AD-A007 340

# COMPARATIVE PERFORMANCE OF HIGH EFFICIENCY SHIP PROPULSION SYSTEMS FOR DESTROYER HULL TYPES. VOLUME I

Alan J. Stewart

Bradford Computer and Systems, Incorporated

Prepared for:

Office of Naval Research
Advanced Research Projects Agency

6 December 1974

BRADFORD

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## VOLUME I

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Contract No. N00014-74-C-0398
ARPA Order No. 2805

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Advanced Research Projects Agency

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER
AD/A-007 340

4. TITLE (and Subtitle)
Comparative Performance of High Efficiency Ship Propulsion Systems for Destroyer Hull Types

5. TYPE OF REPORT & PERIOD COVERED
Final Report
June 1974 - Dec. 1974

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Alan J. Stewart

8. CONTRACT OR GRANT NUMBER(s)
N00014-74-C-0398

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Bradford Computer & Systems, Inc.

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
ARPA Order No. 2805

11. CONTROLLING OFFICE NAME AND ADDRESS
Advanced Research Projects Agency
1400 Wilson Boulevard, Arlington, Virginia 22209

12. REPORT DATE
6 December 1974

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Destroyers, Fuel Consumption, Range (Distance), Marine Propulsion, Electric Propulsion, Drives, Alternators, Electric Generators, Electric Motors, Cryogenics, Superconductors, Gas Turbines, Electrical Equipment, Mathematical Models.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Gas turbines have been assumed as prime movers and twin screw propellers used in all variations. It is concluded that substantial fuel savings and improvements in range can be attained by providing power

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S/N 0102-014-6601

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# ABSTRACT

A comparative study of fuel consumption for destroyer type propulsion systems is made.

Gas turbines have been assumed as prime movers and twin screw propellers used in all variations. It is concluded that substantial fuel savings and improvements in range can be attained by providing power transfer between shafts via electrical alternators, by adding small (5, 000 hp) cruise turbines to supplement the main propulsion turbine or by utilizing a superconductive electrical propulsion system. The use of cruise turbines and alternators shows promise for application to propulsion systems in the near future while superconductive propulsion shows the greatest promise for future systems where the ship is designed around the propulsion system.

# ACKNOWLEDGEMENTS

This research was conducted under the sponsorship of the Advanced Research Projects Agency of the Department of Defense under ARPA Order No. 2805. Work was monitored by Office of Naval Research under Contract N0014-74-C-0398.

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# 1.0 INTRODUCTION

## 1.1 GENERAL

This study was conducted by Bradford Computer and Systems, Inc. with assistance from the firm of M. Rosenblatt & Son, Inc., Naval Architects and Marine Engineers.

The purpose of the study was to examine a variety of proposed propulsion system configurations within the context of a modern Naval vessel to determine the feasibility of improving economy of operation, with an emphasis on fuel economy.

The propulsion configurations selected for study ranged from the use of small cruise turbines, through a propulsion system configured to take full advantage of advanced superconducting propulsion concepts.

Each of the configurations was analyzed to determine size, weight and space requirements (including required ancillary equipment and ship's service power requirements) and propulsion system efficiency, fuel consumption and range, both as a function of ship speed, and over a standard destroyer mission profile.

The study utilized existing destroyer design drawings and gas turbine performance data together with a Standard NAVSEC destroyer mission profile, and data and design information from the current NAVSHIPS superconductive propulsion development program.

The following configurations were studied:

- Baseline system with four 20,000 hp gas turbines geared to two shafts (two turbines per shaft).
- Addition of geared cruise turbines.
- Addition of high performance electrical alternators for cross-over operation with gear drives.
- Substitution of electric drive for turbine/propeller shaft mechanical drives.
- Electric drive system with optimum space configuration (relocation of turbines and reduction in propeller shafting).

The purpose of the cruise turbines is to permit substitution of small (5,000 hp) turbines operating at relatively high thermal efficiency for the large 20,000 hp turbines at cruise speeds, where the large turbines are thermally inefficient due to part-load conditions.

Similarly, the use of electrical alternators permits transferring power from one shaft to the other by using the alternators as a motor-generator set. This allows a single turbine to be used in cases where two would be required without the power crossover. The higher thermal efficiency of a single turbine operating near full load as compared to two turbines operating at half load permits more economical fuel operation.

The use of electric drives provides added flexibility in several respects. Transfer of power between any turbine and either shaft is accomplished electrically and eliminates reduction gears and drive trains; in this respect the electric drive functions as a substitute for the mechanical drive system portion of the propulsion system. In addition, the electric drive impacts the turbine and propeller portions of the system. The ratio of turbine to shaft speeds can be adjusted by changing the magnetic field excitations in the electrical motors and generators, thus providing a wide range of effective "gear" ratios. On the one hand, this makes it possible to operate the turbines close to their most efficient shaft speed at any given power level and, on the other hand, it allows operation with a fixed pitch propeller. In direct gear drives with gas turbines, a controllable reversible propeller (CRP) is needed to provide reversability (existing gas turbines are unidirectional) and for maneuverability at low speeds (the gas turbine speed must be maintained at low power levels and reduction of propeller pitch is necessary to maintain the required speed). In order to operate the turbines at reasonable efficiencies it is necessary, in geared systems, to reduce the propeller pitch below its optimum setting and a tradeoff occurs between propeller efficiency and turbine efficiency. With an electric drive, a fixed pitch propeller can be used, designed for optimum efficiency, and the turbines can be simultaneously adjusted to their optimum operating speeds. This results in increases in overall propulsion efficiency as well as increased operating flexibility.

The feasibility of electric drives has been enhanced by the development of superconducting machinery. Superconducting machinery uses magnets cooled to cryogenic temperatures ($4^{o}$ Kelvin), at which temperature all electrical resistance in the magnet coils vanishes. This permits highly efficient motors and generators to be built which are very compact and relatively light in weight. In order to keep the magnets at superconducting temperatures, it is necessary to provide a source of liquid helium from closed-cycle helium refrigerators(1) to make up for heat losses in the machines. The refrigerators put an additional load (100 to 130 kw) on the ships power supply and auxiliary fuel load but results of the study indicate that even with this added load, the electrical drive system is equal to the mechanical drive system in efficiency, and overall propulsion system efficiency is much improved (primarily because of turbine speed optimization).

Results of the study show that up to 25% improvements in fuel economy over a standard destroyer mission profile are possible with electric drive systems and 22% with cruise turbines and alternators added to the geared drive system; similar improvements, 19% and 13%, in endurance range result. The add-ons in the geared drive system add 32 tons to the propulsion system weight, while the electric drive system reduces weight by at least 38 tons.(2)

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(1) Helium storage tanks can also be used but are not considered feasible for operational use because of logistic problems and consumption losses through venting.

(2) This weight reduction does not include the weight of turbine ducting eliminated or the difference in weight between CRP and fixed pitch propellers.

In addition to weight savings, the electrical drive system provides substantially more efficient space utilization and frees large areas aboard ship which would normally be used for turbine ducting, reduction gears and propeller shafting.

## 1.2 AREAS OF STUDY

The areas studied included physical layout and systems analysis of several propulsion configurations. Included were:

Baseline: Baseline configuration of four 20,000 hp LM-2500 gas turbines direct geared to two propeller shafts (two turbines per shaft) with controllable-reversible pitch (CRP) propellers.

Baseline + Alternators: The addition of electrical alternators to the baseline. The alternators, functioning as a motor/generator set, provide a "crossover" capability by allowing transfer of power from one shaft to the other and permit cruising with a single gas turbine powering both shafts.

Baseline + Cruise Turbines: The addition of 5,000 hp cruise turbines and associated gearing to the baseline. This arrangement allows cruising with the smaller turbines at power levels where the LM-2500 turbines are highly inefficient.

Baseline + Alternators and Cruise Turbines: Simultaneous addition of the cruise turbines and alternators to the baseline configuration.

Electric Drive(1) - No Cruise Turbines: Replacement of the baseline geared drive system with a superconductive electric drive system.

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(1) "Electric Drive", as used in this report, contemplates the use of superconductive machinery.

In this system, the mechanical gears and shafting are replaced by electrical transmission lines connecting electric generators driven by the turbines to electric motors driving the propeller shafts. The electric system provides crossover capability and improves turbine efficiency by allowing turbine operation at speeds independent of the propeller rpm's.

Electric Drive - With Cruise Turbines: Addition of 5,000 hp cruise turbines to the electric drive system.

Three versions of the electric drive systems were studied:

Baseline (Existing Engine Room) Configuration: Installation in the baseline configuration without changes to engine room locations or propeller shafting lengths.

Reconfigured Engine Room: Installation with the gas turbines moved from the present 15 ft. deck level to the 24 ft. deck level and elimination of 228 ft. of propeller shafting by moving the motors aft.

Optimum Cruise Turbine Location: Alternative locations of the cruise turbines in either deck-mounted modules or in the engine rooms.

## 1.3 TECHNICAL APPROACH

In order to provide a realistic basis for the study, and as a study convenience, the engine room and power shafting layouts of the DD963 class destroyer were utilized in studying equipment layouts. Estimates of ships service load, endurance, fuel tank capacity, drag and propeller efficiency were made, based on performance characteristics of existing class destroyers, for purposes of assessing propulsion performance. An efficiency of 96% was assumed for the mechanical drives (turbine to propeller shaft) and used throughout the study.

Available information on superconductive machinery and ancillary equipment developments currently being investigated by the U. S. Navy were utilized for the superconductive configurations.

Math models of the propellers, drag profile, alternators and auxiliary fuel load were developed and incorporated into a computer program, together with existing models of turbines, electrical machines and destroyer mission profile. Through parametric variation of the computer inputs, the following were established:

- Motor and generator characteristics (one new generator was designed; an existing motor design and generator design were examined for optimization of parameters).
- Optimum gear ratios for geared drives (both main and cruise turbines).

- Optimum pitch settings(1) for both geared and electric drives under each condition of operation.
- Optimum electrical transmission line sizes for each configuration (weight vs. electrical resistance).

Required coolant pump capacity and cryogenic helium refrigerator (compressors and expanders) sizes were established through a study of system heat losses at full load and motor and generator helium loss rates.

Electrical switchgear requirements for the electric drives were determined from maximum loadings occuring on each element of the system over the required speed range, and sizes and weights were established to meet these loads.

Detailed layouts were made of each configuration to establish the feasibility of installing the required equipment and determine impact on engine room configurations. Summaries of weight changes between equipment added and equipment removed were also made.

Using the computer program, performance of each of the configurations was assessed over a standard destroyer mission profile with respect to:

- Turbine and propulsion fuel rates, averaged over the mission profile and at each speed; fuel rates were determined in both lbs/hr and tons/mile.

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(1) Pitch settings were optimized for fuel economy on a knot-by-knot basis and optimum fixed settings for each operational mode were determined.

## 2.0 PROPULSION EQUIPMENT CONFIGURATION

### 2.1 INTRODUCTION

In order to demonstrate the feasibility of adding the new equipment to typical modern destroyer type ships, four arrangement drawings were prepared. Each drawing shows the modifications to both forward and after engine rooms to accommodate the required equipment for each proposed propulsion system. The propulsion configuration of an existing destroyer type (DD963) was used as a baseline for the equipment arrangement. This was a study convenience intended to provide a real-life basis for the study and ensure that no aspects of the propulsion design would be overlooked; the effort should not be construed as a redesign of the DD963 propulsion system.

The baseline propulsion system consists of four LM-2500 gas turbines (80,000 hp total), mechanically geared to two independent shafts (40,000 hp each) and is considered representative of modern destroyer type ships. The baseline configuration for the forward engine room(1) is shown in figure 2-1. Four modifications to this baseline system were made as follows:

- Two 5000 hp gas turbines and associated gearing were added, one to each engine room.

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(1) The starboard engine layout is essentially the same; for all modifications only the forward engine room layouts are shown, however detailed layouts were prepared for both engine rooms as discussed in Appendix D.

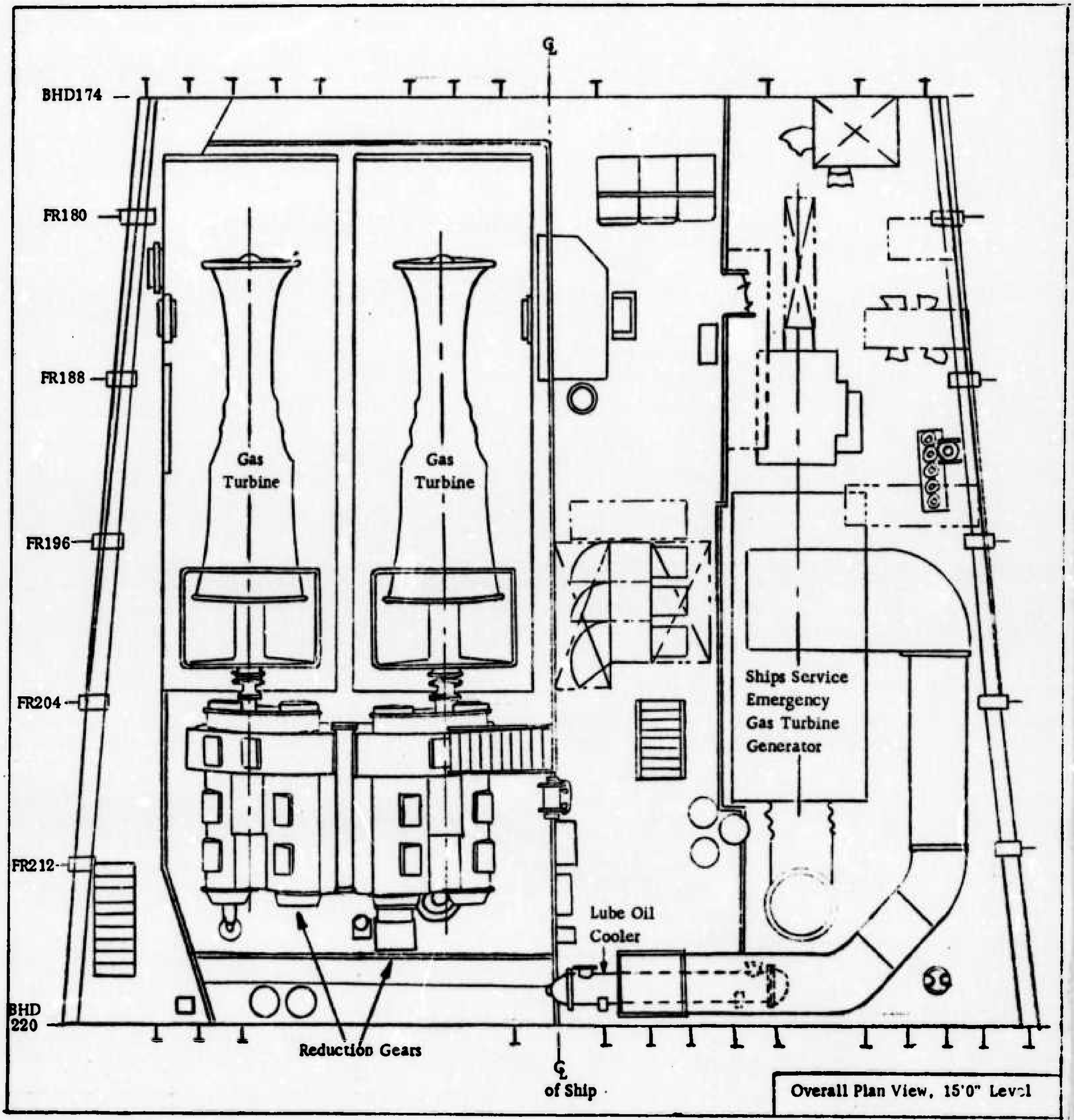

Figure 2-1, Sheet 1. Baseline Configuration

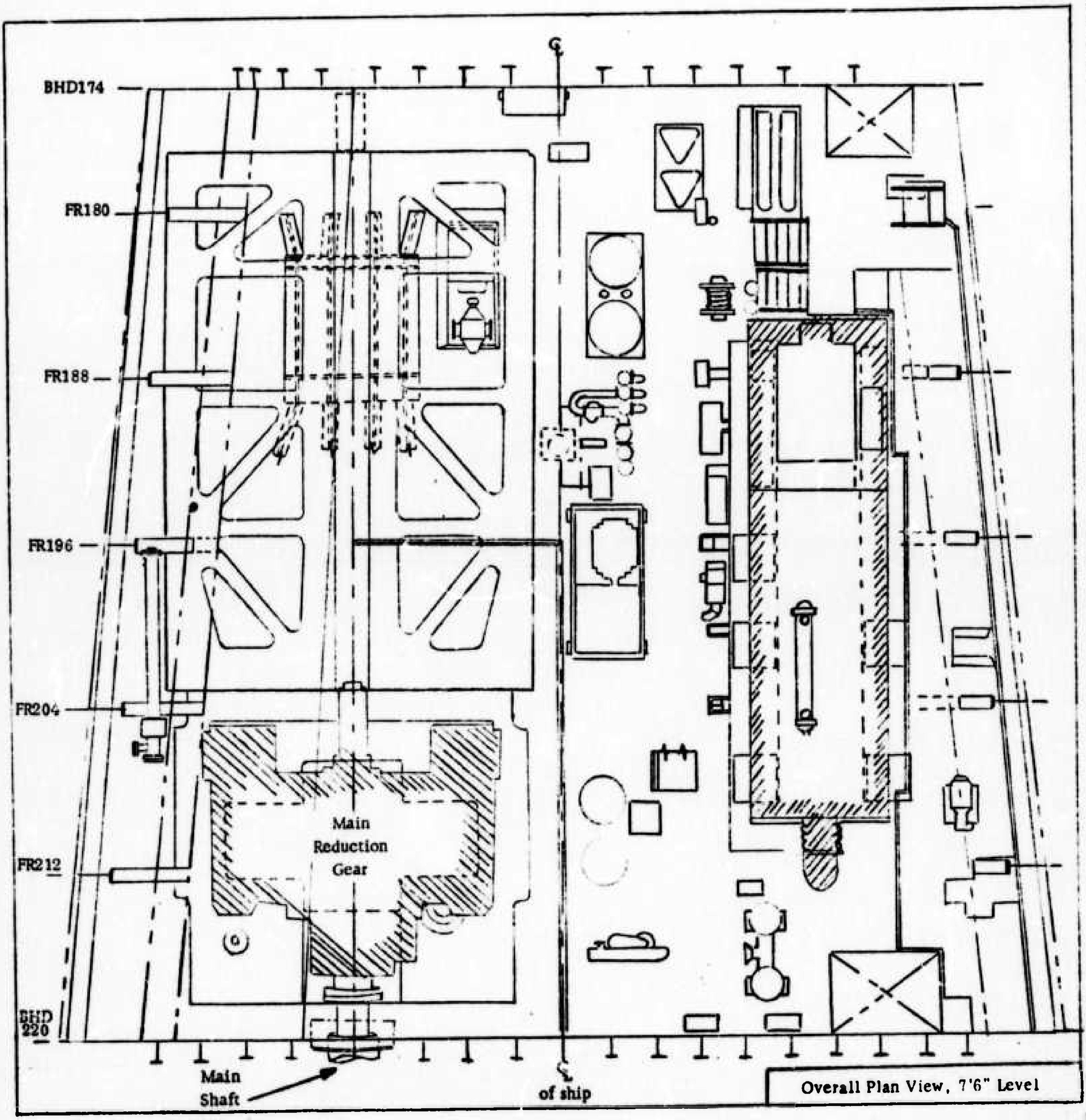

Figure 2-1, Sheet 2. Baseline Configuration

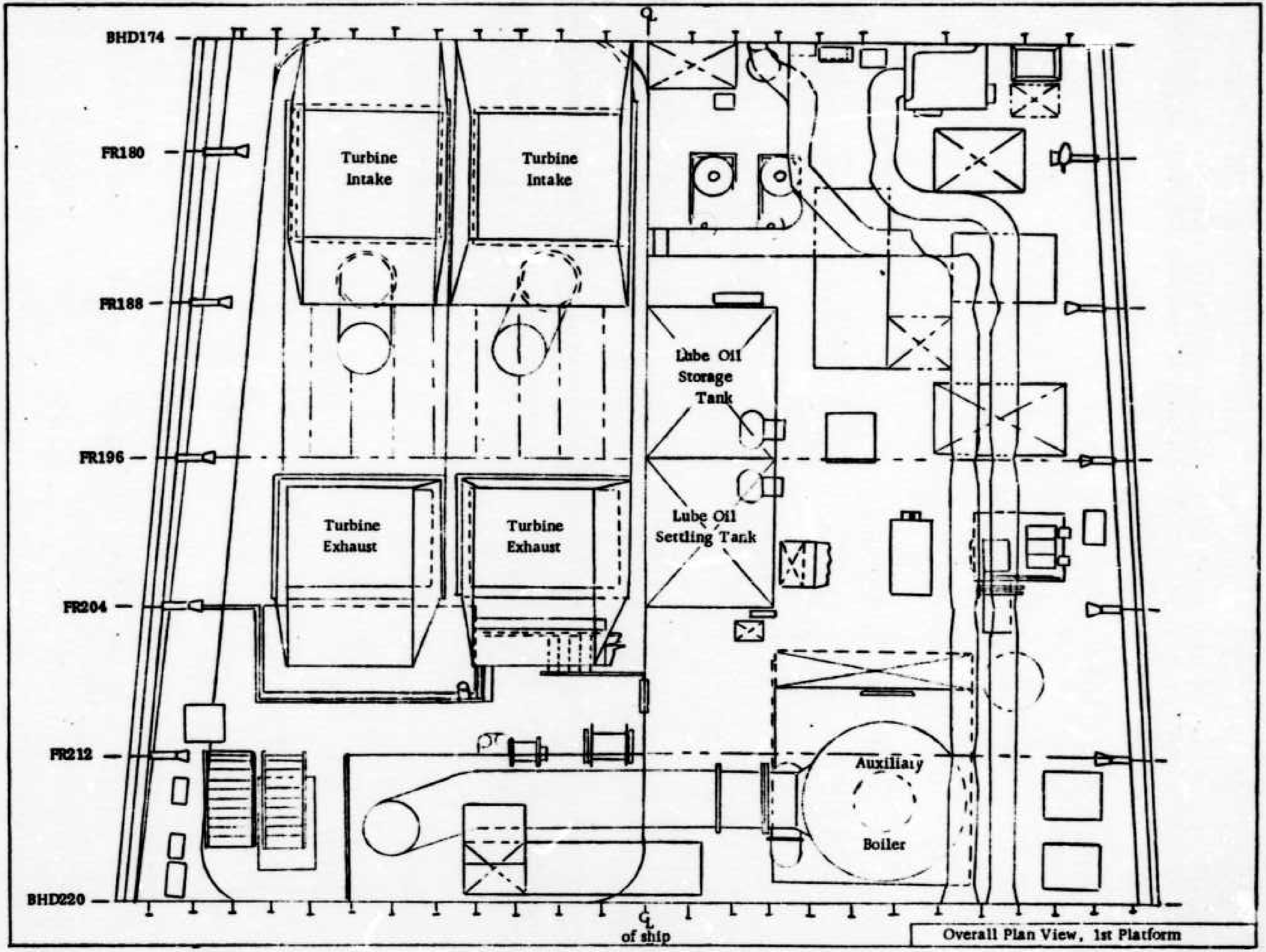

Figure 2-1, Sheet 3. Baseline Configuration

- A 10,000 hp alternator and associated gearing was added to each engine room together with an electrical crossover line between port and starboard propulsion systems.
- Superconducting electric propulsion equipment was substituted for the existing mechanical reduction gearing, while retaining the existing machinery arrangement; cruise turbines were added in optional modules.
- Superconducting electric propulsion equipment was substituted for mechanical reduction gearing, as above, except that the existing machinery space configuration was optimized by moving the propulsion gas turbines up to the next higher deck level to reduce intake and exhaust ducting and the propulsion motors were moved aft to reduce the length of drive shafts between propellers and motors.

