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CEND-150(Pt. I)

ADVANCED INDIRECT CYCLE WATER REACTOR STUDIES FOR MARITIME APPLICATIONS

Part I. Cost Analysis and Future Development

April 1962

Nuclear Division
Combustion Engineering, Inc.
Windsor, Connecticut

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UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

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CEND-150(Pt. I)

REACTOR TECHNOLOGY

ADVANCED INDIRECT CYCLE WATER REACTOR STUDIES FOR MARITIME APPLICATIONS

PART I

COST ANALYSIS

AND

FUTURE DEVELOPMENT

APRIL, 1962
CONTRACT AT(30-1)-2709
U.S. ATOMIC ENERGY COMMISSION

COMBUSTION ENGINEERING, INC.
NUCLEAR DIVISION
WINDSOR, CONNECTICUT

FOREWORD

This is the final report of a study directed toward the evolution, design, and demonstration of the principle design features of interim indirect cycle water cooled and moderated nuclear power plants which will be useful in early cooperative programs between the AEC and the U. S. maritime industry. The basic design involved is generally similar to that proposed by Combustion Engineering, Inc., in Report NYO-2860 (CEND-62). This plant, which was capable of developing 30,000 shaft horsepower for tanker service, has been updated by the inclusion of recent technological developments such as self-pressurization and consolidation of auxiliary service equipment. Emphasis was placed on ideas which permit reduction of costs, simplification of control and mechanical systems, and minimum crew attention requirements during operation.

The studies included the development of the conceptual design of the reference plant for two different operating pressure ranges. A concept of a more advanced minimum attention plant which could logically evolve from the reference plant was developed. In addition, studies were made of several plant features which are significant to the present or future improvements.

The report consists of six parts which are titled as follows:

- Part I - Cost Analysis and Future Development
- Part II - Plant Conceptual Studies
- Part III - Analog Simulation of Reactor Plant Transients
- Part IV - Steam Driven Coolant Pumps
- Part V - Spiked Core Concept
- Part VI - Natural Circulation Capabilities

The work was conducted in compliance with U. S. Atomic Energy Commission Contract AT(30-1)-2709.

ABSTRACT

The competitive position of nuclear energy as a source of commercial propulsive power was determined within the economic framework of 43,000 DWT class, American-built tankers. The current status of indirect-cycle, water reactor plants was assessed by comparing estimated costs for two presently attainable, second-of-a-kind nuclear ships with the cost of a conventional tanker powered by an oil-fired marine boiler. The two nuclear systems differ in that one utilizes latent heat instead of sensible heat for superheating and is more compact.

The short-range and longer-range potentials for this application of nuclear energy were assessed by predicting the effect of evolutionary developments and the influence of full industrial participation. The evaluations of both the current and future status were made by computing annual operating costs for two trade routes - a long voyage to Kuwait on the Persian Gulf from the U. S. East Coast and a shorter trip along the U. S. East Coast.

It was concluded that a competitive nuclear tanker can be constructed in the foreseeable future if emphasis is given to developing the proper present day concepts. A research and development program outlining the key areas for future work was formulated. It was recommended that this program be conducted before persuing a cooperative ship building program with the maritime industry.

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I. INTRODUCTION

In connection with their program of research and development on reactor systems for maritime application, the U. S. Atomic Energy Commission selected Combustion Engineering, Inc. to conduct design and engineering studies and economic evaluations of new and advanced features for application to indirect-cycle water reactors.

A. OBJECTIVE

The studies conducted in this program were to be aimed at the evolution, design and demonstration of the principal features of interim indirect-cycle, water-cooled and-moderated nuclear power plants which will be useful in early cooperative programs between the AEC and the U. S. maritine industry. Advances that have been made in water reactors since previous maritime reactor studies were to be reviewed and assessed for economic impact. The basic reactor system design and referent nuclear powered ship are those proposed by Combustion Engineering, Inc. and George G. Sharp, Inc. in report NYO-2860, "Nuclear Powered Tanker Design and Economic Analysis - Pressurized Water Reactor." Possible affects of the improvements on the referent ship costs and crewing requirements were also to be determined in order to recommend areas where improvements could be made by a ship's designer.

