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September 1989
NSRP 0310

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1989 Ship Production Symposium

Paper No. 3: Producibility in Ship Design

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

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 1989**	2. REPORT TYPE	3. DATES COVERED **00-00-1989 to 00-00-1989**

4. TITLE AND SUBTITLE **The National Shipbuilding Research Program. 1989 Ship Production Symposium, Paper No. 3: Producibility in Ship Design**	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,9500 MacArthur Blvd Bldg 192 Room 128,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**		**18**	

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

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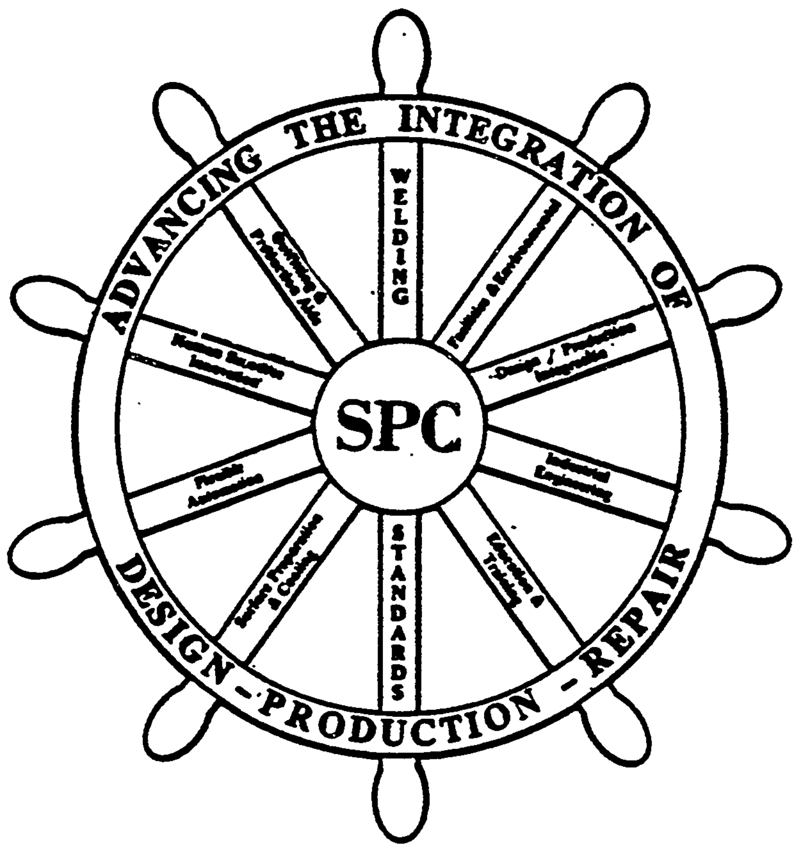
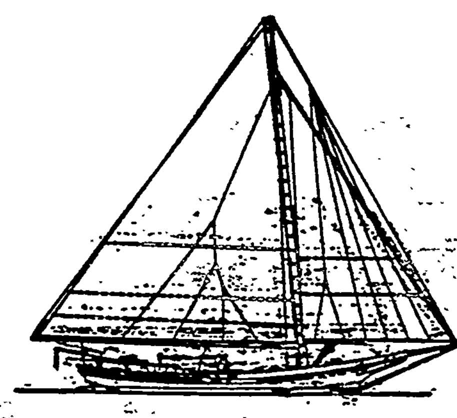
1989 SHIP PRODUCTION SYMPOSIUM

NSRP 0310



SEPTEMBER 13-15, 1989
SHERATON NATIONAL
Arlington, Virginia



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THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Jersey City, NJ 07306
Paper presented at the NSRP 1989 Ship Production Symposium
Sheraton National Hotel, Arlington, Virginia, September 13 - 15, 1989
No. 3

Producibility in Ship Design

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ABSTRACT

Much attention has been given in recent years to the problem of reducing ship construction costs. This has primarily emphasized the improvement of production techniques, processes and management controls. There is a great deal that can be accomplished in reducing ship construction costs, however, by improving the producibility of the design of the ship. The design of a more producible ship requires concurrent product and process design. Various principles and techniques can be applied throughout the design process in order to reduce the construction manhours required by ensuring that the manufacturing attributes are considered. This paper identifies some of the key principles involved and describes the techniques for applying the principles. A practical approach to estimating the cost benefit of alternative designs by estimating the labor input differential between the desiqns 25 also presented. Finally, specific examples of the application of the producibility techniques to several recent ship designs are included.

INTRODUCTION

In recent years there has been a concerted effort by many in the marine industry to reduce the cost of shipbuilding in the U.S. Much of this effort has focused on concepts such as modular construction, preoutfitting, new production processes, improved management control systems and the application of computers. There is an area which has received only limited attention: the reduction of costs as a result of making a ship cheaper to build by making it easier to construct. All too often reducing the cost of a ship has automatically focused on the removal of capabilities such as size, displacement, speed, payload or other features. The application of producibility in design concentrates on reducing the cost of building the ship without a reduction in capabilities.

Producibility in design is not a new concept. It is routinely applied in many industries. Unfortunately, in the shipbuilding industry, perhaps because of the very complexity of the task, we have tended to lose sight of the concept. Even when we talk about "producibility", we tend to use the term in a "ago/no-go" sense. The question here becomes "Can the design be built?" not "Should it be built the way it is designed?"

There is an increasing awareness of the need to put the design engineer and the production engineer back together. It has been termed "concurrent product and process design" by some. In reference (1) the authors have termed it "design to build", but the goal is the same. It is not to make the design merely producible, but to make it producible at the lowest cost.

This team approach to ship construction originated in the U.S. shipbuilding programs of World War II when speed, not cost was the driving factor. Men like Henry Kaiser applied mass production techniques to the construction of a basic ship design such as the Liberty ships. Since then, the approach has been further developed and refined by major shipyards in various countries throughout the world. The goal was to reduce costs. That is the only way to compete in the international market. The techniques have been reintroduced to U.S. shipyards in recent years with the adoption of modular construction and preoutfitting in block. However, there is a step beyond which can be taken. That step is to reflect the production considerations back into the design and to adapt the design to use the lowest cost construction techniques.

In reference (2), Hiroshi Sasaki described the highly successful IHI approach and the technology the Japanese have transferred to some of our shipyards. He emphasized the leadership role which is required of design engineering and the need for design and production engineering to work together. He clearly states *"Design engineers* cannot contribute to cost reduction as long as they consider their job as simply producing drawings. They should be aiming at minimizing production man-hour requirements."

This paper describes specific approaches to the design engineering process which can be used to reduce the required production man hours through the consideration of the manufacturing attributes of ship construction.