## 2.2 GENERAL

All four engine room arrangements include equipment currently under development. The arrangements are based on preliminary information and are, of course, subject to change as a result of future design developments and as additional information is made available.

Those arrangements involving the addition of high performance alternators and superconducting machinery have been based on data previously developed through prior propulsion studies primarily for a SWATH type ship,(1) and additional information developed during the course of this study.

Although there is a convenient similarity between the SWATH propulsion plant and that of the destroyer chosen as typical of modern destroyer types, (twin screw, 80,000 shp total), some modifications were necessary for installation in the destroyer type hull. The SWATH conceptual design has a single large engine room containing both port and starboard propulsion plants. Many of the services for the superconducting machinery on both plants (i.e., helium, cooling oil, etc.) have a common source.

Destroyers, on the other hand, are usually provided with two separate engine rooms, each intended to be as independent as is practicable from the other. Thus, in the destroyer arrangement drawings, several of the systems have been modified to provide independent superconducting machinery support systems, such as helium and coolant systems for each engine room, as shown in figure 2-2. In addition, motor and generator bearing lube oil requirements have been provided from the existing main lube oil system, in lieu of providing each new machine with its own individual lube oil system.

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(1) Studies conducted for Naval Ships Systems Command, by Naval Ship Research and Development Center, Annapolis, and by Bradford Computer and Systems, Inc.

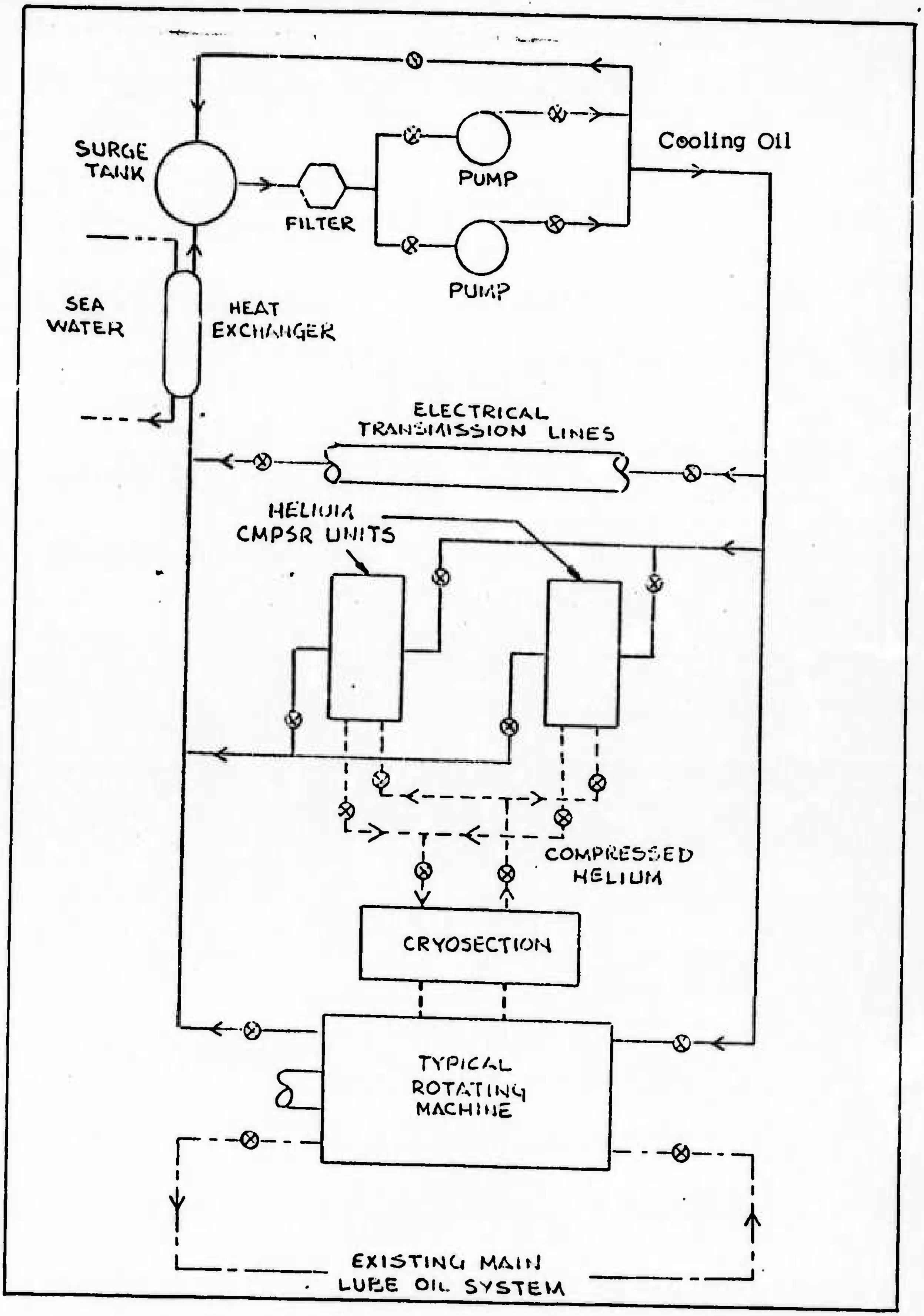


Figure 2-2. Fluid Systems Schematic Diagram (Each Engine Room)

## 2.3 MODIFICATIONS

### 2.3.1 Addition of Cruise Turbines

Figure 2-3 shows the modified forward engine room arrangement for installing a cruise turbine. The cruise turbine size shown was based on available information for modern marine gas turbines of approximately 5000 hp and the space shown accommodates the Garrett GTPF990 engine currently under development for the U. S. Navy. The cruise turbine output is mechanically coupled through angle gearing to the existing main reduction gear which must be modified to accept the cruise turbine input shaft. A 3.44 to 1 speed reduction is made through the angle gearing; combined with the main reduction gear ratio of 21.5 to 1 this gives a 74 to 1 gear reduction between the cruise turbines and propeller shafts.

Other modifications involving relocation of equipment, extension of the machinery platform and auxiliary boiler ductwork necessary to accept the cruise turbine, are detailed in Appendix D.

### 2.3.2 Addition of Crossover Alternators

Figure 2-4 shows the modified forward engine room arrangement for installation of the crossover alternator. The alternator size and the service requirements for it are based on the design information in Appendix B. Transmission line cooling was not considered necessary since output currents are transmitted via normally installed Navy 5KVTSGA cable.

The alternator is mounted alongside the existing reduction gear and mechanically coupled to the existing gear via a new transfer gear. The transfer gear provides a 1.5 to 1 gear reduction, giving an overall gear

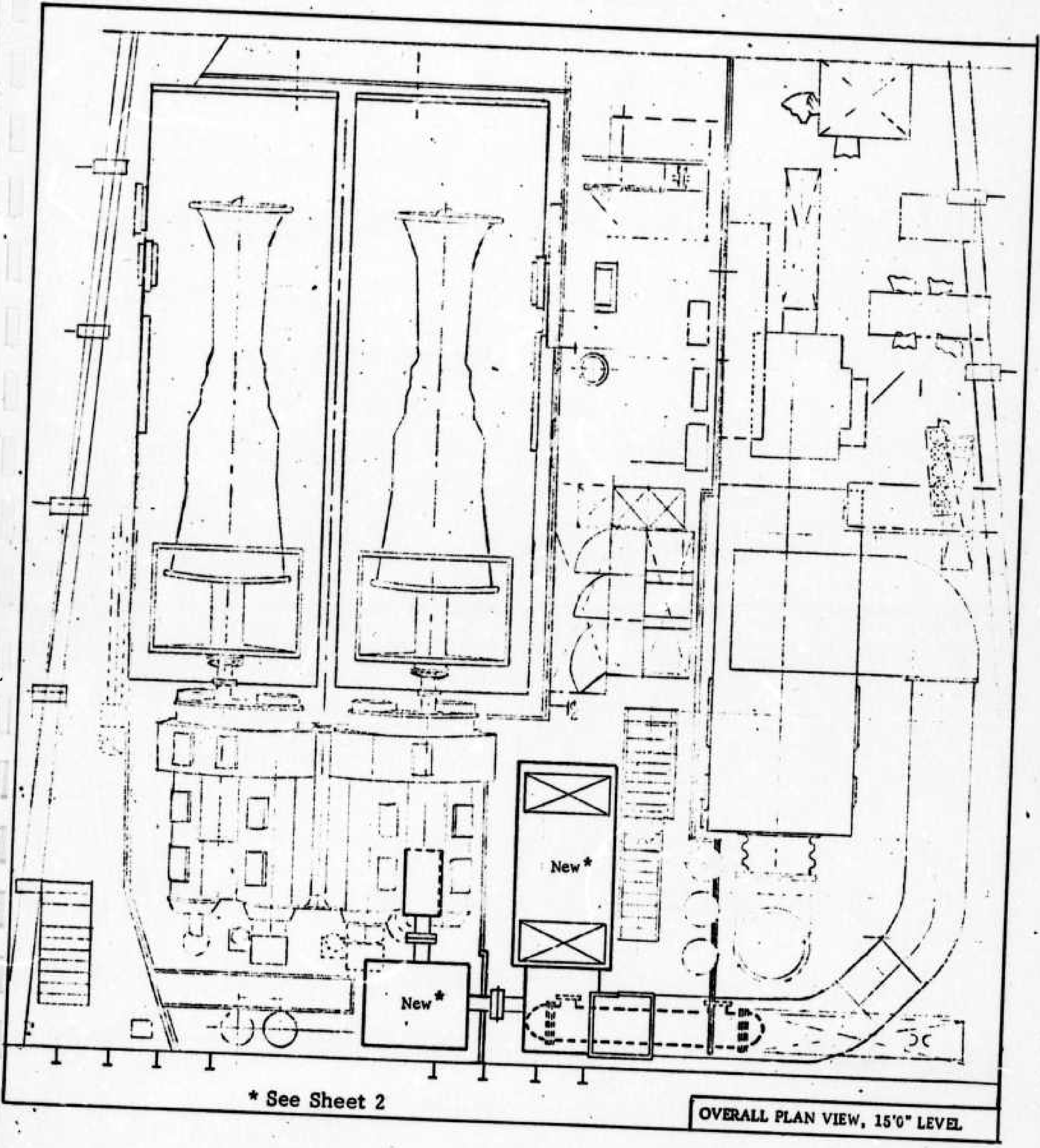


Figure 2-3, Sheet 1. Addition of Cruise Turbines

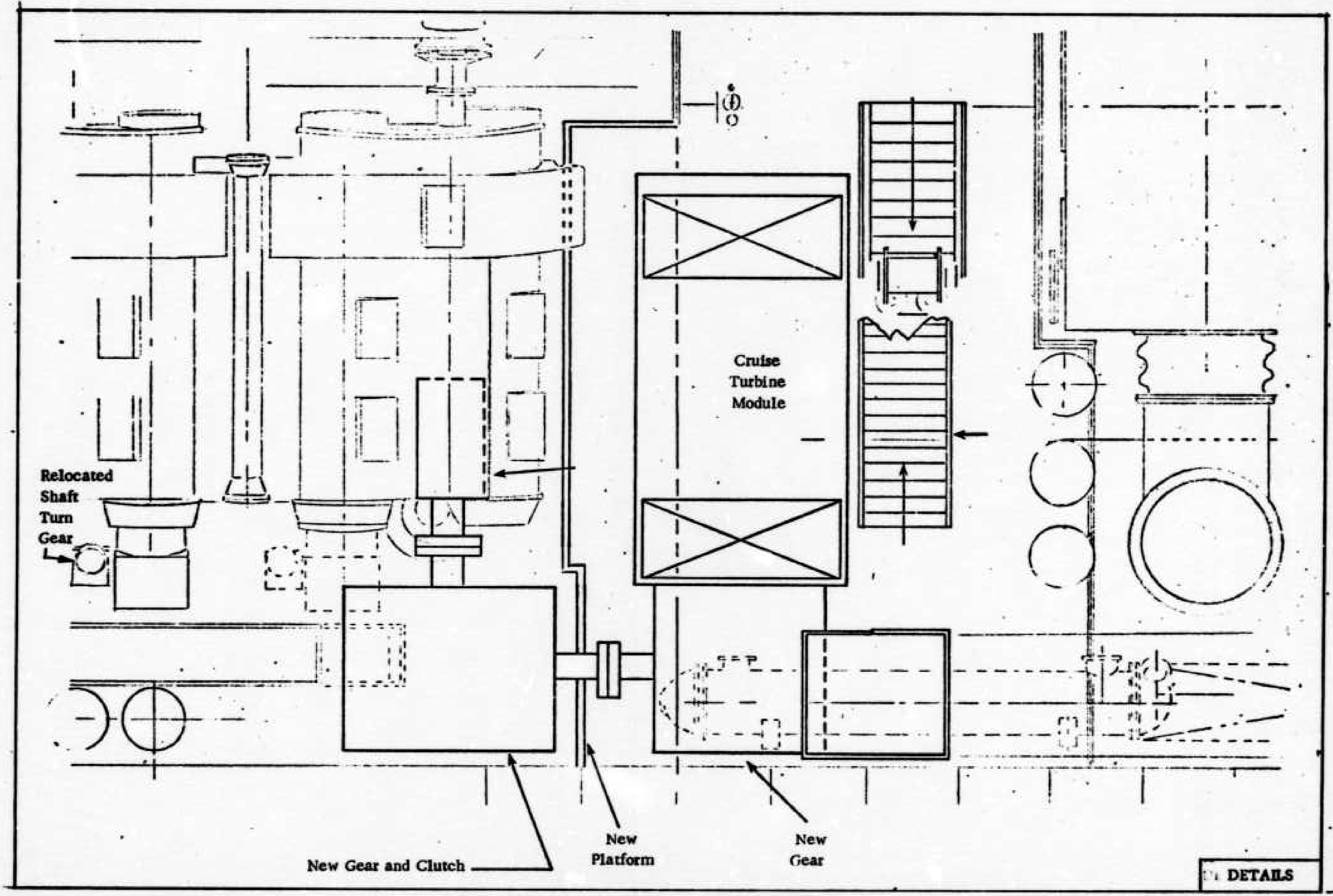
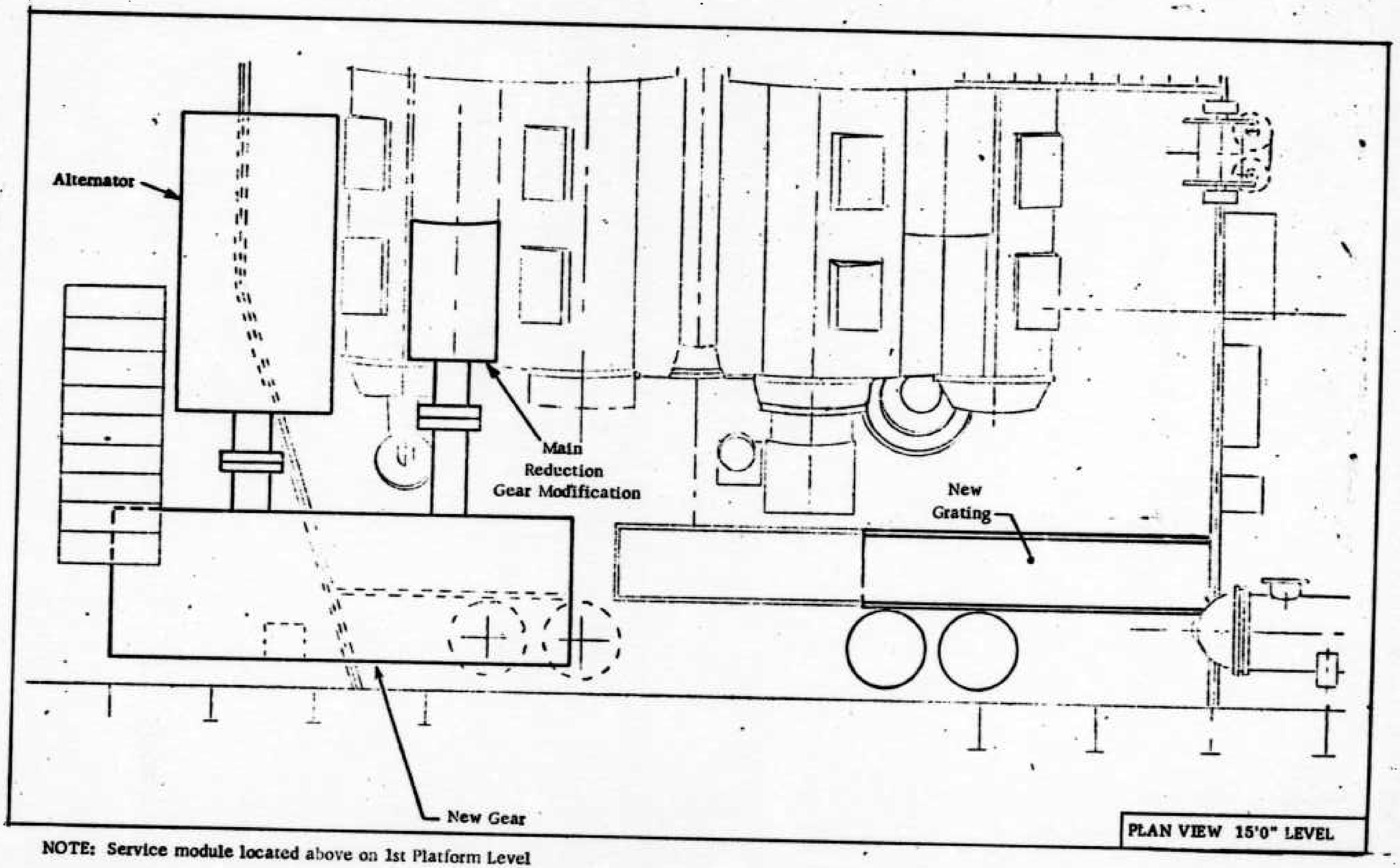


Figure 2-3, Sheet 2. Addition of Cruise Turbines



NOTE: Service module located above on 1st Platform Level

Figure 2-4. Addition of Alternators

ratio of 32.25 to 1 to the propeller shafts. This yields an alternator speed of 5000 rpm at 155 rpm shaft speed (approximately 30 knots ship's speed).