In addition, evaluation was also to be made of further advances considered possible and desirable but on which confirmatory research and development work must be conducted. Emphasis was to be placed on reduction of costs through simplification of control and mechanical systems, reduction of crew members, consolidation of equipment and prefabrication of systems. Recommendations were to be made for the demonstration of these features through research and development programs, application to the N. S. Savannah, and future cooperative ship building programs with the maritime industry.

B. SCOPE

The work done under this contract is a part of a program directed towards the ultimate development of an indirect-cycle nuclear power plant for the maritime industry that would be competitive with conventionally powered ships. The ideas developed and improvements proposed could be applied to a nuclear power plant for any type of merchant ship. The quantitative cost reductions have been evaluated on the basis of a particular type of ship used in a previous study because the design and cost basis was available. Though the actual cost reduction could vary considerably with the application, it is believed that for all major features where a cost reduction exists for this application one would also exist for the other applications.

In the previous study, Report NYO-2860 published in January 1960, Combustion Engineering, Inc. proposed a conceptual indirect-cycle, water-cooled and moderated reactor plant for application to a T-7 type tanker. This plant developed non-radioactive steam with a modest amount of superheat and constant pressure at the turbine throttle. Standard components could therefore be used in the propulsion system. All the heat produced by the core was removed by a sensible heat change of the coolant. Though some boiling was permitted in the hot channels, the average condition at the core outlet was subcooled. The necessary information for adapting the plant to the ship was furnished by George G. Sharp, Inc. The resulting ship operating costs were developed by all cooperating parties.

Using this plant and the associated costs as a referent point, several advances in reactor system design were examined relative to technical feasibility and reduction in operating or capital costs. The more important features examined in this manner were system self-pressurization, natural circulation, steam driven coolant pumps, simplified instrumentation, control due to inherent response characteristics and consolidation of plant equipment and functions. The areas to be studied were selected by examination of the detailed cost estimate of the previously proposed ship. Ideas such as the above were then generated to lower costs in those areas where there seemed to be the greatest cost reduction potential.

The previous reactor plant was then modified by incorporating those ideas that showed an economic advantage and did not require research and development to prove feasibility. Sufficient engineering was done to assure that the major features could be synthezised into a good power plant for a ship which could be built on a forty month design and construction schedule with the required research and development being done concurrently. Important new features in the reactor system were reactor coolant temperature at core exit raised to saturation, elimination of the separate pressurizer, consolidation and pre-assembly of auxiliary systems, and improved core heat removal. This provided an updated interim power plant concept that could be used by the AEC in a cooperative ship construction program with the maritime industry. Costs were estimated for this power plant and incorporated with the hull and propulsion plant costs from the previous study to provide an over-all picture.

Because certain economic advantages could be obtained, another modification of the nuclear power plant was adapted to the tanker for cost evaluation. In this alternative power plant, a small amount of the coolant, about one percent, leaves the core as steam which is condensed to superheat the secondary steam. This modification was proposed by Combustion Engineering, Inc. in another report, N-6019, "Economic Study of Nuclear Propulsion for American Flag Tankers," prepared for the Maritime Administration by George G. Sharp, Inc. and for the U. S. Atomic Energy Commission by Combustion Engineering, Inc. in consultation with Humble Oil and Refining Co. The influence of the power plant modifications on ship costs was estimated by the marine architect-engineer for the above report.