Achieving cost reduction in ship construction through design producibility is not easy. Nor is it a one-time task. It is not a task with one big effort followed by a great savings. Rather it is a series of steps, some large, some small, which result in savings, some large, some small but the total of which makes a big difference in the final cost. It cannot be delegated to a computer, but computers can assist in the process. It requires that detailed howledge of the production process be applied continuously throughout the design cycle.

When successfully applied, producibility in design can produce great rewards. How to incorporate producibility in a ship design and an approach to estimating the cost savings is the subject of this paper.

PRODUCIBILITY PRINCIPLES IN SHIPBUILDING

There are only two principal areas in which to reduce costs in applying producibility principles in ship design: the material costs and the labor costs. While savings in material costs are always possible through better selection, specification and purchasing, the total possible savings is limited. Engineers are traditionally concerned about the cost of the material that they specify. However, the labor cost is not as obvious and is therefore not given equal attention. Producibility in ship design must therefore primarily focus on reducing the manhours required to construct the ship.

The basic principle of the application of producibility principles to shipbuilding is to identify elements of the ship design which, if changed, would allow the ship to be built for fewer manhours and/or less material cost without modifying the ship's operational or maintenance performance requirements.

The overall approach is therefore to: simplify the work processes, reduce the labor input, reduce the number of steps, reduce the number of pieces, reduce the number of <u>different</u> pieces, and increase repetition.

Certain of the principles enunciated below are of significance regardless of the type of construction a shipyard employs. Other principles however, are directed toward facilitating the use of modern modular construction techniques. This is the construction of a ship in units which are almost completely outfitted before erection and assembly. Included in the process is the fabrication of machinery in units comprised of machinery, piping, controls and foundations. These machinery units are normally constructed in the shop and installed in the hull at the appropriate time in the construction process.

The producibility principles are quite general and almost axiomatic. The application of the principles, however, when combined with a thorough understanding of the ship construction process and environment, can be extremely effective in reducing costs. For maximum effectiveness, producibility must be considered at every stage of the design -- from the very earliest stages. Ideally, the designer should be planning the construction of the ship as he places the first line on the paper or on the computer screen. Even during the earliest stages, unrecognized high-cost features may be locked into the design. Every decision made in the design cycle may limit the application of producibility cost-savings changes. As an example, the knuckle locations on the T-AGOS (SWATH "A") were not located near the bulkheads to minimize construction costs but were already fixed by hydrodynamic considerations at the start of a major producibility review.

The following is a description of the producibility principles which should be applied in the design of any ship to minimize construction costs. The application of these principles requires a team effort with the coordinated experience and knowledge of the ship designer, production engineer and production planner focused on the problem of reducing costs.

Limiting Capability

Remove everything from the design which is not required by the operational requirements. Features, equipment, capability and informal margins have a way of creeping into a ship design for a variety of reasons. To minimize costs, these aspects of the design must be found and removed. This is not a one-time activity but must be a continuing function to control costs. Adding capability always increases costs. Adding unneeded capability wastes resources.

Double Curvature

Avoid double curvature surfaces in hull plating. Many of the hull lines can be straight in one direction without loss of hydrodynamic performance or appearance. The curves in the other direction and the radius bends give shape to the hull. A double curvature plate will usually require heat treatment and increased work input to achieve the required shape. Figures 1 and 2 shows the contrast in sections for the bow of similar ships.

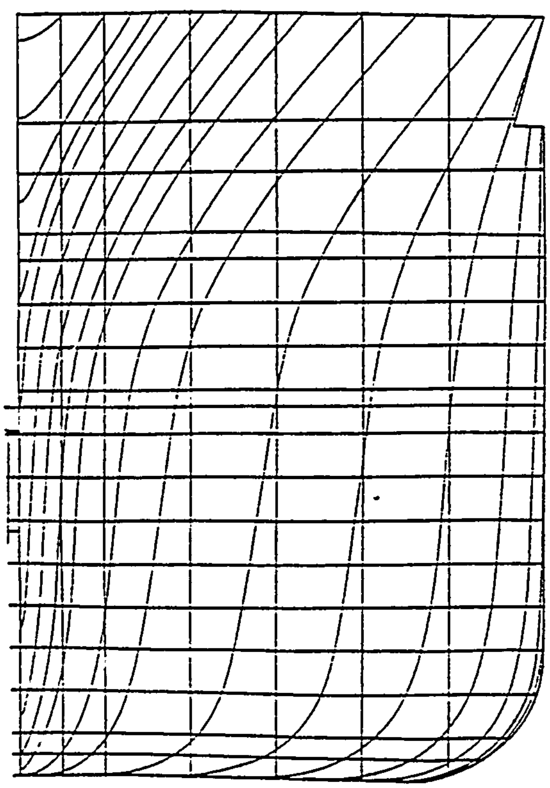

Figure 1. Hull Lines - Curved Sections

Hull Curvature

Do not carry the hull curvature into the structure inside of the hull plating surface. Use straight lines and flat surfaces wherever possible. Even though the hull lines are curved, there is no need to bring the exterior

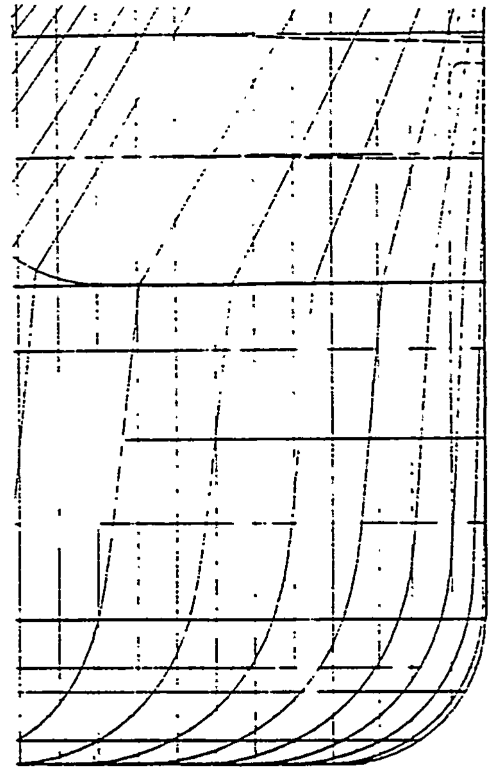

Figure 2. Hull Lines - Straight Sections

hull shape into the interior hull structure. The internal structure must support the hull plating but also serve as a transition between the curves of the hull exterior and the straight lines and flat surfaces of the interior. Figure 3 shows a hull structure which illustrates this concept. Figure 4 shows a hull structural design in which the internal structure follows the external curves.

