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November 1993
NSRP 0408

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1993 Ship Production Symposium

Paper No. 17: Naval Ship Affordability Through Machinery Modularity

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 1993**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **The National Shipbuilding Research Program, 1993 Ship Production Symposium Paper No. 17: Naval Ship Affordability Through Machinery Modularity**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tower Bldg 192 Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**18**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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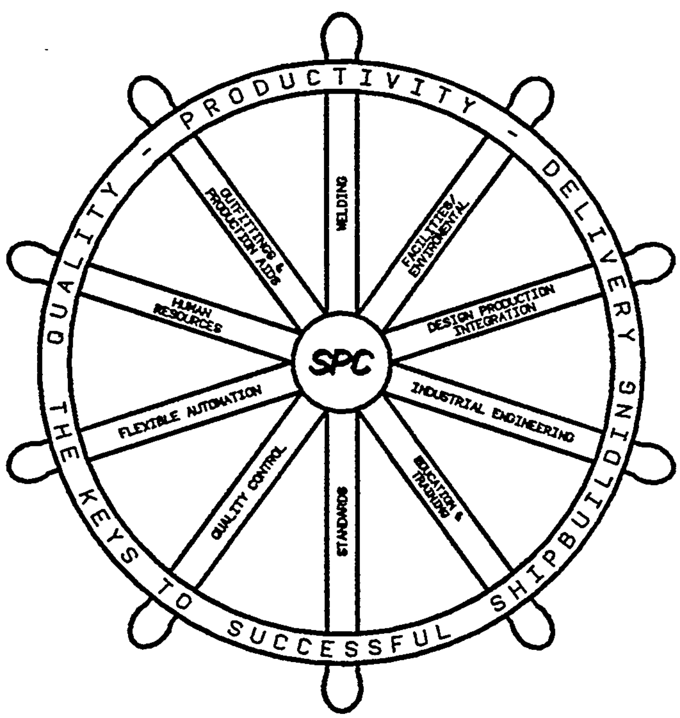

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Williamsburg Virginia, November 1-4, 1993

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Naval Ship Affordability Through Machinery Modularity

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ABSTRACT

The shipbuilding industry has recently taken an increased interest in modularity of machinery and equipment. Through modularity, decentralization of key items such as combat, auxiliaries and propulsion equipment is more feasible. Zonal or compartmental machinery modules often lead to reduced ship volume and hence ship costs. Modularity may also lead to standardization within a ship, a ship class, or across several ship classes. The reward for implementing modularization is partly found in labor savings. Production of modules by moving the installation and construction from the ship or from the blocks to an off-ship shop generates some savings. However, this labor saving must be weighed against the material and labor cost of constructing the module container. The modules may take up increased space compared to a conventional unit, which would cause the ship size and cost to increase. This paper intends to quantify these tradeoffs to determine if it is beneficial to ship affordability to employ any of a series of modularity concepts. The concepts studied include modular propulsion, payload (combat system), auxiliary and habitability installations.

INTRODUCTION

There is an ever growing interest in modularity and commonality to reduce naval ship production costs and improve affordability. The emphasis of the study presented in this paper is to define a set of modularity concepts, and then assess them on a cost and affordability basis, to sort out the attractive approaches for future designs. This study is an initial conceptual level evaluation only. Commonality within the ship and ship class will be achieved, but commonality across several classes will be left to future study. The modularity concepts selected will generally be decentralized units needed in some quantity for each ship ,so that they will be common within the ship and the ship class. Thus, both the advantages of off-ship production and quantity production of standardized units will be weighed against modularized unit construction costs and the ship size(volume) influences of using modules.

The modularity concepts which have been considered for use in combatant ships are propulsion modules called powerpaks, zonal auxiliary modules, zonal auxiliary and power generation modules, compartmental auxiliary modules, compartmental auxiliary and power generation moduldes, habitabilty modules, modular combat system elements and combined propulsion, power generation and auxiliary machinery modules.

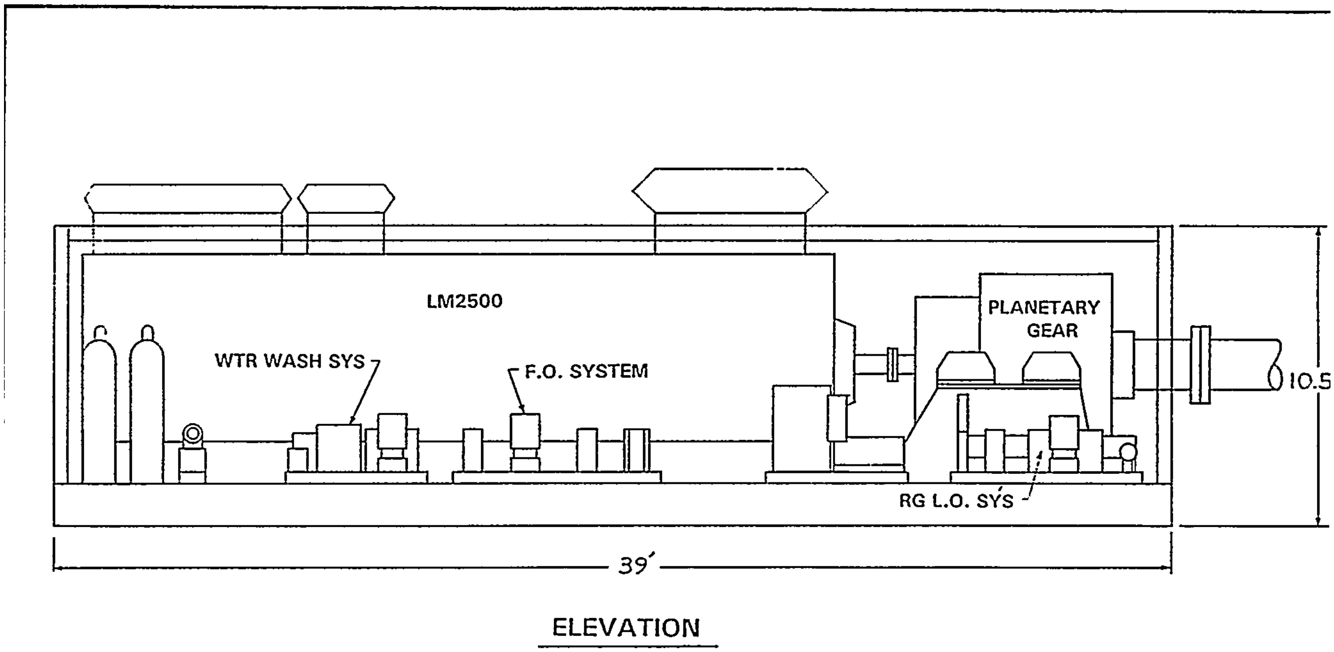
A zone as referenced in the zonal concept is the volume from the hull up through the superstructure between two watertight bulkheads. A compartment is the volume between two watertight bulkheads on one deck level. Typically, there are ten to thirteen zones on a destroyer and thirty to fifty compartments.