From detailed studies of the costs of these two plants, for which design and construction could be started immediately, it was evident that there is considerable opportunity for further improvement through evolutionary changes. The areas where the most could be accomplished were identified, and ideas that appeared to contribute were generated and examined to determine how best to demonstrate their merits. Based on the expectation that a reasonable number of these items, which are only evolutionary and not revolutionary in nature, can be developed to accomplish their indicated cost reduction, a projection was made of the near term potential of a nuclear powered ship. Because experience and application of these simple concepts will help to bring about the type of cost reduction which evolves with all new developments once successfully demonstrated and put into general use, a conservative longer range estimate of operating costs was made for this same type of ship. The program of research and development to be followed by demonstration in cooperation with the maritime industry has been defined. Many of the important features could be demonstrated on the N. S. Savannah after the research work has been done but a specific program cannot be outlined at this time.

The ideas which have proven to be the most fruitful for cost reduction are consolidation of equipment, prefabrication of major assemblies, simplification of controls by use of the inherent load following characteristics of this type of system, avoidance of creating extra costs in the hull or propulsion system by imposing non-conventional requirements on these parts, and improvements in core design for more effective heat removal.

II. CONCLUSIONS

1. An American nuclear powered tanker that is competitive with an American-built conventionally powered tanker can be built in the forseeable future with present day concepts.

2. Costs of presently available designs are not low enough to be competitive.

3. The application of nuclear power does not depend upon a long trip to be competitive.

4. Reducing crew costs will not alone make nuclear power competitive.

5. The big reduction in costs must come from reduced capital expenditures.

6. The capital costs can be greatly reduced by diligent development and ingenious application of present day concepts with only moderate extension of current technology.

7. The design and construction of a nuclear ship must follow the proven engineering practices of cost and schedule control.

8. Core development must be diligently pressed to obtain and exceed the margin needed for nuclear fuel costs over oil costs.

9. Widespread industrial use of demonstrated concepts will cause the fabrication costs of the nuclear plant components to approach those of conventional process and power plant equipment.

10. An American built nuclear ship with present day costs of American hulls and propulsion machinery will not be competitive with a foreign built conventionally powered ship.

III. RECOMMENDATIONS

These design and cost studies indicate that the following recommendations are the most important guidelines to be followed in developing a competitive, indirect cycle, light water cooled and moderated nuclear power plant for maritime service.

A. PROGRAM

1. Pursue a research and development program to establish the necessary design information for utilization of the important features of this system.

2. Pursue an equivalent development program on the rest of the ship.

3. Based on the results of the research and development, plan with the maritime industry a cooperative ship for cost demonstration.

4. Plan a continuing cooperative program with the maritime industry for further savings through broad experience in building nuclear ships.

B. AREAS FOR EMPHASIS

1. Concentrate on reducing capital costs and shortening the construction schedule.

2. Do the necessary research relative to the core to reduce parasitic absorption and improve the heat removal capabilities.

3. Avoid making cost reductions in one area at the expense of another within the plant or the rest of the ship.

4. Do the necessary application engineering development to synthesize the special features of a nuclear ship with its mode of operation to obtain the lowest over-all cost.

5. Simplify systems and controls by the full utilization of the inherent characteristics of this system.

6. Concentrate on consolidation of equipment and systems and reduction of in-hull assembly.

IV. COST RESULTS

A cost analysis was made of the relative position of nuclear energy as a source of propulsive power within the framework of tanker economics. The future, as well as the current status of indirect-cycle, water reactor plants was assessed by comparing the estimated costs with those given for a conventional, oil-fired boiler for use in a 43,000 DWT class American Tanker.[1] The conclusions and recommendations stated above were based on the results of this cost study. In addition, the findings led to the formation of the research and development program presented below, since they pointed out the most fruitful direction for future efforts.

Cost estimates were made for two presently attainable, second-of-a-kind nuclear plants. Both are updated versions of the previously proposed system [1, 2] and are described in Appendix A, Plant Descriptions, of this part of the report. The presently proposed reference self-pressurized system is more completely discussed in Part II, Plant Conceptual Studies. The alternative plant, which is based on the combined energy or C.E.-Cycle, was included to show the gains that could be attained by incorporating additional current technological improvements and by adjusting certain other costs as seems proper. As for the previously proposed plant, the estimates were based on manufacturers' quotations, generally accepted cost formulae for equipment and its installation, and on the cost rules and bases furnished by the Technical Program Branch of the Office of Maritime Reactors, Division of Reactor Development, U. S. Atomic Energy Commission.