Frame Spacing

Maximize frame spacing to both reduce the number of pieces and improve access to the work. Frame spacing can have a major impact on construction cost. For various reasons, 24-inch frame spacing has been common design practice for the bow and the stern in the U.S. However, a two-foot space is difficult to construct. The shipyard worker is forced to work in tight spaces where movement is restricted, accessibility is awkward and the working position is difficult to maintain. Using a larger frame spacing of 33 to 36 inches simplifies the construction problems and allows for the removal of up to one-third of the frames. The weight of the removed frames can be applied to increasing the scantlings of the remaining structure to maintain strength. This will not only reduce the construction man-hours due to the fewer pieces but may also reduce the structural weight. The

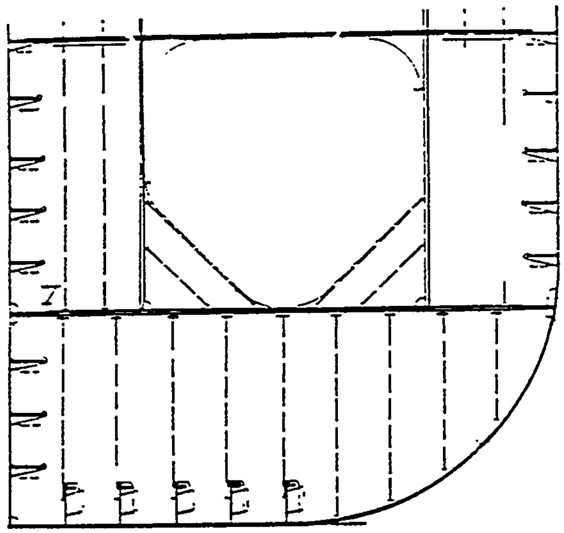

Figure 3. Hull Structure Straight Interior

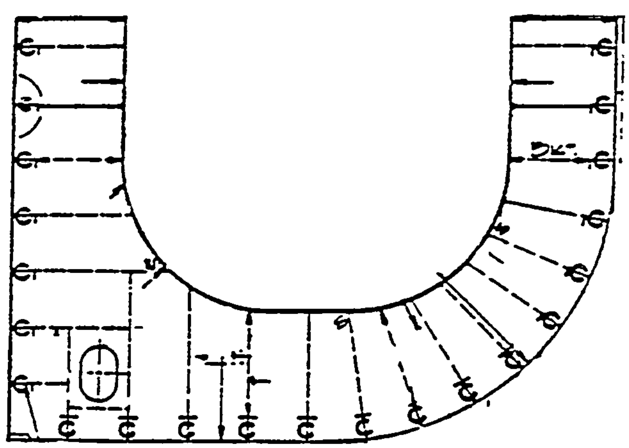

Figure 4. Hull Structure - Curved Interior

larger space will also improve the worker's productivity by easing the problem of gaining access to and working in the narrower spaces.

Number of Parts

Reduce the total number of pieces which have to be manufactured, tracked, assembled and installed. Following the reasoning contained in the frame-spacing discussion, there are many areas in the hull where moderate increases in the size or thickness of some of the pieces can be traded for a decrease in the total number of pieces required. Decreasing the number of pieces represents a savings in man-hours required for the design, fabrication, material handling and tracking, welding and fitting of the pieces. Furthermore, the trade-off can usually be accomplished with little or no increase in structural weight and may even result in a weight reduction. As an example, Figure 5 shows a section of the cargo tank structure of the T-A0187 while Figure 6 shows the structure of a producibility enhanced

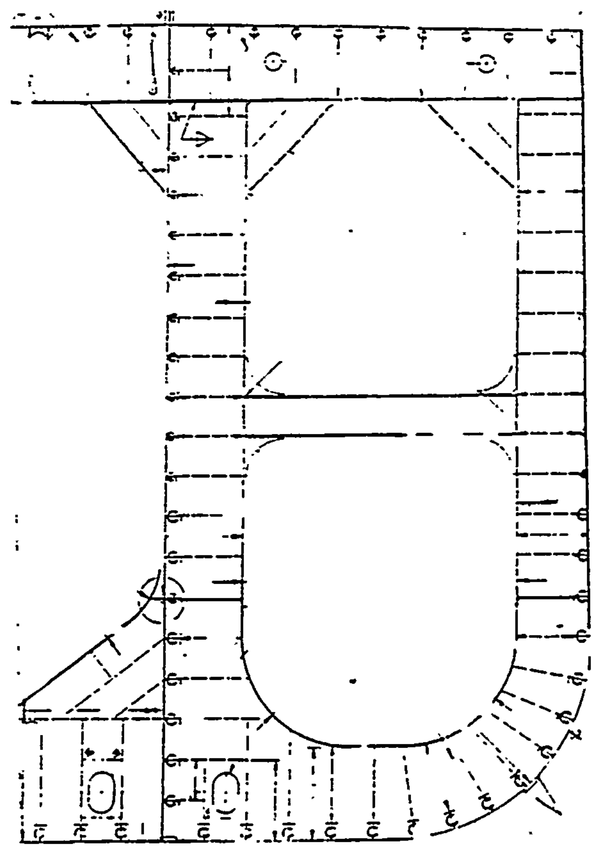

Figure 5. T-A0187 Cargo Tank Structure

Design for Modular Construction

Design the ship to facilitate assembly and erection with structural units, machinery units and piping units. This is the key to modular (unit) construction. By building the ship in units, the work can be spread