CONCEPT DEFINITIONS

Propulsion Module (Powerpak)

Although the currently used LM-2500 gas turbine engine is packaged in a module for installation, it could be further modularized by including the engine, a reduction gear box, and the ancillary equipment in a module. Much of the installation cabling and piping would be installed in a shop. This concept facilitates testing before shipboard installation. Installing an entire powerpak module in the engine room as a unit reduces the installation labor. Figure 1 illustrates a powerpak unit.

Zonal Auxiliary Modules



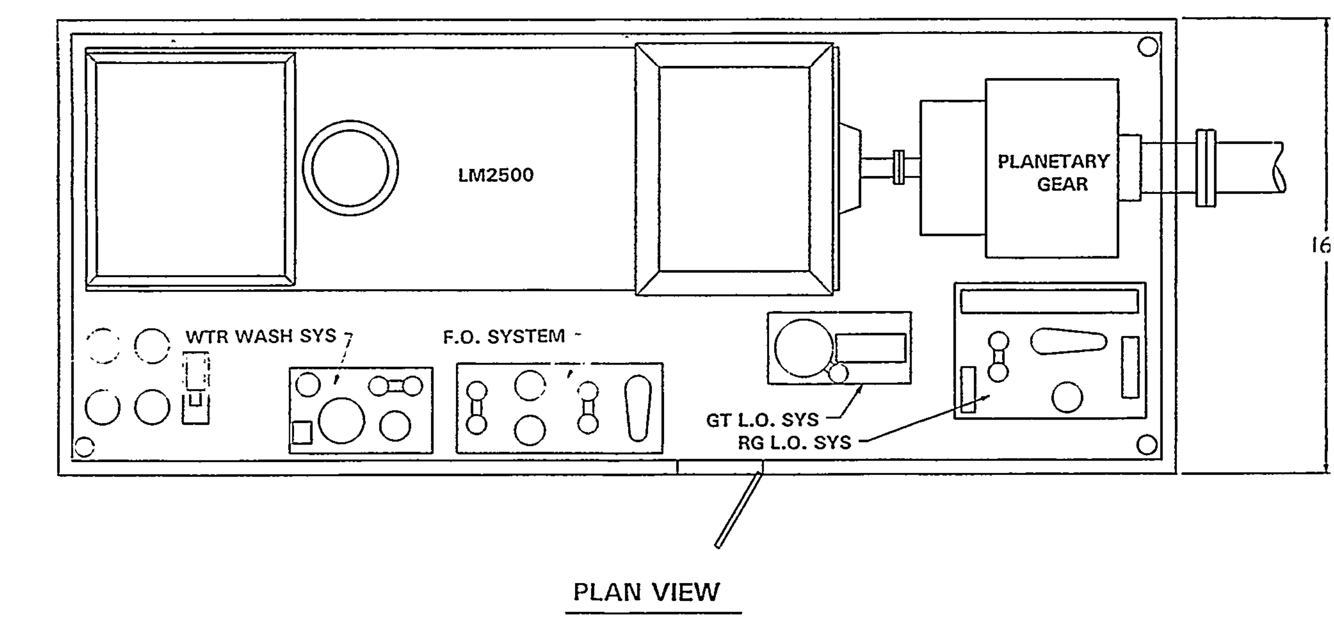


Figure 1. Powerpak Module

A zonal auxiliary module may include one or more of the auxiliary units required for a zone. Several zonal modules maybe used in each zone for different auxiliary systems. There could be a zonal fire pump, zonal sea water pump and zonal HVAC units, all mounted separately in a zone or combined in one or two units. A desalination unit could also be added as well as an air compressor where needed. The fire pump, HVAC and saltwater pump units would be standardrized for the ship. The zonal units would be cross-linked to provide redundancy for a damaged or failure condition. For example, the HVAC unit would have an eighty ton capacity for a large destroyer. Figure 2 illustrates a typical zonal module.

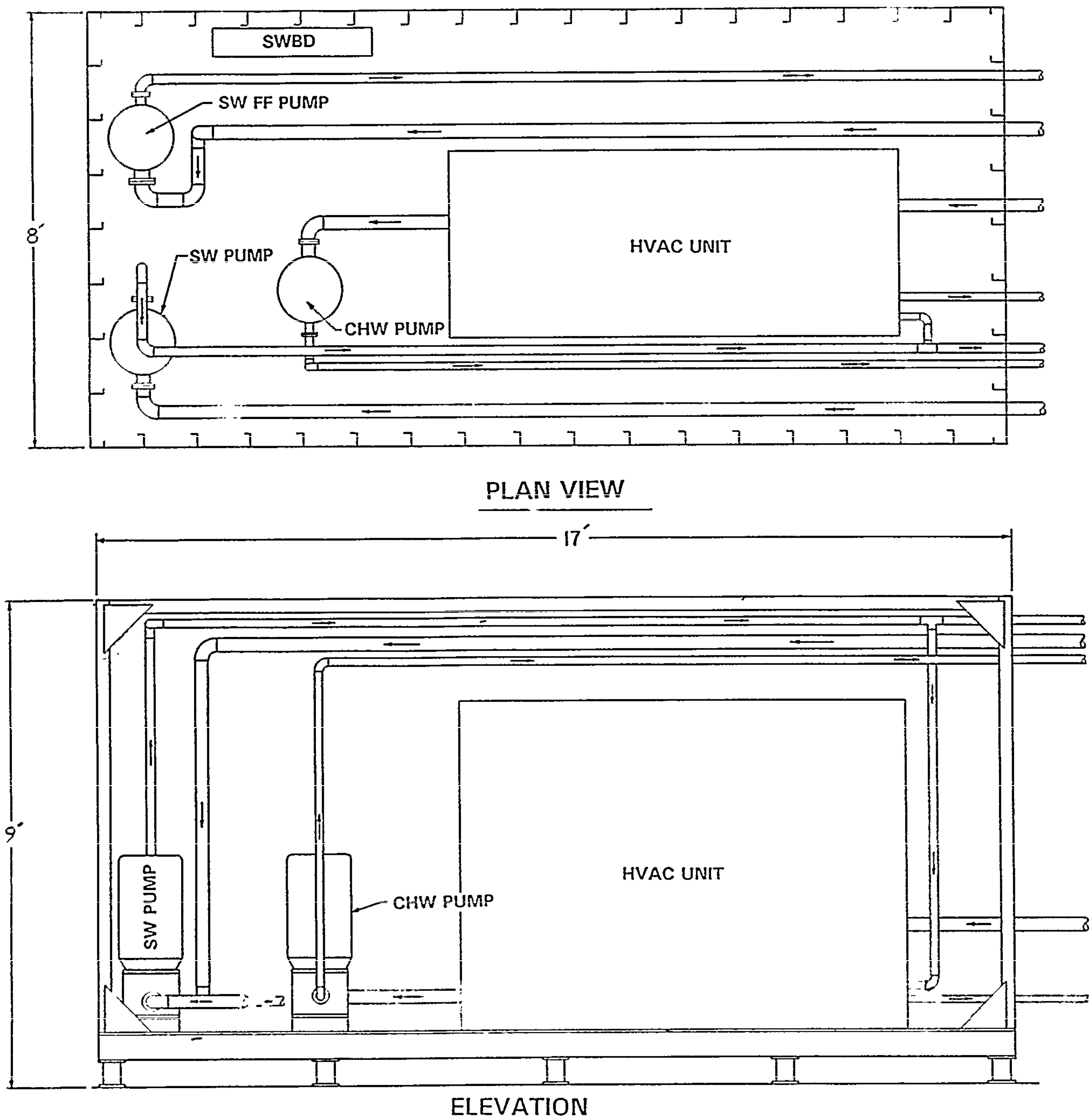


Figure 2. Zonal Auxiliary Module

The use of zonal auxiliaries eliminates the need for specialized auxiliary rooms. If the modules can be efficiently arranged in the ship, volume savings can be achieved. Studies indicate that the savings are on the order of five percent of the ship volume.