The short-range and longer-range potentials for this application of nuclear energy were assessed by predicting, with conservatism, the influence of evolutionary developments and the effect of full industrial participation. By nature, the cost forecasts were not as rigorously developed as the cost estimates. However, the same general format and ground rules were followed. The numerical values generated for both the estimates and the forecasts, together with the explanations of the factors involved in arriving at them, will be found in Appendix B, Costs, as will the cost rules and bases.

In order to evaluate the competitive position of these nuclear plants for tanker use, the operating costs were computed for two synthetic but typical trade routes, which were previously defined.[1,2] A long voyage to Kuwait on the Persian Gulf from the East Coast and a shorter U. S. Coastwise trip from the Gulf of Mexico to the East Coast were used.

Current depressed-market costs for ships were not utilized in the comparative study since any gain available in the cost of bottoms for a conventional ship would also benefit a nuclear tanker, and the comparison is more realistic

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(1) TID-8528, "Three Design Studies for Selecting a Prototype Reactor for a Nuclear Tanker."
(2) NYO-2860, "Nuclear Powered Tanker Design and Economic Analysis - Pressurized Water Reactor."

on more nearly normal market prices. Furthermore, the furnished depressed-market cost is to a large extent explained by the difference between the construction schedules being used in the industry and the schedule originally assumed for the study.

The results of the cost analysis are presented in this section of the report.

A. SCOPE OF THE RESULTS PRESENTED

The results of the cost analysis will be presented in five bar charts, each of which contains information relating to the costs for six different tankers. They are all second-of-a-kind ships. The charts show (a) the annual operating cost for each of the six on the long trade route and an indication of the portions contributed by the capital, fuel, crew, service, and miscellaneous costs; (b) a breakdown of the capital costs; (c) a separate breakdown of the nuclear steam supply system costs; (d) an itemization of the annual fuel cycle costs in terms of the constituent factors; and (e) the annual operating costs for the shorter U. S. Coastwise trade route. The six tankers, which differ principly by their power plants and the development status of them are as follows:

1. Conventional Tanker

It is the oil-powered ship for which costs were developed by the Maritime Administration for use in the earlier comparative study[1], with the exception that, based on a recent investigation, it is assumed that it can be constructed in 16 rather than in 30 months as originally specified, and further that no additional time is needed for research and development.

2. Previously Proposed Tanker

This is the nuclear powered tanker that resulted from the previous design and economic evaluation [1,2]. It contains a subcooled pressurized water reactor plant that produces superheated steam via a one-loop indirect cycle. Although it possessed certain advanced features for the state of reactor development at the time of its proposal, it has become outdated and is no longer appropriate for assessing the present competitive position of nuclear energy. It is included because it provided the foundation for the presently available plants. The proposed schedule of 40 months duration with concurrent research and development was unaltered.

3. Presently Proposed Tanker

The current reference tanker contains a reactor plant improved over the previously proposed plant by the incorporation of self-pressurization, consolidation and pre-assembly of auxiliary systems, a larger water-to-moderator ratio, a lower coolant flow, and by several minor changes. All its features are based on present-day technology, and accordingly, it is attainable on a 40 month schedule with application research and development performed concurrently with construction.

4. Alternatively Proposed Tanker

The alternative is distinguished by the use of latent heat for superheating, a greater degree of consolidation, and by a smaller size for the whole power plant. These improvements represent no change in the status of the attainability of its features, and the tanker is thus available in the same sense as the reference plant. Adjustments were made in its cost due to a reassessment of certain items in accordance with the implications of information supplied informally by ship designers and the Maritime Administration.