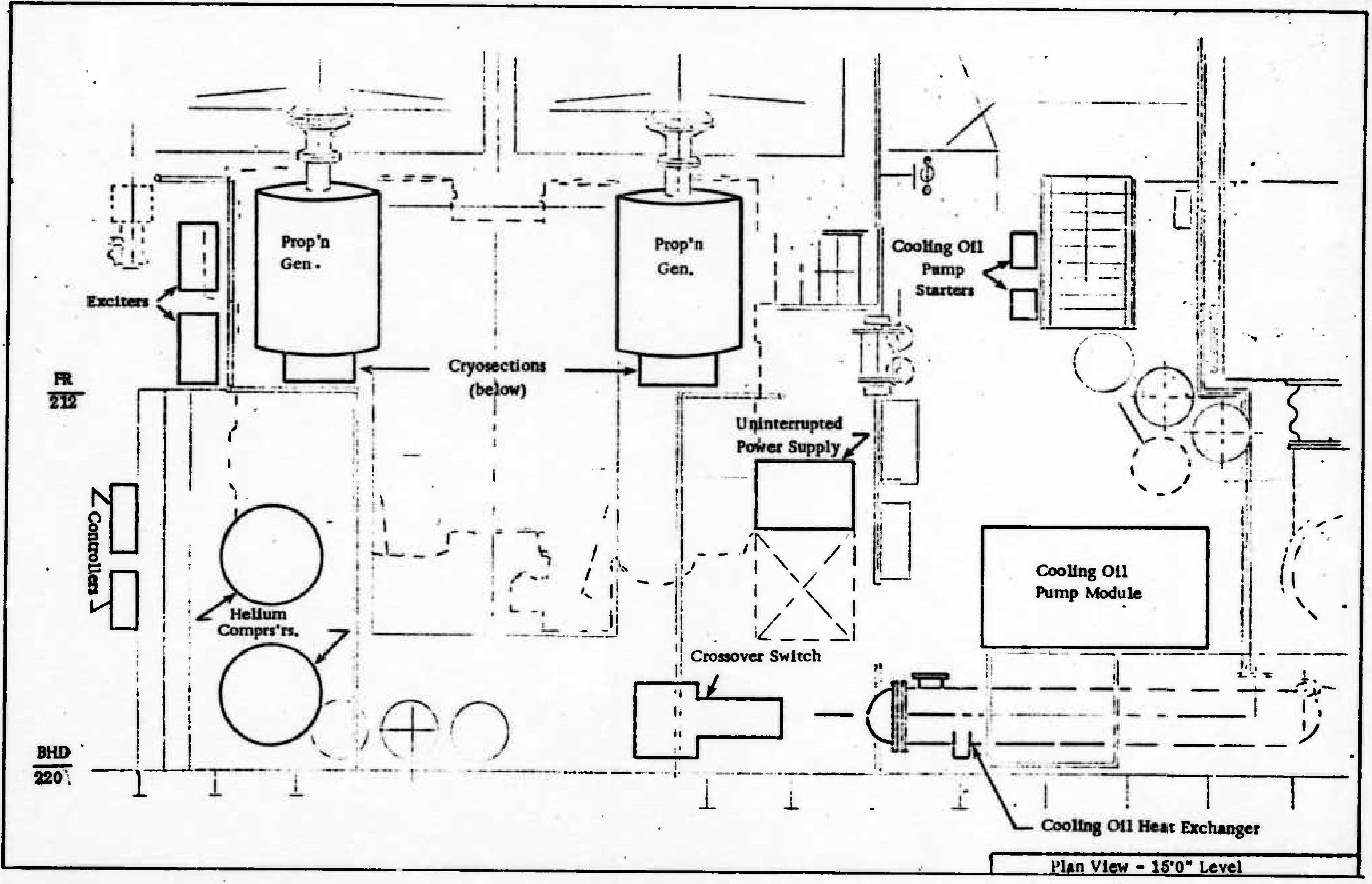
Few other modifications to the existing engine room arrangement are required to accommodate the new equipment. These modifications consist mainly of relocating a few minor items (air starting flasks, fire fighting hose reels and cylinders, etc.) and modifying existing gratings, as discussed in Appendix D.

Addition to Alternators and Cruise Turbines

Both alternators and cruise turbines may be added simultaneously; each would be installed as shown in the arrangement drawings for the separate options.

### 2.3.3 Installation of Superconducting Electric Propulsion in the Existing Engine Room Configuration

In this configuration (figure 2-5) a superconducting electric propulsion system is substituted for the mechanical drive portion of the system. The reduction gears are eliminated and electric motors and generators are installed in the space made available. A 20,000 hp propulsion generator is direct coupled to each turbine and a 40,000 hp propulsion motor is direct coupled to each propeller shaft, the motor and generator being connected by electrical transmission lines. Necessary support equipment (helium compressors and expanders, switchgear, controls, coolant oil, power supply, piping, etc.) are installed in available spaces.



NOTE: Generator switches are located above generators on 1st Platform Level; Cooling Oil Surge Tank on 1st Platform Level (replaces existing CRP head tank).

Figure 2-5, Sheet 1. Installation of Superconducting Electric Propulsion in Existing Engine Room Configuration.

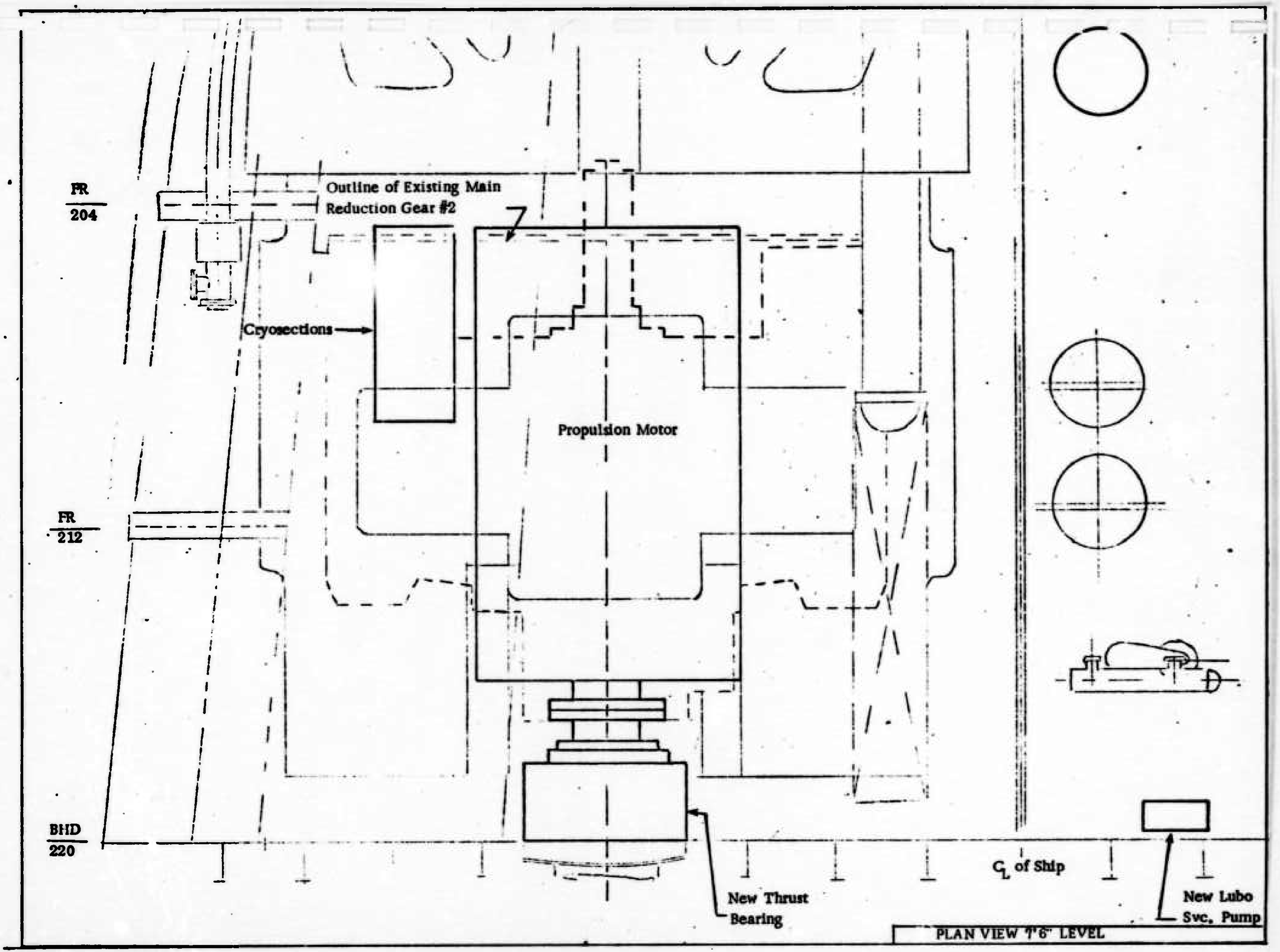


Figure 2-5, Sheet 2. Installation of Superconducting Electric Propulsion in Existing Engine Room Configuration.

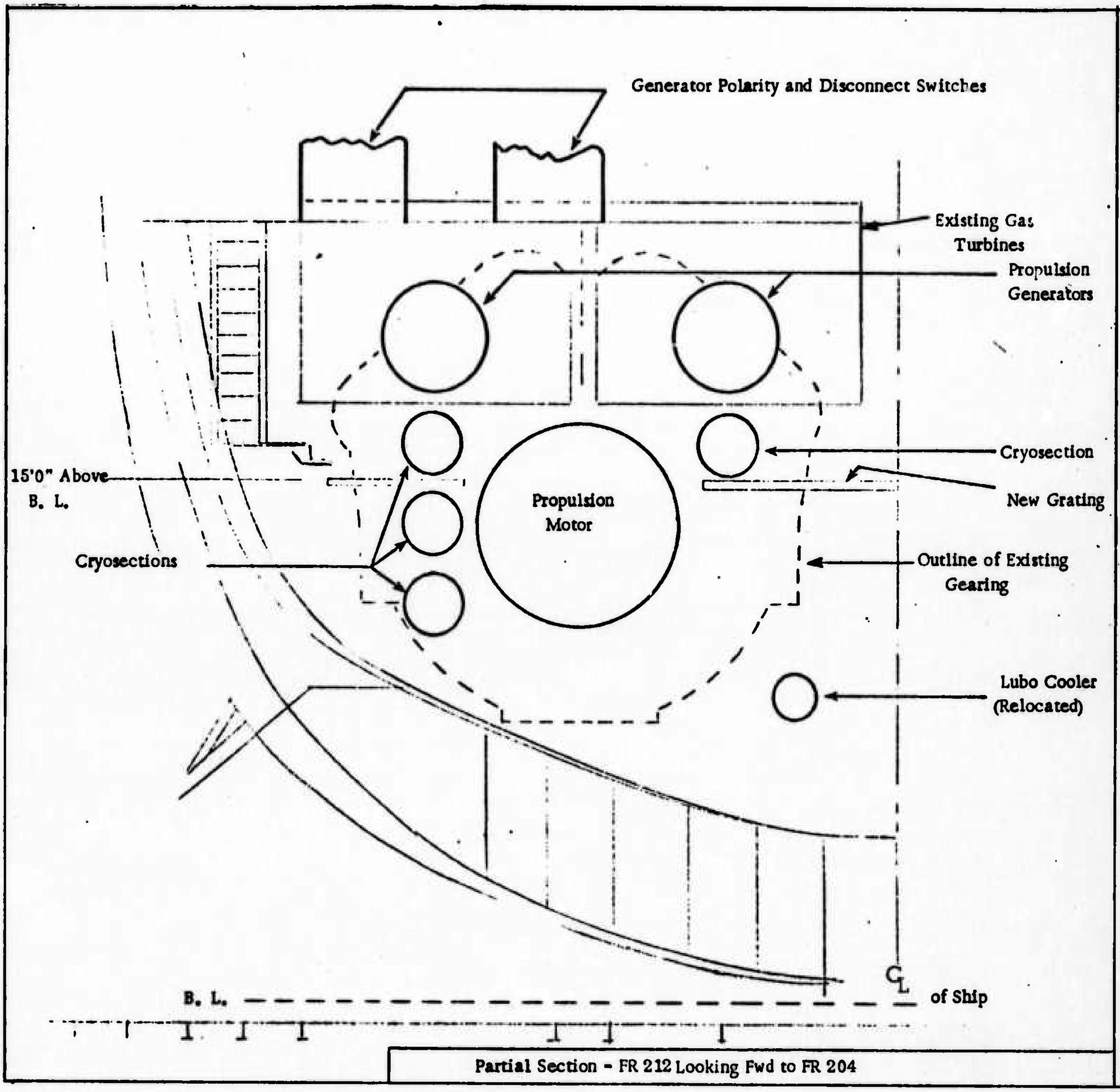


Figure 2-5, Sheet 3. Installation of Superconducting Electric Propulsion in Existing Engine Room Configuration.

The controllable reversible pitch propeller (CRP) used in the geared drive systems is locked into a fixed position and the CRP hydraulic system is removed. Alternately, the CRP could be replaced by a fixed pitch propeller, however the resultant change in efficiency is considered to be small. The difference in weight between the CRP and a fixed pitch propeller was not estimated.

Modifications were made to the lube oil system to provide for a new coolant system for the electrical machines and transmission lines.. The existing thrust bearing has been replaced by a new pedestal type thrust bearing at the after bulkhead in each engine room.

The new helium and coolant systems are installed mostly on the 15'-0" level which has been extended into the space formerly occupied by the main reduction gear. A new uninterrupted power supply (UPS) power panel and automatic bus transfer switch (ABT) are also installed on the 15'-0" level. Generator disconnect and crossover switches are located at the 24'-0" level except for the forward engine room, where the crossover switch is located at the 15'-0" level.

With the exception of the air starting flasks in the forward engine room, almost no other modifications are required to the existing engine room equipment.

The 5000 hp cruise turbines, if used, can be modularized as shown in figure 2-6 and installed on top of the deck house adjacent to the machinery casing as shown in figure 2-7. Electrical transmission lines and service

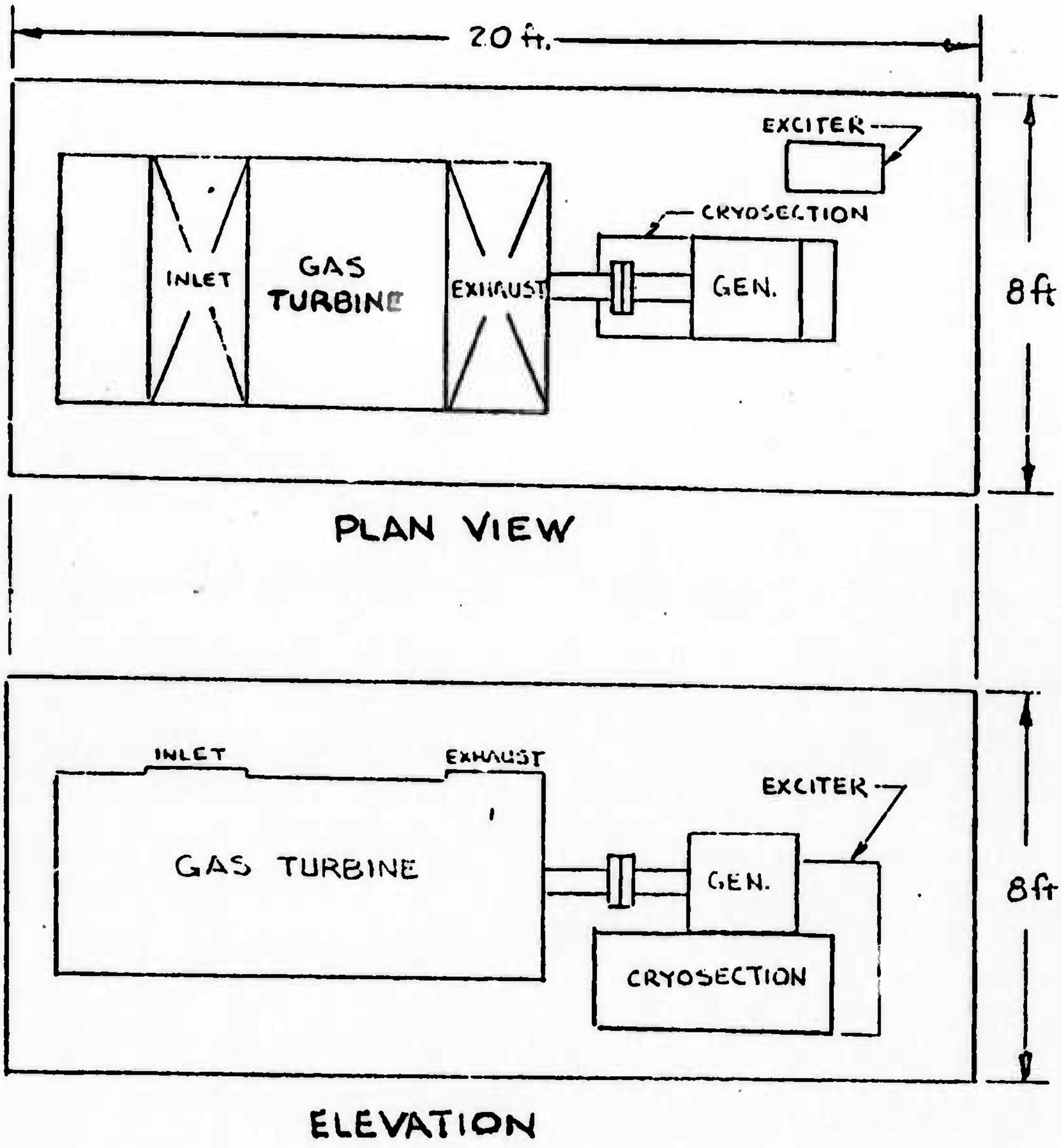
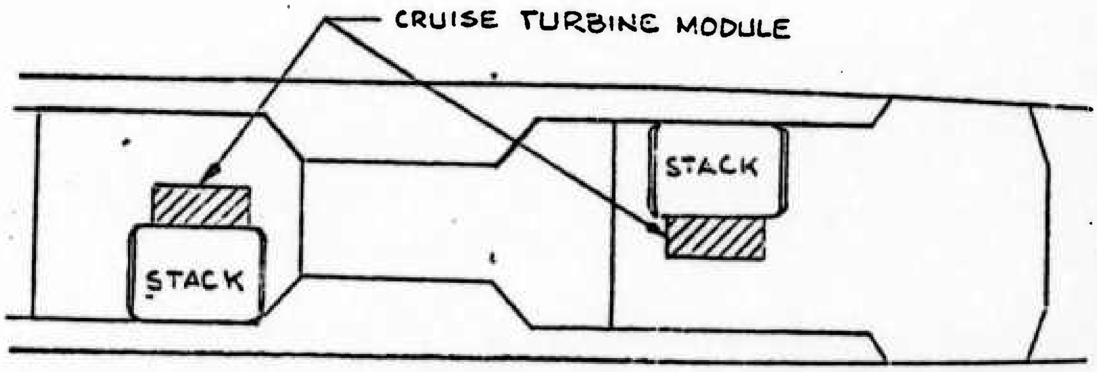
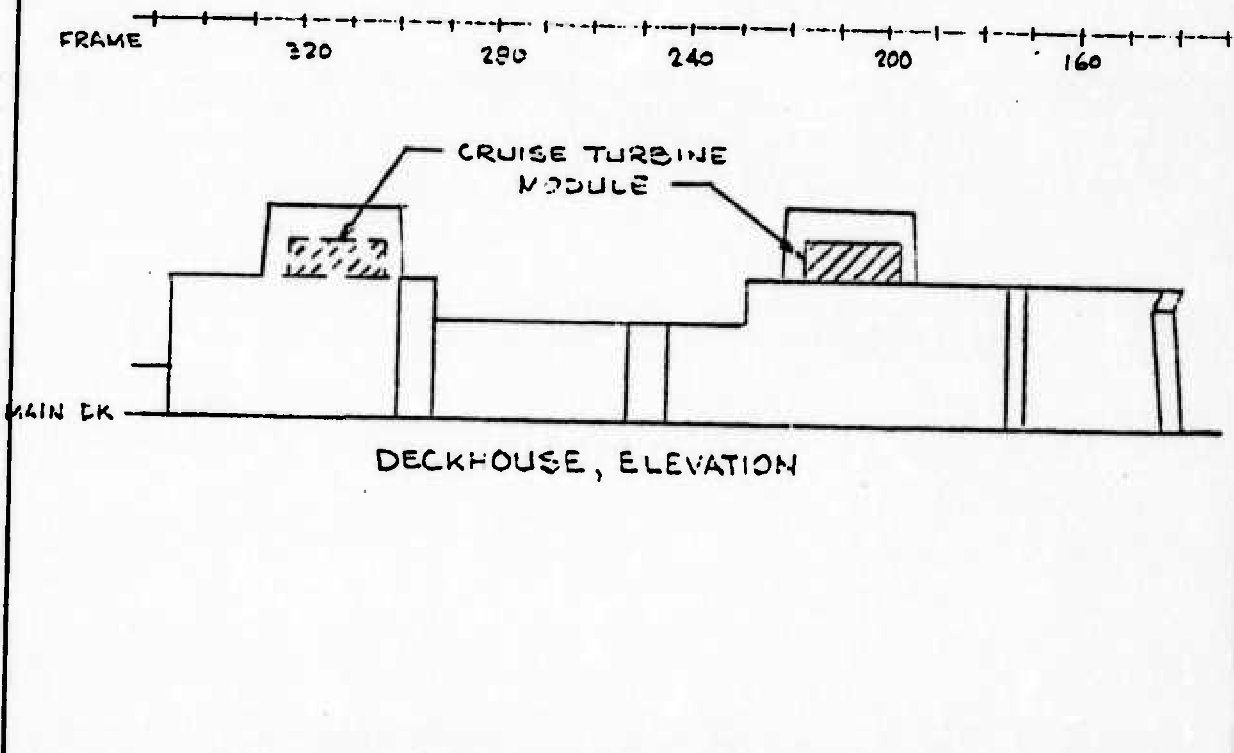


Figure 2-6. Cruise Turbine Module



DECKHOUSE, PLAN VIEW



DECKHOUSE, ELEVATION

Figure 2-7. Location of Cruise Turbine Modules piping will be run within the machinery casing between the cruise turbine module and the engine room with disconnect devices in the engine room in the event of damage to the module. Separate disconnect devices are also provided in each engine room to isolate the electrical cross-connect between engine rooms in the event of damage. It should be noted that the cruise turbine module can be easily installed within a standard 8'x8'x20' shipping container.