Zonal Auxiliary Power Generation Module

When a small gas turbine or diesel generator is added to the zonal modules, all of the power/auxiliary functions can be favorably located as needed in each zone. These units are standardized. Multiple units generally would be required in the zones using the most power, such as zones where major combat system elements are located. However, most zones would require only one unit. the units could be integrated with the HVAC unit into one module. It is likely that pump modules would be located low in the ship near the inner bottom, while the HVAC and power modules would be located near the main deck where the needed air enters the ship. There is a significant ship volume reduction of about ten percent gained by using this concept because of the elimination of auxiliary and generator spaces. Figure 3 illustrates this type of **modular installation.**

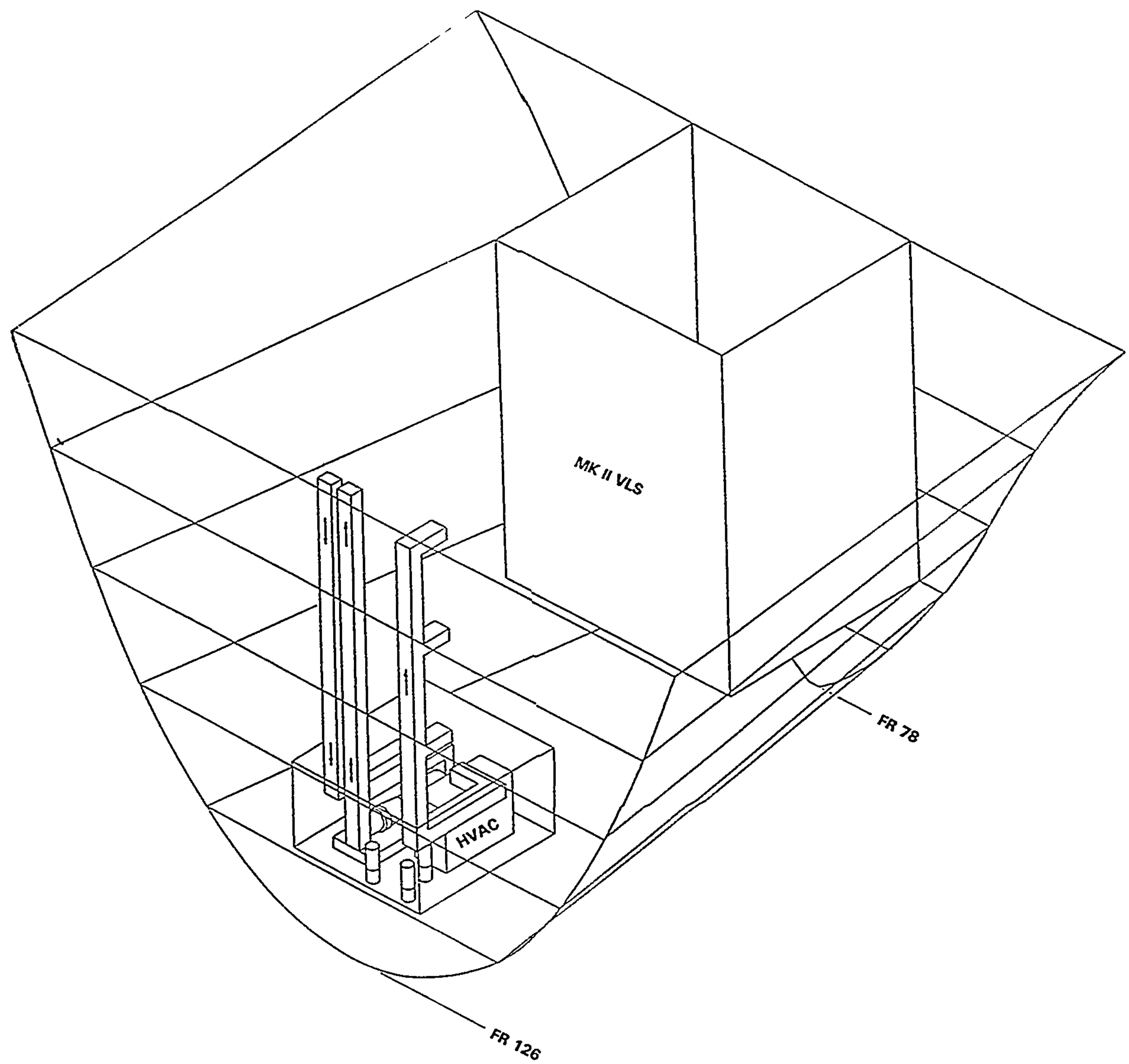


Figure 3. Installation of Zonal Auxiliary/Electric Module

Compartmental Auxiliary Modules

Comparmental auxiliaries are limited to compartmentalizing the HVAC units. The pumps and compressors are zonal because they need to be located near the water source. The HVAC units are small and could be. mounted in the overhead. These units will be built in quantity so standardized production is of benefit. The volume reduction expected is not as much as for zonal units, but a two and a half percent saving is expected. Figure 4 illustrates a compartmental installation. Figure 5 shows one of these units.