5. Short-Range Potential Tanker

The short-range potential tanker is the product of evolutionary developments in indirect-cycle water reactor plants as the technology advances slightly beyond current-day practice. The additional improvements it will possess, such as once-through heat exchangers, the use of less expensive materials, reduced instrumentation and more favorable prices are foreseeable, although as yet unrealized. It is a fourth-or a fifth-of-a-kind ship with modifications included and costs lowered as successive ships are built, or it is a second-of-a-kind that can be constructed in 24 months if the necessary application research and development is performed before start of construction.

6. Longer-Range Potential Tanker

The central feature of this future tanker is that it will be a normal industrially-produced ship, and therefore its cost will benefit from a relatively short 18 month construction schedule, with no research and development needed, and from lower-priced components as they become standard commercial commodities. It will be installed in six to twelve packages and its shielding and containment will be notably advanced. During operation, it will require a minimum of attention.

B. PRESENTATION AND DISCUSSION OF RESULTS

The annual operating costs for the six tankers on the long trade route from the East Coast to the Persian Gulf are given in Figure I-1, Long Trade Route Annual Operating Cost Summary, which also includes the annual cargo capacities and the cargo delivery costs. An indication of the relative importance of capital, fuel, crew, service, and miscellaneous costs is given by the labeled segments of each bar. The title of service is used for the sum of the stores and supplies, maintenance and repair, and refueling. Port and canal fees, radiation surveys, and operating overhead are included in the miscellaneous item. The cost reductions obtained by progressing from the referent, previously proposed plant are shown separately by the inverted bars at the top of the figure. The heavy dark line connecting the total operating costs for the various nuclear ships shows the progress made as the technology advances in accordance with the above definitions of the six tankers.

By comparing the total costs along this line with the total operating cost given for the oil-powered tanker, it can be seen that the short-range potential is competitive with the conventional, that the alternative is somewhat more expensive to operate on this voyage than the conventional, and that a really favorable position will be attained sometime later when nuclear tankers are not uncommon. This is more clearly revealed by the bars representing delivery costs. As shown by the changes in the component sections of the operating costs, the competitive status will be obtained primarily by reducing the capital and fuel cycle costs, although less prominent decreases in crew and service will also contribute. An explanation of the factors that lead to these reductions is in Appendix B, Costs.

Most obvious from this chart is that the difference between the operating costs for the previously proposed and the conventional ship is almost entirely in the capital cost portion. The costs in this category will be brought closer to the conventional as the ideas generated in this study are applied to the successive ships. It is important to note that even for the longer-range potential tanker, the capital costs are higher. Accordingly, lowering of fuel cycle costs by the amounts indicated is essential for achieving competitive nuclear power. This observation is consistent with the long-known fact that the potential for nuclear plants resides in the possibility of obtaining a less expensive fuel. An examination of the annual cargo capacities discloses another interesting result pertaining to the use of uranium as a better fuel. Contrary to early-day claims for the employment of nuclear energy for ship propulsion, the use of the more compact fuel, uranium, does not lead to much of an increase in cargo capacity.

Since the cost for a similar ship built in foreign yards is about one-half of the cost for American bottoms, it is evident from the capital costs given in Figure I-1 that nuclear energy is not a means for making the operating costs for American tankers cheaper than for foreign vessels.

The reductions in the long trade route annual operating costs from the referent to the presently proposed tanker and from the latter to the short-range potential are more prominently presented in Figure I-6, Reductions in Annual Operating Costs, which also indicates the portion of the reductions attributable to capital, fuel, and crew costs.

Figure I-2, Capital Cost Summary, shows the contribution to the capital costs made by the direct costs associated with the hull and outfitting, the main-propulsion plant, and the nuclear steam supply system, as well as the total indirect costs. It also gives the actual construction schedule for each tanker. The indirect costs are separated from the direct in order to point up their importance; in each case they constitute about 30 percent of the total ship cost. In the main, the indirects are influenced by the time required to perform the whole job. This is the reason for the emphasize on the reduction of installation time through consolidation and pre-fabrication.

