Generators

http://www.shipspotting.com/gallery/photo.php?lid=1485302



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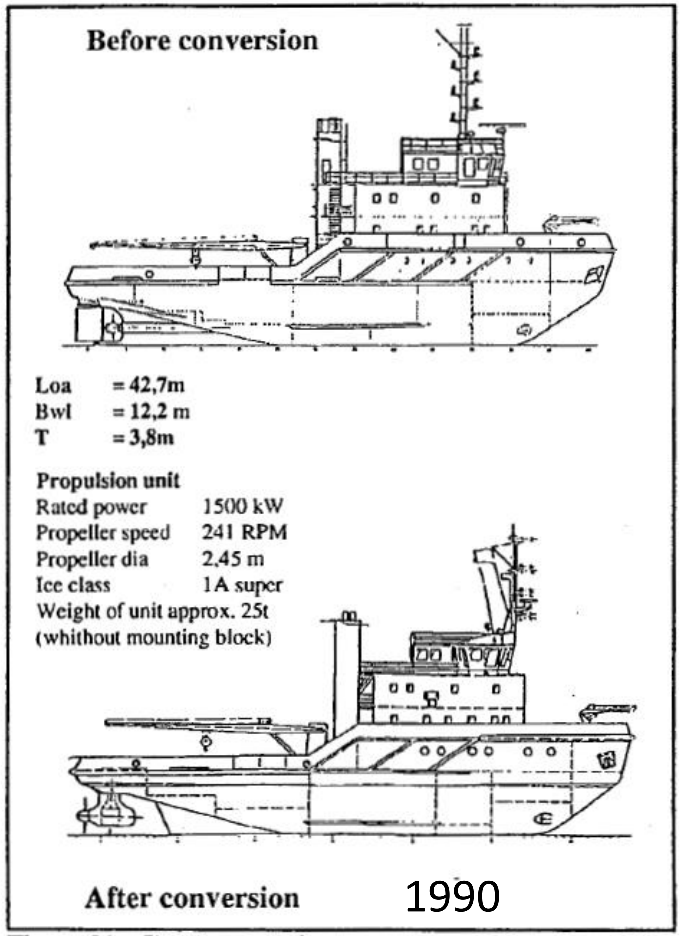
SEILI Azipod Conversion



1990

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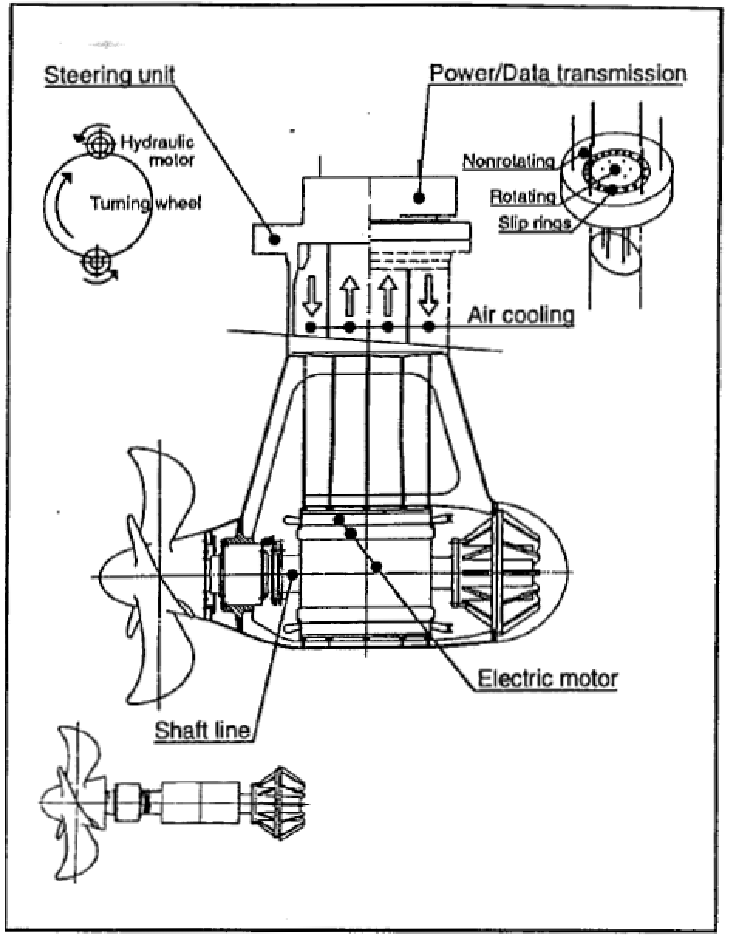

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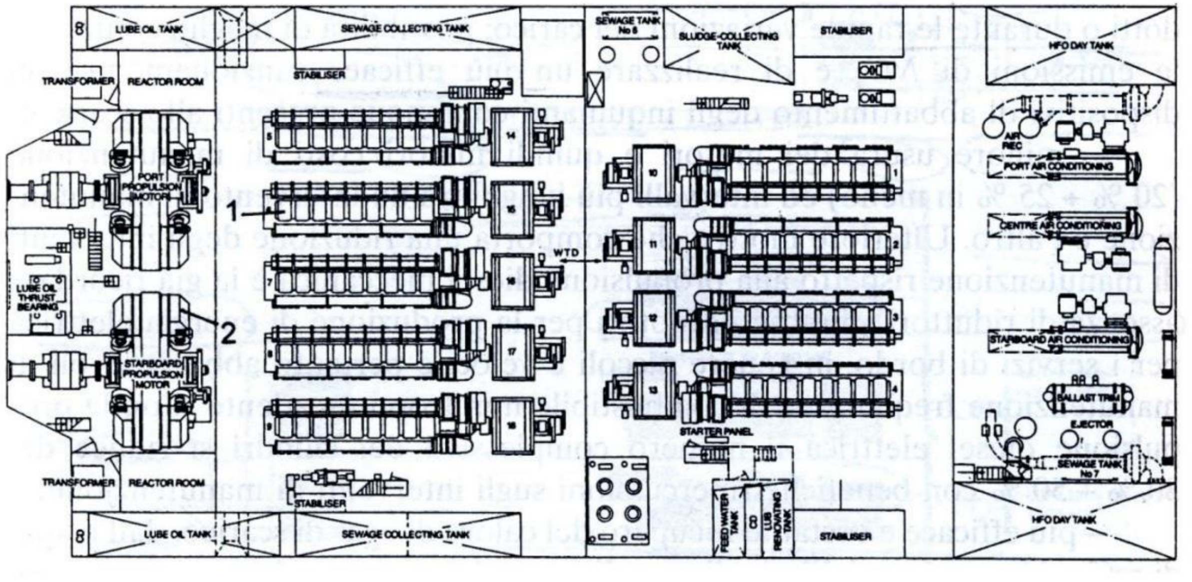
Commercial Ships (since 1988)

- A.C. integrated systems more common (especially on larger ships)
- IGBT power electronics based variable speed drives
- A.C. motors
- Podded propulsion applications
- Some 1 kV D.C. systems in past decade
  - Incorporation of Energy Storage
  - Variable Speed operation of diesel engines (fuel economy)

Queen Elizabeth II

- 1988 Retrofit with diesel electric integrated propulsion system
- Introduction of a.c. integrated electric drive in commercial ships
- 9 diesel generators
  - MAN BW 9&L58/64
  - 88 MW total capacity
  - 10 kV a.c.
- 130,000 HP propulsion
- 34% fuel savings

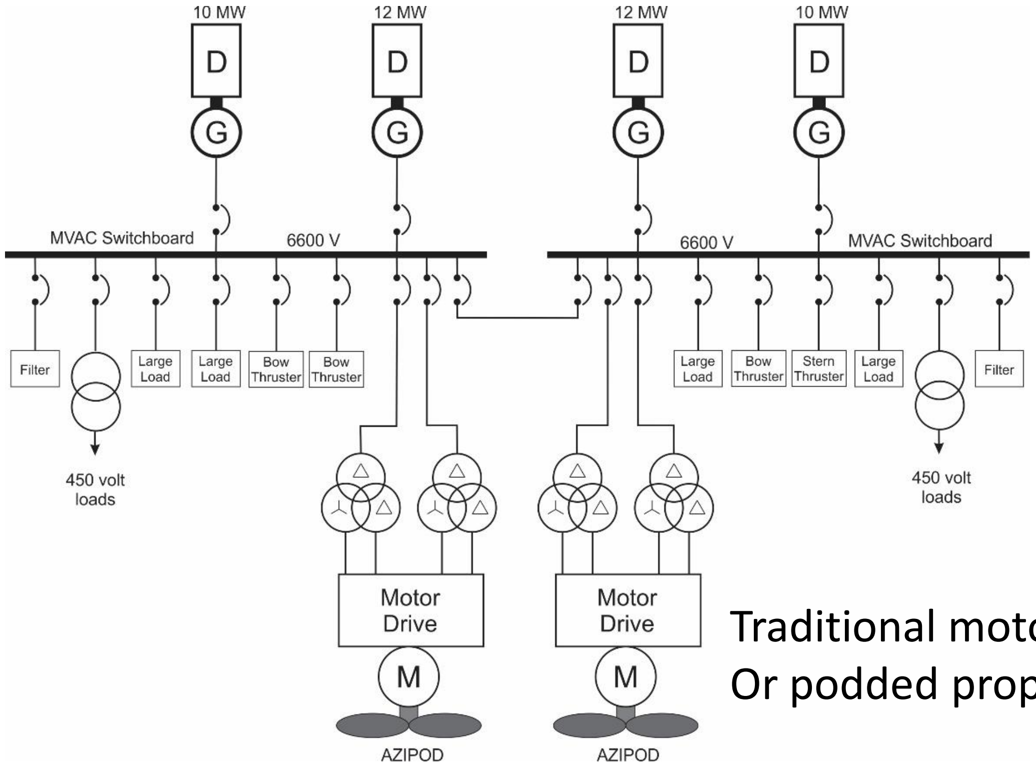
Trondheim Havn from Trondheim, Norway



Tao Yang, Tom Cox, Michele Degano, Serhiy Bozhko, Christopher Gerada, "History and Recent Advancements of Electric Propulsion and Integrated Electrical Power Systems for Commercial & Naval Vessels."

Cruise Ship

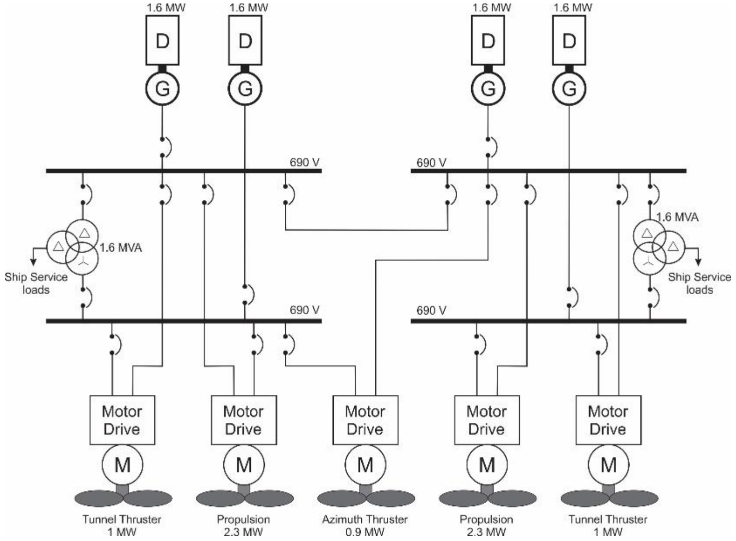
Regal Princess (Photo by Norbert Doerry)

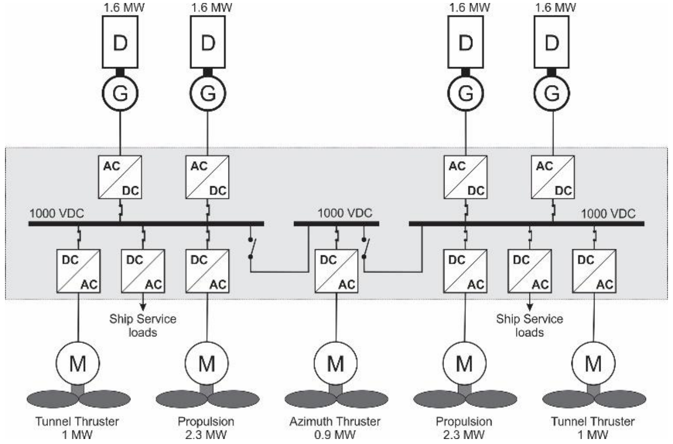


Traditional motors
Or podded propulsion

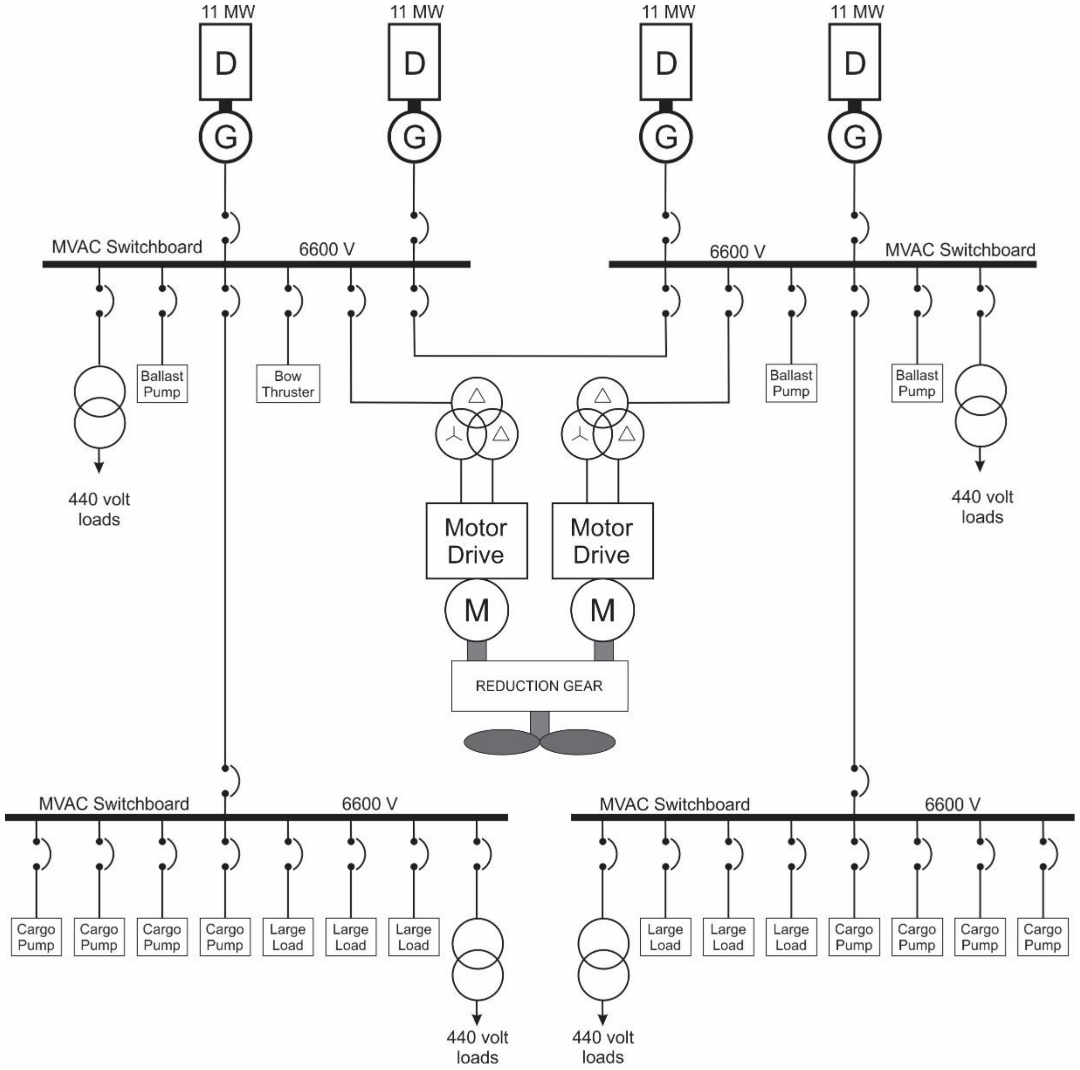
Platform Supply Vessel

Siem Symphony
(photo by DXR: https://creativecommons.org/licenses/by-sa/4.0/)