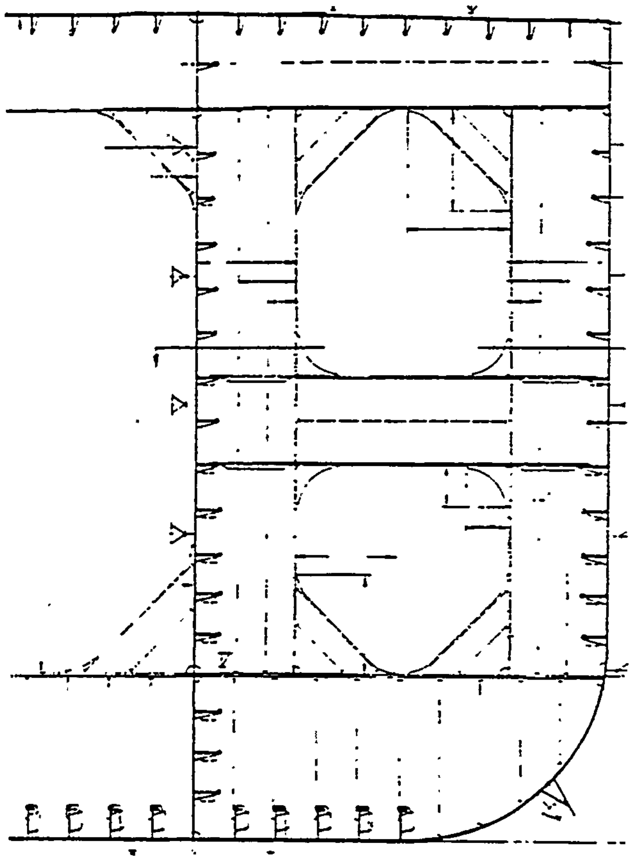

Figure 6. Producibility Enhanced Cargo Tank Structure

over the area of the shipyard. This improves access to the work and reduces interference in contrast to the older approach of assembling the ship, piece-by-piece on the building ways which concentrates all of the work in one small area. Further, with the ship to be constructed by units, the ship must be designed by units. The units should therefore be designed to simplify the construction and erection processes to attain the greatest cost savings from modular construction. Figure 7 shows the planned unit breakdown of a single screw tanker.

Unit Breaks

Establish the unit breaks EARLY in the design process and locate them for repetitive design and construction of the units. The location of the unit breaks (the lines identifying the units in unit construction) can be critical to cost reduction. For some ships, such as tankers and other bulk carriers, the structure is repetitive. By careful location of the unit breaks, the units to be fabricated can then be made nearly identical. All of the identical units can be built from one set of plans with a resultant savings in engineering manhours. This not only allows for assembly-line type construction with the cost benefits of line production, but also reduces the manhours required to design the ship.

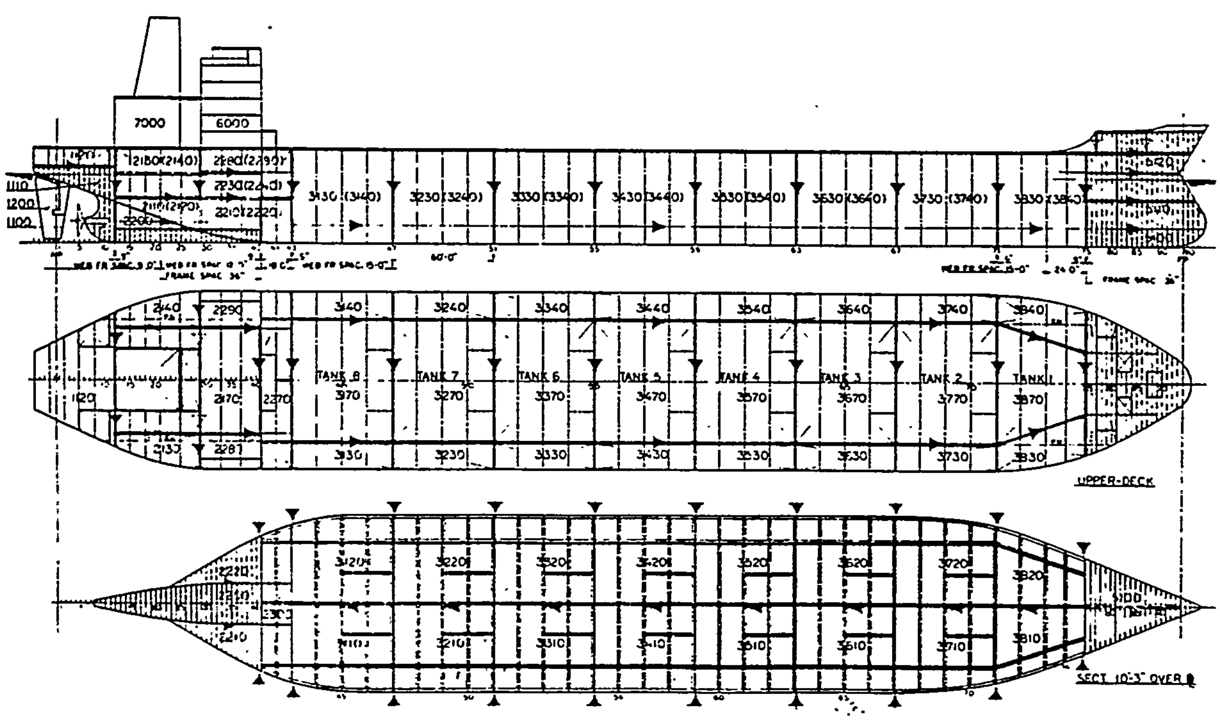

Figure 7. Unit Breakdown Plan

The location of unit breaks also affects the ease of erection. Joining two units is easier if the joint in one unit is stiff (near a joint) and the other flexible (distant from a joint). Joining two units also is easier if a unit is designed to be landed on a flat surface instead of joining two plates edge to edge. Figure 8 shows an erection sequence for a design employing these design features.

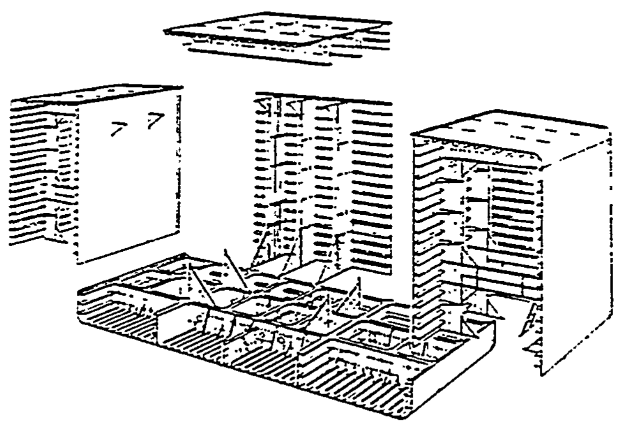

Figure 8. Cargo Tank Erection Sequence

The early location of unit breaks provides another benefit by permitting the designer to locate the various items of machinery and equipment in positions which facilitate unit outfitting. Any equipment which happens to be located across a break cannot be installed until after the units have been erected. Equipment which cannot be installed until after the unit is erected on the building ways is normally more costly to install. Arranging the machinery and equipment within a unit and avoiding the breaks is possible only if the unit break is known before the arrangement is designed.

Limit Unit Size

Avoid excessively large units. Unit sizes are frequently established by the maximum lifting capacity of the shipyard. However, as the unit increases in size, the problems of access, congestion and interference at the work site increase. A very large unit may present problems on the order of building a small ship. Making use of the maximum lifting capacity may not be the lowest cost construction approach.