As can be ascertained from Figure I-2, Capital Cost Summary, it is a substantial reduction in these indirect costs, together with an equivalent reduction in the costs associated with the nuclear steam supply system (including its engineering and installation) that yields the first competitive tanker. The hull and outfitting and main propulsion system costs remain essentially constant throughout the evolution. They decrease to the same value as for the conventional at the short-range potential tanker, since the nuclear steam supply system imposes no really special requirement on the propulsion plant or hull. It should be noted that the direct hull and outfitting and main propulsion system costs constitute about half of the total capital costs and, therefore, work should be conducted in these areas also.

Figure I-7, Reductions in Capital Costs, better depicts the reduction in capital costs from the previously proposed tanker to the present reference and from the latter to the short-range potential ship. It makes apparent the large contributions of changes in engineering and installation for the steam plants. It also points out that most of the cost reductions to be made in reaching a competitive position are in time-influenced items rather than in equipment and structure costs. Accordingly, it is of utmost importance to follow proven engineering practices for controlling the adherence to a tight schedule, as well as to control the direct costs of hardware items. For example, design changes cannot be permitted once construction is underway.

Breakdowns of the nuclear plant costs are given in Figure I-3, Nuclear Steam Supply System Capital Costs. Separately indicated are the costs for the reactor, the instrumentation, the containment (which includes the shielding and collision barrier) the engineering, the heat transfer system, and the installation. The dramatic contrast between the cost for the nuclear and conventional steam supply systems emphasizes that the capital costs of the nuclear system may always be higher. Therefore, the fuel and crew costs must be reduced without an appreciable increase, and preferably with a concomitant decrease, in capital expenditure. For example, automation requiring a large investment is not a favorable method for reducing crew members.

The chart, Figure I-3, reveals a 45 percent cost reduction in the nuclear plant between the referent and the short-range potential ship. Major contributions are made by improvements in the costs of installation, heat transfer components, and in engineering. It is interesting to note that for the previously and presently proposed plants, each of these items is more costly than the entire oil-fired boiler.

The engineering can be lowered by pre-definition and design of the nuclear plant and by fully developing a particular system. The heat transfer system and its installation costs will decrease about as shown by consolidation and evolutionary developments in the components, and by the establishment of a true second-of-a-kind price basis as these become commercial commodities. In the longer-range, the cost of the heat exchangers, vessels and other equipment of the nuclear plant will approach the cost for conventional power and process plant equipment. By then the truly necessary requirements for these items will have been established. And, based on the fact that it now costs several times more to fabricate carbon steel into a nuclear item than into a conventional one, a large cost reduction is expected.

The fuel cycle costs for the long trade route are expressed in terms of their constituent costs in Figure I-4, Long Trade Route Annual Fuel Cycle Costs. Each bar representing the total cycle cost is sectioned to show the costs for uranium-235 depletion minus credit for recovered plutonium, the spent fuel reprocessing costs leading to recovery of the valuable isotopes, the fuel element and cluster fabrication costs, and the total use or rental charges for the fuel. This chart makes it apparent that the nuclear fuel costs for the previously proposed plant were at a stand-off with oil fuel costs, and that a large step in the right direction has been made since then. As can be seen from Figure I-8, Reductions in Annual Fuel Cycle Costs, much of this reduction was due to the changes in government regulations pertaining to the pricing of uranium fuels. A nearly equivalent amount was gained by improved core heat removal.

The largest portion of the fuel cycle cost is the depletion charge, even after accounting for the plutonium credit. The use and fabrication costs are close seconds. Further reductions in these areas will attend the anticipated simplification in core manufacturing procedures and the lowering of fuel enrichment as parasitic neutron captures are minimized by decreasing the steel content in the core region.