Liquefied Natural Gas (LNG) Carrier

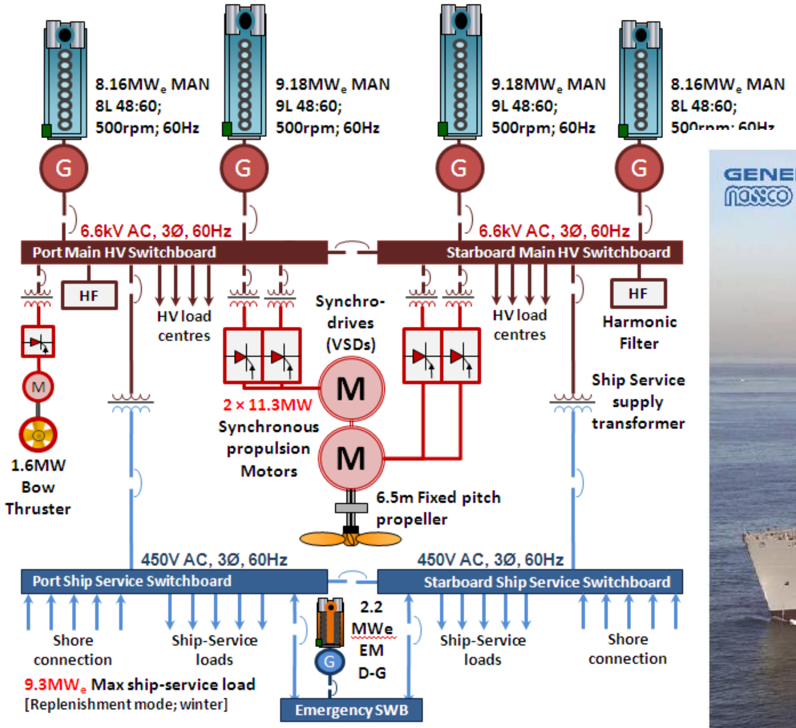


U.S. Navy Commercial Based IPS since 1990

- T-AKE 1 class (2006-2012)
- LHD 8 / LHA 6 / LHA 8 (2009 – ongoing) - Hybrid Electric Drive
- T-AGOR 23 class (1991-1997)
- T-AGOR 26 (2002)
- T-AGOS 19 class (1991-1993)
- T-AGOS 23 (2001)
- T-AGM 25 (2012)
- T-AGS 45 (1993)
- T-AGS 60 class (1994-2001)
- T-AGS 66 (2016)
- T-ESD-1 / ESB-3 (2013 – ongoing)

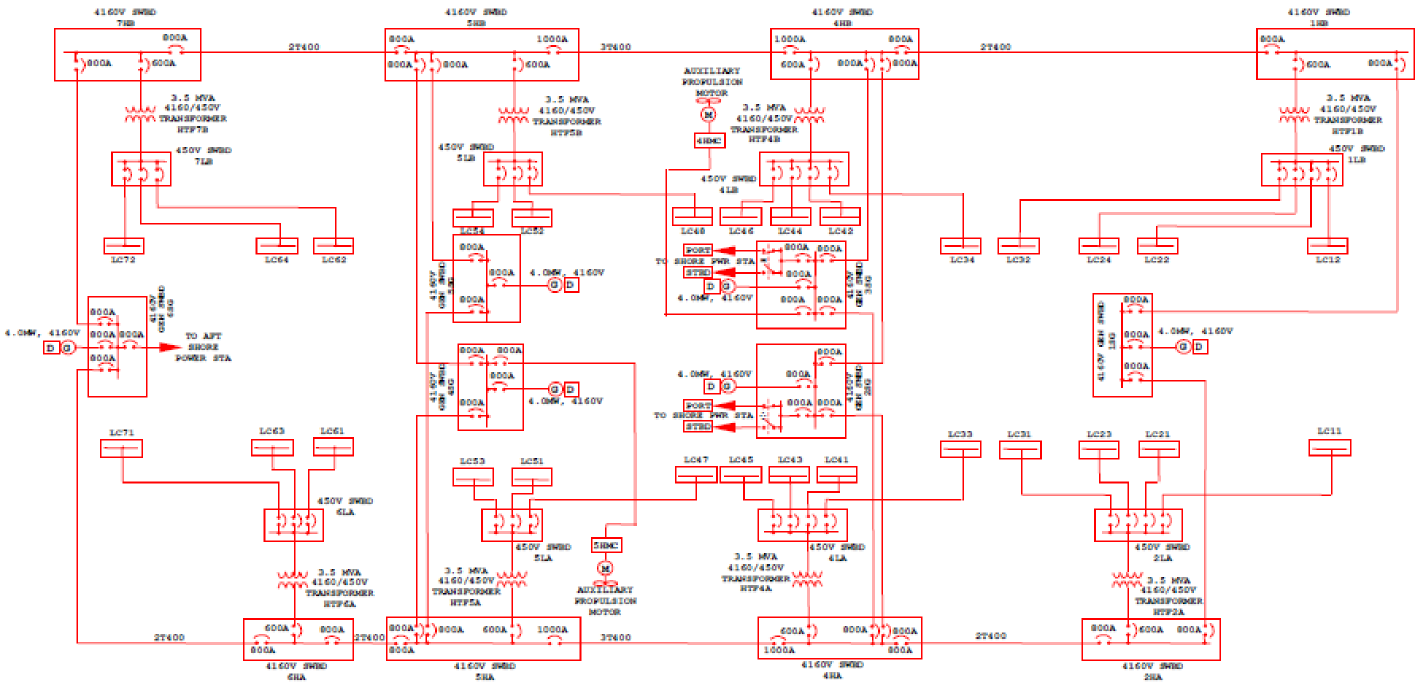
T-AKE 1 Class

- Displacement: 41,000 MT
- Length: 210 m
- 6.6 kV distribution system
- Propulsion plant meets American Bureau of Shipping R1 redundancy requirements
- Four FM/MAN B&W 9L and 8L 48/60 diesel generators with total installed power of 35.7 MW
    - 11.5 MVA and 10.2 MVA generators
- Two passive harmonic filters
- Four 7.2 MVA propulsion transformers
- Four 5.5 MW Synchroconverters (LCI)
- Twin synchronous, variable speed, reversible, double-wound, Alstom propulsion motors with brush/slip-ring excitation, each rated at 11,262bkW at 120 rpm and mounted in tandem
- Single fixed-pitch propeller
- 1 Bow Thruster
- Two 5 MVA ship service transformers



NSWCCD-CISD–2011/0013 October 2011

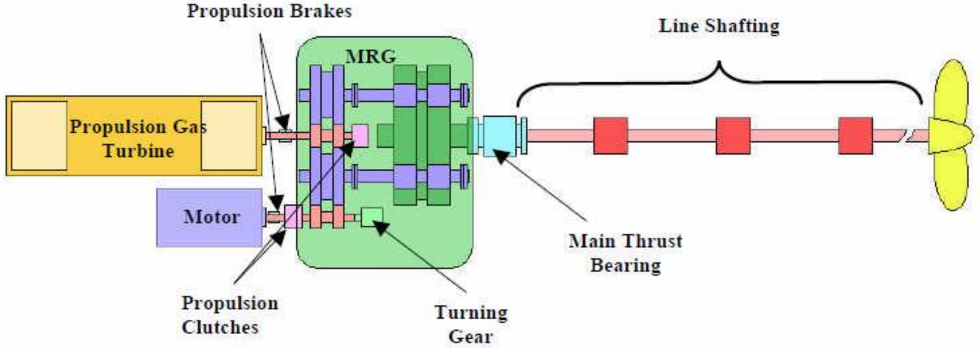
U.S.S. Makin Island
LHD 8



NOTES:
1) ALL LOAD CENTERS ARE 2000A
2) "*", "◆", "⊹", "⊹" = INTERLOCKED
3) ALL 4160V CABLE TO BE TYPE LS5KV

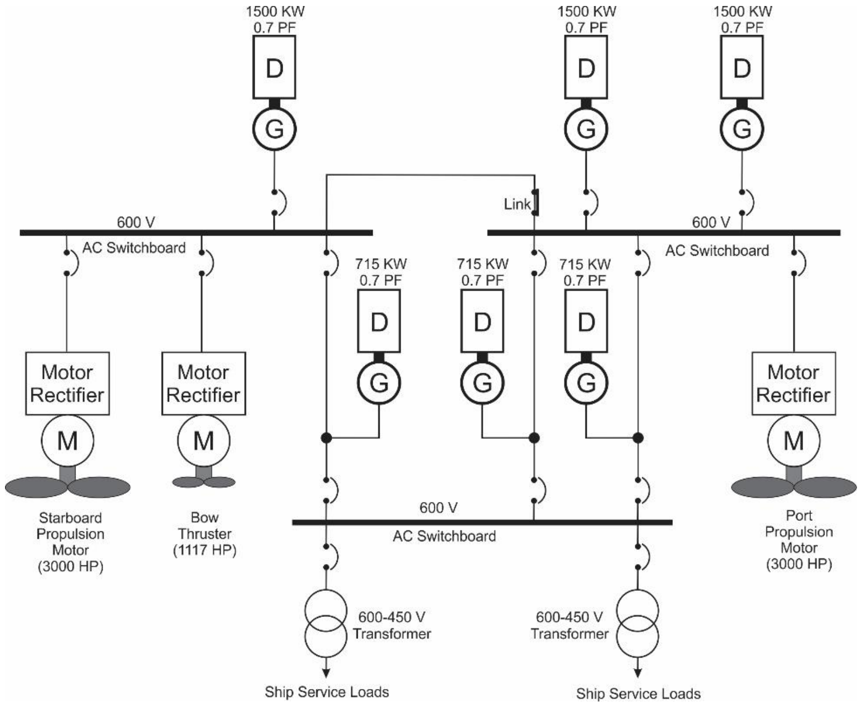
Thomas Dalton, Abe Boughner, C. David Mako, and CDR Norbert Doerry, "LHD 8: A step Toward the All Electric Warship", presented at ASNE Day 2002.

US Navy photo by Brett A. Anderson



T-AGOR 23
Thomas G. Thompson

Photo by Doug Russell, University of Washington



In Service 1991
Displacement: 3250 lt (full load)
Length: 243 ft
Beam: 53 fet
Draft: 19 ft
Speed: 15 knots

T-AGOS 23
Impeccable

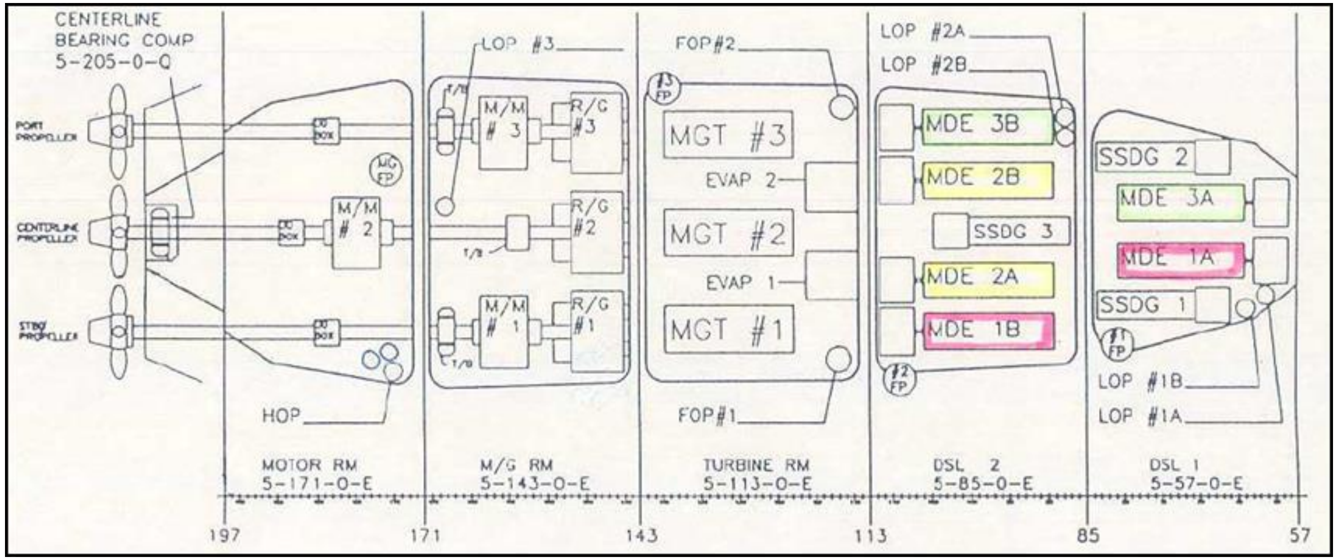
- In Service 2001
- Displacement: 5362 lton
- Speed: 12 knots
- 3 x 2000 kW Diesel Generators
  - 450 VAC 900 RPM
- 1 x 350 kW Emergency Diesel
- 12 pulse SCR drives for propulsion motors
- 2 x 2500 HP DC Propulsion Motors
- 2 x 900 HP Thrusters