### 2.3.4 Installation of Superconducting Electric Propulsion in the Reconfigured Engine Room

This modification (figure 2-8) requires that the existing main reduction gear be replaced by superconducting electric propulsion, as does the previous modification. However, in this case an attempt was made to optimize the engine room arrangement by raising the main propulsion turbines and by relocating the main propulsion motors aft into the shaft alley area.

In this arrangement, the propulsion gas turbines and the 20,000 hp propulsion generators are moved up onto the 24'-0" level. In addition, the 24'-0" level is extended from the centerline to the shell to fill in the area formerly occupied by the gas turbine ductwork. The generator cryosections are located in the overhead of the 15'-0" level, directly under the propulsion generators.

The 15'-0" level is also extended from the centerline area to the shell. The helium and coolant systems and the 20,000 hp generator disconnect switches are located on this level. The CRP system is locked in a fixed

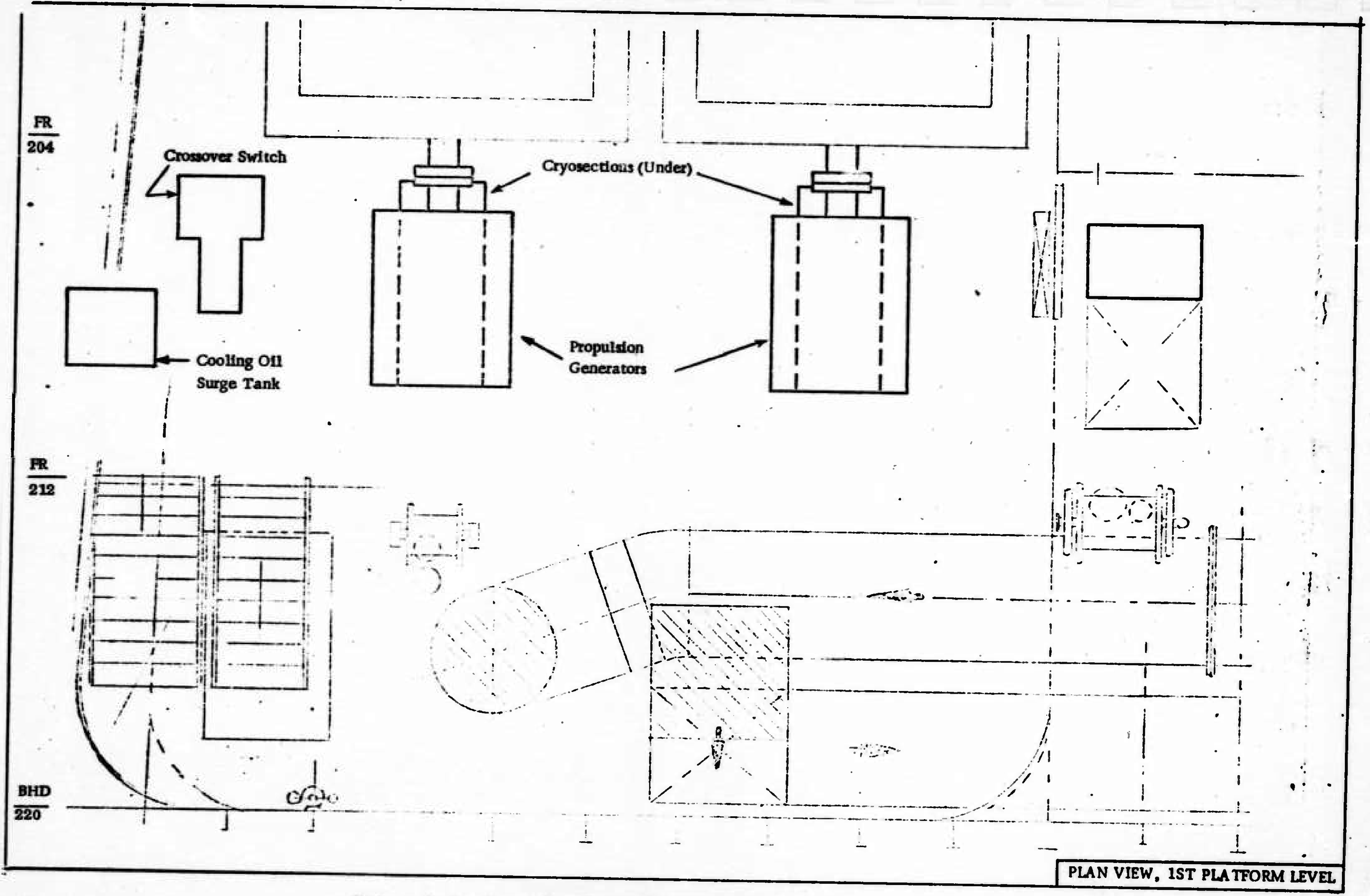
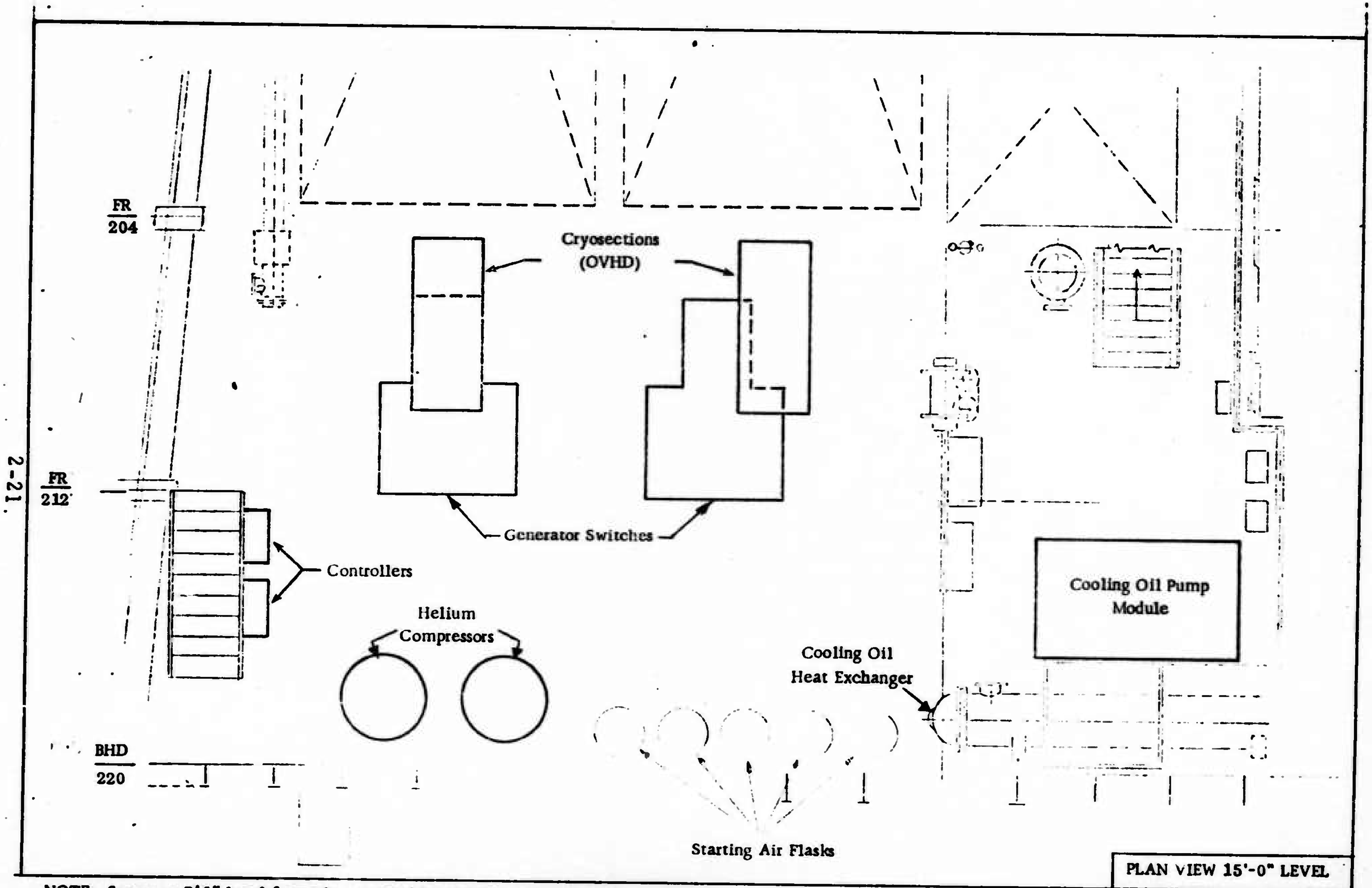


Figure 2-8. Sheet 1. Reconfigured Engine Room



NOTE: Space on 7'6" level formerly occupied by turbines and gearing is now vacant.

Figure 2-8, Sheet 2. Reconfigured Engine Room position as in the last arrangement (Section 2.3) and the existing attached lube oil pump. The main lube oil cooler is relocated to the 7'-6" level.

Necessary relocation of other equipment, including lube oil storage and settling tanks, electronics cabinets, power panels, fuel oil service heaters, air filter, ladders, various fire fighting hose reels and cylinders, and air starting cylinders, are detailed in Appendix D.

The location of the 5000 hp cruise turbines is as shown in figure 2-9. Only one crossover switch is provided in the aft engine room, since both electric transmission lines must pass through this space.

The location of the propulsion motors is shown in figure 2-10. The propulsion motors displace sewage treatment equipment which is relocated to the space gained under the main propulsion turbines in one of the engine rooms. No attempt was made at this time to optimize the shaft angles or relocate the shaft tubes. Additional studies are required into the serviceability of the propulsion motors in the location shown and into the possibility of providing a third set of helium-cooling oil-lube oil service equipment in lieu of piping these services aft from the engine rooms.

### Cruise Turbine Relocation to Engine Rooms

The cruise turbines are shown mounted in deck house modules adjacent to the stacks for both the existing and reconfigured engine room layouts. The arrangement has advantages in terms of ductwork, accessability and engine room space. However, the systems studies show a 1 to 2% improvement in range and fuel economy if the turbines are located in the

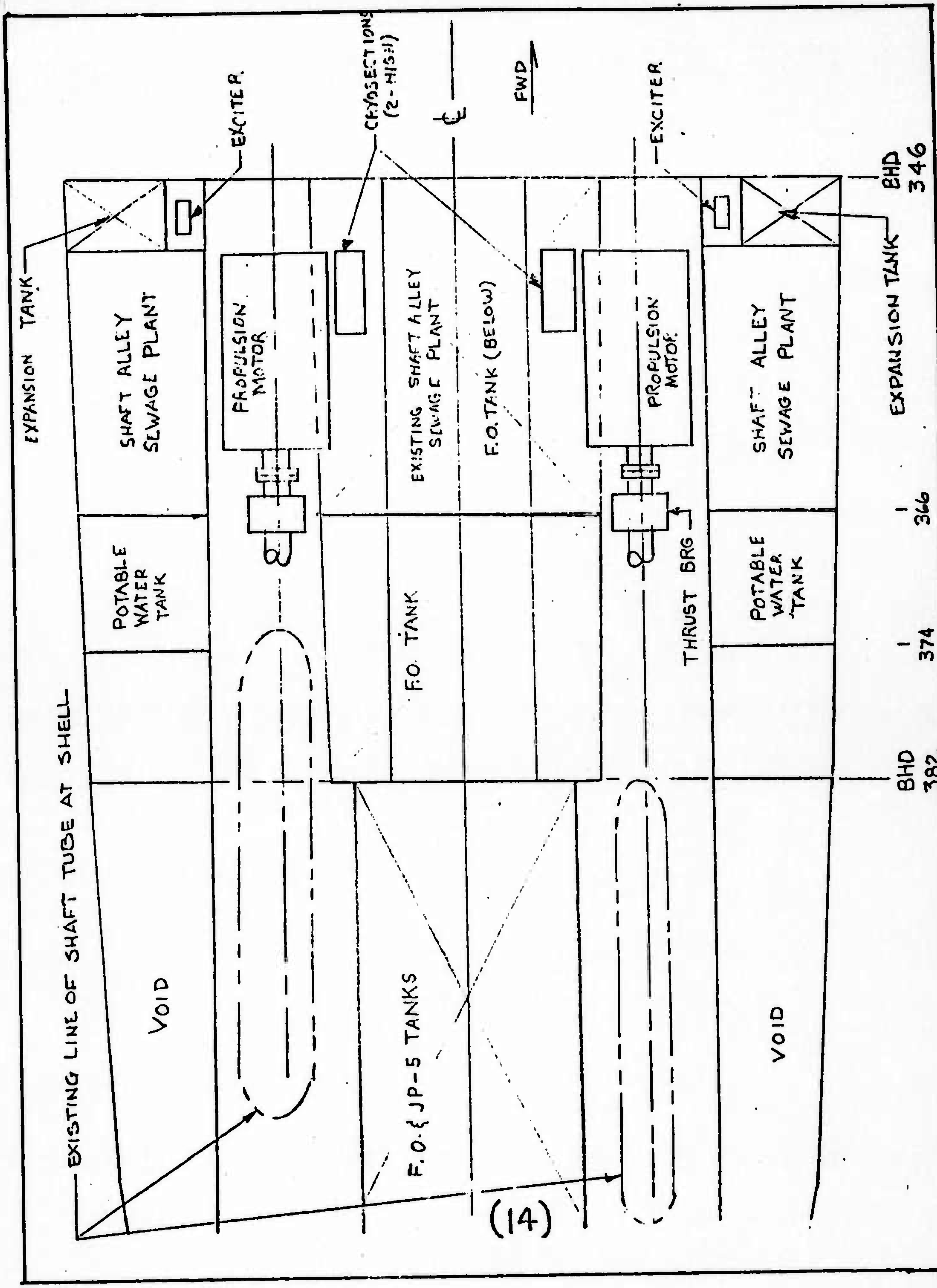


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Figure 2-9. Location of Propulsion Motors - Plan View

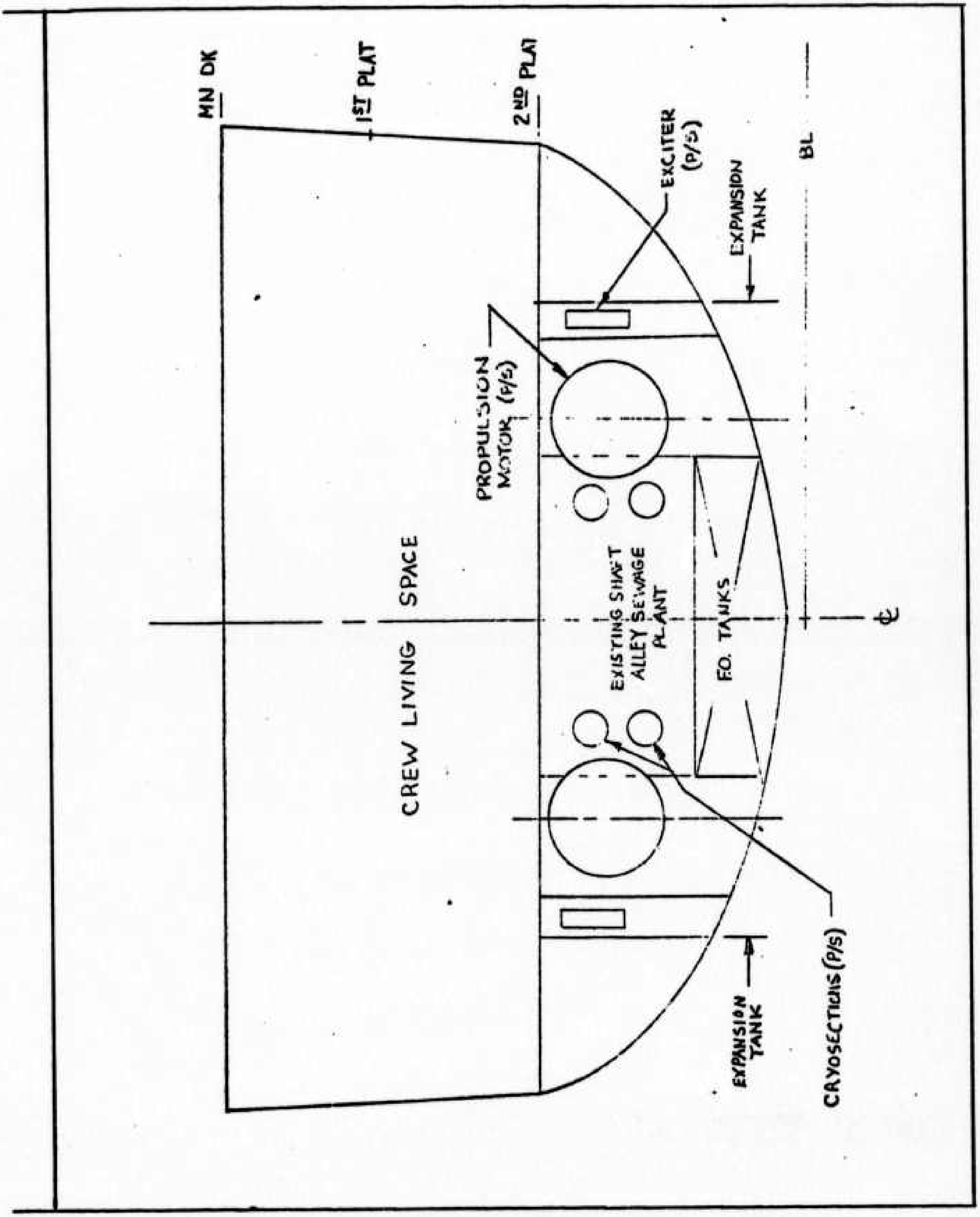


Figure 2-10. Location of Propulsion Motors - Looking Aft

engine rooms, due to weight reductions and elimination of long electrical transmission lines. If located in the engine rooms, the turbines would be placed in the approximate locations occupied by the cruise turbines in the geared drive case.

## 2.4 ESTIMATE OF WEIGHT CHANGES

The equipment removed and added as a result of the modifications and the estimated weights for the various pieces of equipment are given in Appendix D. (Note: Due to the preliminary nature of much of the available information, no attempt was made to estimate changes in structural weights or changes in various ship systems caused by these modifications.) A summary of the total weight changes is given in table 2-1. It will be noted that weights for some modifications are not included. The weight savings in replacement of the CRP propeller by a fixed pitch propeller and the reduction in main turbine ductwork weight for the reconfigured engine room could represent substantial savings for the electrical drive systems but insufficient information was at hand in the available time to make reliable estimates for these weights.

In the absence of sufficient data for reliable computation of reduction in ductwork weight, and other structural modifications required to adapt the electric drive to the existing hull, the effect on ship stability of placing the cruise turbine modules topside and of moving the main turbines from the

15 ft to the 24 ft level was not computed (These configurations involve the superconductive electric propulsion systems only). It is assumed that future electric drive designs will involve new ship designs and that satisfactory balancing of moments will not be a problem.