Knuckles

Locate knuckles at unit breaks. Do not place knuckles either at or between bulkheads cr decks but 9-12 inches from the balkhead or decks where the breaks will be made. Knuckles are easier to fabricate if they occur at a unit break than if they occur midway in a unit. As unit breaks should be located 9 to 12 inches above a deck or away from a bulkhead, that is also the preferred location for a knuckle. A knuckle has little or no hydrodynamic effect if it is above the waterline. The proper location of a knuckle requires coordination between the lines, arrangements and structure at an early stage of a design.

Standardized Parts

Use standardized parts whenever possible. The use of standardized parts, such as brackets, can reduce the variety of pieces that the shipyard has to fabricate, keep track of and install. For example, the cost nf using 100 identical pieces is obviously less than the cost of using 25 each of four different pieces. The cost differenitial may be difficult to evaluate, but it is real.

Machinery Arrangement

Arrange machinery to minimize piping runs and improve operation and maintenance. Machinery arrangements can contribute to decreased costs by reducing the amount of piping, electrical cable, exhaust pipes, etc. which must be installed. Arranging machinery symmetrically in a space can result in unnecessary additional costs as contrasted to careful grouping. Also, grouping pipe runs and treating them as units can transfer work from the machinery or other shipboard space to the shop, where greater productivity can be achieved.

Machinery Units

Plan machinery installations for shop assembly and testing. Assembling machinery on skids for installation aboard ship as a fully tested, complete unit permits the work to be accomplished in the more efficient shop as opposed to the shipboard space.

Welding

Design for use of automatic welders and other high-productivity tools. The welding processes to be used should be considered during the design. The use of straight sections and single-curvature plates improve welding productivity by facilitating the use of automatic welding machines for the work. Similarly, care in design can permit the erection sequence to be planned for increased downhand or automatic welding. Finally, care in the design of welding details not only can decrease the man-hours required but can also improve the quality of the welds. Examples of improved producibility welding details are shown in Figure 9.

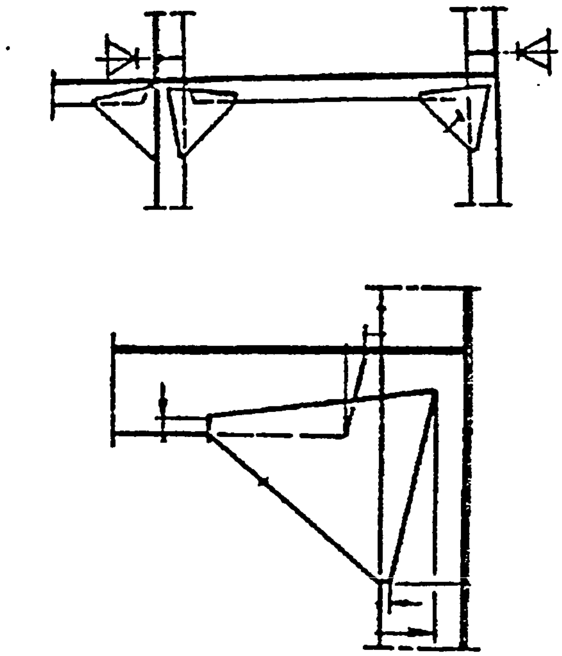

Figure 9. Welding Details

Weight vs Cost

Use limited increases in material weight, i.e., thickness, size, etc., as a trade-off when a decrease in manhours can be achieved. The increased material cost is more than compensated for by the reduced labor cost while the change in total light ship weight may not be significant. This has been validated by calculation and actual construction results. However, a small increase in light ship weight might well be acceptable to realize a significant reduction in construction manhours. Frequently limits on displacement, light ship or full load, are attempts to limit the cost of the ship. Trade offs between weight and cost therefore are possible.

DESIGNING FOR PRODUCIBILITY

In applying the producibility principles to a ship design, the design engineer and the production engineer must work concurrently and interactively. The earlier in the design process that the production engineer is brought into the effort, the more effective he can be. Every decision that is made in the design process before producibility considerations are introduced reduces the potential for cost reductions. The concurrent effort should begin as early as the feasibility/preliminary design stage.

It is obvious that incorporating producibility in the design requires extensive knowledge of the production processes used in the construction of a ship. The production processes are of course dependent to some extent upon the facilities and capabilities of a specific shipyard. This might appear to undermine the case for early involvement of the production engineer. The standard approach to ship design in the U.S. separates the early design from the building shipyard. While a commercial owner may well develop the contract package in consultation and negotiation with a shipyard, the U.S. Navy normally prepares a preliminary and contract design including a set of specifications before awarding the work to a specific shipyard. The Navy cannot deal with only one shipyard before contract award, but has invited shipyard participation during the design process. More than one yard will normally participate. The Navy's acquisition approach complicates the introduction of producibility into the process but does not prevent it.

The size, type and other characteristics of a ship normally dictate the group of shipyards with the capability to build the ship. While the capabilities of the shipyards vary to some extent, the number of similar capabilities is greater than the number of differences. There is a common set of capabilities which each shipyard in the group possesses and which can be used for the production engineering decisions that must be made.

With this approach, every shipyard in the group will find the resulting contract design a buildable design for their facility. The Navy/owner will have a contract for a ship which can be competitively bid on by a group of shipyards but which will also be designed for the lowest construction cost by those yards as a group. Further producibility refinements may be possible by the shipyard winning the contract and should be considered after award. However, the most cost-effective, basic producibility decisions will have been made.

There are two basic questions which must be considered in designing for producibility. First, does the design meet the operational requirements? Second, is it the lowest cost? In comparing designs, cost therefore becomes a major driver. The cost of constructing alternative design features can be estimated and the decision can be reached in a rational, logical manner. Using this approach, the decision process will lead, step by step, to the lowest cost ship design.

ESTIMATING COSTS

General

Cost estimates are normally developed from different approaches -- the macro, cost-down, historical and the micro, cost-up, engineering analysis. In the macro approach, historical data is used to develop cost estimating factors. These factors are usually based upon weight, i.e., fabrication manhours per net steel ton. The factors reflect past practices and experience. The alternative approach is to break down the project into elements of work and build up a cost estimate in a detailed engineering analysis. This approach also uses cost factors but they are based upon work studies of elements of the operation, i.e., manhours per foot of weld.

The macro cost estimates are easier to apply and can provide earlier results than the alternative. Macro cost estimates can provide a gross estimate before the design is completed. However, from a producibility point of view, there are four major deficiencies to macro estimates. First, they are based upon historical cost returns. Shipyards are traditionally poor sources of cost information. The data is frequently skewed reflecting pressures on the first line managers and other factors. Second, by being based on historical data, macro estimates tend to continue past practices. Third, by being based upon weight, any change which increases weight will automatically increase the cost estimate regardless of the effect on cost. Cost reductions which result from weight increases tend to be ignored. This aspect of macro estimates leads to an over-emphasis upon weight as a means of cost control. Finally, macro estimates do not permit the cost comparison of the features or details of a design which is so necessary for selecting the lowest cost design approach at each step. Clearly, macro estimazes are not supportive of improving producibility in ship design.