Post WW II U.S. Coast Guard Electric Drive Ships

- WAGB 10 Polar class Ice Breakers (1976-1978)
- WAGB 20 *Healy* Ice Breaker
- WLBB 30 *Mackinaw* Ice Breaker
- WTGB 101 Bay class Icebreaking Tugs (1979-1988)
    - Diesel Electric – 2,500 SHP
- Several acquired ferries

Polar Star and Polar Sea

- Commissioned 1976 – 1978
- CODLOG plant (3 shafts)
  - 6 Main Diesel Generators (3,000 HP each)
  - 3 Main Gas Turbines (20,000 HP each)



Department of Homeland Security

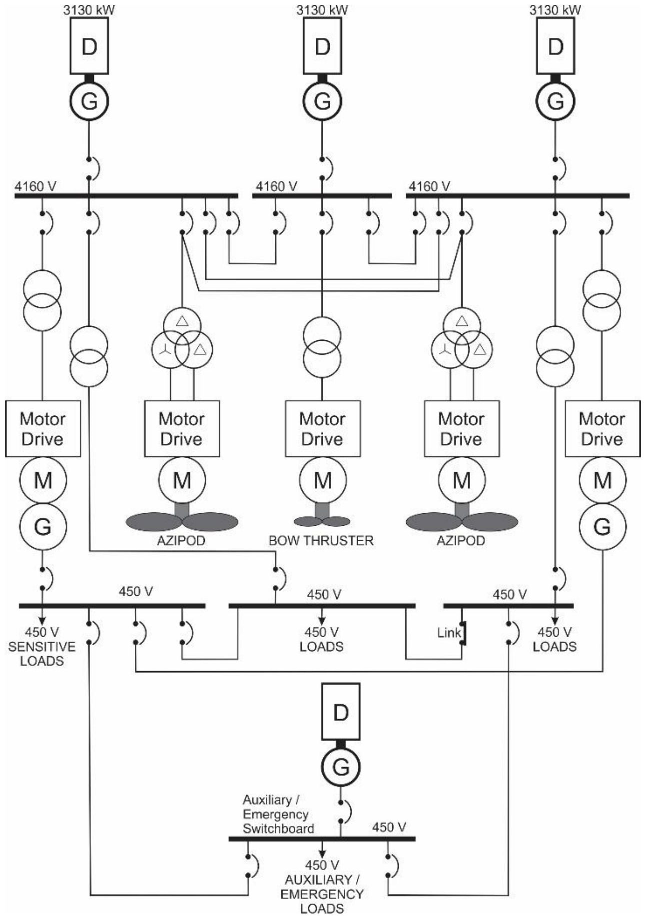
Department of Homeland Security

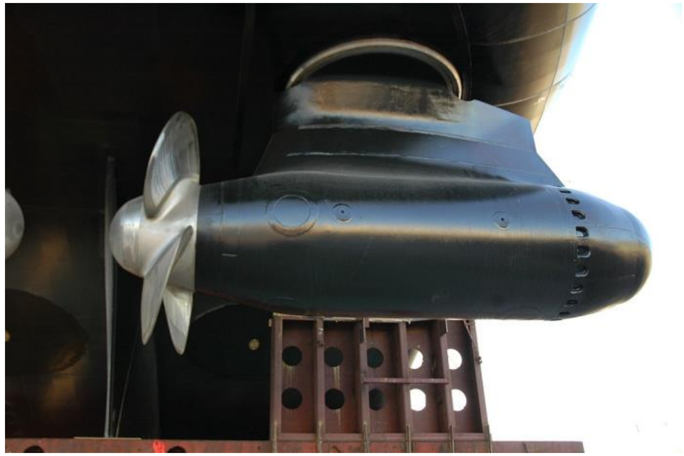
WABG-20
USCGC *Healy*

- Commissioned 1999
- Length 420 ft
- Displacement 16,400 lton
- 2 shaft
- 30,000 SHP
  - 2 shafts
  - 2 motors on each shaft
- 4 x Diesel gensets
- Cycloconverters

WLBB 30
USCGC Mackinaw

Great Lakes Icebreaker
Commissioned: 2006
Displacement: 3500 tons
Length: 240 ft
Speed: 15 knots

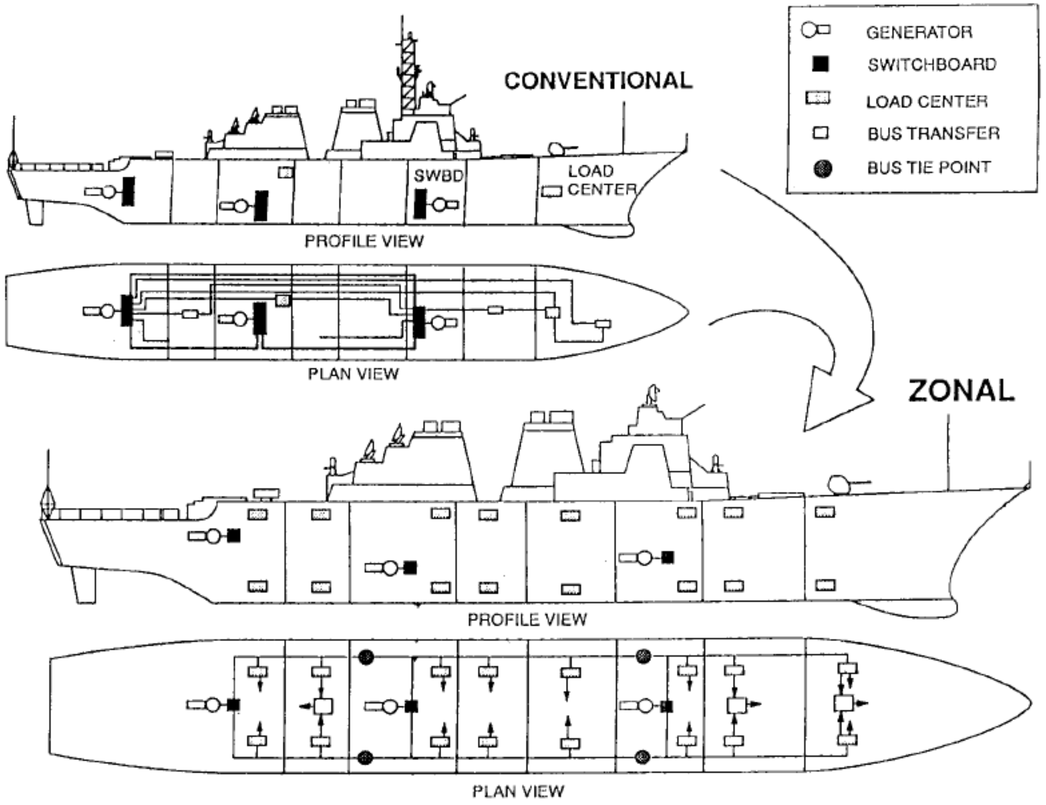




3.35 MW Azipod

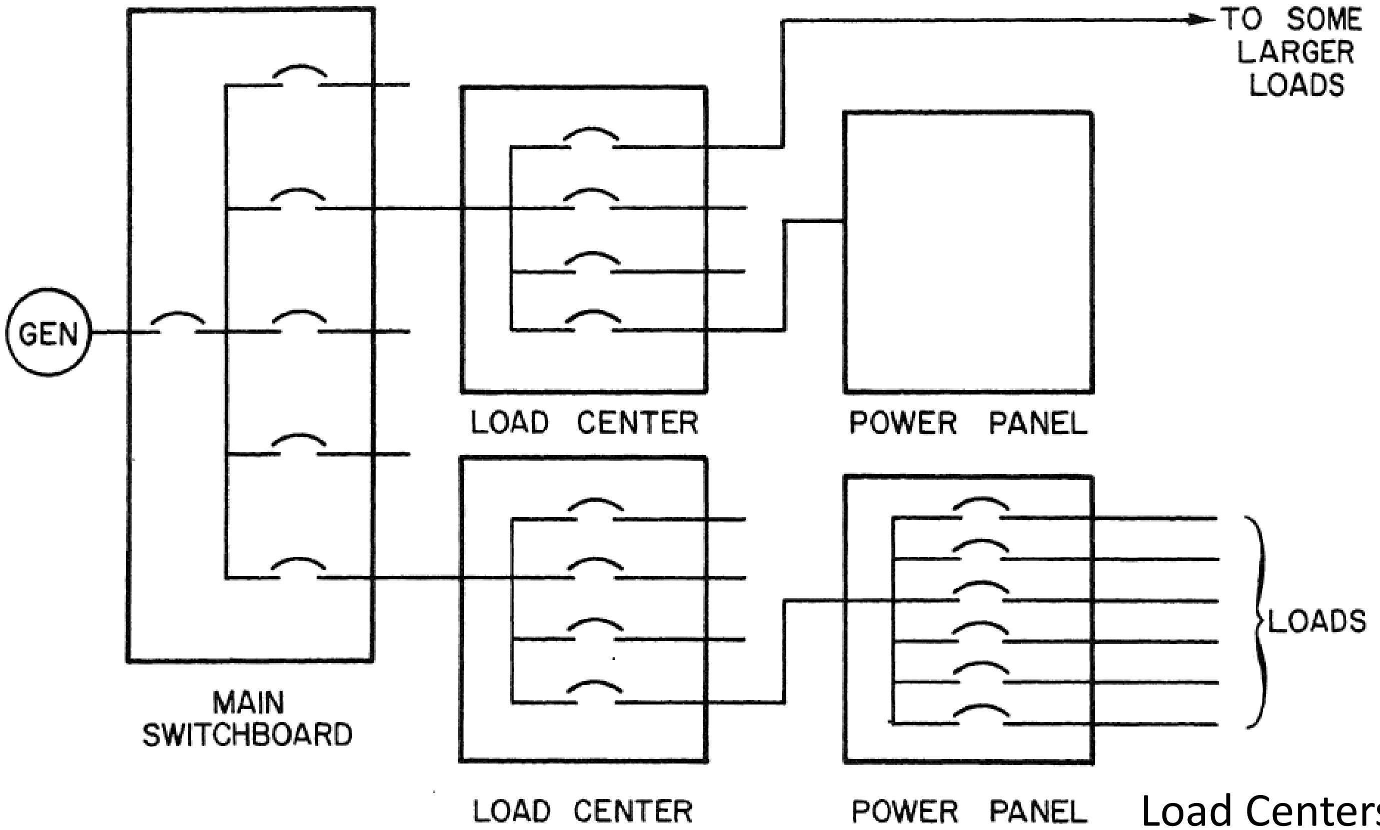
Ship Service Distribution

- Prior to 1932: DC
  - DC motors easier to control
  - U.S.: Initially 80 volts d.c. – in 1905 standard voltage became 125 volts d.c.
    - 1916 used 3 wire 120/240 volts d.c. on U.S.S. Arizona
  - U.K: Initially 100 volts d.c. – in 1908 220 volts d.c. employed for major warships
    - 1921: n+1 rule established
    - Increased to 110 volts d.c. for smaller warships
- Starting in 1932: 440 V 3 phase A.C. in U.S. Navy
  - Primarily radial distribution
  - Shift to a.c. based on ability to increase ship production in case of war.
  - Enabled use of less maintenance intense squirrel-cage induction motors
- DDG 51-Flight 2A / LPD 17
  - 440 LVAC zonal distribution
- LHD 8 / LHA 6 / DDG 51 Flight 3
  - 4160 MVAC zonal distribution
- DDG 1000
  - Integrated Fight Through Power (IFTP) LVDC zonal distribution



Petry, Chester, and Jay Rumburg, "Zonal Electrical Distribution Systems: An Affordable Architecture for the Future", ASNE NEJ, May 1993.

Radial Distribution



Load Centers: deck mounted
Power Panels: bulkhead mounted

NAVEDTRA 10864-D of 1976

Switchboard

- MIL-DTL-16036
- Deck Mounted
- Generally have instrumentation and controls in addition to circuit breakers
- Usually interface to Generators or MV/LV transformers
- Casualty Power Interface

DRS Technologies Catalog

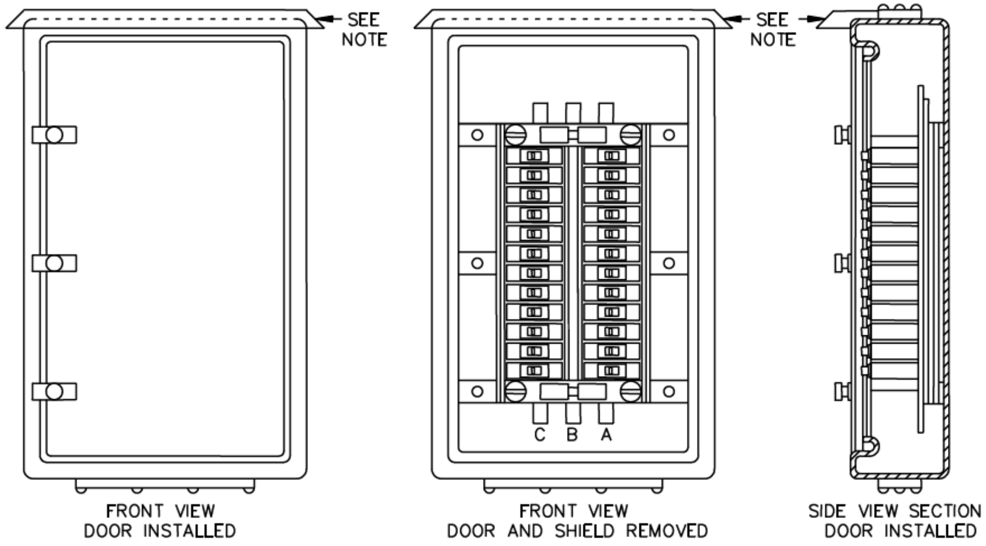
Load Center

- MIL-DTL-16036
- Deck Mounted
- Circuit Breakers
  - May be remotely monitored and operated (load shedding)
- Feed loads either directly or through Power Panels
- Casualty Power Interface
- Can implement Manual Bus Transfer with interlocked breakers