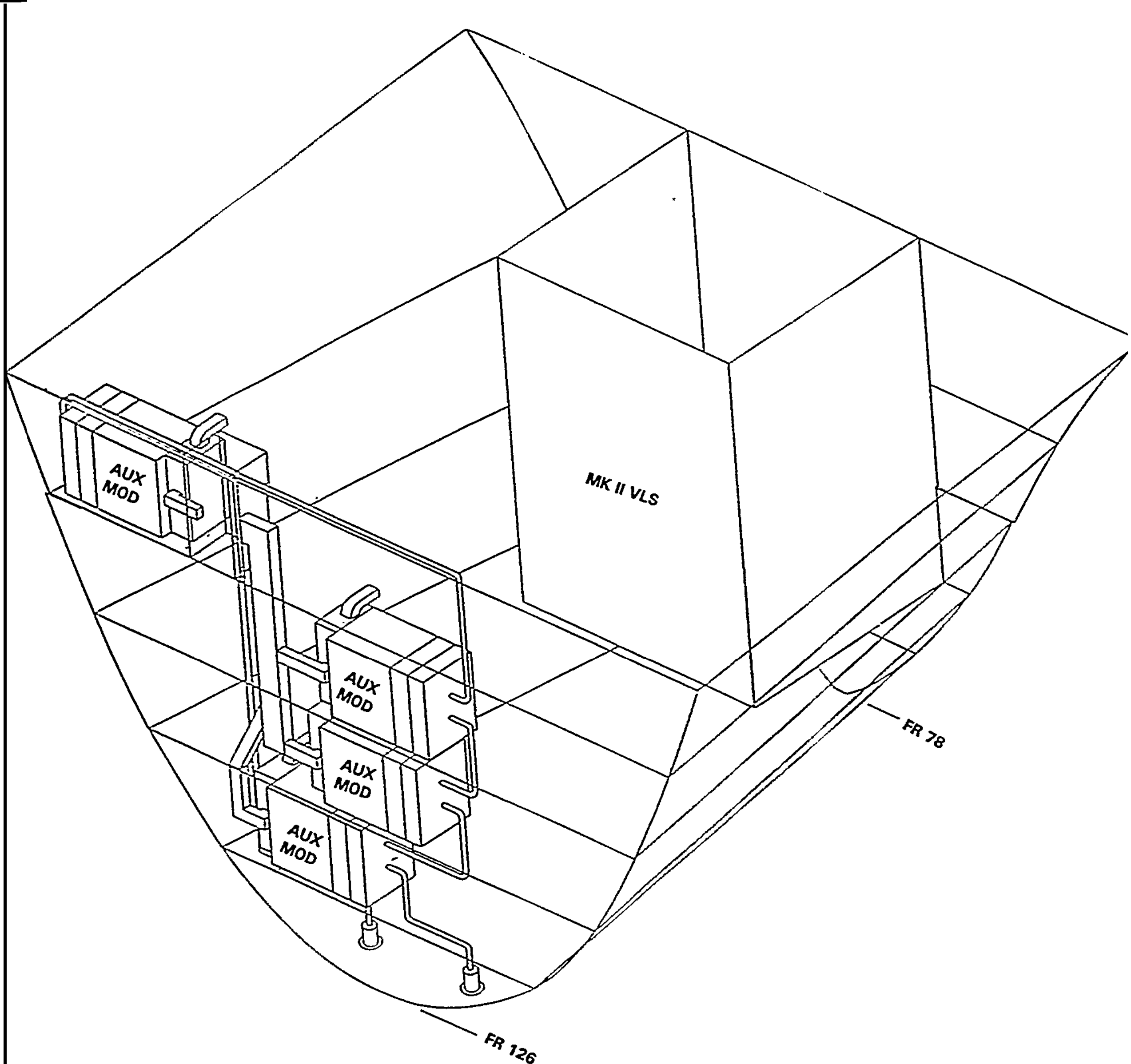


Figure 4. Installation of Compartmental Auxiliary Module

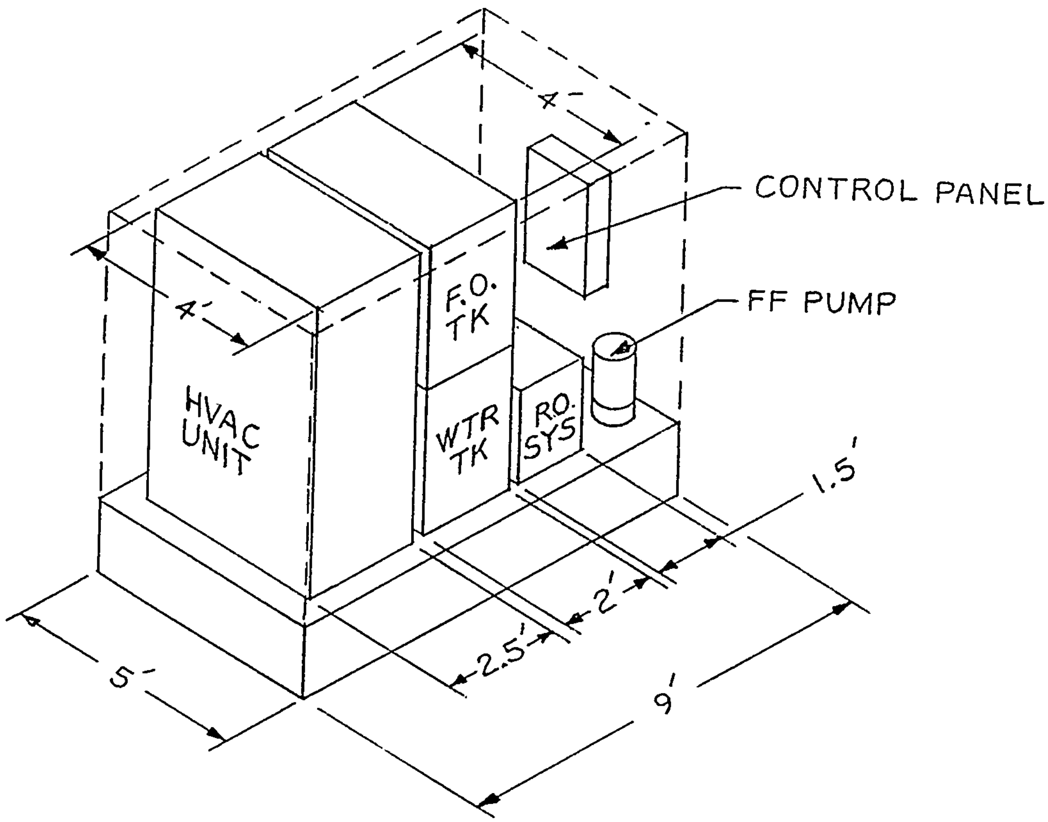


Figure 5. Compartmental Auxiliary Module

Compartmental Auxiliary Power Generation Module

When a small diesel generator is added to a module, the auxiliary and power generation equipment is located efficiently in each compartment. Figure 6 illustrates this concept. The volume reduction gained by this concept is about