## Table 2-1

### Summary of Weight Changes

| Geared Drives | Wt. Removed | Wt. Added | Wt. Change |
|---|---|---|---|
| Addition of Alternators | 0 | 49,000 lbs (1) | 21.9 tons |
| Addition of Cruise Turbines | 0 | 22,000 lbs (1, 2) | 9.8 tons |
| Addition of Alternators + Turbines | 0 | 71,000 lbs (1, 2) | 31.7 tons |
| **Electric Drive With Main Turbines Only** | | | |
| Existing Engine Room Configuration | 390,000 lbs (3) | 421,378 lbs | 14.0 tons |
| Reconfigured Engine Room | 538,200 lbs (3,4) | 416,303 lbs | (-54.4) tons |
| **Electric Drive With Main Plus Cruise Turbines** | | | |
| Existing Engine Room Configuration | 390,000 lbs (3) | 457,047 lbs | 29.9 tons |
| Reconfigured Engine Room | 538,200 lbs (3, 4) | 462,769 lbs | (-33.7) tons |
| Cruise Turbines Located in Engine Room | 538,200 lbs (4) | 453,769 lbs (5) | (-37.7) tons |

(1) Does not include weight modification in main reduction gear.

(2) Does not include duct work, service piping and cables for cruise turbines.

(3) Does not include replacement of CRP propellor by fixed pitch propellor; CRP is considered locked in place with hydraulics removed.

(4) Does not include reduction in turbine duct work resulting from moving the turbines closer to the main deck.

(5) Same as reconfigured engine room less 9,000 lbs for cruise turbine container structure and transmission and cryo line weight reductions.

## 3.0 PERFORMANCE ANALYSIS

Each of the configurations was studied to determine the effect on performance over the standard destroyer profile shown in figure 3-1. The operating regions shown for the various turbine combinations mean that the systems nominally operate as follows:

Baseline: 2 Main Turbines to 27 Knots
4 Main Turbines from 28 to 32 Knots

Baseline + Alternators and Electric Drive with Main Turbines:

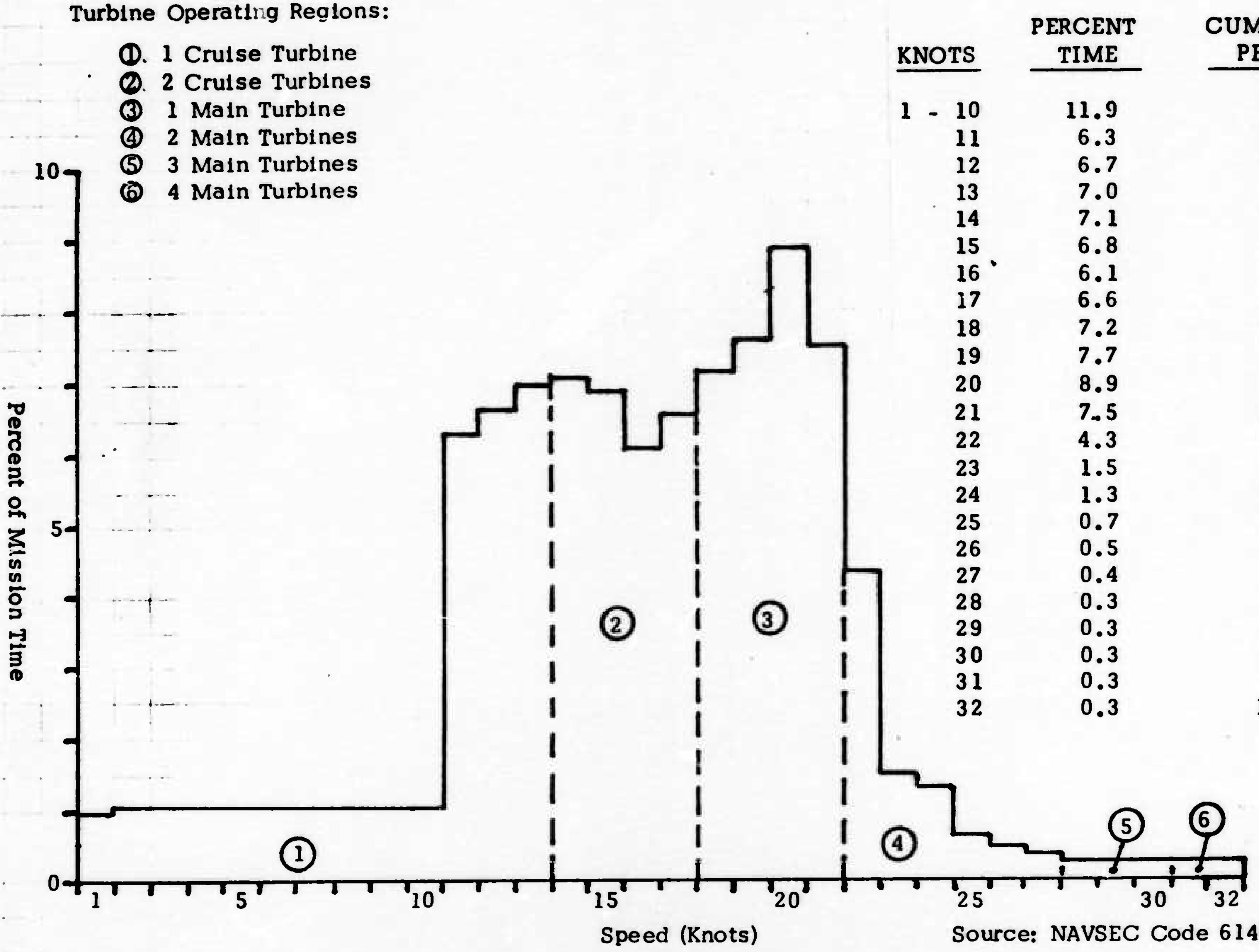
1 Main Turbine to 21 Knots
2 Main Turbines from 22 to 27 Knots
3 Main Turbines from 28 to 30 Knots
4 Main Turbines from 31 to 32 Knots

Baseline + Cruise Turbines:

2 Cruise Turbines to 17 Knots
2 Main Turbines from 18 to 27 Knots
4 Main Turbines from 28 to 32 Knots

Baseline + Alternators and Cruise Turbines:

1 Cruise Turbine to 13 Knots
2 Cruise Turbines from 14 to 17 Knots
1 Main Turbine from 18 to 21 Knots
2 Main Turbines from 21 to 27 Knots
3 Main Turbines from 28 to 30 Knots
4 Main Turbines from 31 to 32 Knots



| KNOTS | PERCENT TIME | CUMULATIVE PERCENT |
|---|---|---|
| 1 - 10 | 11.9 | 11.9 |
| 11 | 6.3 | 18.2 |
| 12 | 6.7 | 24.9 |
| 13 | 7.0 | 31.9 |
| 14 | 7.1 | 39.0 |
| 15 | 6.8 | 45.8 |
| 16 | 6.1 | 51.9 |
| 17 | 6.6 | 58.5 |
| 18 | 7.2 | 65.7 |
| 19 | 7.7 | 73.4 |
| 20 | 8.9 | 82.3 |
| 21 | 7.5 | 89.8 |
| 22 | 4.3 | 94.1 |
| 23 | 1.5 | 95.6 |
| 24 | 1.3 | 96.9 |
| 25 | 0.7 | 97.6 |
| 26 | 0.5 | 98.1 |
| 27 | 0.4 | 98.5 |
| 28 | 0.3 | 98.3 |
| 29 | 0.3 | 99.1 |
| 30 | 0.3 | 99.4 |
| 31 | 0.3 | 99.7 |
| 32 | 0.3 | 100.0 |

Source: NAVSEC Code 6144B, 18 Mar. 71

Figure 3-1. Standard NAVSEC Destroyer Profile

Representative fuel consumption for each turbine is shown in figure 3-2 in terms of miles per ton of fuel vs. speed. Also shown is the resultant nominal range, based on burning 1200(1) tons of fuel. The miles per ton and ranges given would occur only if the turbines were the sole drain on the ship's fuel tanks. In actuality, the turbines must share the available fuel with the auxiliary fuel load (ships service electric and other loads). The effect of adding a 3520 lb/hr auxiliary fuel load to the turbine fuel rates is shown in figure 3-3; the turbine fuel rates at low speeds are much less than the ship service load, resulting in drastic range capability reduction, while the effect at very high speeds is relatively minor.

In order to assess each drive system configuration on a common basis, the following were done:

- Turbine fuel rate was computed for each speed in the mission profile.
- Cooling, lubrication and refrigeration(2) loads were computed for each configuration in terms of lbs/hr of fuel.
- Endurance fuel load (tons of fuel available in the tank) was assumed to be 1430 tons(3), plus any weight difference between

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(1) Represents a 1400 ton tank with 87% of the fuel utilized.

(2) Power required to run the helium refrigeration systems required in the case of superconducting equipment.

(3) Endurance fuel load was estimated at 1430 tons for the baseline systems based on 4500 miles endurance at 20 knots; see Appendix A.

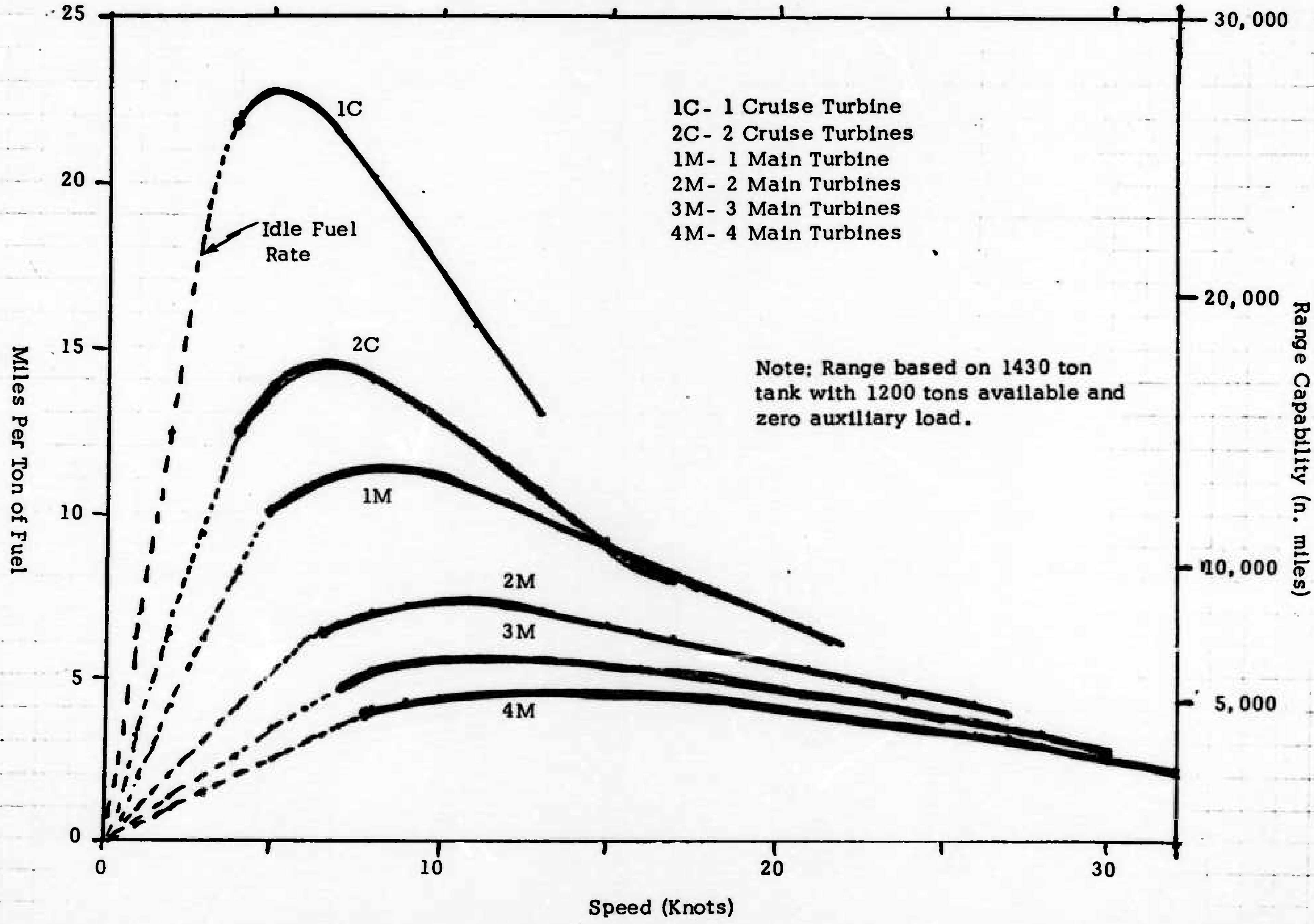
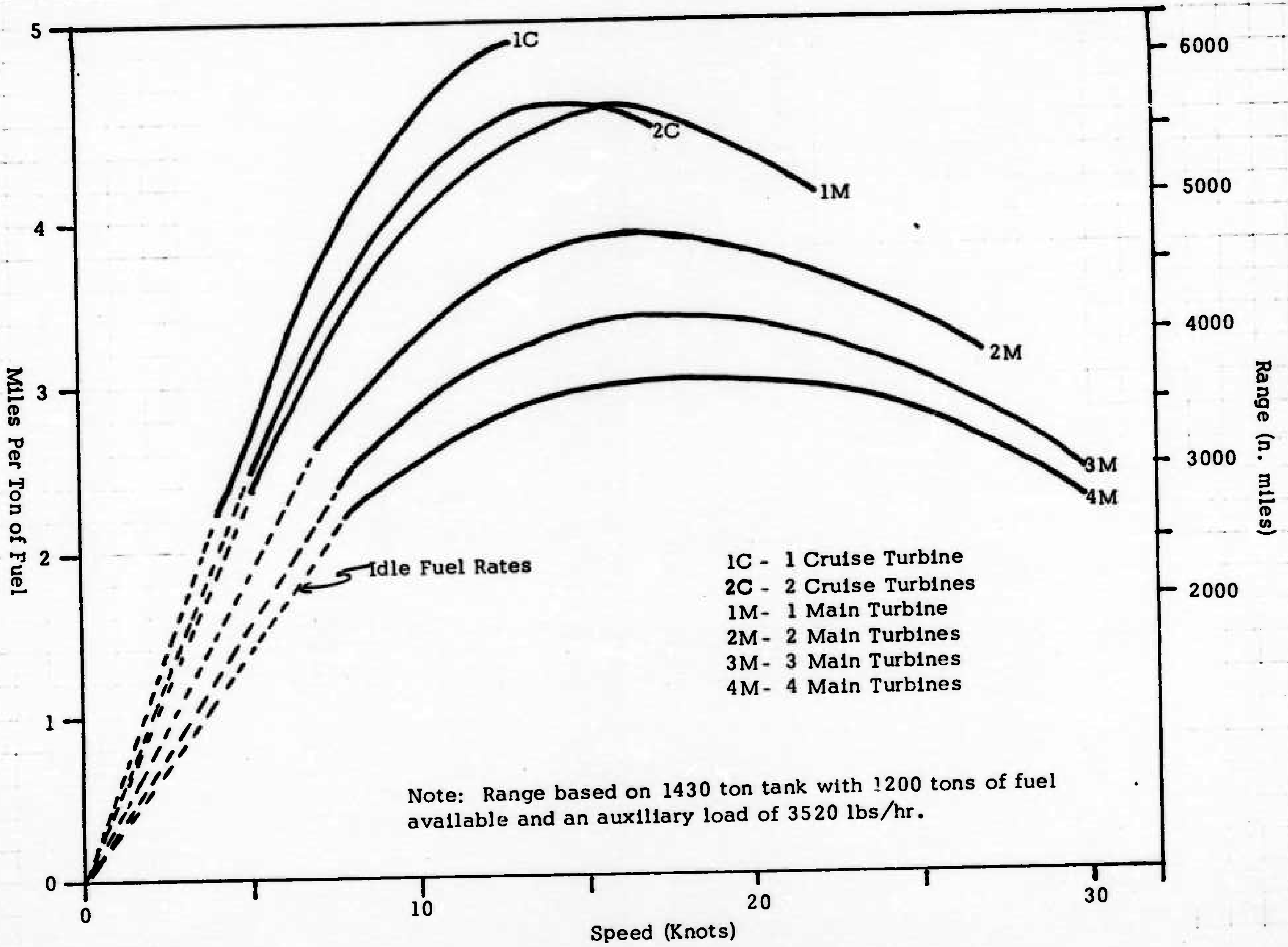


Figure 3-2. Turbine Range Capabilities With No Auxiliary Fuel Load



Note: Range based on 1430 ton tank with 1200 tons of fuel available and an auxiliary load of 3520 lbs/hr.

Figure 3-3. Turbine Ranges With Auxiliary Fuel Load the configuration under study and the baseline (i.e. the ship's displacement was held fixed).

- A fixed auxiliary fuel load of 3520 lbs/hr was applied throughout the mission (see table A-4, Appendix A).
- Range was computed for each speed based on the endurance fuel load and the total fuel rate (turbines + cooling, lube and refrigeration load + auxiliary load).
- Average range and average propulsion fuel rate over the mission profile were computed.

Computer printouts of the results for each configuration are contained in Appendix C and a summary of results is given in table 3-1. As shown in figure 3-4, the total propulsion fuel rate, which is independent of both the auxiliary fuel rate and the endurance fuel load, is reduced by as much as 21% by the geared drive modifications and 25% by the electric drive modifications. Increases in range are affected by the auxiliary fuel load and weight of equipment added and show increases ranging from 12.5% for the geared drive to 18.1% for the electric drive. The smaller percentage increase in range capability, as compared to the propulsion fuel rate improvement, results from the auxiliary fuel load rate. The large range variations in configurations having nearly equal fuel rates results from differences in equipment weight (which affect the endurance fuel load).

Table 3-1. Summary of Performance Results

| Geared Drives | Endurance Fuel Load (Tons)(1) | Propulsion System Average Tons/Mile(2, 3) | Average Range(2) | 20 kt Range | Max. Range |
|---|---|---|---|---|---|
| Baseline | 1430 | 0.181 | 4440 | 4696 | 4836 @ 16.5 kts |
| Baseline + Alternators | 1408 | 0.151 | 4885 | 5167 | 5450 @ 15.6 kts |
| Baseline + Cruise Turbines | 1420 | 0.157 | 4822 | 4660 | 5772 @ 14.5 kts |
| Baseline + Alternators & Cruise Turbines | 1398 | 0.142 | 5036 | 5142 | 6012 @ 12.7 kts |
| **Electric Drives-No Cruise** | | | | | |
| Baseline | 1416 | 0.144 | 5073 | 5390 | 5745 @ 15.8 kts |
| Reconfigured | 1480 | 0.144 | 5304 | 5659 | 5865 @ 15.8 kts |
| **Electric Drives-With Cruise** | | | | | |
| Baseline | 1400 | 0.138 | 5143 | 5306 | 6082 @ 12.7 kts |
| Reconfigured | 1464 | 0.138 | 5377 | 5573 | 6339 @ 12.7 kts |
| Optimum Cruise Turb. Location | 1468 | 0.136 | 5423 | 5588 | 6468 @ 13.5 kts |

(1) 87% of fuel considered available (5% below tailpipe; 5% allowed for average 2 year aging; 4% arbitrary measurement factor - see Appendix A, Section A.5).

(2) Over Standard Destroyer Mission Profile; Avg. speed: 15.8 kts.

(3) Propulsion system including auxiliary load for cooling system (all configurations) and refrigeration system (electric drives only); add 0.100 tons/mile over mission profile, for auxiliary fuel load (3520 lbs/hr ÷ 15.8 kts) for total tons/mile.