171205-N-IR859-229 ATLANTIC OCEAN (Dec. 5, 2017) Senior Chief Electrician's Mate Franklyn Munroe, an inspector from the Board of Inspection and Survey (INSURV), inspects a load center aboard the guided-missile destroyer USS Cole (DDG 67). Cole is underway conducting INSURV, which is a periodic inspection to ensure the ship meets Navy standards. (U.S. Navy photo by Chief Mass Communication Specialist Jen Blake/Released)

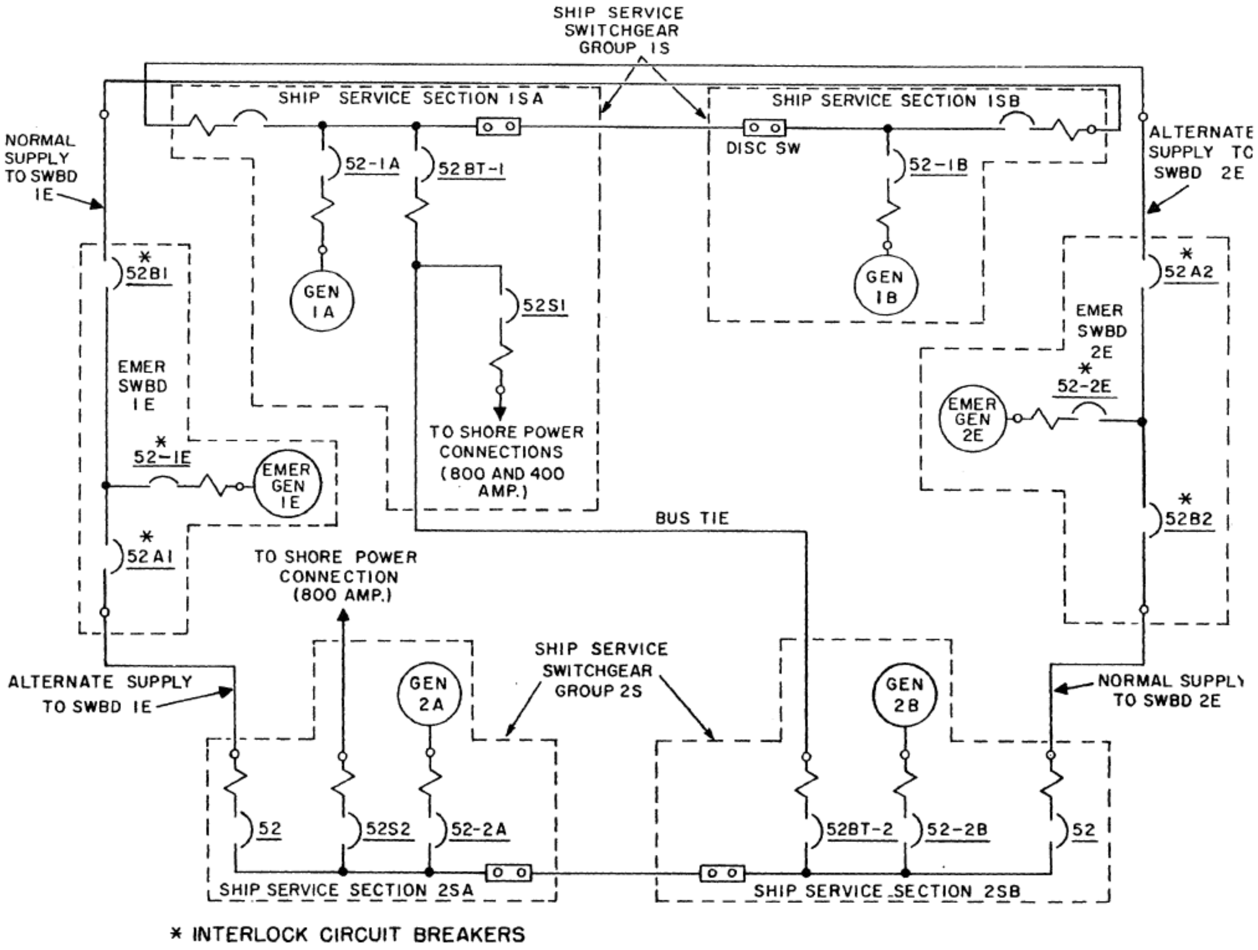
Power Panel

- MIL-DTL-23928
  - Maximum of 400 amps (~300 kVA)
  - Bulkhead Mounted
- AQB and NQB circuit breakers IAW MIL-DTL-17361 (440 VAC)
  - 100 AMP: AQB-A102 or AQB-A103
  - 250 AMP: AQB-A252 or AQB-A253
  - 400 AMP: AQB-A402 or AQB-L400
- ALB and NLB circuit breakers IWA MIL-C-17588
  - 125 volts AC or DC
  - Up to 50 amps
- Can implement Manual Bus Transfer with interlocked breakers



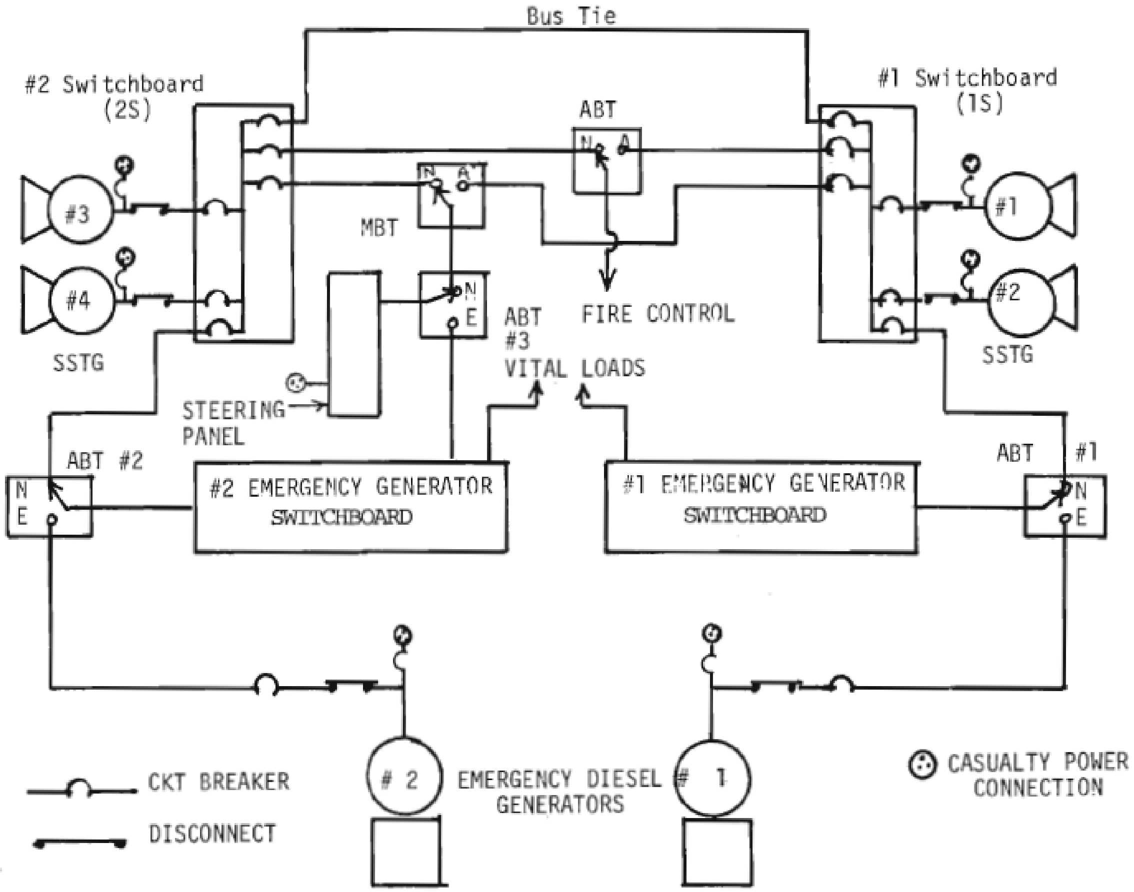
170425-N-HV059-034 NORTH SEA (April 25, 2017) Machinist's Mate 3rd Class Zaeeda Walters verifies that a power control panel has been properly tagged out aboard the guided-missile cruiser USS Leyte Gulf (CG 55). The ship is conducting naval operations in the U.S. 6th Fleet area of operations in support of U.S. national security interests in Europe. (U.S. Navy photo by Mass Communication Specialist 2nd Class Sonja Wickard/Released

Representative steam destroyer / cruiser ship service distribution



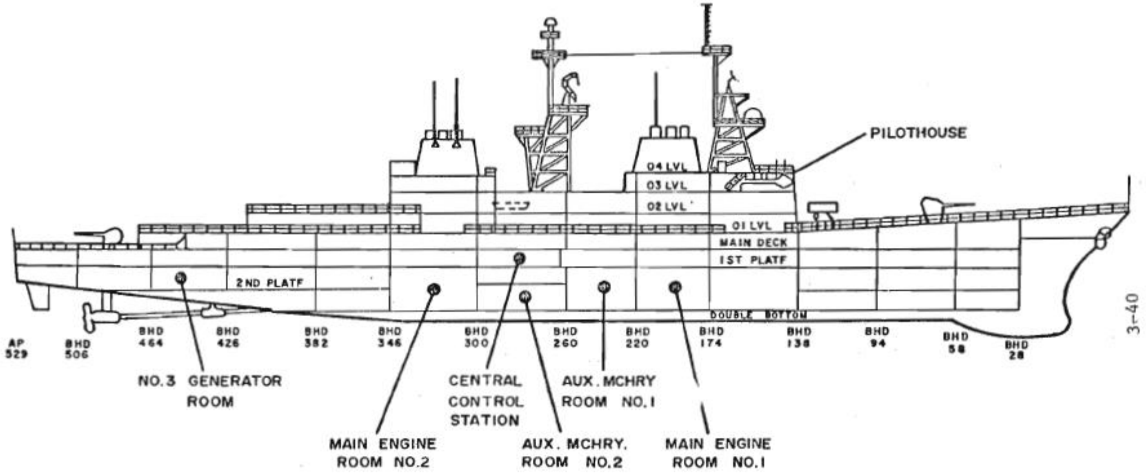
NAVEDTRA 10864-D of 1976

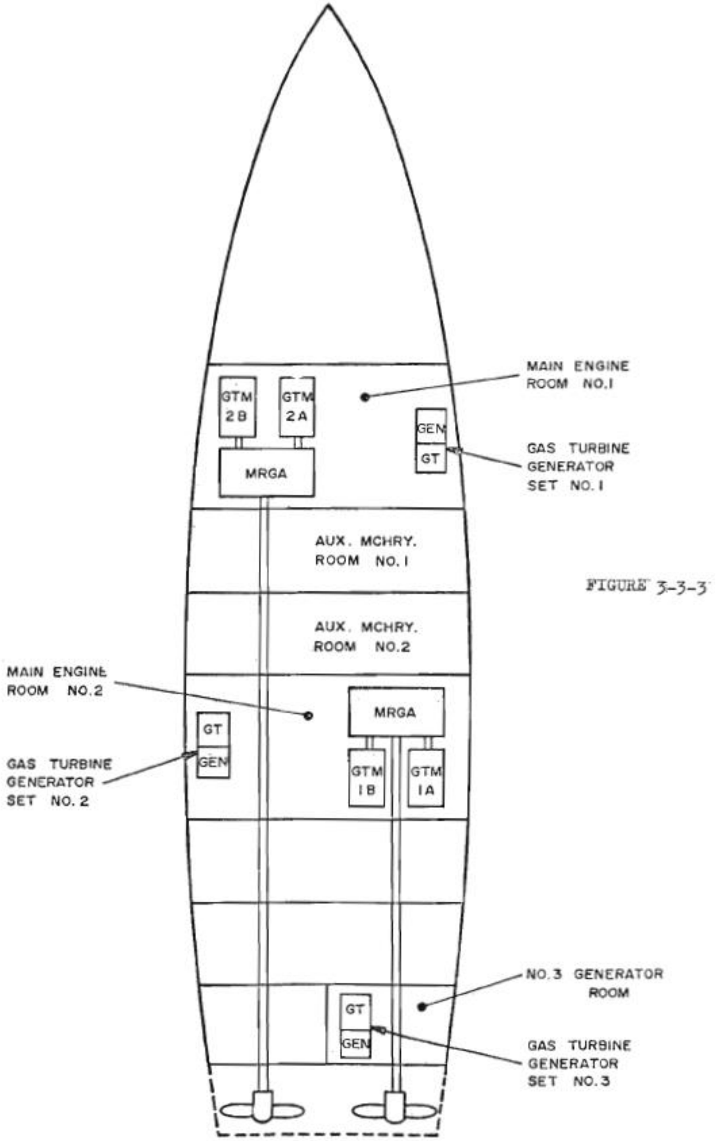
U.S.S. Charles F. Adams (DDG-2)