The NAVSEA ship cost estimating model is of the macro, historical, cost history type. As Such, it has an inherent dampening effect upon innovation.

The micro or engineering cost estimate is more difficult to develop but can be applied to specific features of a design as they are developed and the construction process selected. The results of an engineering analysis are inherently more accurate and flexible. Finally, because micro estimates are prepared in considerable detail, actual cost returns can be more readily compared to the cost estimates to pinpoint divergences, problems and needed corrections.

Comparative Cost Estimates

For producinlity" decisions, it is fortunately not necessary to develop a total-ship, detailed cost estimate, either macro or micro. Rather, a comparative cost estimate will suffice to demonstrate the potential cost impact of a proposed producibility change, i.e., this change will result in a reduction of x feet of weld. The comparative cost method applies a form of engineering analysis but limits the extent of the application to the differences in the alternative designs.

Inherent in the comparative cost estimate is the assumption that the construction plan has been developed. It is difficult if not impossible to divide the work into elements if the basic construction plan for the unit or feature has not been developed.

Example

The application of the comparative cost estimating techniques to the SWATH "A" project will be used as an example. During the course of a producibility review, a producibility enhanced design (PED) for the lower hulls was proposed. This design was compared to the lower hull design under consideration which was similar to the TAGS-19 design.

For the analysis, a construction plan was assumed for the NAVSEA baseline design similar to that being followed by McDermott Shipyards on the TAGS-19 project. For the lower hull, this includes laying the keel, erecting the bulkheads, installing the longitudinal frames and then wrapping the hull plating around the structure. Modular construction is not possible and preoutfitting can be only minimally used. This is a rational construction approach for the complex structure of the TAGS-19 and the baseline NAVSEA design for the SWATH "A".

The producibility enhanced design was developed to permit the use of modular construction techniques and preoutfitting. The planned construction/erection sequence for a section of the lower hull is shown in Figure 10. The construction of the producibility enhanced design does not require capabilities or facilities beyond that customarily found in U.S. shipyards. The producibility enhanced SWATH "A" design could be constructed in different erection sequences but it is believed that any of these would require more construction manhours than the proposed erection sequence.

In developing the comparative cost estimate for the lower hulls between the NAVSEA baseline design and the PED, the following approach was used: An 18 foot section of the lower hulls, equal to one compartment length was selected. For both hulls, a detailed weight estimate was prepared. The manhours required to fabricate and erect each section was them analyzed in detail.

Weldinq. For an 18 foot section, the total length of welding required was measured and calculated. The basic welding technique to make the welds, i.e., downhand, overhead, and automatic, were also identified and lengths for each technique totaled, with downhand welding assigned a factor of difficulty of 1, overhead welding assigned a conservative factor of

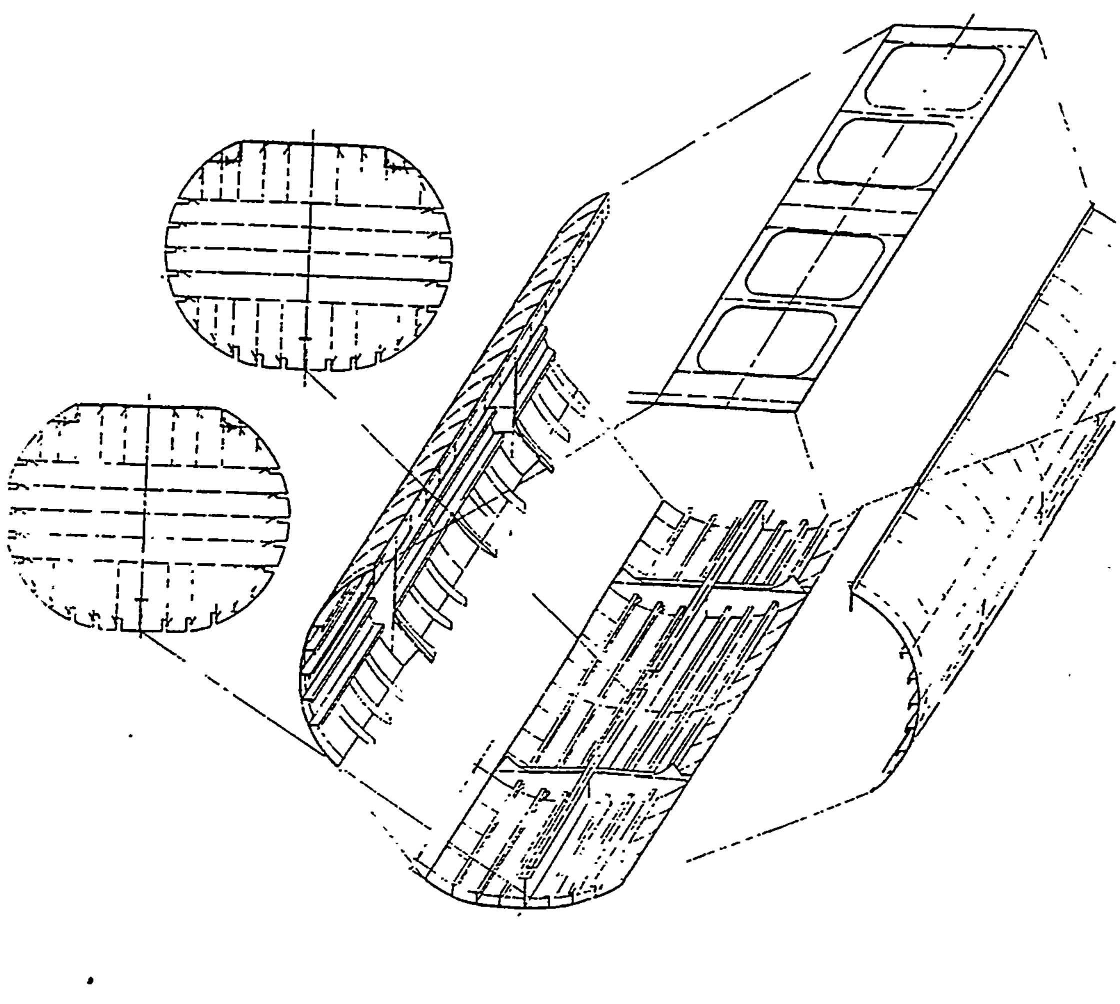

Figure 10. SWATH "A" PED-Lower Hull Construction Sequence

difficulty of 2, and automatic welding a factor of 0.2. The equivalent lengths of welding for both designs were then calculated and compared. It is estimated that the PED would require 35 percent of the welding effort of the baseline design.