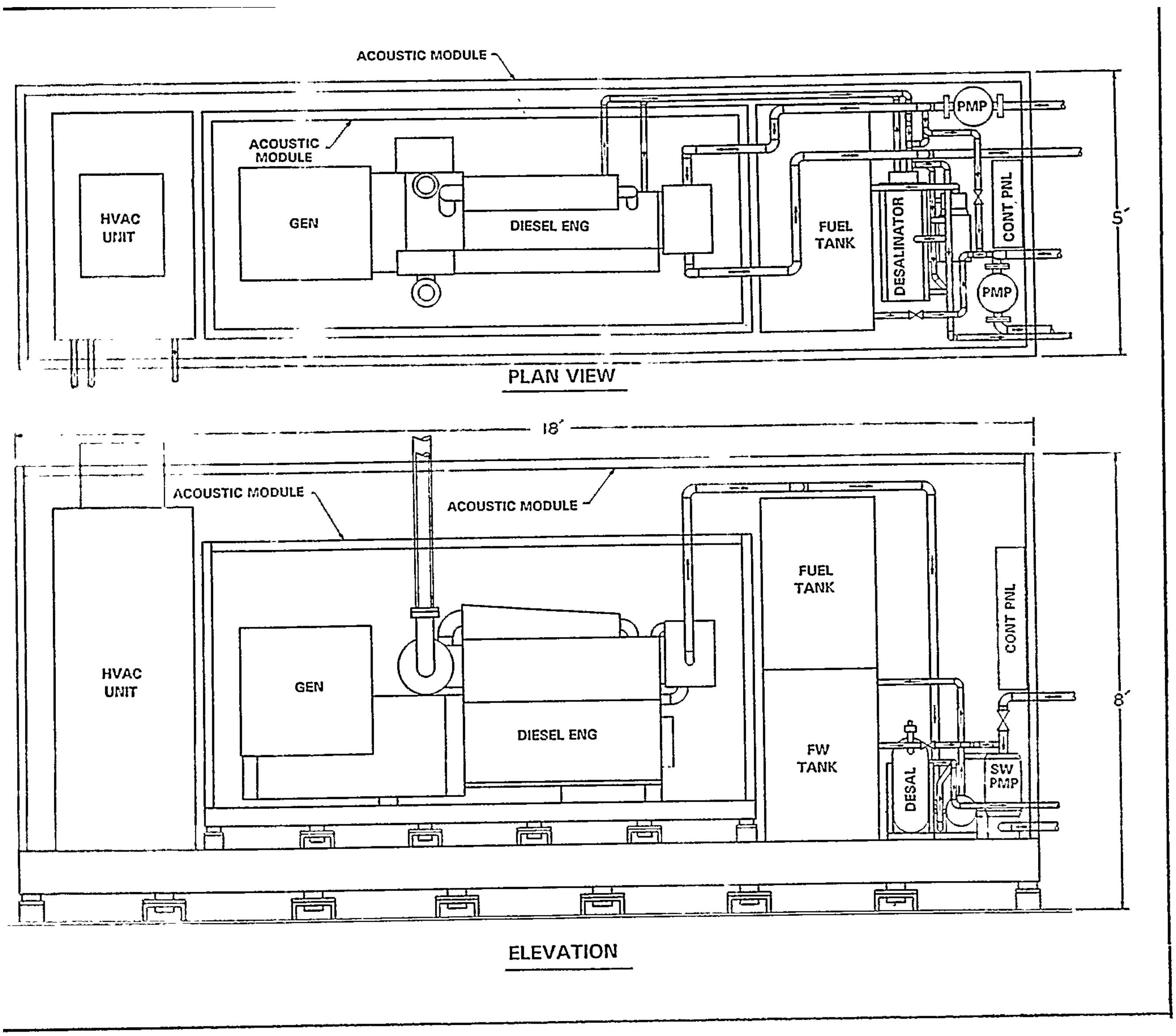


Figure 6. Zonal Auxiliary/Electric Module

seven percent of the ship volume, based on arrangement studies.

Habitability Modules

Outfitting of equipment associated with crew berths, offices, galleys, mess rooms, etc. can be accomplished in modules. The modules can be somewhat standardized. Figure 7 illustrates a crew living module. The module has a foundation of non-structural bulkheads. Decking, lighting and cables are installed in the modules in a ship. However, ship layout studies have shown that fitting the best optimized size assortment of modules in a combatant leads to a seventy-five percent volumetric **efficiency. This is** a significant volume penalty. If non-standard modules are used, then this penalty can be reduced, but there is still a significant penalty. the volumetric penalty has to be balanced against the labor savings from standardized shop construction.

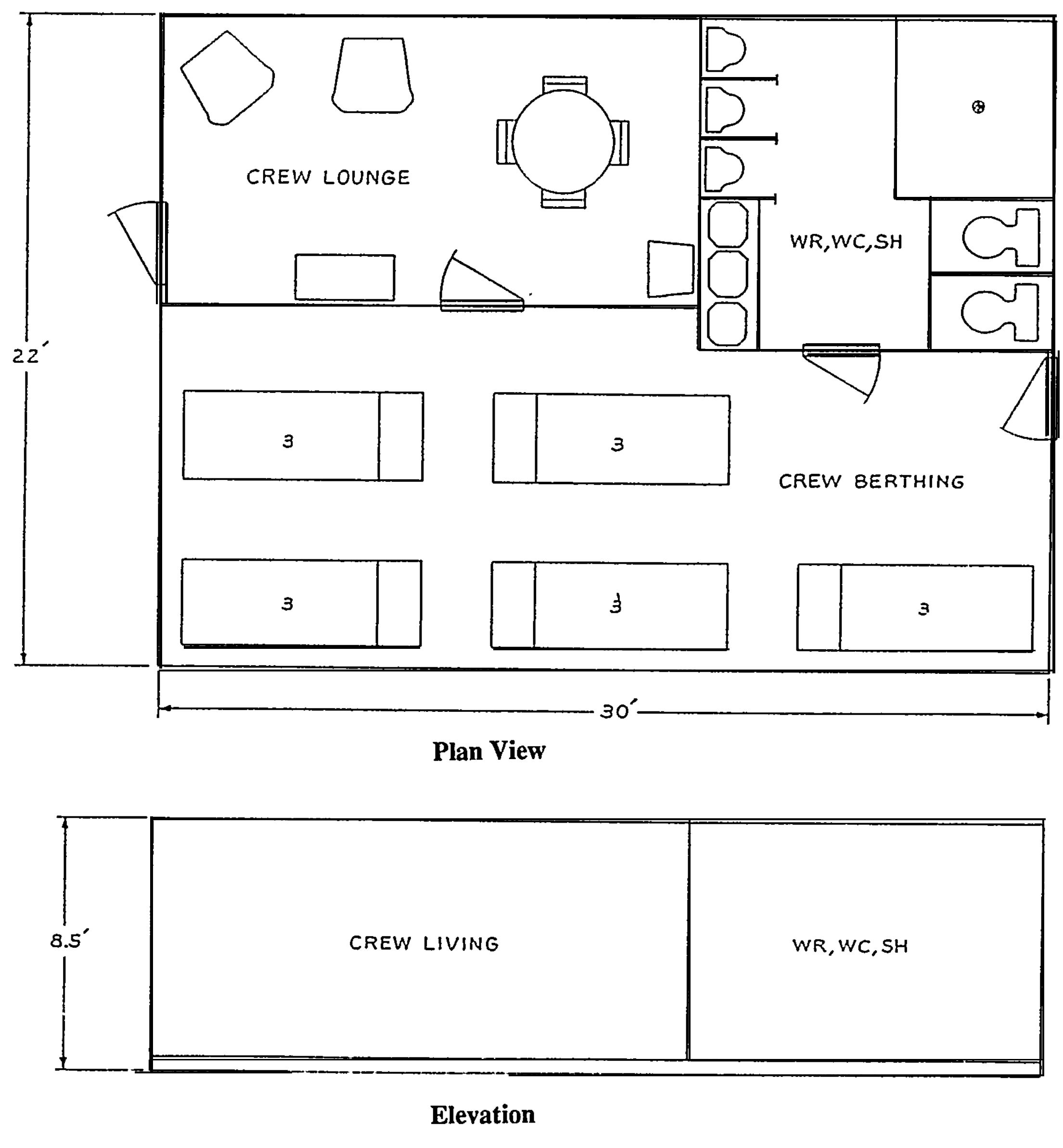


Figure 7. Crew Living Module

Modular Combat Systems

Vertical Launch Systems (VLS), guns, radar units, etc. can be outfitted in modules for ease of outfitting and testing. The principal ship influence of using modules is a six percent increase in combat system unit volumes. The weight penalties are small, since many of the combat system elements are already palletized.