U.S.S. Spruance (DD 963) class

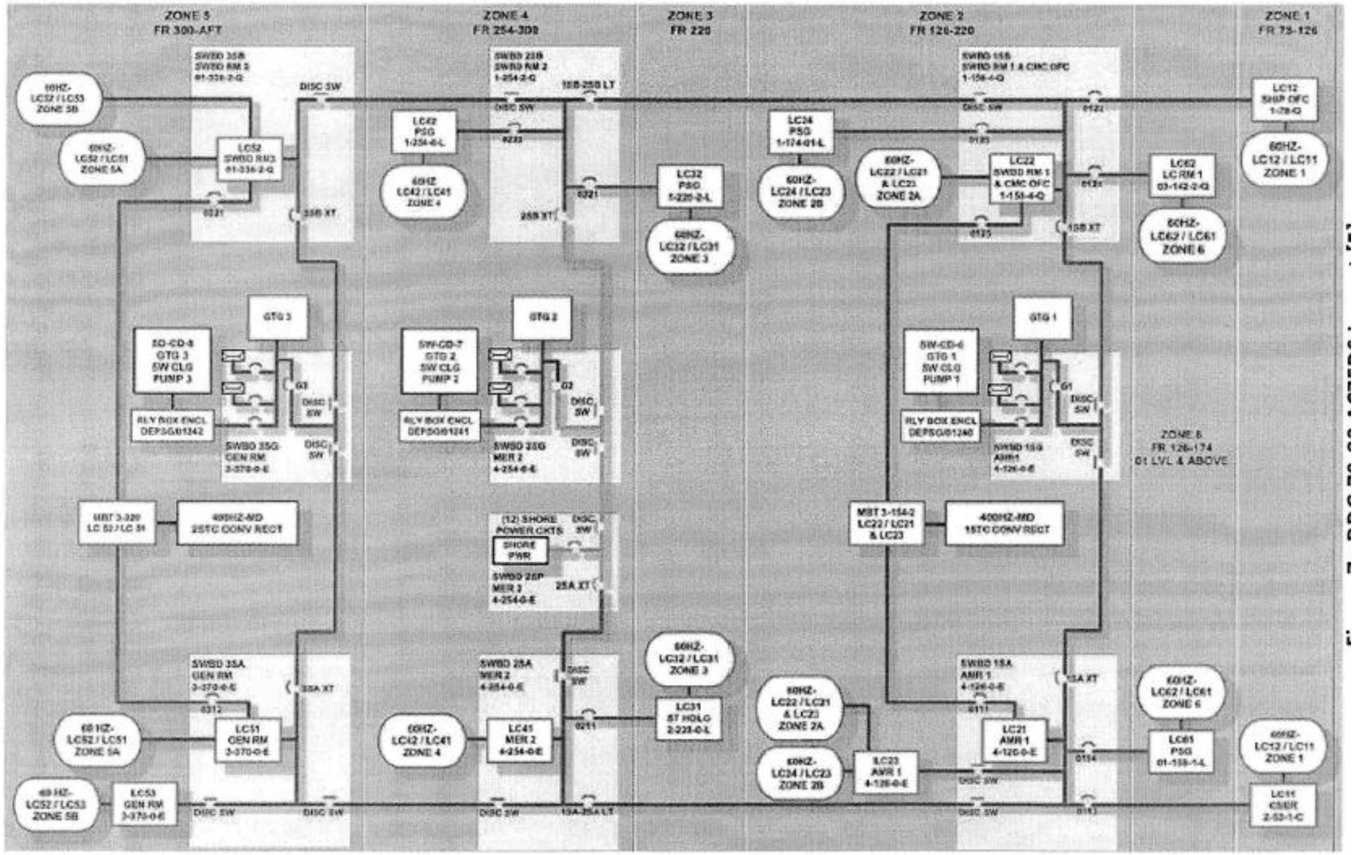
- 3 x 2000 kW Gas Turbine Generators
- Commissioned in 1975
- Displacement: 8040 lton
- Length: 529 ft (waterline)





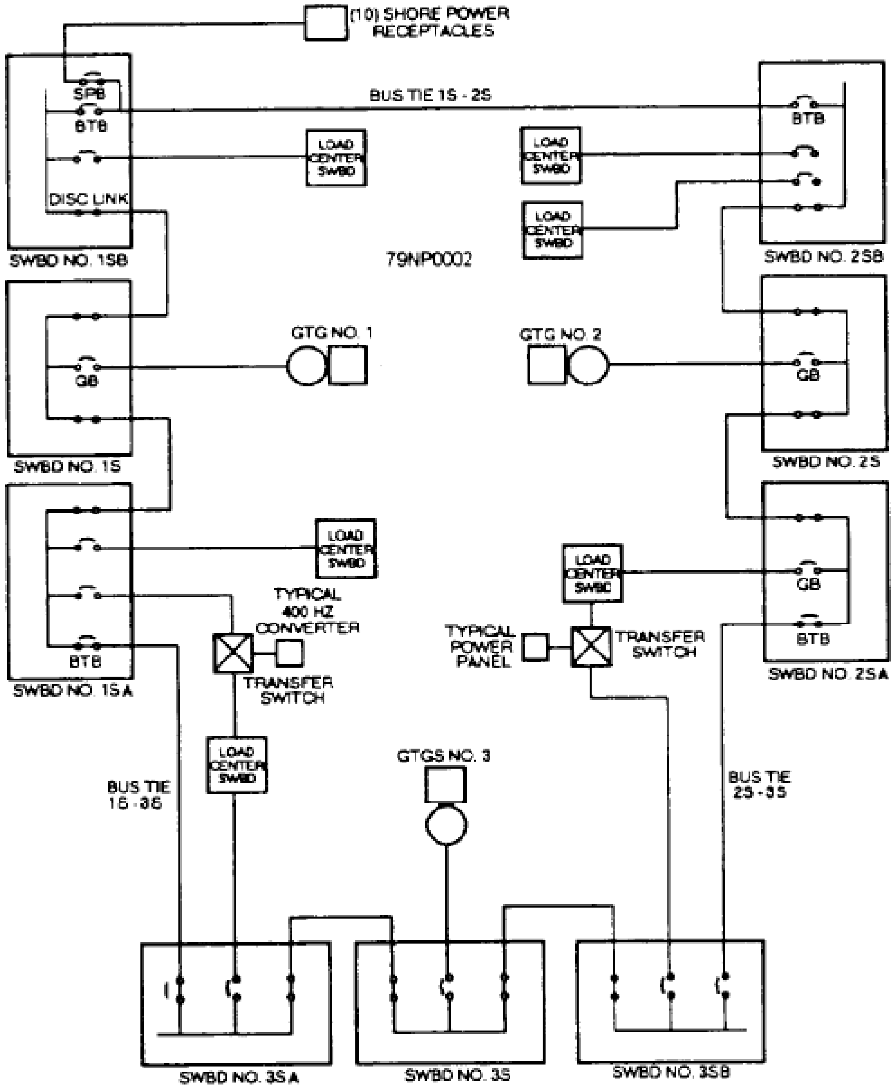
DDG 51 class destroyer

Zonal



Tidd, C, “Hardware Model of a Shipboard Zonal Electrical Distribution System (ZEDS): Alternating Current / Direct Current (AD/DC), MIT, 2010.

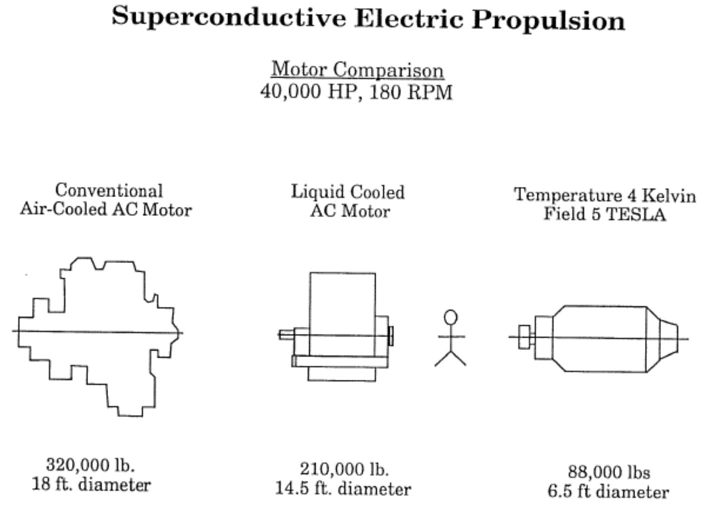
Radial

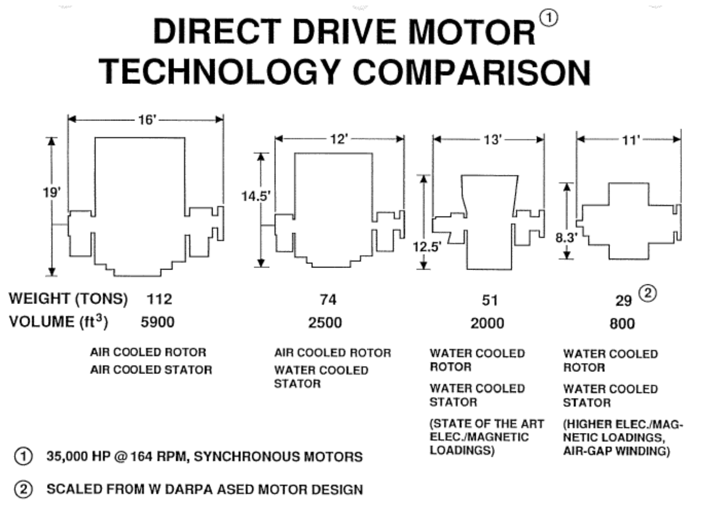


NAVEDTRA 14344 of 2003

The Road to IPS

- Late 60's / 70's: Studies conducted on superconducting homopolar motor drives
- 1979-1981 Advanced Integrated Electric Propulsion Plant Conceptual Design (AIEPP) project: Near Term Electric Drive
- Early 1980's: DDG(X) (future DDG 51)
  - Electric Drive chosen during Preliminary Design
  - Decision reversed in Contract Design over perceived risk and lack of expertise within the U.S. Navy
  - DDG 51 has traditional mechanical drive propulsion and ship service distribution derived from DD 963 and CG 47 classes.





Advanced Integrated Electric Propulsion Plant

Jolliff, J. and D. Greene, "Advanced Integrated Electric Propulsion A Reality of the Eighties," ASNE NEJ, April 1982

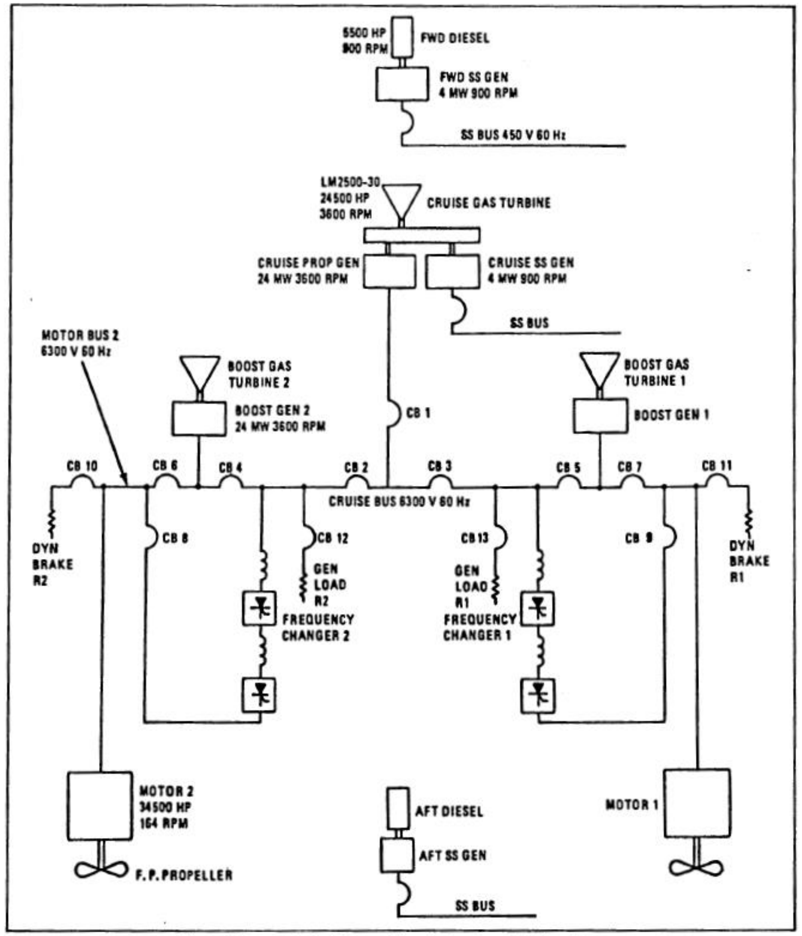
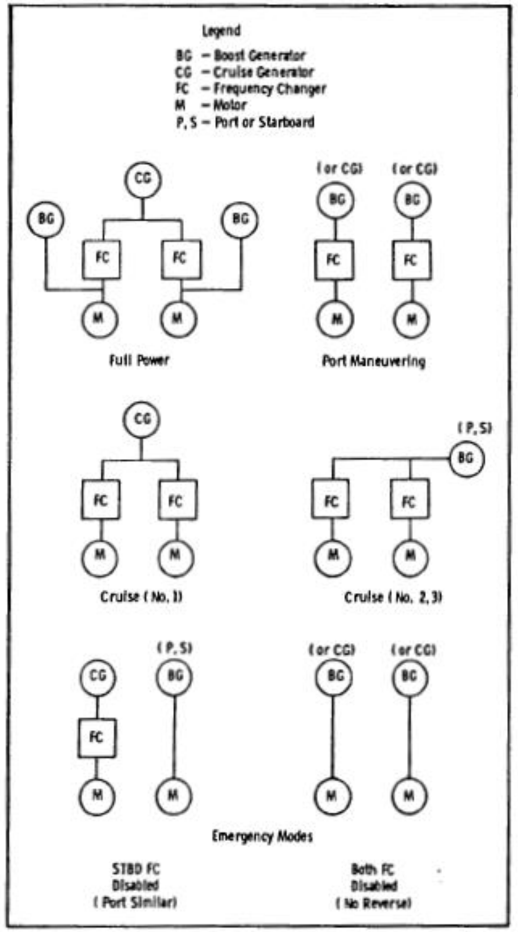
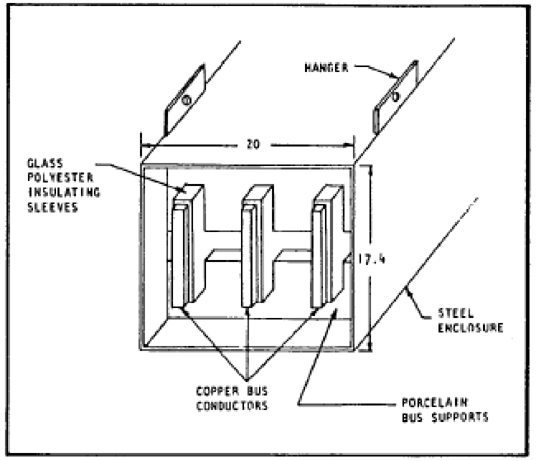
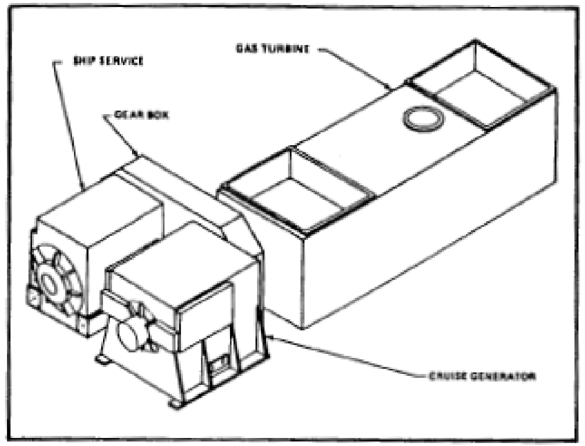


Figure 4. Integrated electric propulsion plant system, single-line diagram.