Fitting. The number and type of individual pieces in an 18 foot section of the lower hull were identified for each design. The number of pieces, the variety of pieces and the difficulty of positioning the pieces were used to derive a factor of difficulty of fitting. With the PED assigned a factor-of 1.0, the baseline design was conservatively estimated to be 1.5 times as difficult. The product of the number of pieces times the factor of difficulty was compared for each design. It is estimated that the PED would require 28 percent of the fit-up effort of the baseline design.

Savinas. Since 40 percent of the structural construction effort is normally in welding and 60 percent in fit-up, the cost factor for each category was multiplied by the factors and summed. The resulting estimated average cost for the lower hull construction of the producibility enhanced design was 30 percent of the baseline design. The data and calculations are provided in detail in Table 1.

PRODUCIBILITY EXAMPLES

Some specific examples of the application of producibility concepts to three specific ship designs are provided in this section. While these examples represent potential cost savings, due to various circumstances, not all of them have been acceptea or incorporated in the design. If the

COMPARATIVE COST ANALYSIS

NAVSEA SWATH "A" BASELINE
VS
PRODUCIBILITY ENHANCED DESIGN
LOWER HULL : 18'-0" FOOT SECTION

	NAVSEA BASELINE	PRODUCIBILITY ENHANCED DESIGN		
WELDING				
WELD LENGTH-TOTAL (FT)	2186	1386		
OVERHEAD LENGTH (FT)	855	55		
OH FACTOR OF DIFFICULTY	2	2		
AUTOMATIC WELDING LENGTH (FT)	215	550		
AUTO FACTOR OF DIFFICULTY	0.2	0.2		
EQUIV LENGTH OH WELDING (FT)	1710	110		
EQUIV LENGTH AUTO WELDING (FT)	43	110		
REMAINING WELD LENGTH (FT)	1116	781		
EQUIV WELD LENGTH-TOTAL (FT)	2869	1001		
COST FACTOR(CF)- WELDING		34.9%		
FIT UP				
PIECES- TOTAL NUMBER	334	139		
DIFFERENT PIECES	20	14		
FIT UP DIFFICULTY FACTOR	1.5	1		
FIT UP -EQUIVALENT EFFORT	501	139		
COST FACTOR(CF)- FIT UP		27.7%		
	% OF EFFORT	COST FACTOR		WEIGHTED COST
WELDING % OF EFFORT x CF	40% x	34.9%	=	14.0%
FIT-UP % OF EFFORT x CF	60% x	27.7%	=	16.6%
COMPARATIVE COST - LOWER HULL				30.6%

Table 1. SWATH "A" - Comparative Cost Estimate

proposed producibility changes had been available earlier in the design cycle, more of them might have been included in the final designs.

T-AGOS (SWATH "A") LOWER HULL STRUCTURE

The structure of the lower hull of the design under consideration by NAVSEA was not compatible with modular construction techniques. The design required the lower hull to be constructed piece by piece. The construction sequence is: the keel is laid, bulkheads erected, longitudinal framing installed and the hull plating wrapped around the framing. Manual welding must be employed extensively and, much of that in inaccessible or awkward locations. Access for outfitting is restricted. The design limits the building yard from employing a more efficient unit construction and preoutfitting approach.

The initial NAVSEA structural design, shown in Figures 11 and 12, hdd the following features:

The lower hull was longitudinally framed with 36 T-profile longitudinal installed perpendicular to the curved hull plating, requiring difficult fit-up and welding procedures.

The 36 longitudinal represented a stiffener-to-plate ratio of over 51 percent, which is not considered to be optimum for strength and weight considerations.

TWO heavy girders were installed in each hull for pier loadings.

The bulkheads were designed with vertical webs, a horizontal stringer, and 13 vertical stiffeners.

The upper (internal) surface of the hull was curved, an unnecessarily costly detail. Hull strength can be provided equally well with straight structural members.

Each hull had 28 T profile web frames.

The lower hull structure of the PED, shown in Figures 12 and 13, was designed for unit construction and extensive preoutfitting. In lieu of requiring construction on the ways, each subunit in the producible hull structure is designed for fabrication in a horizontal "position on the ground and assembly into units on the flat. The bulkheads are erected on the bottom unit, and the side units are assembled around the bulkheads. The top unit, which closes the hull, is not to be installed until the outfitting is completed. The erection sequence is shown in Figure 10.

Some specific features of the producible lower hull design include:

The use of 16 L profiles per hull for the longitudinal framing, each of which is oriented either vertically or horizontally. The pier loading girders are deleted.

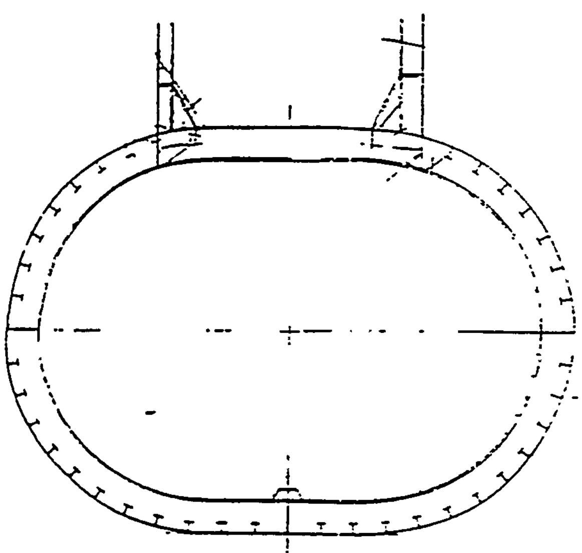

Figure 11. T-AGOS (SWATH "A") -Lower Hull Structure

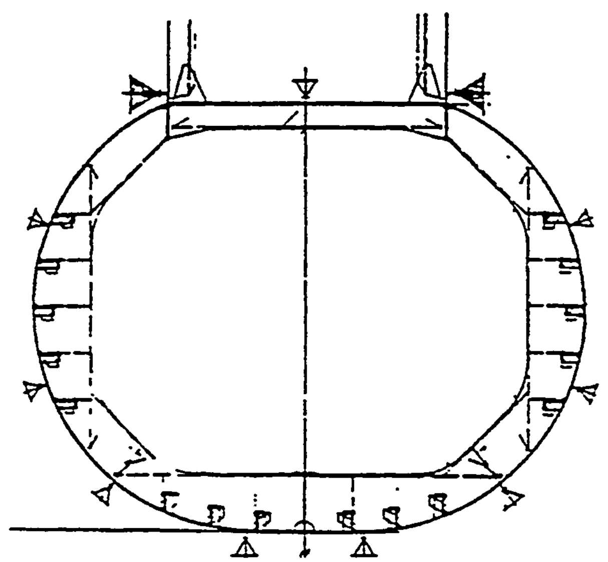

Figure 12. Lower Hull Structure Producibility Enhanced Design (PED)