Combined Propulsion/Power Generation/ Auxiliary Modules

These modules are located in four or six zones toward the center of the ship. The module contains a mid-size gas turbine (i.e. LM-1600 or 571 KF) driving a waterjet through a gearbox, a propulsion derived ship service generator (PDSS generator), and auxiliaries such as the pump units. The waterjet intake and exhaust nozzle are attached separately. The waterjets can be operated singly, in pairs, or in all units operating for good performance loading control. The HVAC unit can also be included in the module. The HVAC units provide chilled water for distribution as needed. The concept is shown in Figure 8.

DISCUSSION OF ZONAL AND COMPARTMENTAL OUTFITTING

Zonal and compartmental units have advantages and disadvantages. These attributes are documented in several references. Reference (1) shows that zonal fire pumps lead to significant weight and cost savings. Reference (2) shows that zonaI electrical systems also have major savings in weight and cost. The lengths of piping and cable are significantly reduced. A recent report (Reference (3)) compares zonal and compartmental HVAC. Zonal HVAC demonstrates the greater cost savings. Compartmental auxiliary modules also provide cost savings, but zonal systems have lower total equipment cost. Zonal and compartmental systems offer excellent reliability and availability through redundancy, but will probably require more preventative maintenance manhours. The zonal and compartment boundaries can be better protected against fire spread because of the fewer bulkhead penetrations.

In general, the unit or component weights go up for zonal/compartmental systems, but decreases in piping, ducting and cable weights more than offset these increases. The weight reductions are on the order of fifteen to twenty-five percent. Similarly, cost reductions of ten to twenty percent are indicated.

The dispersed nature of the zonal and compartmental systems leads to improved ship survivability and battle damage control. Zonal and compartmental modules should be easier to build and install than their centralized counterparts. The maintenance for each unit should be less, but the larger number of units will probably increase the total manhours per year.

MODULARITY INFLUENCES

Module Characterization

A computer model was developed to design and cost modules based on size and weight of equipment installed. A bedplate was sized to carry the lifting loads on the module. The enclosure was sized and weighed to provide an acoustic enclosure taking no structural loads. Habitability modules are different in weight and size than machinery modules because of the bedplate loads. The non-structural sidewalls are the same and are weighed and calculated by the following factors

Weight	28 lbs/square foot
cost	$31 /square foot
Labor	2.25 hours/square foot

Learning Curves

Repeated construction of common or standard modules leads to improved efficiency, generally characterized by a learning curve. A ninety to ninety five percent labor learning curve is typical. A learning curve is defined as the fraction or percentage multiplier when the quantity manufactured is doubled For example, the labor for an item is reduced by x.95 going from eight to sixteen units if there is a ninety five percent learning curve. A general labor multiplier can be computed for any case by the equation:

$$TF = \sum_{x=1}^{x=N} (LF)^{\log x/\log 2} \qquad (1)$$

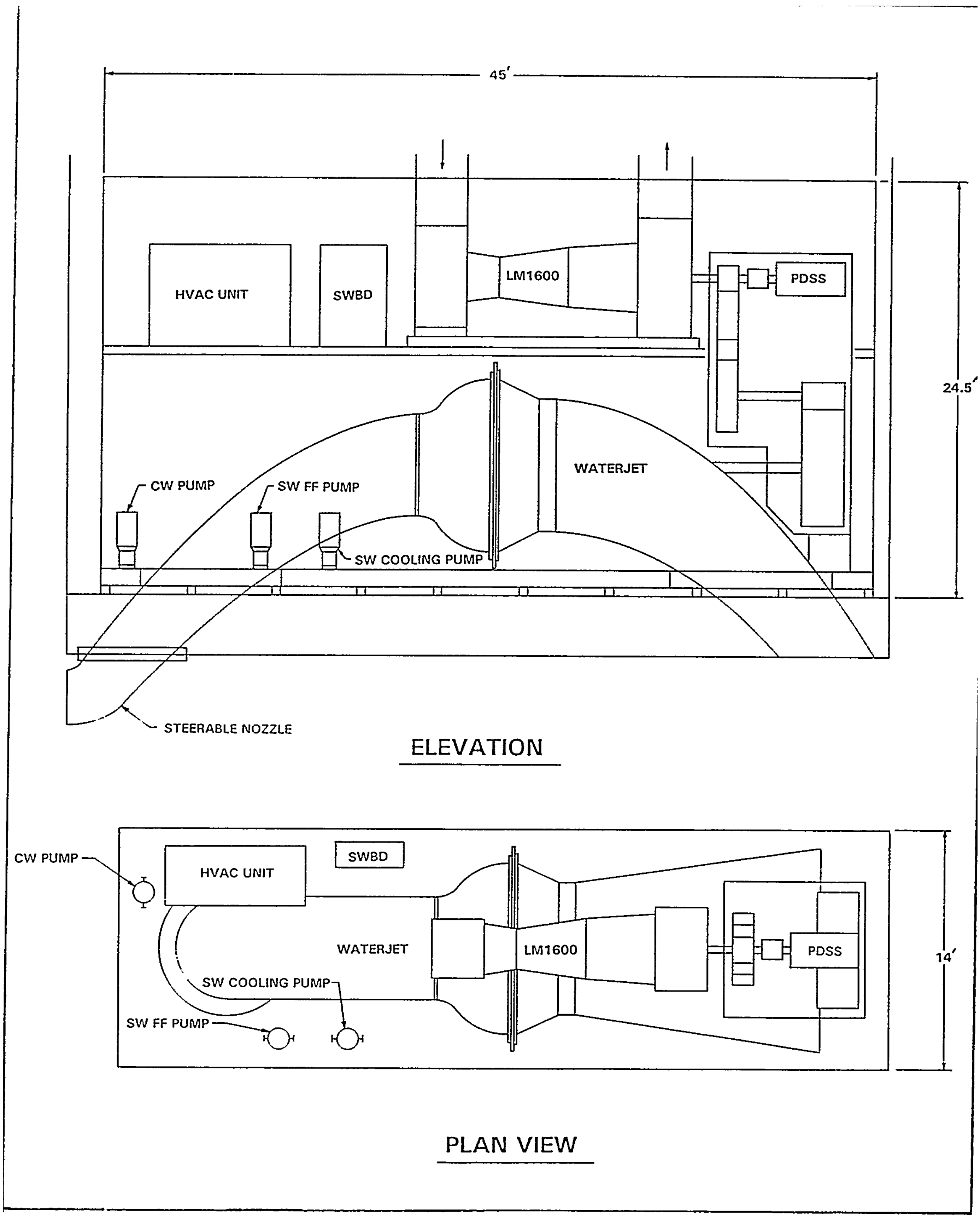


Figure 8. Propulsion/electric/auxiliaries Module

where

x = counting variable
LF = learning curve factor
N = number of units built
TF = total learning factor

TF multiplied by the labor for the first unit gives the labor total for all N units.