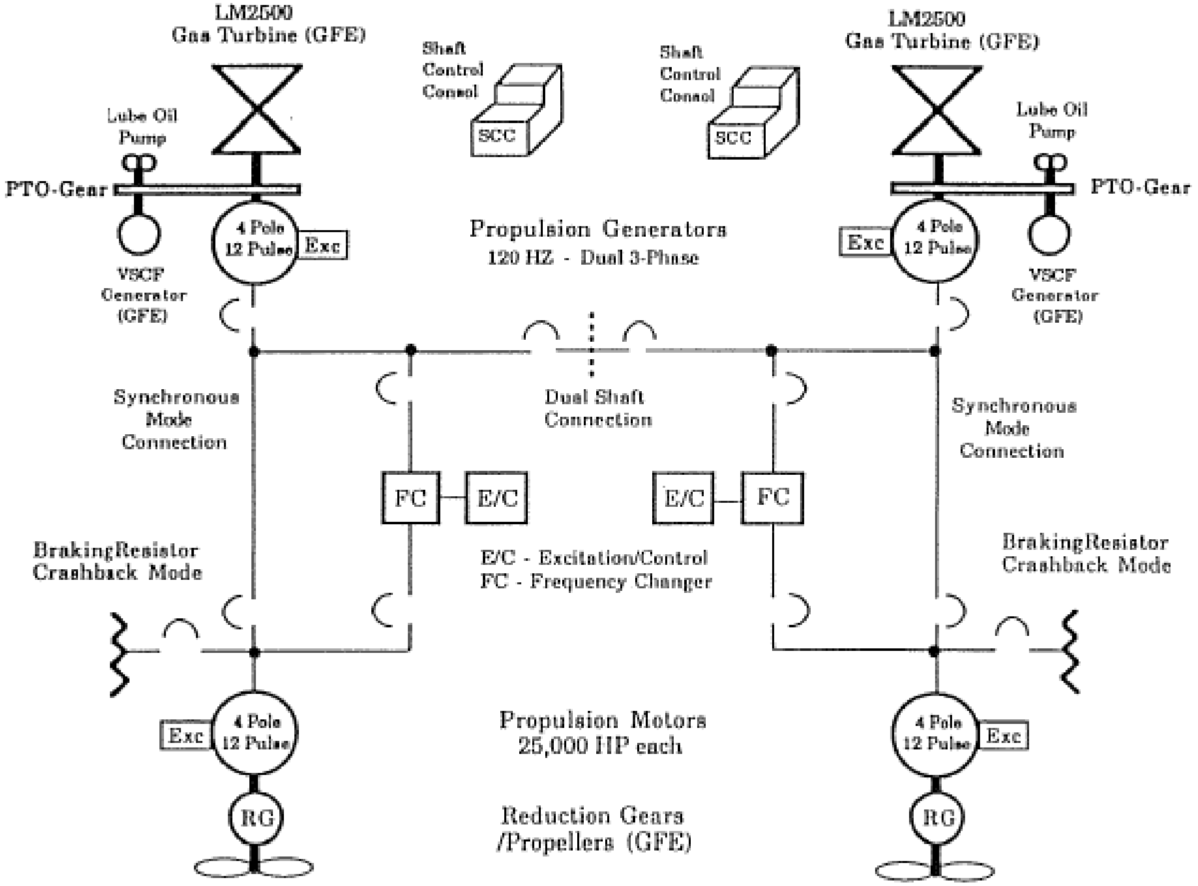




The Road to IPS (Continued)

- 1984 FFG(X) Study – IED favorable
- 1986-1989: Battle Force Combatant (BFC) ship studies
- 1988: Formation of Integrated Electric Drive (IED) Program
  - Geared high speed machines (3600 RPM, 120 Hz. 6 phase 4160 VAC, 25,000 HP)
- 1989: Cluster A
  - Integrated Electric Drive
  - Advanced Propulsor System (pods)
  - Intercooled Recuperated (ICR) Gas Turbine
  - Integrated Electrical Distribution with Pulse Power (to support Cluster E)
  - Machinery Monitoring and Control
  - Advanced Auxiliary Systems
  - Low observability / loiter power system
- Late 1980's: Studies for DDG 51 Flight III (first flight III):
  - IED system only way to achieve desired acoustic performance
- 1989 - 1991: Cold War Ends – Peace Dividend - acoustic performance not valued

Integrated Electric Drive

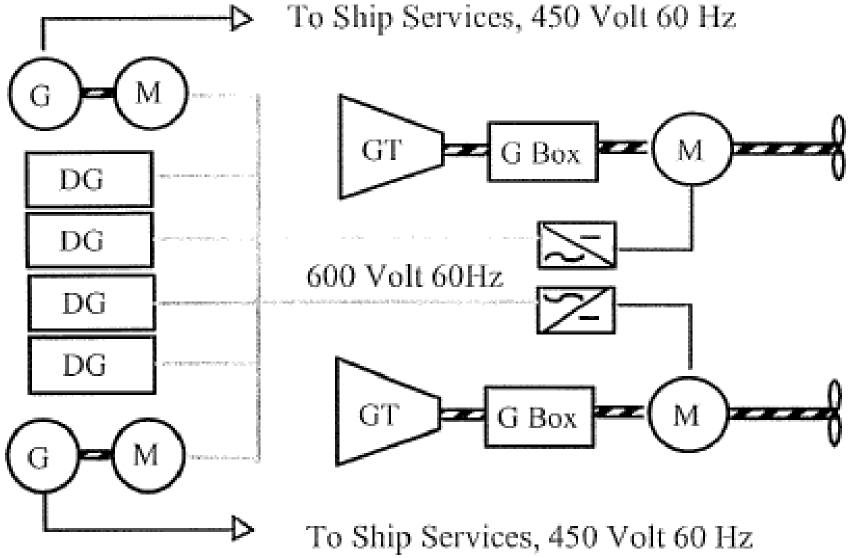


IED, Two Shaft Schematic.

UK Type 23 Frigate

- 16 ships placed in service between 1990 and 2002
- Hybrid Electric Drive
- 2 x 1.5 MW d.c. Propulsion Motors
- 2 x 1200 kVA Motor Generator Sets
  - Provide clean power
- Diesel Generators being replaced with MTU 4000’s rated at 1.3 MW.

(U.S. Navy photo by Mass Communication Specialist 1st Class Peter Burghart/Released)



The Road to IPS (continued)

- 1992: Integrated Power System (IPS) Advanced Surface Machinery Program (ASMP)
  - IED not affordable
  - Reduced-Scale Advanced Development efforts (Permanent Magnet machines) and systems engineering studies
  - IPS designed to provide an open architecture approach to power system design and development
  - Propulsion Derived Ship Service (PDSS) studies – commitment to power electronics
  - A.C. Zonal Electrical Distribution System (AC ZEDS) transitions to DDG 51 Flight IIA
    (and later to LPD 17 and LHD 8 / LHA 6)
  - D.C. Zonal Electrical Distribution System (DC ZEDS -- Later Integrated Fight Through Power (IFTP)) development begins
- 1995: IPS Full Scale Advance Development (FSAD) commences
- 1996: SC-21 (predecessor to DDG 1000) study found IPS resulted in lower cost, smaller ships
- 1998: IPS integrated into the DD-21 (predecessor to DDG 1000) program
- 1998: IPS FSAD Testing

Propulsion Electrical Subsystem Baselines

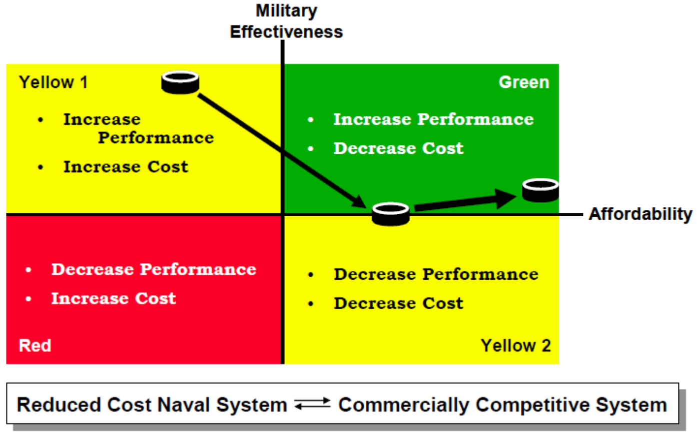
P.E.S. Baseline 1 (1991-2001)
- Near Term: Surface Combatant.
- G.E. Phase A on Admiral Callaghan.

P.E.S. Baseline 2 (1996-2006)
- Near Term: NonCombatant and Amphibious Warfare.
- Affordability.

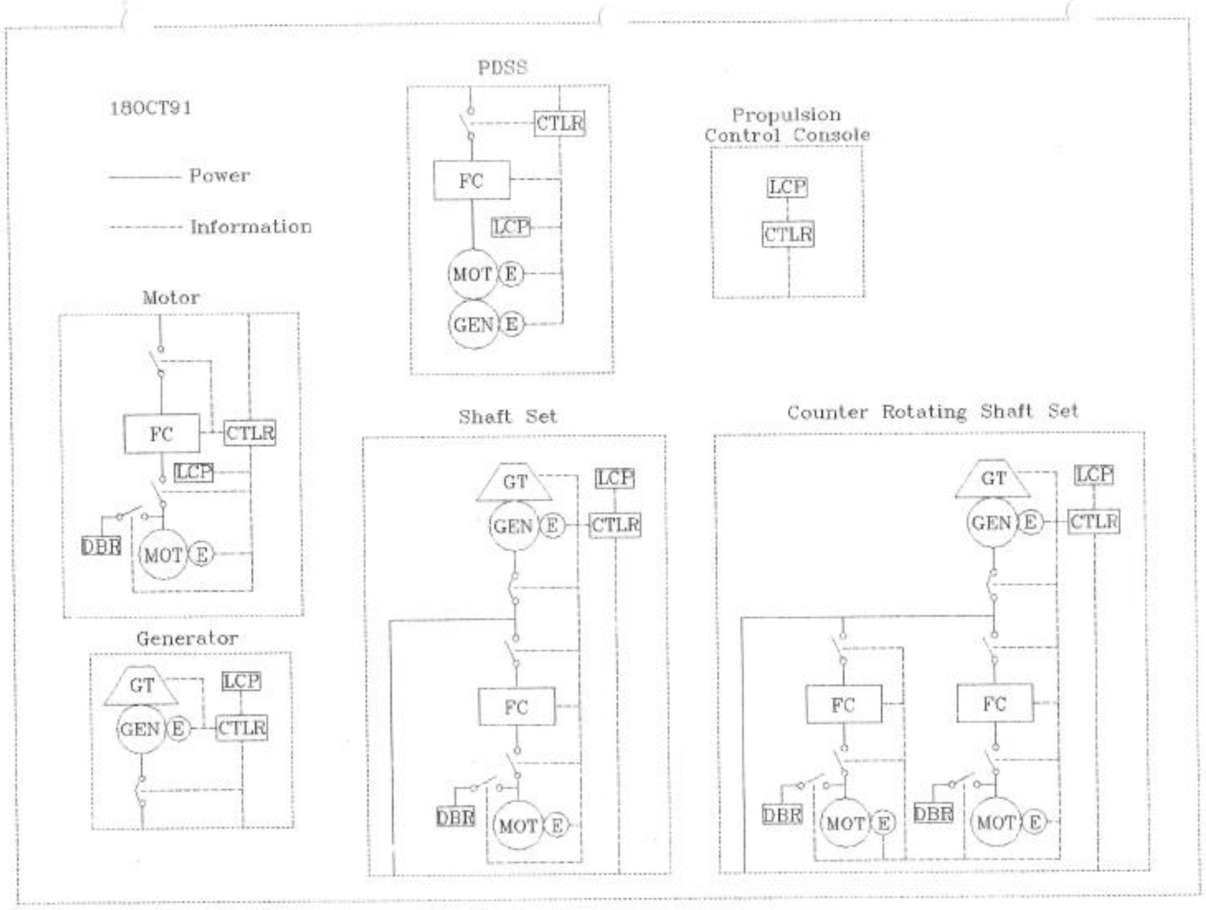
P.E.S. Baseline 3 (2001-2011)
- Mid Term: Surface Combatant.
- Pulse Power Capable.

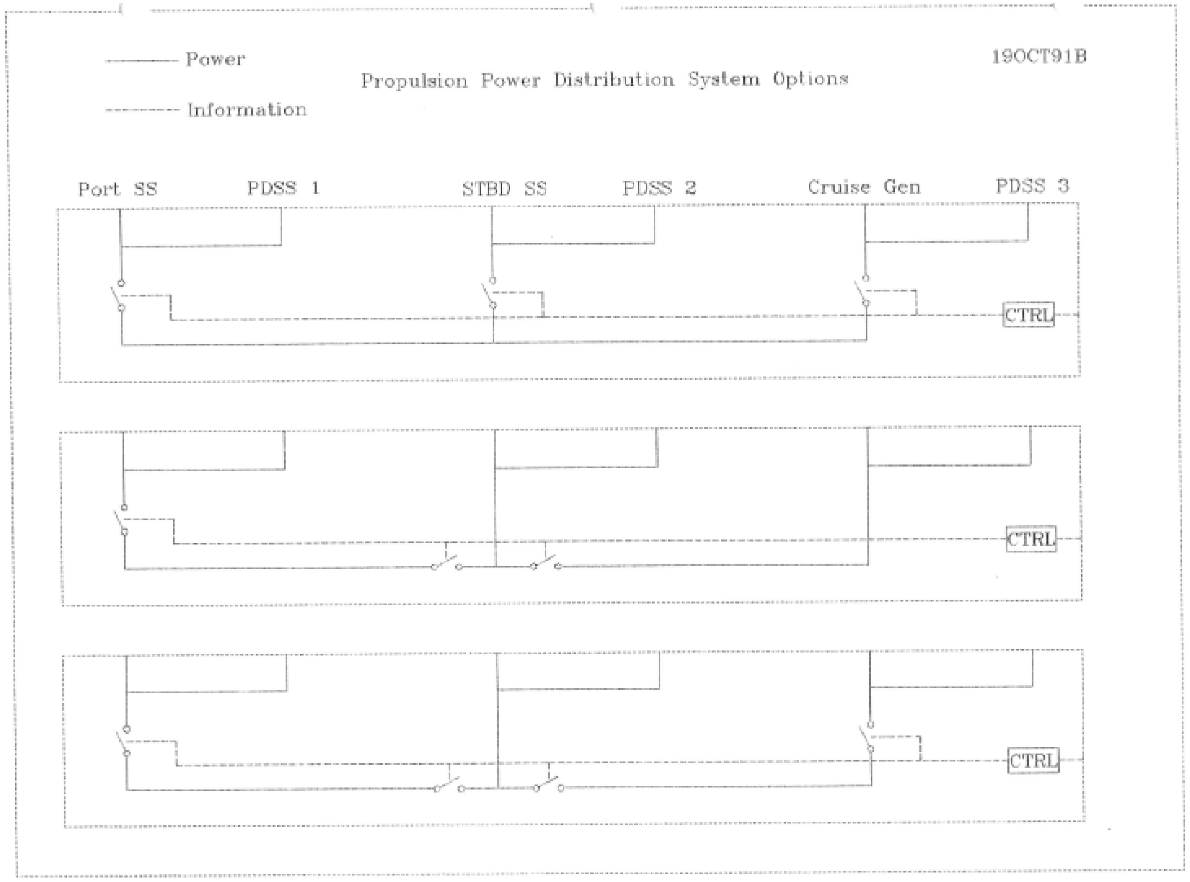
P.E.S. Baseline 4 (2006-2016)
- Far Term: Replacement for Baseline 2.