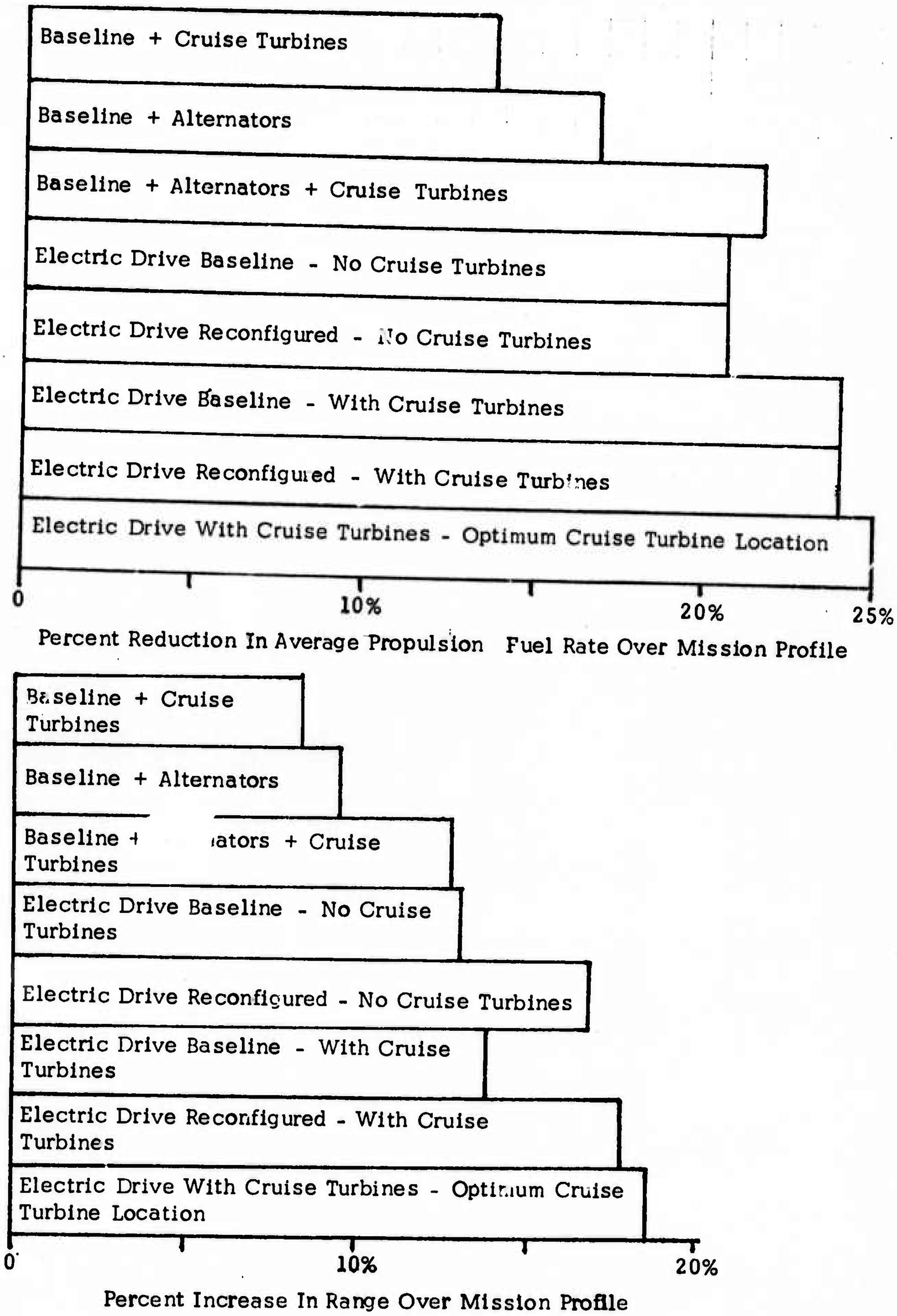
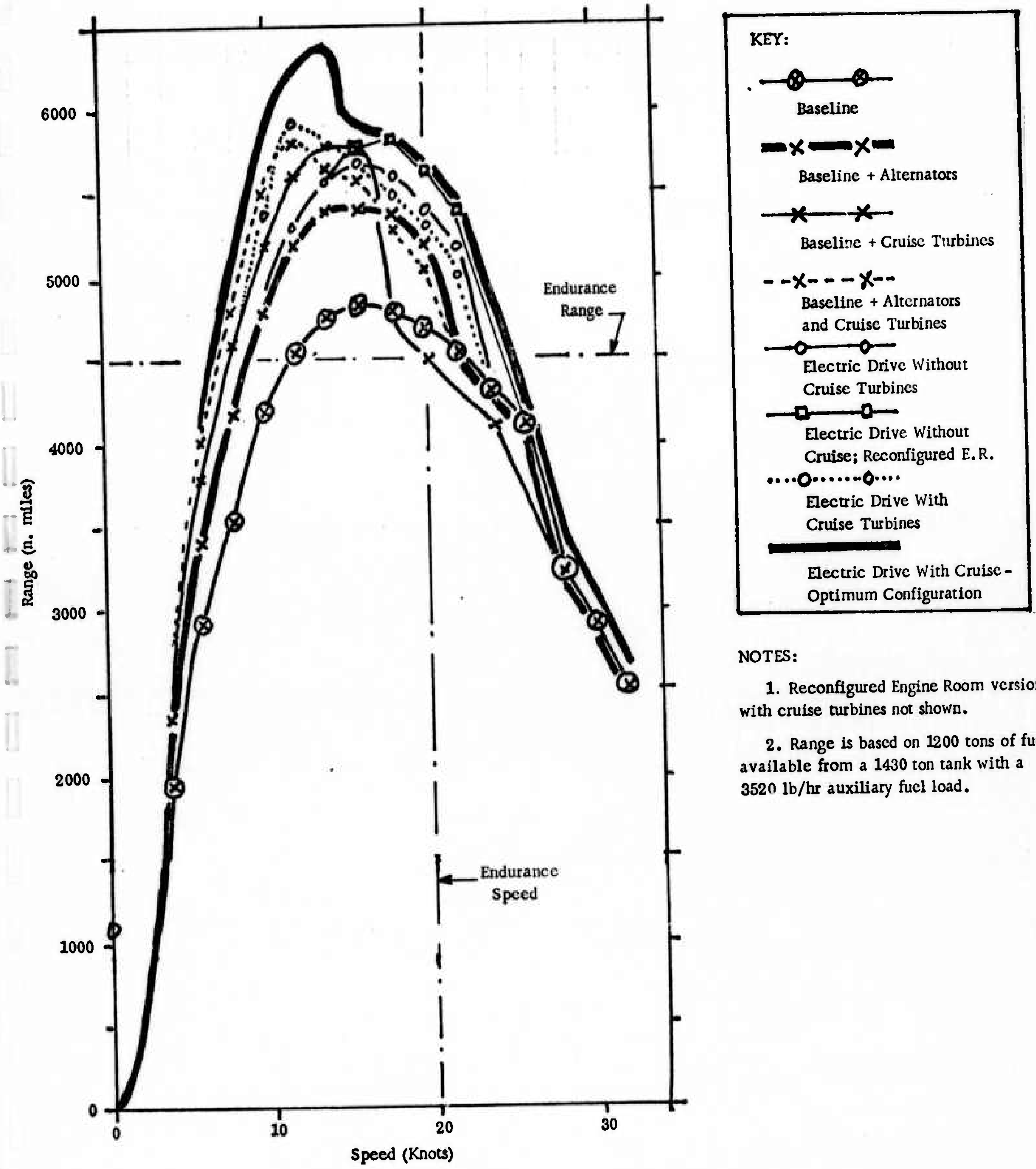


Figure 3-4. Fuel and Range Improvements Over Mission Profile

As would be expected from the individual turbine performances, see figures 3-2 and 3-3 increases in range capabilities are much greater at lower cruising speeds, as shown in figure 3-5. Percentage increases at each speed are shown in figure 3-6.

Changes in average range over the mission profile for auxiliary fuel loads of other than 3520 lbs/hr may be evaluated from figure 3-7. The heavy line shows change in range vs. auxiliary fuel load for electric drive systems and the geared system with alternators and cruise turbines, while the dashed line shows results for the baseline system; other configurations lie between these two curves. It will be noted that the baseline is less sensitive to auxiliary fuel changes than the other configurations because the baseline fuel rates are higher than for the modified systems and thus less sensitive to the added fuel load.

Fuel consumption per 1000 hours of operation is shown in figure 3-8, which shows a skewing of the fuel rate because of the mission time profile (figure 3-1). A comparison of minimum fuel rates over the mission profile is given in table 3-2. With no auxiliary fuel load, the speed for maximum range would lie between 5 knots for the mechanical system with alternators and cruise turbines and 10.5 knots for the baseline configuration. When a 3520 lb/hr auxiliary fuel load is added, the corresponding speeds for maximum range increase to 12.7 and 16.7 knots.

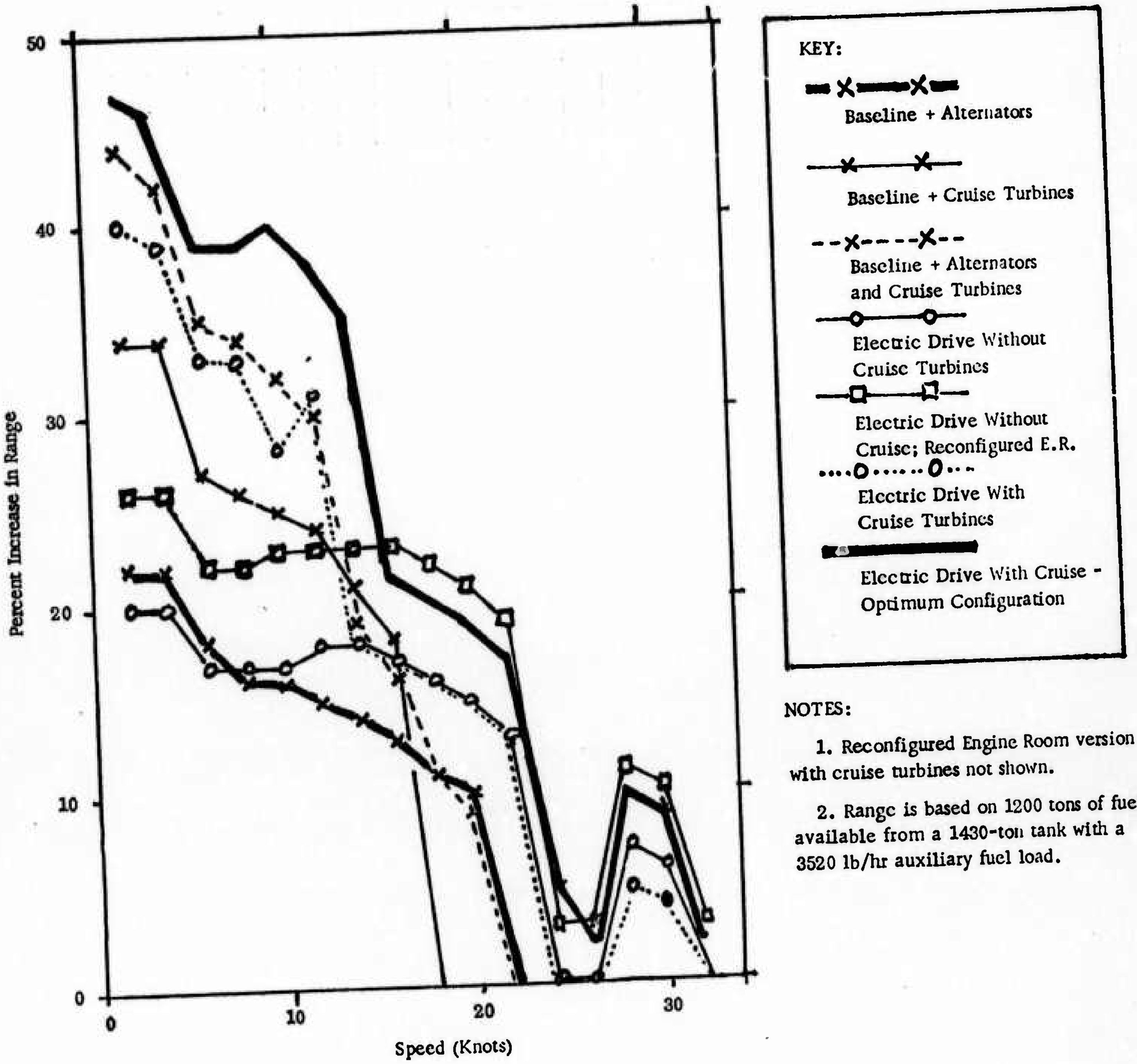


NOTES:

1. Reconfigured Engine Room version with cruise turbines not shown.

2. Range is based on 1200 tons of fuel available from a 1430 ton tank with a 3520 lb/hr auxiliary fuel load.

Figure 3-5. Range Versus Speed

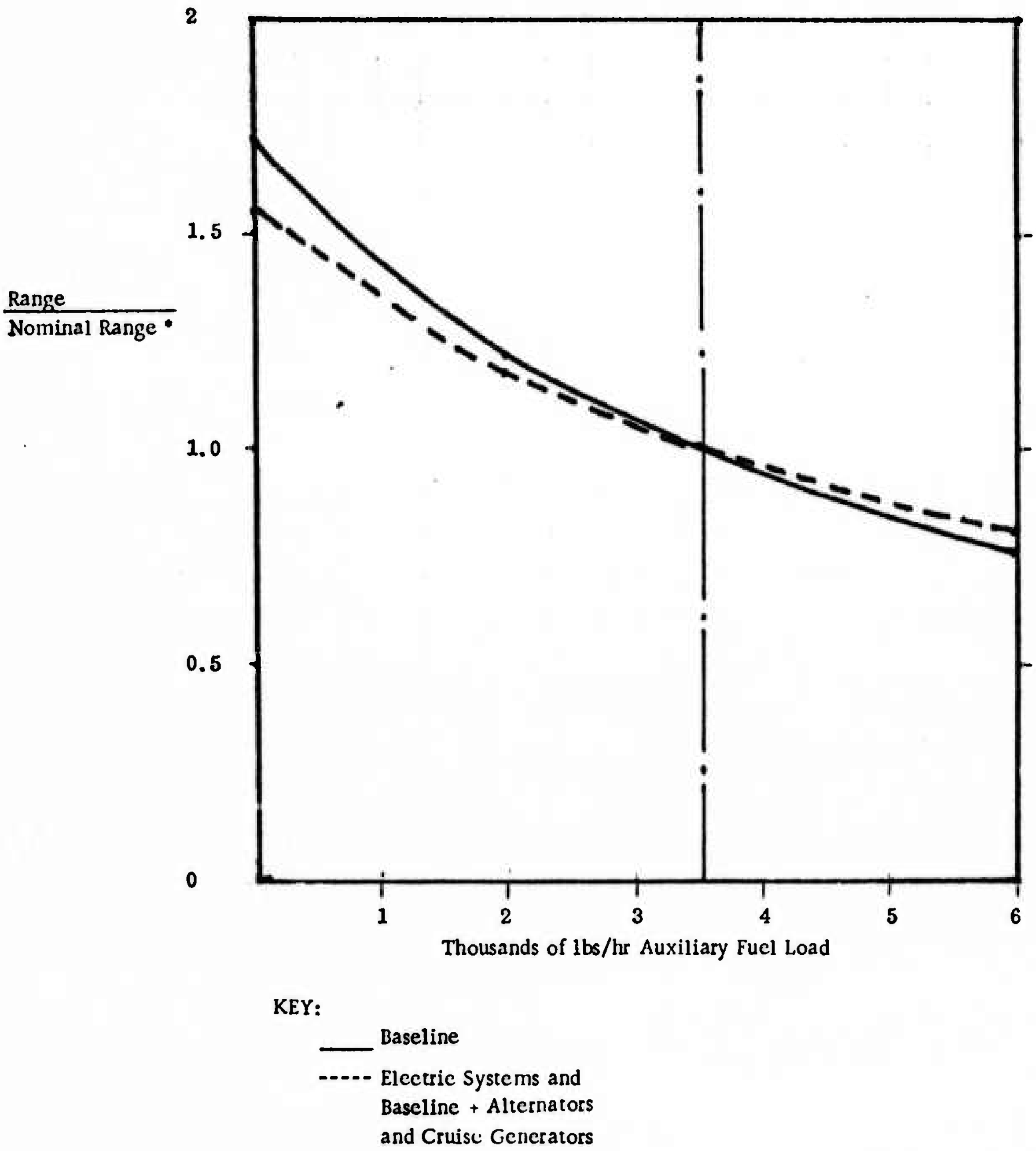


NOTES:

1. Reconfigured Engine Room version with cruise turbines not shown.

2. Range is based on 1200 tons of fuel available from a 1430-ton tank with a 3520 lb/hr auxiliary fuel load.

Figure 3-6. Percent Range Increase Versus Speed



* Nominal range = range with 3520 lb/hr auxiliary fuel load.

Figure 3-7

Variation of Range With Auxiliary Fuel Load

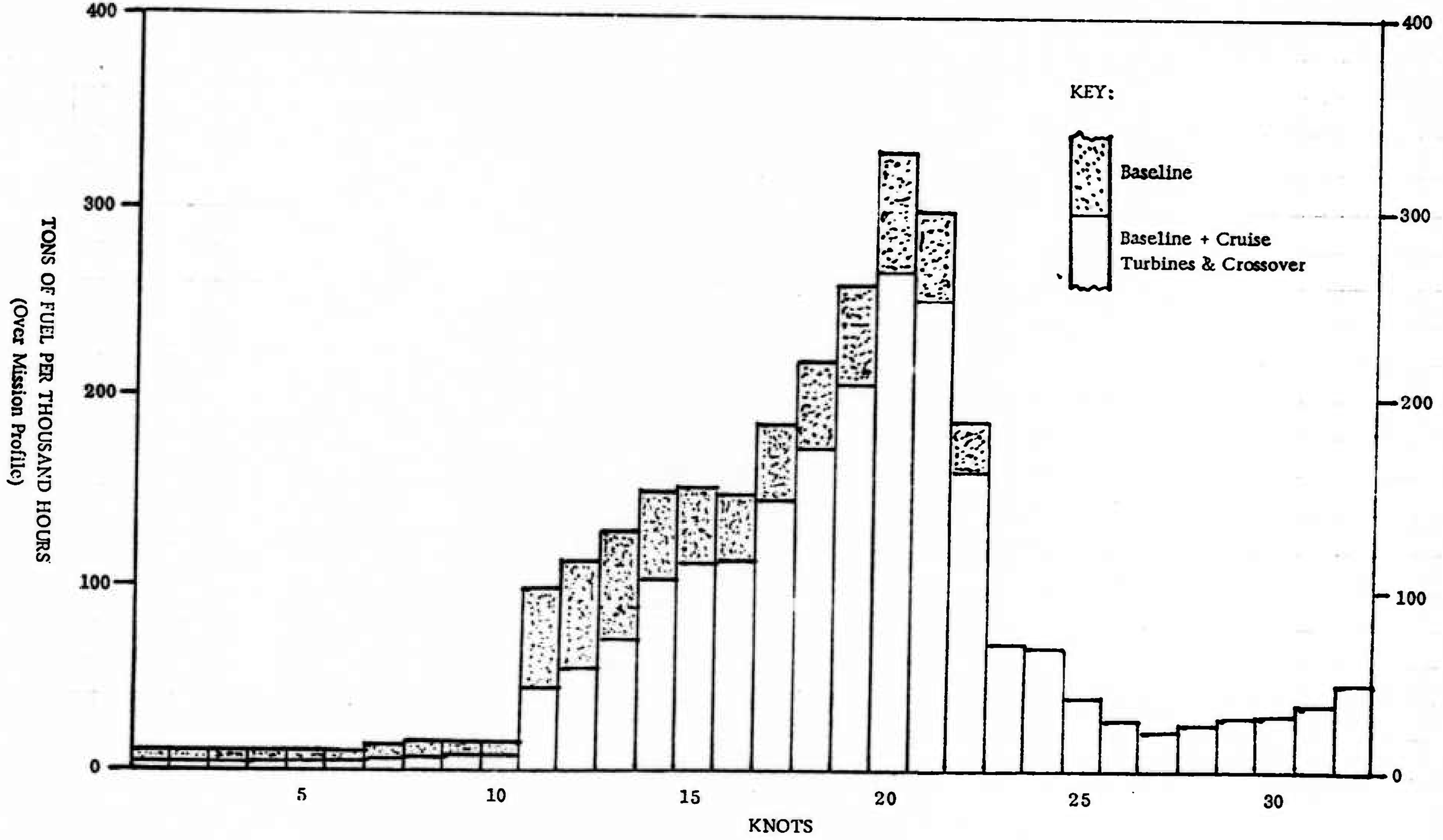


Figure 3-8

Fuel Consumption Versus Speed

Table 3-2. Fuel Rate Comparison

| Geared Drives | Minimum Propulsion Tons/Mile | Minimum Propulsion + Auxiliary Fuel Tons/Mile |
|---|---|---|
| Baseline | 0.141 @ 10.5 kts | 0.162 + 0.095 = 0.257 @ 16.5 kts |
| Baseline + Alternators | 0.092 @ 7.5 kts | 0.126 + 0.100 = 0.225 @ 15.6 kts |
| Baseline + Cruise Generators | 0.070 @ 6.0 kts | 0.106 + 0.108 = 0.214 @ 14.5 kts |
| Baseline + Alternators & Cruise Generators | 0.046 @ 5.0 kts | 0.079 + 0.124 = 0.202 @ 12.7 kts |
| <u>Electric Drives-No Cruise</u> | | |
| Baseline | 0.091 @ 8.5 kts | 0.115 + 0.099 = 0.214 @ 15.8 kts |
| Reconfigured | 0.091 @ 8.5 kts | 0.119 + 0.099 = 0.220 @ 15.8 kts |
| <u>Electric Drives-with Cruise</u> | | |
| Baseline | 0.052 @ 6.0 kts | 0.076 + 0.124 = .200 @ 12.7 kts |
| Reconfigured | 0.052 @ 6.0 kts | 0.077 + 0.124 = .201 @ 12.7 kts |
| Optimum Cruise Turb. Location | 0.052 @ 6.0 kts | 0.081 + 0.116 = .197 @ 13.5 kts |

## 3.1 SYSTEM LOSSES AND EFFICIENCIES

In order to compare propulsion system efficiencies between various configurations, the optimum specific fuel consumption (SFC) for the main turbine(1) was used to establish an "ideal" efficiency for the turbine. A figure of merit (FOM), defined as optimum SFC divided by actual SFC, is used as a measure of efficiency for the turbine (ranges from zero at idle to 1.0 at full power) and the optimum SFC is used to convert fuel rate to equivalent "100 percent efficient" horsepower and vice-versa. As shown in figure 3-9, this equivalence permits apportionment of the propulsion system losses between the turbines, drive system and propellors. The turbine efficiency, or FOM, represents the efficiency of the turbine in converting fuel to power as compared to its efficiency at full load. The drive system efficiency includes gear and alternator losses and associated cooling load for the mechanical systems and includes all motor, generator and transmission line losses and associated cooling, generator lubrication and helium refrigeration loads for the super conducting systems. Propellor efficiency is included as a part of the propulsion system efficiency because the variable pitch propellor is an integral part of the geared drive systems and propellor efficiency differs over the mission profile (different pitches are used for different turbine combinations).