Shop Construction

Labor performed for a given construction task in a shop has been shown to be markedly less than required to perform the same task on board a ship. Shipyard surveys have shown a wide variety of results for the reduction factors. The table below indicates the ratios from blocks to shop, and ship to shop, from a conservative and optimistic viewpoint.

	Conservative	Optimistic
Block/shop	2/1	3/1
Ship/shop	3/1	4/1

Optimistically, the labor for a task on a ship could be performed in a shop with one-fourth of the labor hours, while a task on the blocks could be accomplished with one-third of the labor hours. Conservatively, the reductions are one-third shop to shop and one-half blocks to shop. The conservative values are used in the affordability analysis to follow.

Habitability and combat system modules use the ship/shop ratio, while the machinery modules use the block/shop ratio in the labor reduction analysis.

SHIP INFLUENCES

Affordability Analysis

An affordability analysis procedure has developed over the last few years to express the relative affordability of a new approach or concept applied to a ship when compared to a baseline ship. Both acquisition and operating costs are included in a discounted life cycle cost analysis. A ten percent discount rate is used. A future dollar value in year N is reduced by the ratio $\{1/(1+ .1)\}^N$ to give its present value. A standard scenario is used in the analysis as follows:

- 100 ships are constructed, 5 per year for twenty years,
- Ship funding begins five years after program initiation,
- Ships are delivered five years after funding,
- Ships operate for forty years after delivery.

Affordability is then defined as the number of ships which can be acquired and operated for the same discounted budget as 100 baseline ships.

Baseline Ship

The baseline ship for study is the DDG-51. This ship was chosen because of its familiarity to the naval engineering community

Analysis Method

The acquisition cost and affordability analyses are carried out by using a ship design and cost model. The model uses weight and volume iterative loops to size the ship, while the payload and ship performance are held constant. The ship particulars are then computed, including hull dimensions, ship weight breakdown, etc. Once these particulars are computed, the ship acquisition cost is computed by adding labor and equipment costs. The operating and support (O&S) cost is also computed, including annual crew, fuel, maintenance, and training costs. These costs are based on ongoing naval O&S cost data. A separate affordability model then computes the discounted life cycle cost and affordable fleet size compared to 100 baseline ships.

Acquisition Cost Results

Each of the modularity concepts described above was evaluated on any acquisition cost and affordability basis. The ship cost results are shown in Table I. The ship acquisition cost results are plotted in Figure 9. The results are indicated as differences from the baseline ship acquisition cost for a single ship. The ship costs are the average costs over thirty ships. The results are also broken down into changes due to each contributor as listed below

1. Ship/shop or block/shop labor reductions,
2. Learning curve reductions,
3. Cost of module construction,
4. Ship change costs including piping, wiring, volume and weight changes.

These result breakouts are shown on Table II.

These results do not include changes in operating cost.

Baseline	Powerpak	Habit-ability	Zonal Aux.	Zonal Aux/Elect	Compart Aux	Compart Aux/Elect	Propulsion/Power/ Auxiliaries
829.84	830.68	853.49	840.71	808.36	796.42	751.56	771.06

Table I. Ship Acquisition Cost Comparison (millions of dollars)

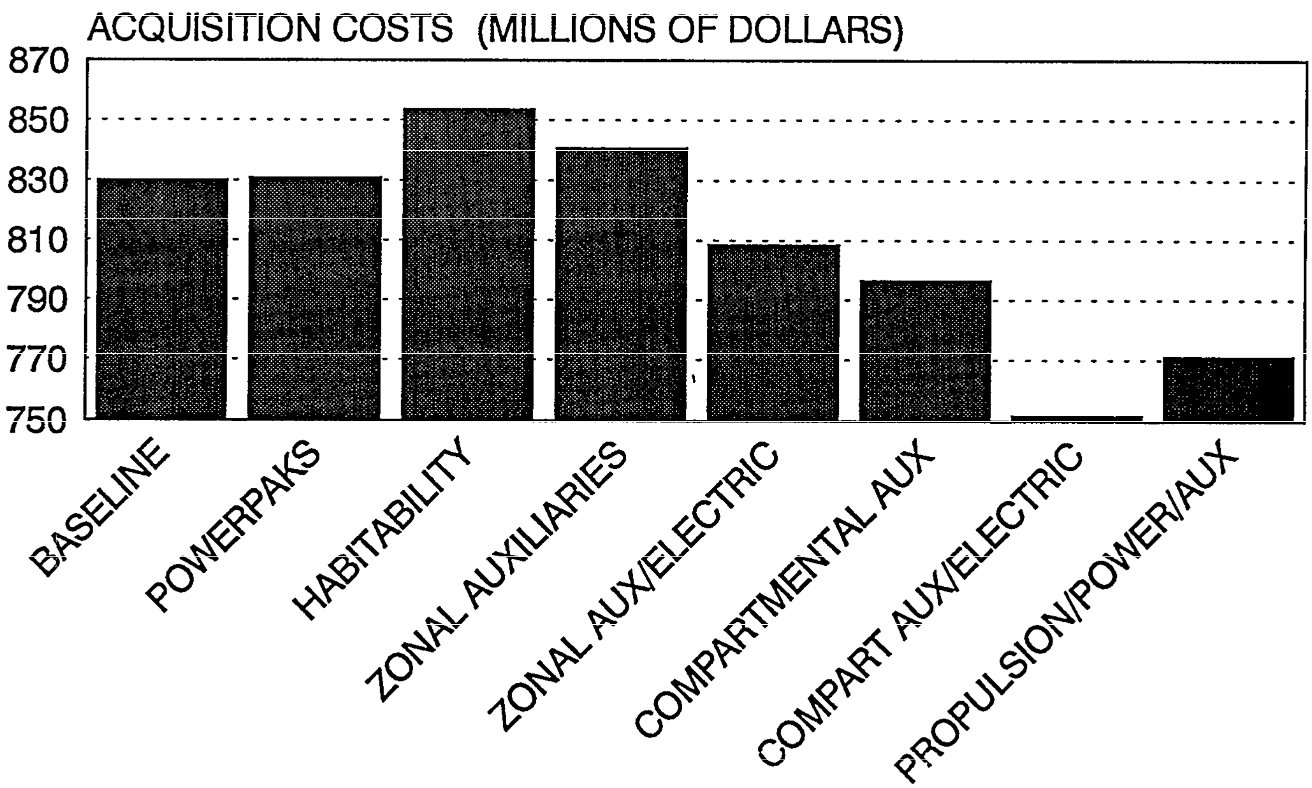


Figure 9. Ship Acquisition Cost Comparison

	Powerpak	Habitability	Zonal Aux	Zonal Aux/Electric	Compart Aux	Compart Aux/Electric	Propulsion/ Power/Aux
Ship/shop	-1.05	-3.27	0.00	-1.12	-0.41	-0.39	-1.07
Learning	-0.18	-0.44	0.00	-0.27	-0.12	-0.12	-0.21
Modules	2.07	11.76	7.05	3.08	3.63	3.81	5.63
Concept	0.00	15.60	3.82	-23.17	-35.73	-81.58	-63.13
Overall	0.84	23.65	10.87	-21.48	-33.42	-78.28	-58.78

Table II. Cost Sensitivities (in millions of dollars)

The powerpak concept shows little advantage from learning or block/shop labor ratios. The cost of the modules is significant. The use of the powerpak has little ship volume significance. Overall, the powerpak is slightly more expensive. However, the powerpak concept maybe useful for improved noise isolation and survivability.