ASMP
Investment in Affordability

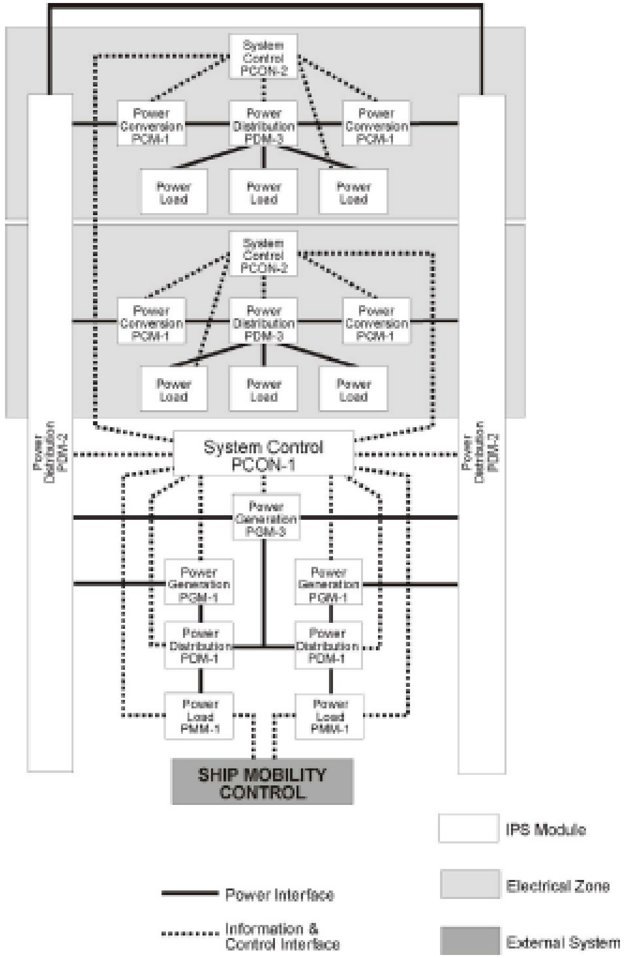


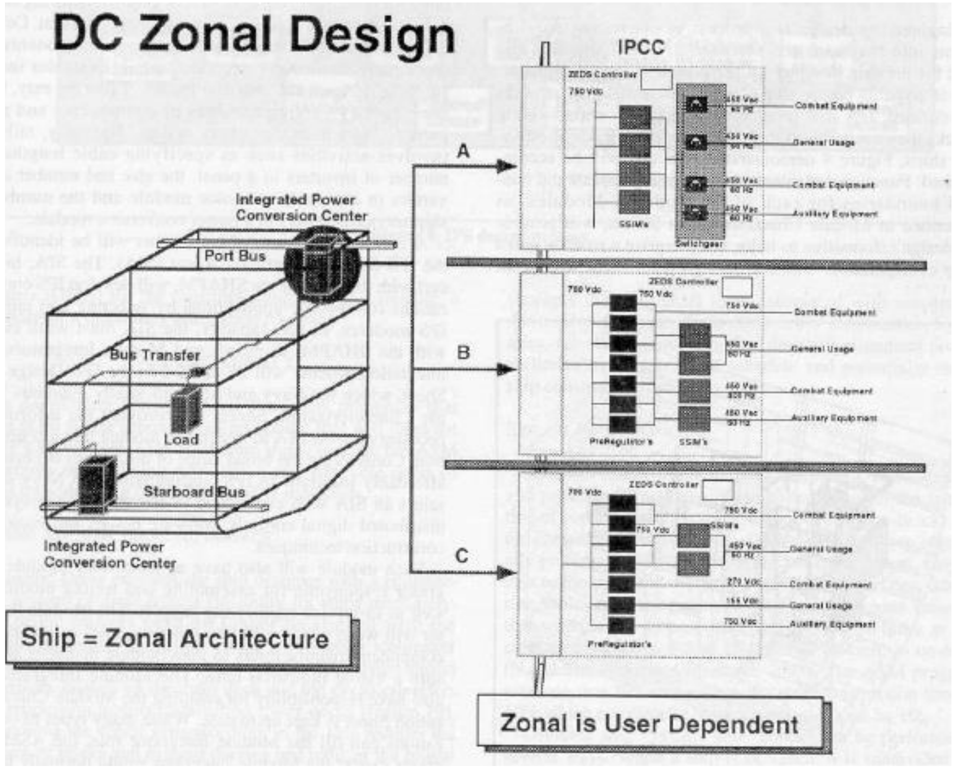
Early IPS Module Diagrams (1991)

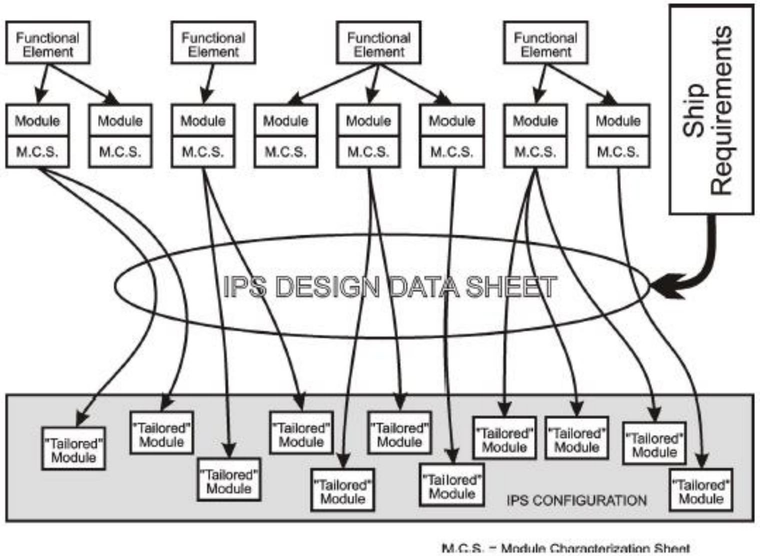




Integrated Power System (1992 - 1994)







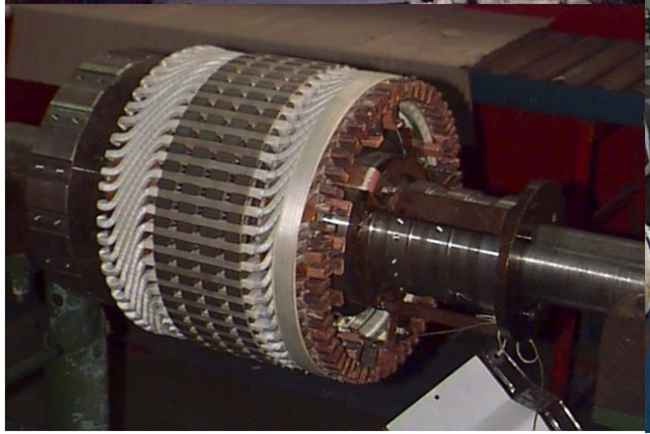
The Road to IPS (Continued)

- 2000: SECNAV announces IPS part of DD-21 baseline
- Early 2000's trials on U.K. technology demonstration ship *Triton*
- Early 2000's IPS re-architected into Low Voltage Power System (LVPS) and High Voltage Power system
- 2005: Permanent Magnet Motor fails testing (passes them later)
  - DDG 1000 design reverts to Advanced Induction Motor (AIM)
  - Integrated Fight Through Power (IFTP) incorporated
- 2011-2012: Testing of DDG 1000 IPS
- 2011: DDG 1000 laid down
- 2016: DDG 1000 commissioned

IPS Propulsion Generator

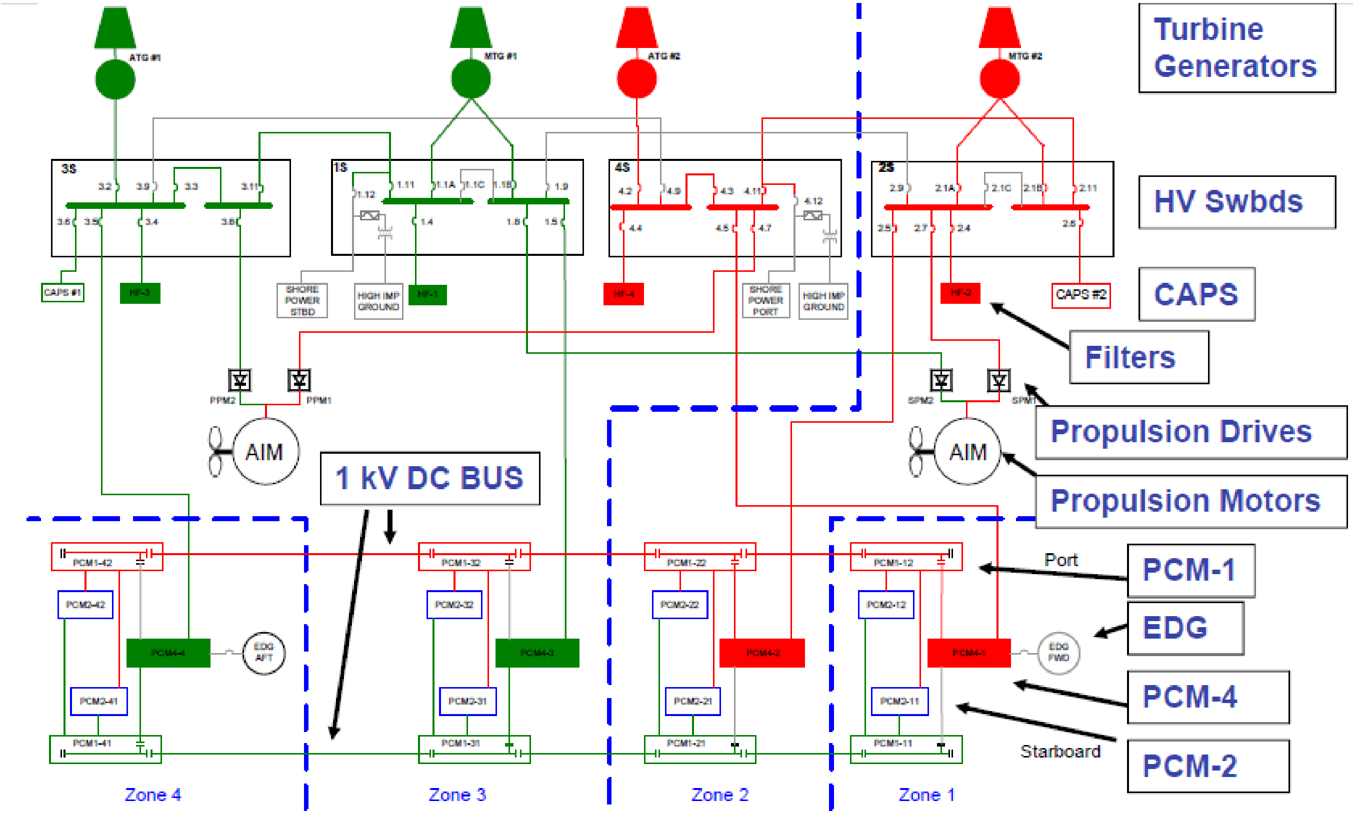
- 21 MW - 26.25 MVA
- 4160 V - 3 Phase
- 60 HZ - .8 Pwr Fctr
- 2 Pole - 3600 RPM
- 97 % Efficiency
- 50,050 KG
- 3.4m(H) x 4.7m(L) x 4m(W)
- Mfd. by: Brush Electric Machines Company (UK)

Courtesy of Timothy J. McCoy © 2003



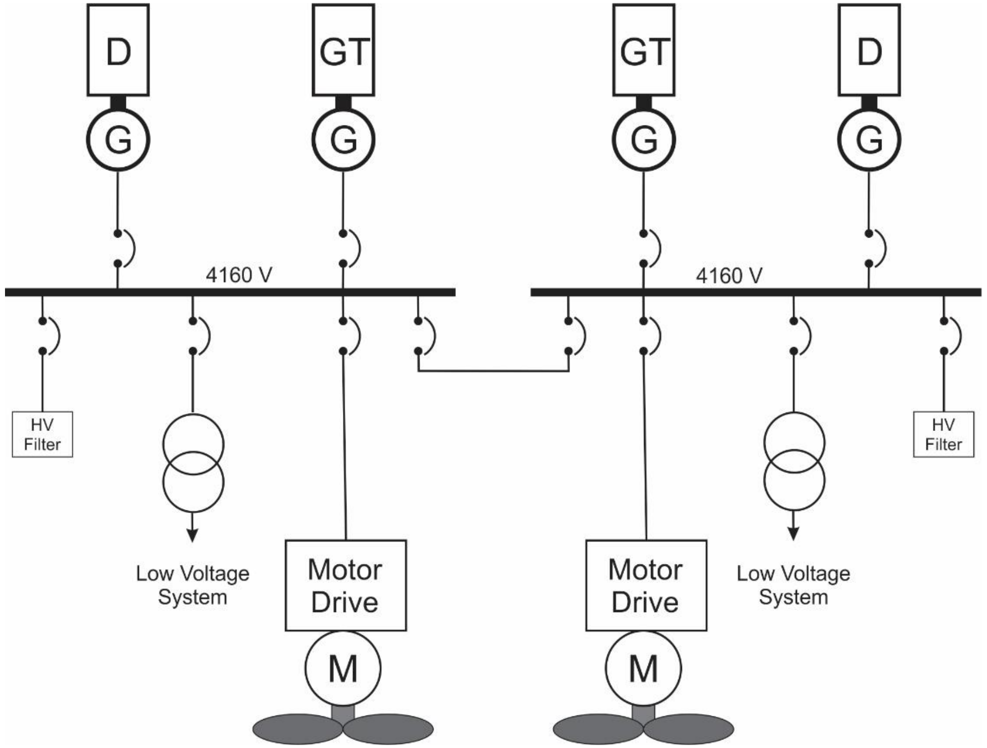
USS Zumwalt
DDG 1000

Sposato, Bill, “DDG 1000 Class Destroyer” Presented to U.S. Navy Port Engineers, 31 August 2011