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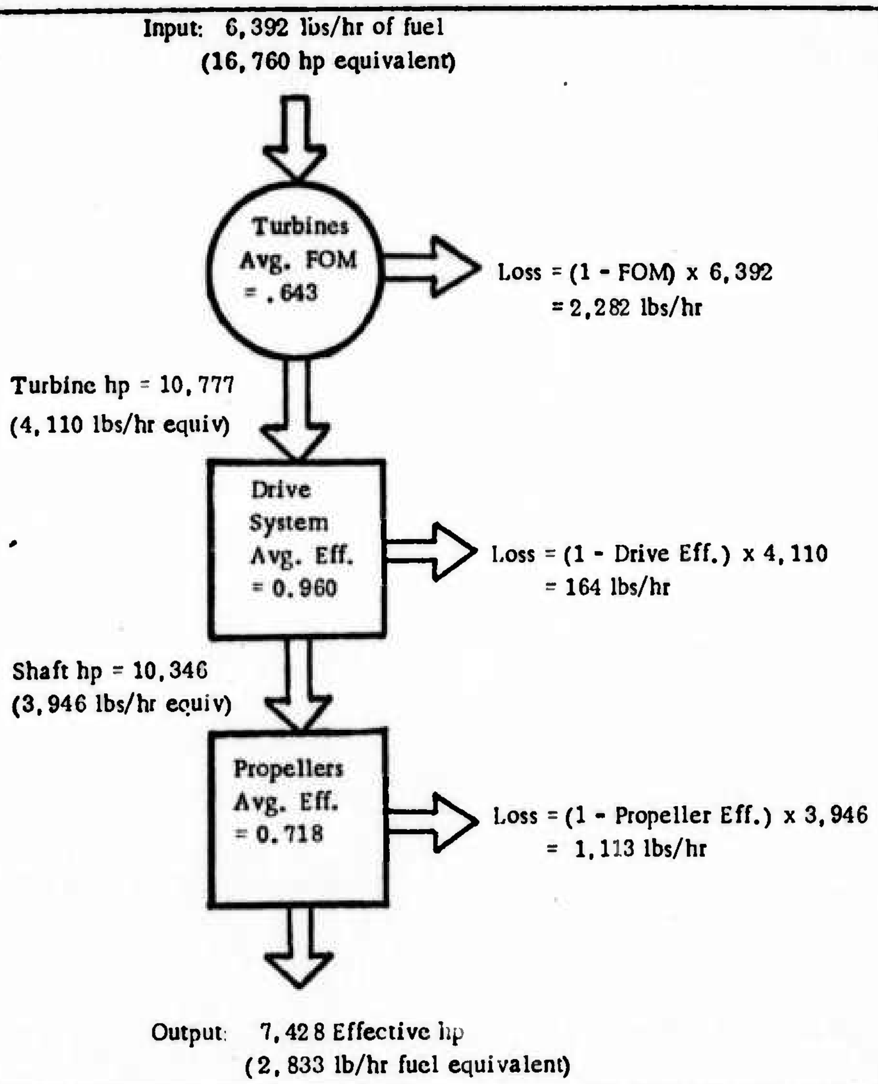
(1) 0.3814 lbs of fuel/hp-hr at full power; see Appendix A.



TURBINE Average FOM $= SFC_0 \times \frac{THP}{W_F}$

DRIVE SYSTEM Average Eff. $= \frac{SHP}{THP}$

PROPELLER Average Eff. $= \frac{EHP}{SHP}$

OVERALL EFFICIENCY $= \left(\begin{matrix}\text{Avg.}\\ \text{FOM}\end{matrix}\right) \times \left(\begin{matrix}\text{Avg. Drive}\\ \text{System Eff.}\end{matrix}\right) \times \left(\begin{matrix}\text{Avg. Propeller}\\ \text{Eff.}\end{matrix}\right)$

$= SFC_0 \times \frac{EHP}{W_F} = \frac{2,833}{W_F}$

EHP = Avg. Effective Horsepower (= 7,428 hp over mission profile)
SHP = Avg. Shaft Horsepower over mission profile
THP = Avg. Turbine Horsepower over mission profile
$W_F$ = Avg. Turbine Fuel Rate over mission profile (lbs/hr)
$SFC_0$ = Optimum Specific Fuel Consumption for Main Turbine (= 0.3814)
FOM = Turbine Figure of Merit

**NOTE:** All horsepower/fuel rate equivalences are based on the main turbine optimum SFC of 0.3814 lbs/hp-hr

Figure 3-9. System Efficiencies and Equivalent Fuel Losses

A breakdown of system efficiencies averaged over the standard mission profile is given in table 3-3 and the equivalent losses in terms of fuel rate are given in table 3-4; figure 3-10 shows the results of table 3-4 graphically.(1) It is clear that the turbine efficiencies are the primary determinant of overall efficiency. The addition of cruise turbines to the baseline results in a negligible (3%) decrease in propellor losses and a large decrease (36%) in turbine losses as a result of the lower fuel rate required for the cruise turbines at low speeds. When alternators are added to the baseline the reduction in turbine losses is even greater (54%) but is partially offset by an 80% increase in drive system losses (due to the alternators being used for 91% of the mission time) and a slight (4%) increase in propellor losses.

The superconductive electric drive system without cruise turbines is comparable to the geared system with alternators. The electric drive system has a drive system loss comparable to the baseline geared system - about one-half that of the alternator system. However, if the added load required for the cryogenic helium compressors is added to the electric drive system loss, the total is comparable to the alternator drive system loss. The net improvement of the electric drive over the alternator drive comes from the cumulative effect of small efficiency improvements in each

---

(1) The magnetic field variation cases shown in the tables and figures are discussed in the next section.

## Table 3-3

### Average Propulsion System Efficiency Over Mission Profile

| | Average Efficiency | | | |
|---|---|---|---|---|
| | Propellors | Drive System | Turbines (FOM) | Overall Propulsion System Efficiency |
| **Geared Drive Systems** | | | | |
| Baseline | 0.718 | 0.960 | 0.643 | 0.443 |
| Baseline + Alternators | 0.710 | 0.931 | 0.802 | 0.530 |
| Baseline + Cruise Turbines | 0.725 | 0.960 | 0.735 | 0.511 |
| Baseline + Alternators & Cruise Turbines | 0.714 | 0.938 | 0.843 | 0.565 |
| **Electric Drive Systems-No Cruise Turbines** | | | | |
| Baseline | 0.726 | 0.961 | 0.814 | 0.568 |
| Reconfigured Engine Room | 0.726 | 0.961 | 0.814 | 0.568 |
| Baseline with No Field Adjustments | 0.726 | 0.964 | 0.738 | 0.517 |
| Baseline with Nearest 10% Field | 0.725 | 0.960 | 0.812 | 0.565 |
| **Electric Drive Systems-With Cruise Turbines** | | | | |
| Baseline | 0.726 | 0.960 | 0.856 | 0.596 |
| Reconfigured Engine Room | 0.726 | 0.959 | 0.856 | 0.596 |
| Optimized Cruise Turbine Location | 0.726 | 0.961 | 0.863 | 0.602 |
| Baseline with No Field Adjustments | 0.726 | 0.962 | 0.798 | 0.557 |
| Baseline with Nearest 10% Field | 0.726 | 0.959 | 0.862 | 0.600 |

Note: If the electric load due to cooling is considered as part of the drive system loss, both geared and electric drives have comparable efficiencies.

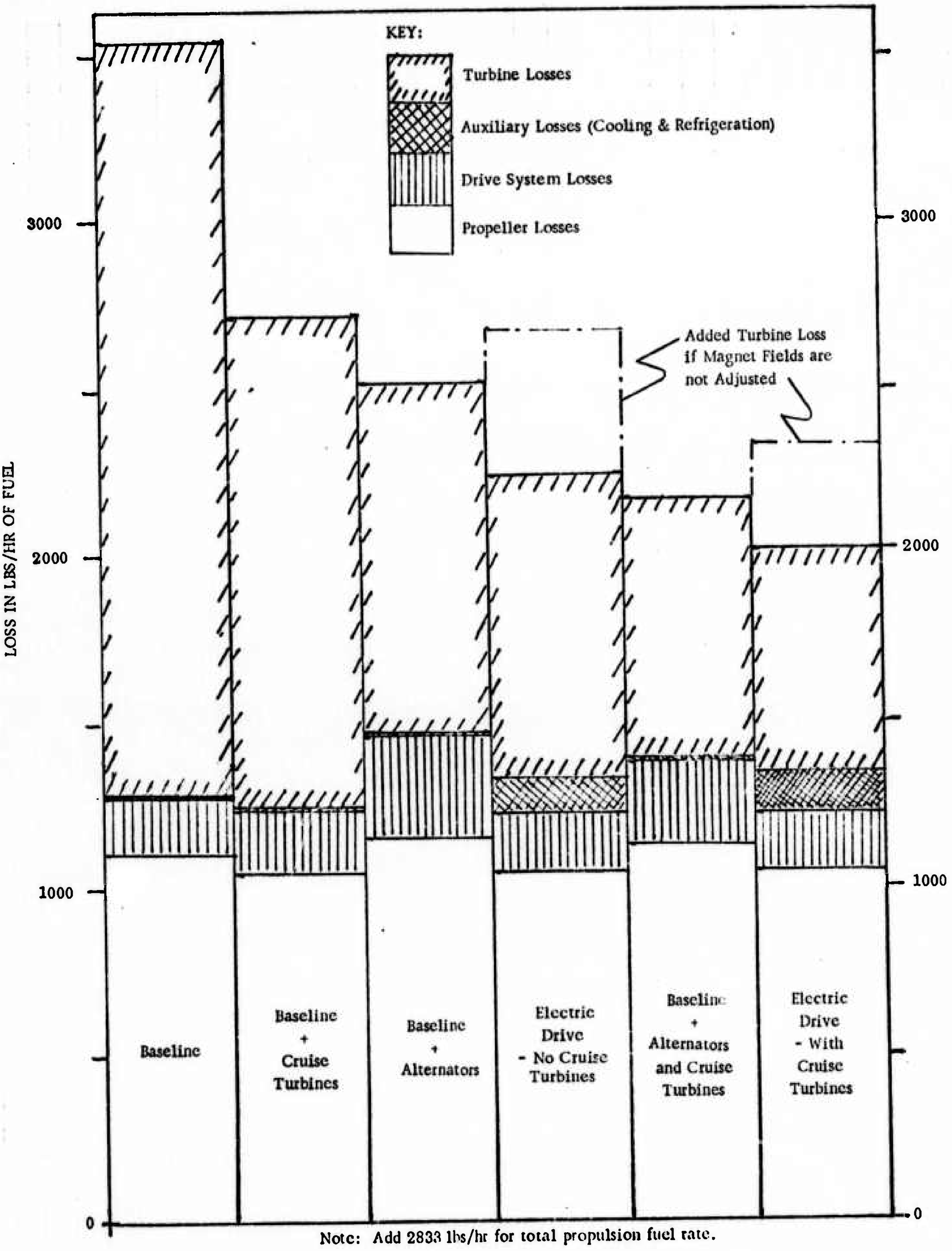
| Configuration | Drive Efficiency |
|---|---|
| Baseline & Baseline + Cruise Turbines | 0.958 |
| Baseline + Alternators | 0.935 |
| Electric Drive - No Cruise Turbines | 0.940 |
| Baseline + Alternators and Cruise Turbines | 0.935 |
| Electric Drive with Cruise Turbines | 0.934 |

## Table 3-4

### Average Losses Over Mission Profile

| | Losses (lbs/hr) | | | | | |
|---|---|---|---|---|---|---|
| | Propellers | Drive System | Turbines | Electric Load | Total Losses | Total Propulsion System Fuel Rate (lbs/hr) |
| **Geared Drive Systems** | | | | | | |
| Baseline | 1113 | 164 | 2282 | 7 | 3566 | 6399 |
| Baseline + Alternators | 1156 | 297 | 1057 | 13 | 2524 | 5357 |
| Baseline + Cruise Turbines | 1076 | 164 | 1470 | 7 | 2717 | 5550 |
| Baseline + Alternators & Cruise Turbines | 1134 | 263 | 787 | 11 | 2195 | 5028 |
| **Electric Drive Systems - No Cruise Turbines** | | | | | | |
| Baseline | 1069 | 160 | 926 | 88 | 2243 | 5076 |
| Reconfigured Engine Room | 1069 | 156 | 927 | 88 | 2240 | 5072 |
| Baseline with No Field Adjustments | 1069 | 145 | 1433 | 87 | 2734 | 5567 |
| Baseline with Nearest 10% Field | 1076 | 164 | 942 | 88 | 2270 | 5103 |
| **Electric Drive Systems - With Cruise Turbines** | | | | | | |
| Baseline | 1069 | 164 | 684 | 112 | 2029 | 4862 |
| Reconfigured Engine Room | 1069 | 168 | 683 | 112 | 2032 | 4865 |
| Optimized Cruise Turbine Location | 1069 | 160 | 643 | 112 | 1984 | 4816 |
| Baseline with No Field Adjustments | 1069 | 153 | 1029 | 112 | 2362 | 5194 |
| Baseline with Nearest 10% Field | 1069 | 168 | 650 | 112 | 1999 | 4832 |

Note: Total fuel rate minus Total Losses = Effective Fuel Rate = 2833 lbs/hr.



Note: Add 2833 lbs/hr for total propulsion fuel rate.

Figure 3-10
Average Propulsion System Losses

of the propulsion system elements (from 80.2% to 81.4% for the turbines, 92.8% to 94.0% for the combined drive system/electric load and 71.0% to 72.6% for the propellers)(1) which contribute to an overall reduction of 11% in propulsion system losses for the electric drive.

When both alternators and cruise turbines are added to the baseline system, a further decrease in turbine losses occurs (66% compared to the baseline) and drive system losses more nearly approach those for the baseline because the alternators are used less (64% of mission time). As a result, total propulsion system losses are decreased 38% from the baseline configuration.

The superconductive electric drive with cruise turbines is comparable to the geared system with alternators and cruise turbines. As in the case of the system without cruise turbines, small efficiency improvements in propeller and turbine efficiencies lead to a relatively large (8%) reduction in losses over the comparable geared system with alternators and cruise turbines, althrough the drive system plus electric load losses are now equivalent (275 lbs/hr each). The electric drive with cruise turbines shows a 43% reduction in fuel losses over the baseline configuration.

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(1) Note that the effect of these improvements is magnified; for example the improvement in propeller efficiency from 71.0% to 72.6% reduces the required shaft horsepower by 2.2% from 10,460 hp to 10,230 hp. These represent increases over the effective horsepower of 3,034 and 2,803 hp - a 7.6% reduction.

## 3.2 EFFECT OF GENERATOR MAGNET FIELD VARIATIONS

The results given for the superconductive electric drive systems assume that the generator magnet fields are adjusted at each speed to permit the turbines to run at their optimum speed for best fuel consumption(1). The fields are adjusted by changing the magnet excitations; this must be done relatively slowly to prevent loss of superconductivity and because of the high time constant (several hours) of the coil windings. As a result, adjustment of the magnet fields to the exact value required for optimum fuel consumption is feasible only for prolonged operation at constant speed. In order to assess the impact of operation with non-optimum fields, system performance was examined with:

- Fixed (90% of full field) fields at all speeds.
- Magnet fields adjusted to the nearest 10% of optimum at all speeds.

The results have been tabulated in tables 3-3 and 3-4 and the effect of fixed 90% fields on propulsion system losses is indicated in figure 3-10. With the fields fixed, turbine fuel consumption rises considerably and causes the electric drive system to be less efficient than the comparable geared drive systems(2), although substantial advantages still exist relative to the baseline system. On the other hand, there is negligible difference from optimum

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(1) Reducing the magnet field reduces the generator voltage output at a given speed. This allows the turbine to run at a higher, more efficient speed for the same generator output voltage.

(2) This is a result of using fixed pitch propellers for the electric drive system. If controllable pitch propellers were used, performance would be comparable to the adjusted field cases.

when operating at the nearest 10% field value (the losses increase 0.6% for the system with no cruise turbines and decrease by 0.6% for the system with cruise turbines)(1). Additional runs with fixed fields based on the number of turbines in use (similar to the fixed pitch ratios used for the geared drives) using:

- 90% field for one or two cruise turbines
- 60% field for one main turbine
- 75% field for two main turbines
- 90% field for one or two main turbines

gave negligible change in overall fuel consumption compared to the nearest 10% field cases (zero change for main turbines, 0.2% increase for main + cruise turbines). It is concluded that it should be possible to operate the electric drive systems at close to the performance levels given for these systems with field optimization, and, in fact, the cruise turbine fields can be held fixed during all normal operations.

From the standpoint of fuel economy, operations may be carried out at fixed full field under dockside or harbor maneuvering conditions, with little effect on overall mission performance. However, transient analysis of performance would be required to confirm satisfactory operation and it may be desirable to replace the superconducting cruise generators with non-superconducting AC/DC generators capable of rapid field changes. These

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[1] The decrease is caused by the fact that the cruise turbines operate up to 14 and 16 knots instead of 13 and 15 knots as established by the computer optimization program. The optimization program switched sooner because the turbines could not run at 14 and 16 knots at optimum field due to turbine overspeed limitations; with fields reduced from optimum, the turbines did not overspeed.

generators develop AC power which is then rectified to DC; a possible candidate for such use, being developed for the U.S. Naval Ships Systems Command, is shown in Appendix B. Such generators would weigh 6070 lbs each against 3850 lbs for the superconducting generator and would add 2 tons to the total equipment weight (size is such that they could be used in the space available for the superconducting generators). Efficiency would be approximately 96.5% against 99.2% for the superconducting machine. On the plus side, the AC/DC generators would require no helium and would reduce the refrigeration load by about 20 lbs of fuel per hour. The impact of using the AC/DC cruise generator was not investigated in detail, but it is estimated that drive system efficiency would drop from 96.0% to not less than 94% and that the average propulsion system fuel rate would not increase by more than 2%.

The use of non-superconducting generators has been considered only for the small, high-speed cruise generators; similar generators for main generator use would be three to four times as large as the superconducting machines and have relatively high losses.(1)

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(1) This does not preclude the possibility that a full trade-off study of superconducting versus AC/DC main generators would show the AC/DC machines to be advantageous when all factors (cryogenics and other ancillary requirements) are considered. However, it should be noted that the generators are candidates for non-superconductive design only because of their high speed and resultant low volt/rpm requirement; on the other hand, motors require a high volt /rpm output because of their low speed and are not considered possible candidates for non-superconductivity.

## 3.3 EFFECT OF IDLING TURBINES ON PERFORMANCE.

When cruising with reduced power, the ability to accelerate to higher speeds depends upon the sufficiency of the on-line power. At speeds where the system is operating at the maximum speed attainable with the existing turbine configuration (e.g., 17 knots with two cruise turbines) it is necessary to bring an additional turbine on line to reach a higher speed. In such cases it may be desirable to have a turbine warmed up and idling in a standby condition. The effect of such standby operation was investigated by assessing the impact of idling turbines on the average range over the mission profile. The need for standby conditions would depend on the actual mission speed variations with time, rather than on the percentage of time spent at each speed over the mission; from the averaged mission profile there is no way of knowing what speed change would be required from, say 17 knots; it might be an increase or decrease, large or small. However, in order to assess the impact of keeping turbines idling in reserve, it was arbitrarily assumed that:

- The number of turbines required for an increase in speed of "X" knots are kept available at each speed on the averaged mission profile.

For example:

- Two idling main turbines are added to the two propulsion turbines for "X" knots before 31 knots (the speed at which four turbines are required) for the baseline system.
- One idling cruise turbine is added at "X" knots before 14 knots, and one main turbine at "X" knots before 18 knots, 22 knots, 28 knots and 30 knots for the geared drive with alternators and cruise turbines.

The number of propulsion turbines required and the amount of idling time resulting are shown for the latter case in figure 3-11 as a percent of mission time for X= 1, 2 and 3 knots.