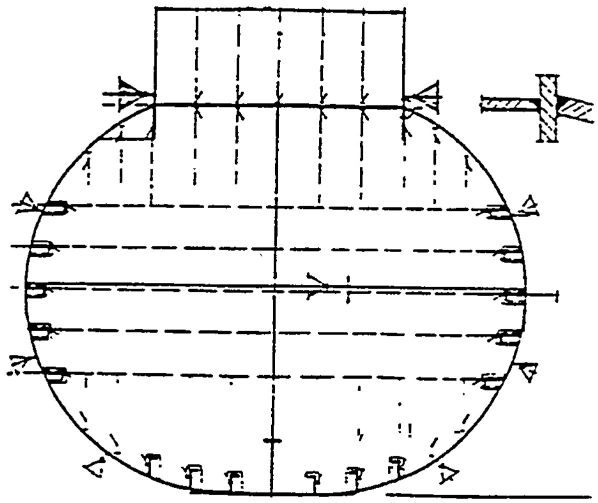

Figure 13. Lower Hull - Bulkhead - PED

The web frame spacing has been increased from 6 to 9 feet and web frames reduced to 15 of built-up construction.

The bulkheads have a vertical web and five main horizontal stiffeners.

The upper (internal) surface of the lower hull is flat and part of the material inside the tanks has been removed.

The PED lower hull design is planned for construction of each hull unit in five sections (including the transverse bulkheads) and assembly in the fabrication shop. The top segment is to be installed after outfitting is complete.

The PED lower hull structure can be constructed by any U.S. shipyard with reasonable capabilities. Construction in 36 foot long units is planned, but 18 foot units may be substituted if necessary. There is no feature of the design which limits competition or would place any reasonably equipped shipyard at a disadvantage in competitive bidding.

The benefits of the producible lower hull design include:

Thirty-six "T" profiles and two horizontal girders have been removed per hull and replaced by 16 "L" profile longtudinals.

The installation and welding of the longitudinal has been simplified.

Thirteen web frames have been removed per hull.

In the bulkheads, 13 vertical stiffeners have been replaced by five horizontal stiffeners.

Finally to erect the haunch unit to the lower hull in the NAVSEA design, the upper unit must be landed on the surved upper surface of the lower hull. The lower edge of the haunch unit must then be aligned with the interior stiffeners -- which are not visible. In the PED sequence, the upper subunit of the lower hull contains the connection of the haunch to the lower hull. The lower edge of the haunch is welded to the upper edge of the penetrating section.

These changes resulted an estimated decrease in construction manhours of approximately 30 to 35 percent for the lower hulls.

AOE-6 Frame Spacinq

The web frame spacing of the AOE-6 varies between 9, 10 and 11 feet in various sections of the ship. The changes in web frame spacing cause variations in the dimensions and design of the units from which the hull is constructed. This in turn prevents standardization of the design of similar units and thus reduces the production line "learning Curve" benefits from the repetitive construction of identical units.

The variations in frame spacing also impacts the length of shell and longitudinal bulkhead plating which must be procured. This increases the material costs including procurement, handling, tracking and storage.

The variations in web frame spacing will have a significant impact upon construction costs as opposed to the use of a constant web frame spacing.

A further disadvantage to the variation in web frame spacing is the unnecessary weight. The longitudinal throughout the ship are sized by the required longitudinal dimensions for the maximum spans. In the shorter span areas, the longitudinal will be oversized for the span. This represents an inefficient use of the weight resource of the design. Some of the structural lightship weight is devoted to material which does not contribute to the strength of the ship.

Finally, the web frame spacing of 9 to 11 feet is excessively close for a ship of the size of the AOE-6. A spacing of 13′9″ (5 x 33″) or 15′0″ (5 x 36") would be more suitable for this design. A rearrangement of the web frames was recommended.

T-A0187 Machinery Arrangement

In the T-AO **187** design, the machinery arrangement did not locate the various items for minimum construction cost. The auxiliary machinery was not grouped together by function nor arranged to facilitate skid mounting of identical units.

Pipe, duct and electrical runs were not planned to minimize the material required, the installation cost nor the use of valuable machinery space volume. For example, the diesel generator location required the routing of the main electrical cables the length of the Engine Room. Further, the auxiliary boiler is located well aft while the uptakes are forward in the space over the main diesels. This requires the boiler exhaust to pass through, horizontally, a major part of the machinery space before turning up. Not only does the exhaust duct present a major obstacle for other necessary routings, but the horizontal run may well prove to be an operating and/or maintenance problem in the future.

The T-AO 187 Cargo Pump Room uses two motor rooms, three pump rooms and voids to separate the cargo from the motor rooms. This cargo pump room arrangement consumes excessive space, requires convoluted runs of large diameter piping and the installation of unnecessary structural material for bulkheads and voids. An alternate cargo pump room arrangement using a single motor room with a pump room at either end would be a major cost saver. The pump rooms would provide the required separation of the cargo from the motor rooms saving the strucural material needed for the voids and one high cost motor room would be eliminated. Further major savings would have been possible from this change, if it had been made early in the design cycle and the resulting reduction in volumetric requirements were used to reduce the overall size of the ship.

CONCLUSION

Clearly, there are distinct benefits to be gained by bringing the concepts of producibility into the ship design process and as early in the process as possible. There are sizable savings in manpower possible by the concurrent process of design and production engineering. This is particularly true if the goal for the concurrent effort is not merely "Can it **be built?" but** "Is it the lowest cost **design?"**

To gain the full benefits of producibility it must be started early in the design spiral and continued throughout the design and construction of the ship. It requires a continuing effort with many apparently small victories, but the final results can have an appreciable effect on cost.

Even after the ship is delivered, the design and production engineers with the assistance of the production personnel should continue with a detailed review of the actual results they achieved. Were they right in their producibility changes? Where did they make mistakes? Did they miss **aspects** of the design which could have been done better or cheaper? Without this follow-up effort, the learning process may stagnate and producibility become yet another tired, old watchword.

Finally, we must always keep in mind that we are trying to deliver the best ship at the lowest cost. When we succeed, we all benefit, even the taxpayer.

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