HMS Daring

HMS Daring (CC-BY-SA-3.0/Brian Burnell)

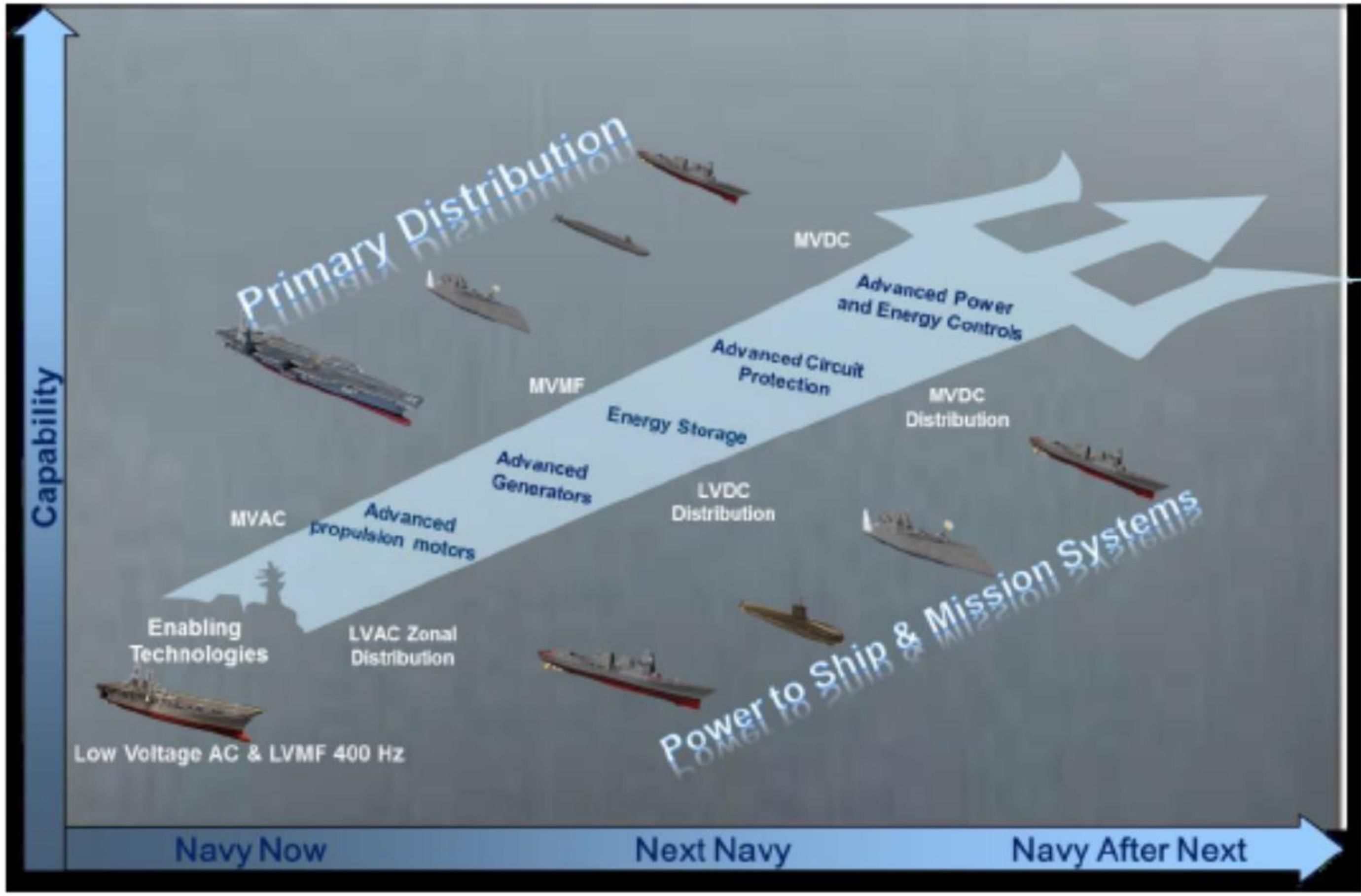


Naval Power and Energy Systems

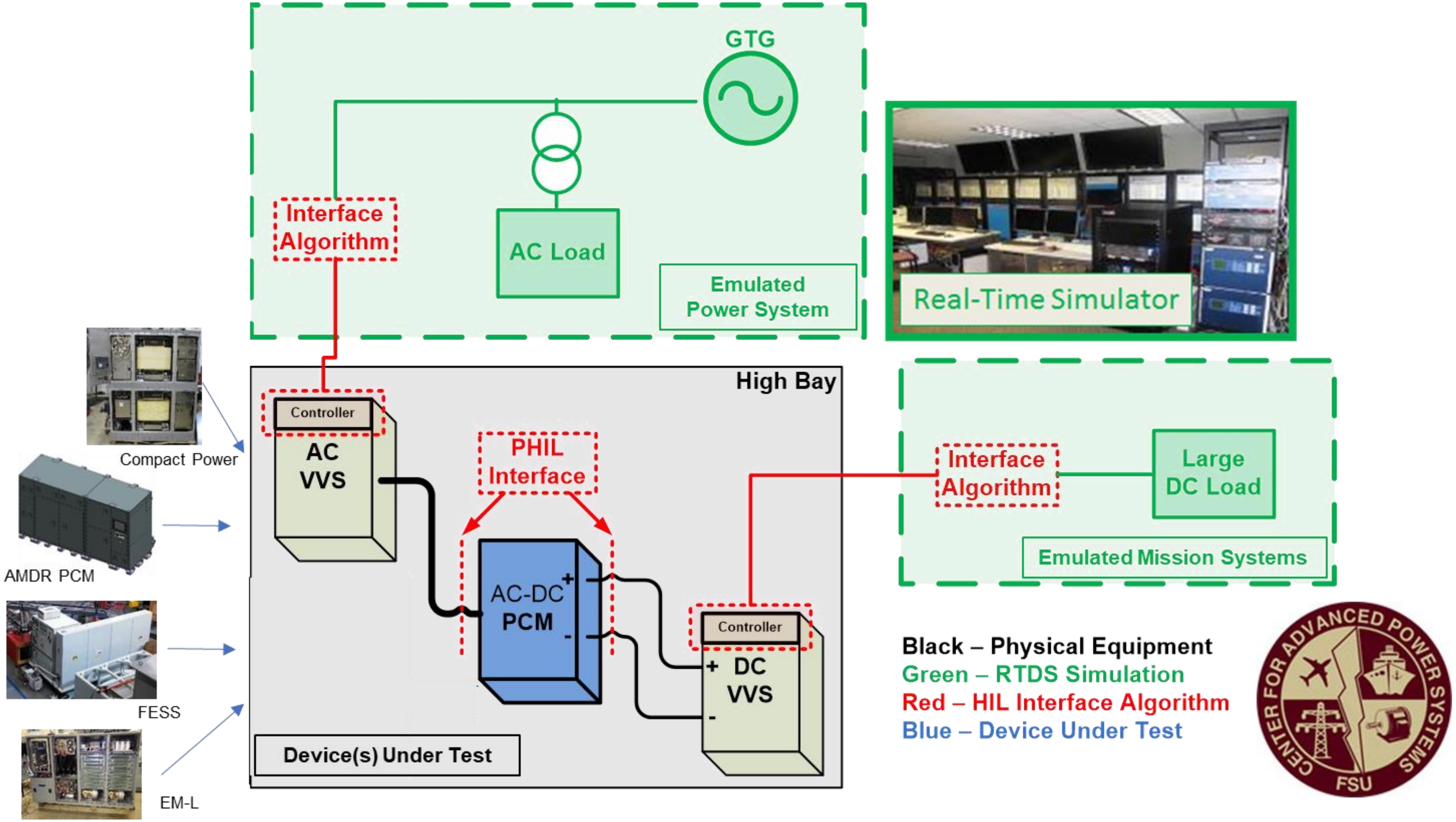
- 1999: Proposed Corporate Development Program for IPS
  - IPS focused on DDG 1000, needed corporate approach for commonality
  - $503M proposed budget deemed unaffordable
- 2002: Electric Ship Research and Development Consortium (ESRDC) Established
- 2006-2007: CNO Flag Steering Board for Next Generation IPS (NGIPS)
  - $100M to $300M proposed budgets deemed unaffordable
  - 2007: Issue first Technology Development Roadmap
    - Minimize new investment by aligning existing investments
- 2007: Formation of Electric Ships Office (ESO) PMS 320
  - Coordinate existing efforts and "fill the gaps"

Electric Ship Office and ONR investments

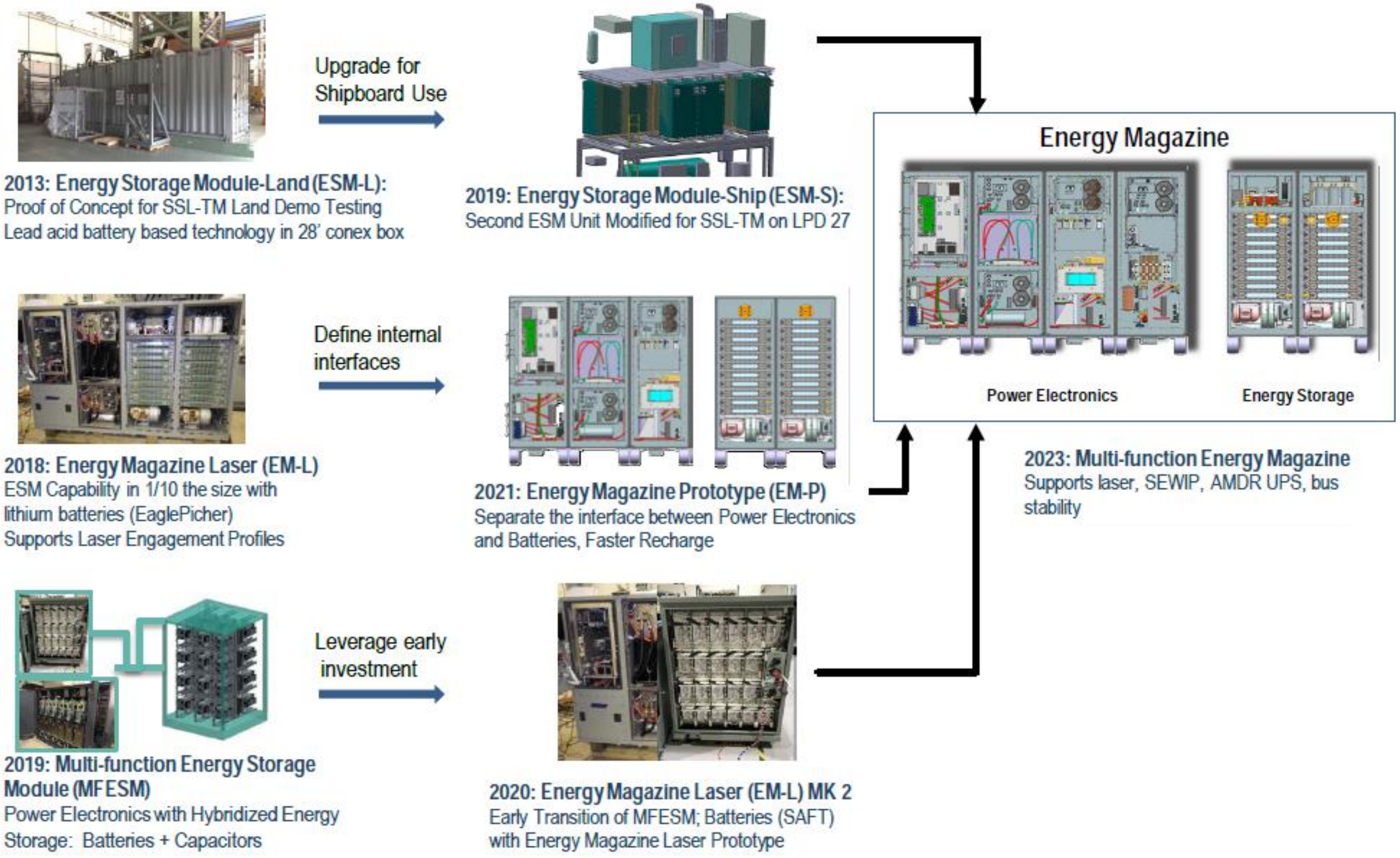
- AMDR Power Conversion Module (PCM)
- DDG 51 Hybrid Electric Drive (HED)
- DDG 51 Flight III AG9160RF (GTG)
- Advanced Power Generation Module (APGM)
- Energy Magazine
- DC solid state circuit protection
- MVDC technology development
- Advanced Controls
- Modeling and Simulation
    - System Modeling
    - Power Hardware in the Loop (PHIL)
    - Control Hardware in the Loop (CHIL)



Power Hardware in the Loop Testing



Energy Magazine



Recap: Electrical System on Ships

- Prior to ~1903: Special Purpose and Lighting only
- ~1903 to ~1945: Electric Propulsion = "Electric Reduction Gear"
    - Match prime mover (steam turbine / diesel) RPM to propeller RPM
    - DC Ship Service Distribution for most ships (between 100 and 240 volts)
    - AC Ship Service Distribution (440 VAC) for U.S. Navy since 1932
- ~1945 to 1988: Electric Propulsion used for special applications
    - A.C. Ship Service
    - DC drives (SCR based)
    - AC Cycloconverters, Load-Commutated Inverters
- Since 1988: Increased Commercial Application
    - IGBT based variable speed drives
- Since 1960's: U.S. Navy investment
    - Super Conducting Motors
    - Advanced Integrated Electric Propulsion Plant
    - Integrated Electric Drive
    - Integrated Power System (DDG 1000)
    - MVAC power distribution (LHD 8, DDG 51 flight III, CVN 68, CVN 78)
    - Hybrid Electric Drive (LHD 8, LHA 6, DDG 51 Flight IIA)
    - Next Generation Integrated Power System
    - Integrated Power and Energy Systems / Naval Power and Energy Systems

161208-N-SI773-0293 (U.S. Navy photo by Petty Officer 1st Class Ace Rheaume)