The percent of idling time which results over the mission profile for each configuration is shown on the left side of figure 3-12. The idling time shown is for the main turbines only (the cruise turbines add less than 25 lbs/hr to the fuel rate per knot of idling) and their effect on the mission average fuel rate is also shown (1100 lbs/hr idle rate). The right hand side of figure 3-12 shows the impact of the idling rates (main + cruise) on range over the mission profile. Percent reduction in range is very nearly linear for all configurations except the baseline and electric drive without cruise turbines, as follows:

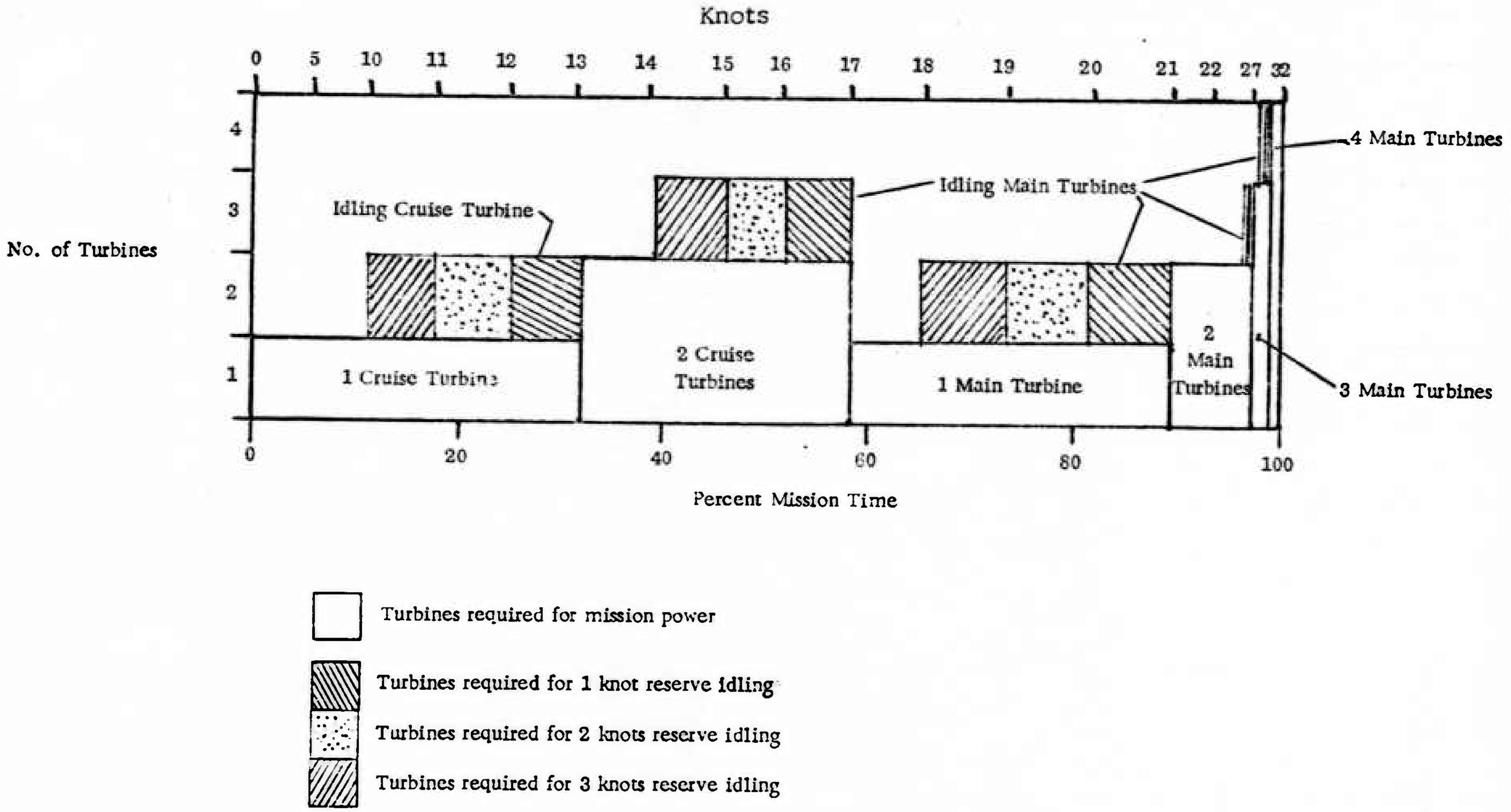

Figure 3- 11

Example of Turbine Idling Requirements

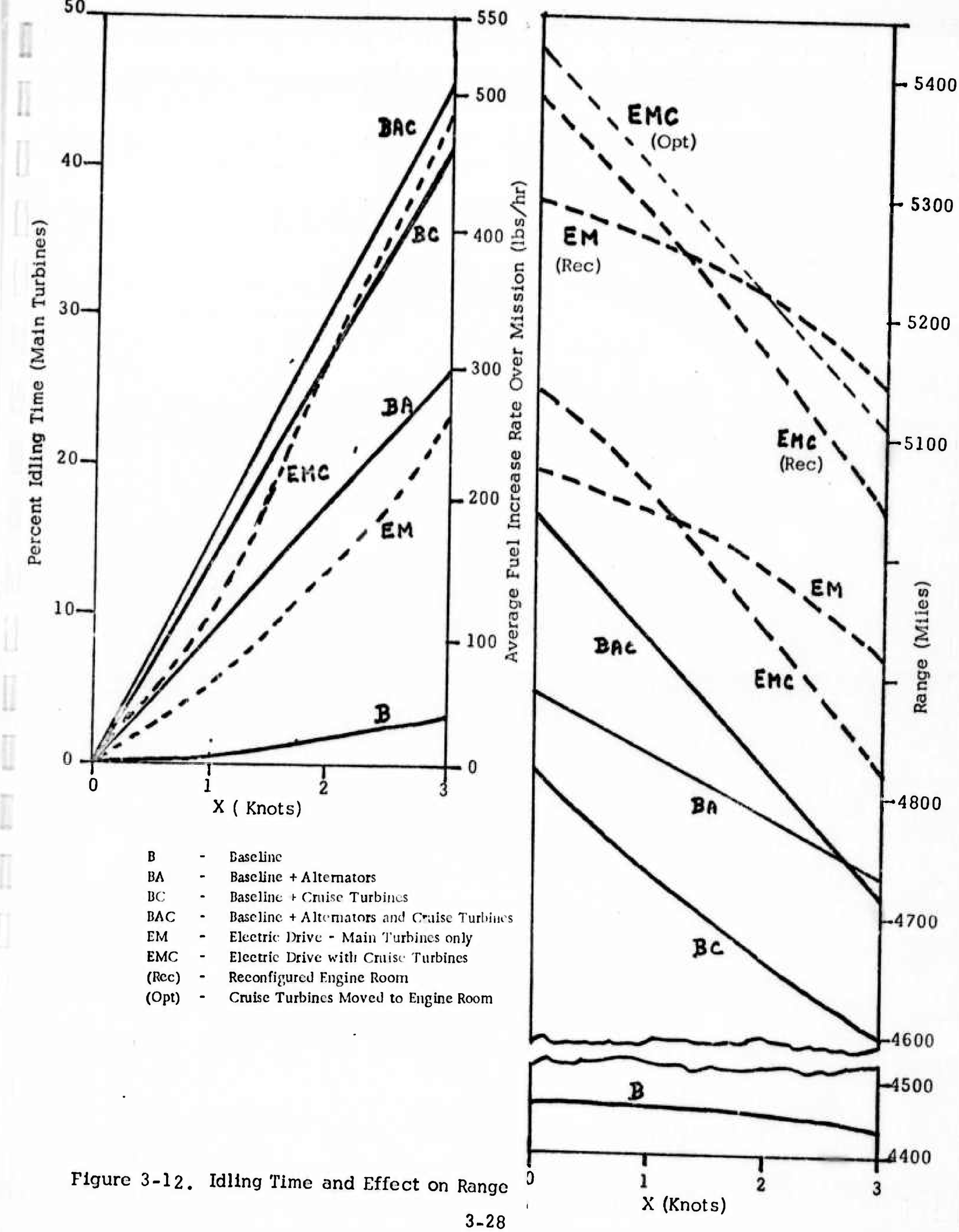

Figure 3-12. Idling Time and Effect on Range

| | |
|---|---|
| Baseline + Alternators: | 1.1%⁽¹⁾ |
| Baseline + Cruise Turbines: | 1.6% |
| Baseline + Alternators, and Cruise Turbines: | 2.2% |
| Electric Drive with Cruise Turbines: | 2.0% |

The baseline range decrease is less than 0.4% over the entire 3 knot range. The electric drive without cruise turbines shows a non-linear reduction in range as follows:

| X (Knots) | Percent Range Reduction |
|---|---|
| 1 | 0.6 |
| 2 | 1.7 |
| 3 | 3.0 |

It may be seen from figure 3-12, that all configurations retain substantial range advantages with respect to the baseline system. A possible exception is the baseline + cruise turbine configuration; however this system still retains a 5% range advantage over the baseline even under the extreme case of a 3 knot idling factor, which represents more than 40% of the mission time spent with an idling turbine.

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(1) Percent range reduction per knot of idling duration.

Relative to one another, the configurations exhibit a larger drop in range when cruise turbines are used, primarily because of main turbine idling time in the 14 to 17 knot range which constitutes nearly 20% of the mission time. As a result, the curves for systems with and without cruise turbines cross one another. For the geared systems this does not occur until the idling factor is nearly 3 knots but for the electric drives in either the baseline or reconfigured engine configurations, the cruise turbine version losses its advantage at about 1 knot.

This analysis of the effect of idling is arbitrary in that detailed mission profiles would need to be studied in order to obtain accurate results but this type of qualitative analysis does lead to the following conclusions:

- All configurations should retain an advantage over the baseline configuration in spite of increased idling of turbines.
- The use of cruise turbines in the electric drives deserves further study to determine whether they will add encugh to performance to justify their inclusion.

### 3.3.1 Turbine and Crossover Utilization

The percent utilization of each turbine over the crossover profile for each configuration is given in table 3-5. Cruise turbine are used 42% of the time for geared drives and 42 to 54 % of the time with electric drives. The geared drive system alternators are used 91 to 95% of the mission time, while the electric drive crossover is used 64 to 81% of the mission.

Table 3-5

Percent Turbine and Crossover Utilization over Mission Profile

| | 1 Cruise | 2 Cruise | 1 Main | 2 Main | 3 Main | 4 Main | Total for Cruise | Total for Main | Total for Crossover |
|---|---|---|---|---|---|---|---|---|---|
| Baseline | - | - | - | 98.5% | - | 1.5% | - | 100% | - |
| Baseline + Cruise Generators | - | 58.5% | - | 40.0% | - | 1.5% | 58.5% | 41.5% | - |
| Baseline + Alternators | - | - | 89.8% | 8.7% | 0.9% | 0.6% | - | 100% | 90.7% |
| Electric Drive W/O Cruise Turbines | - | - | 94.1% | 4.4% | 0.9% | 0.6% | - | 100% | 95.0% |
| Baseline + Alternators & Cruise Turbines | 31.9% | 26.6% | 31.3% | 8.7% | 0.9% | 0.6% | 58.5% | 41.5% | 64.1% |
| Electric Drive with Cruise Turbines (1) | 31.9% | 13.9% | 48.3% | 4.4% | 0.9% | 0.6% | 45.8% | 54.2% | 81.1% |

Speed Ranges:
1 Cruise - up to 13 kts
2 Cruise - up to 17 kts for geared systems; 15 kts for electrical systems
1 Main - up to 21 kts for geared systems; 22 kts for electrical systems
2 Main - up to 27 kts
3 Main - up to 30 kts
4 Main - up to 32 kts

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(1) With cruise turbines moved to the engine room, operation from 1 to 14 knots is with a single cruise turbine (two cruise at 15 knots only); single cruise utilization is 39.0%, two cruise is 6.8% and crossover utilization is 88.2%.

## 3.4 USE OF SINGLE CRUISE TURBINE

The mission profile results show that while a single cruise turbine is beneficial over a wide-range of speeds in configurations with crossover, two cruise turbines are of benefit over a very small speed range. A study of the impact of deleting the second cruise turbine showed that average fuel rates over the mission profiles is increased by less than a half of one percent. If the second cruise turbine were deleted, the following weight savings would accrue:

Geared Systems: 4.9 tons
Electric Systems with Cruise Turbines Topside: 8.9 tons
Electric System with Cruise Turbines in Engine Room: 3.8 tons

The overall impact on range is negligible (from 0 to +0.8% improvement depending upon configuration). Unless warranted by redundancy or maintenance conditions, it is clear that a single cruise turbine is preferable to dual turbines.

## 3.5 VARIABLE PITCH VERSUS FIXED PITCH

While variable pitch propellers are needed with direct geared systems for maneuverability and reversing, the value of variable pitch for purposes of fuel economy is minimal for the geared drive systems and unnecessary for the electric drive systems. Optimum fuel economy for the geared drive systems was achieved by selecting different fixed pitch settings for each combination of turbines in use. When compared with results for complete optimization of pitch at each speed,(1) a reduction in fuel economy of less than 0.1% was found.

For the electrical drive systems, a fixed pitch propeller was used; when the pitch setting was fixed at its single "optimum" pitch,(1) the reduction in fuel economy was less than 0.3% as compared to that attained by setting the pitch to the optimum value for each speed on a knot-by-knot basis.

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(1) See Appendix A, Section A.4.2.

## 4.0 OPERABILITY AND FEASIBILITY CONSIDERATIONS

### 4.1 HARDWARE DEVELOPMENT STATUS

Five thousand horsepower gas turbines (Garrett GTPF990) are currently undergoing evaluation with the first military qualification prototype scheduled for delivery in late 1976 or early 1977.(1)

High performance ac alternators are being developed by Airesearch Manufacturing Company for use in the Navy's superconductive propulsion program.(2) The units now being developed are being designed with integral rectification for generation of DC power; for application as AC crossover alternators. New development work would be required for this specific application before feasibility could be definitely established.

Superconductive motors, generators and related equipment are under active development in several countries. For naval applications, the U.S. Navy is sponsoring development of shipboard propulsion equipment and cryogenic refrigeration equipment for shipboard use. A small (400 hp) superconducting DC motor has been built at the Naval Ship Research and Development Center (NSRDC), Annapolis to demonstrate feasibility of the concepts and a companion generator is under construction. The motor has been successfully operated within its designed speed and power limits and shipboard tests of the motor-generator combination are currently anticipated during FY77.

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(1) Gas Turbine World September 1974, pps. 10-13.

(2) Contract No. N0024-73- C-5487.

Airesearch Manufacturing Company and General Electric Company are developing superconductive propulsion equipment under contract to NAVSHIPS.(1) The program consists of three phases:

- Phase I: Feasibility study of superconducting propulsion concepts for a variety of ship applications.
- Phase II: Preliminary design of full scale shipboard systems and of a reduced scale (3,000 hp) prototype system.
- Phase III: Detailed design, construction and test of a 3,000 hp system aboard a small craft for purposes of demonstrating full-scale feasibility.

Phase II was completed in November of 1974 and Phase III is currently in work; delivery of the first systems for test and evaluation is anticipated during calendar year 1978.

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(1) Contract No. N0024-73-C-5487.

## 4.2 SYSTEM RELIABILITY CONSIDERATIONS

Reliability of the systems was not investigated quantitatively, however, the following comments can be made on failure effects on system performance.

### 4.2.1 Cruise Turbine Failures

Failure of one, or both, cruise turbines would affect fuel economy but would have no effect on overall mission capability unless range were critical.

### 4.2.2 Alternator Failures

Same effect as cruise turbine failures.

### 4.2.3 Helium Refrigeration Failures

Even if there were a total failure of the complete refrigeration system in a superconducting system, it would be several hours before superconductivity would be lost in the machines.(1) In terms of the system, total refrigeration failure is unlikely; four separate compressors are used (two per engine room) of which only two are needed after the system is cooled down and in normal operation. Each generator has its own expander

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(1) A substantial portion of the magnet enclosure is filled with liquid helium during normal operation. As liquid is vaporized, due to heat leakage, the refrigeration system serves to re-liquify the vapor and replenish the liquid. Without re-liquification, several hours are required to vaporize the liquid to the point where coil temperature reaches a critical point.

and each motor has two expanders, with only one required after initial cool-down. If a motor expander fails, the second expander can be switched in without loss of performance. If both motor expanders fail or a generator expander fails or three of the four compressors fail, the machines will eventually cease to be superconducting if repairs cannot be made in time. If superconductivity is lost, the machines must be shut down (unless the magnet is designed with sufficient copper to permit low power operation at much reduced magnet current - generally not desirable). Alternative back-up means would include maintenance of liquid helium storage tanks to be used in event of compressor failures or a small "take-home" system consisting of a conventional electric motor, driven from ships service power supplv, turning a small propelier in order to attain a few knots speed.

### 4.2.4 Cruise Generator Failures(1)

Failures of cruise generators have the same effect as cruise turbine failures - a reduction in fuel efficiency but no effect on mission performance.

### 4.2.5 Main Generator Failures(1)

Failures of main generators are less severe than failure of turbines would be in the baseline case because of the switching flexibility of the electric system. Crossover can be used to maintain power to both shafts in the event of failures on either the port or starboard side. Hence, the effect is to limit top speed as follows:

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(1) Due to either mechanical reasons or loss of refrigeration.

- Failure of 1 main generator: 30 knots
- Failure of 2 main generators: 28 knots
- Failure of 3 main generators: 21 knots

### 4.2.6 Electric Motor Failures(1)

Failure of an electric motor will require alternate take-home means (see 4.2.3) or operation on a single screw. The possibility of single screw operation is enhanced by the ability to change "gear-ratios" by adjusting the motor/generator fields. This permits adjustment of the propeller operation for low speed power with a large rudder angle to maintain course.

## 4.3 TRANSIENT PERFORMANCE CONSIDERATIONS

Transient performance of the system has not been examined in this study. Other studies have shown(2) the electric propulsion system to be highly flexible and responsive to maneuvers, with rapid slowdown and reversal possible through reversal of the general polarity. However, detailed transient performance for the destroyer system, particularly under harbor maneuvering conditions is required to establish quantitative performance.

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(1) Due to either mechanical reasons or loss of refrigeration.

(2) "Twin Series SWATH Superconductive Drive System," Naval Ship Research and Development Center, Annapolis, Md., 1974.

## 5.0 CONCLUSIONS

As a result of the study, it has been concluded that:

- High performance alternators for crossover are the most attractive candidates for propulsion system efficiency improvement in the near future. They should provide a substantial reduction in fuel consumption (approximately 17%) and should require only a moderate development effort to become operationally feasible. The added system weight is more than offset by the reduced fuel load required.

- The addition of geared cruise turbines is considered the most feasible in terms of development risk. Five thousand horsepower turbines should be available in the very near future for operational use and could be incorporated into propulsion drive trains using standard engineering techniques. While providing a lesser fuel savings than alternators (approximately 13%), the added propulsion weight is much less and consequently overall range improvement benefits are nearly equal to the alternator system (9 to 10% for each).

- The value of both cruise turbine and alternators used simultaneously is doubtful in view of questions about turbine operational usage and idling. If cruise turbines are used with crossover, the use of only a single turbine should be considered.

- Superconductive electric drives are highly attractive and appear to hold the greatest promise for long-term propulsion development. While the attractiveness of electric drives as a substitute for geared drives in existing configurations is compromised by the available space arrangements, significant improvements in range and fuel economy are possible compared to the best of the comparable geared drive configurations. With new configurations of ship design, the full potentials of superconducting propulsion should be realizable. Fuel economy should show an improvement on the order of 22 to 25% as compared with straight gear drive systems and, with optimized configuration arrangements, range increases approaching 20% should be attainable with the same payload. Alternatively, additional space would be available for increased payload as a trade-off against range. With both range and payload held constant, the total ship displacement could be reduced, leading to even greater fuel economy.

## 6.0 RECOMMENDATIONS

It is recommended that:

- The use of small (approximately 5,000 hp) turbines be considered for short term application to destroyer propulsion.
- The possibility of developing high performance alternators for mid-term application to destroyer propulsion be considered through a detailed feasibility study.
- The current NAVSHIPS superconductive propulsion program should be considered as an important source of future propulsion for destroyer class vessels; planning for applications, with concrete development milestones, should be done well in advance of the availability of the first shipboard systems to ensure maximum use is made of the advantages of this new propulsion methodology.

Further studies to amplify upon, or confirm, the results of the present study should be made in the following areas:

- Transient performance of the electric drive systems should be examined to ensure satisfactory operation with respect to detailed mission performance requirements.
- The feasibility of dc superconducting cruise generators versus ac/dc non-superconducting generators should be examined from the standpoint of harbor maneuverability (i.e., a study of the need for rapid magnet field changes and the ability to attain them).

- The need for CRP propellers should be examined in detail in terms of harbor maneuverability (related to the AC/DC versus DC generator study above).
- The desirability of using crossover when operating with 3 main turbines should be examined in more detail (it provides only a small fuel savings and requires the alternator to be set to a lower gear ratio than would be needed if crossover were used only up to 22 knots).
- Actual mission requirements should be examined to determine the need for idling of standby turbines and the effects on economy of operation.
- The desirability of locating cruise turbines topside as opposed to location in the engine room should be examined in more detail.
- The desirability of providing separate helium, coolant and lube oil services for the motors (as opposed to piping from the engine rooms) should be explored.
- If the application of electric drive to existing hull types is contemplated, further study should be made of the space and weight savings accruing from ductwork and CRP propeller elimination.
- Vulnerability, reliability, maintainability and availability studies should be performed to ensure system feasibility.