The zonal auxiliaries concept is attractive due to reductions in piping and auxiliary room space. The other factors are of small consequence.

The zonal auxiliary/electrical power generation concept is similarly benefited by a smaller volume, and less piping and cable. Fuel savings are also beneficial.

Compartmental auxiliaries and compartmental auxiliaries/power generation both have large paybacks due to volume, cable, ducting, and piping savings. The other influences are negligible.

Habitability modularity is a poor cost performer, resulting in considerable ship cost increases. These increases stem horn the volume inefficiency of the modules and the additional cost of the modules themselves.

Modular combat system elements are not cost effective for the same reason as the habitability modules. The space and module cost penalties overshadow some of the other advantages. Modular payloads are of most benefit for ease of modernization and rapid change out of combat elements.

The propulsion/power/auxiliaries module is one of the most cost effective concepts. Again, the volume, piping and electrical wiring savings make up the major elements of the cost savings.

Affordability **Results**

Using the affordability analysis methods described previously, the relative affordabilities of each concept were assessed. Table III shows the ship cost and affordability results. Figure 10 plots the affordability results. The ship concepts of advantage have affordable fleet sizes greater than one hundred. The zonal and compartmental concepts plus the combination machinery module show major improvements in affordability compared to the baseline DDG-51. Powerpaks are neutral, while habitability and payload modules are affordability drawbacks.

CONCLUSIONS

With a steadily decreasing naval ship acquisition budget, cost saving and producibility improvements are of great interest. This study has shown that several machinery concepts can lead to major savings. These savings are mostly due to reduced ship size and outfitting, rather than the use of standard modules constructed in a shop. Habitability modules and payload modules show a negative cost advantage because of their volume inefficiencies.

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1. **Shiffler,** Mark, "Development of a Zonal Architecture Fire Main System for Combatant Ships," Naval Engineers Journal, May, 1993.
2. Petry, Chester R. and Rumburg, Jay W., "Zonal Electrical Distribution Systems: An Affordable Architecture for the Future," Naval Engineers Journal, May, 1993.
3. "Zonal versus Compartmental Auxiliary Systems," Decision Engineering Report, March, 1993.

Concept (Modules)	Average Acquisition Cost (M$)	Operating and Support Cost (M$/yr)	Affordable Fleet Size
Baseline	**829.8**	17.15	100.0
Powerpaks	**830.7**	17.23	99.9
Zonal Auxiliaries	**808.4**	16.24	103.0
Zonal Auxiliaries/Power	**796.4**	14.94	105.3
Compartmental Auxiliaries	**772.8**	15.59	107.7
Compartmental Auxiliaries/Power	**751.6**	13.89	111.7
Habitability	**853.5**	18.19	96.9
Combat System	**840.7**	17.56	98.6
Propulsion/Power/Auxiliaries	**771.1**	14.23	108.9

Table III. Ship Cost and Affordability

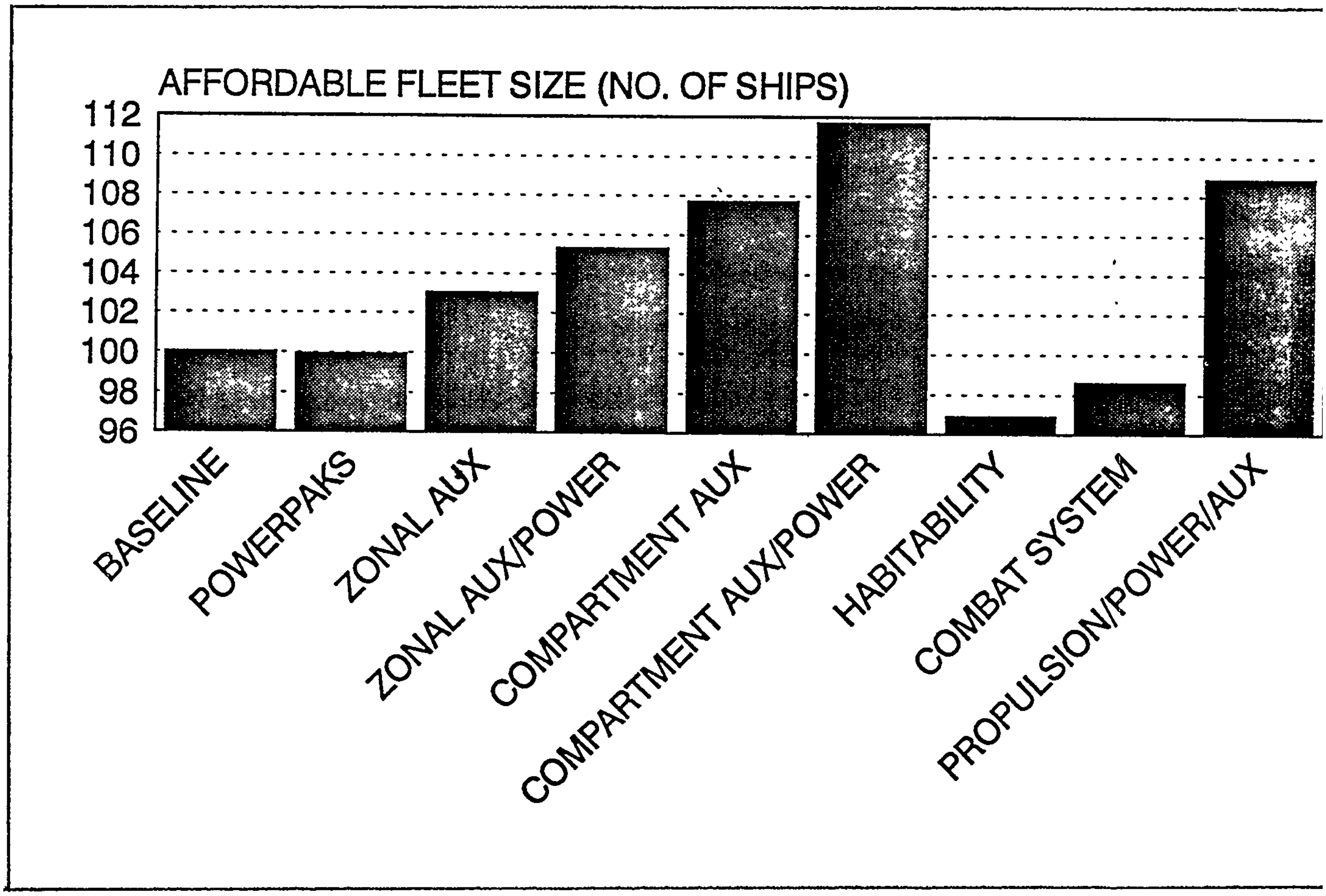

Figure 10. Affordable Fleet Size for Different Type Modules

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