The annual operating costs for the six tankers on the shorter trade route are presented in the same manner as for the long trip in Figure I-5, U. S. Coastwise Trade Route - Annual Operating Cost Summary. As revealed by the cargo capacities, less cargo can be carried on this voyage by the nuclear tankers than by the conventional ship, whereas, for the long trip the cargo capacities conformed to expectations by being at least somewhat greater. Accordingly, the margin of savings in delivery costs is slimmer for the competitive tankers on the U. S. Coastwise Trade Route than on the long voyage. However, the return on additional capital invested is about the same for each trip. [It is about five percent for the short-range, and 45 percent for the longer-range potential tanker.] Therefore, once sufficient development has been accomplished to lower the capital, crew, and fuel costs enough for nuclear energy to be seriously considered as a competitive source of propulsive power, the particular trade route will not be the criterion for its use; it will only influence the degree of savings. The important criterion in this respect is a high use factor for the ship, since using the ship as much as possible will lead to the greatest return on invested capital. In addition, it should be brought to mind that the greatest gain will be achieved by applying a nuclear ship in such a way that its special features are fully utilized.

V. RESEARCH AND DEVELOPMENT PROGRAM

In developing the cost analysis for present day and projected plants presented in this report, the importance of actual construction and in-service experience was continuously evident. This experience can be gained through step-by-step improvement in the various plant areas both through construction of successive ships and through modification of an existing ship. In the latter case, full value of a particular improvement cannot always be realized on that ship but, on the other hand, a larger number of steps can be made within a given time interval at a lower total expenditure. In either case, there is a demonstration of the improvement which provides a basis for the next step. This is development through evolution from experience which has proven in the past to be a fruitful development direction. At best, however, this is a costly process since it involves the construction and operation of ships. In a commercial atmosphere each step must be large enough to realize an appreciable gain, and the first step must be sufficiently attractive to give reasonable assurity of achieving the goal in the near future. To provide this assurity, a vigorous research and development program is required.

For the greatest gain, the program should be substantially completed before committing a next ship to construction. It can easily be seen from the computation of the capital costs, that when ship construction is initiated, the major plant decisions must have been made and backed with sufficient information to insure that the construction schedule will not be compromised.

A. KEY AREA PROGRAM

The proposed program consists of ten key research and development areas which are central to an orderly and expeditious program of maritime reactor plant improvement. Its objective is to obtain the information needed for acquisition of the cost advantage associated with the short-range potential plant. Although the program's contribution to cost reductions has been assessed within the framework of tanker economics, the goals of each area are pertinent to the development of nuclear energy as propulsive power for all maritime applications. Accordingly, the scope of the program is broader than one designed for performance concurrent with the construction of a particular ship.

It is estimated that the key area program would cost approximately $2,000,000 and that it could be completed within 30 months, or sooner if desired. It should be noted that the total program cost is less than the capital cost reduction alone between the present and short-range potential plants, even when compared on a second-of-a-kind ship basis. The estimate for each item is based on performing enough work to permit a construction start on the short-range potential plant and realize its gains without building the presently proposed plant as a development step. The program is presented in greater detail in Appendix C. The key research and development areas are as follows:

1. Self-Pressurization Tests

A self-pressurized reactor combined with a superheated steam cycle results in reduced propulsion system costs, elimination of the pressurizer, reduction of control and instrumentation equipment, and improved inherent load following characteristics. The principal uncertainty in design is the thermodynamic behavior of the steam following a load change. Since the resulting pressure transient is strongly dependent upon the thermodynamic path followed by the steam, knowledge of the path followed is needed to properly design the reactor vessel. It is proposed that a test loop be built to investigate the transient behavior of a self-pressurized system. Comparison of experimental with computed results would reveal the process followed by the steam.

2. Consolidation and Preassembly Application Development

Since installation costs constitute a major portion of the nuclear steam supply system capital cost, appreciable economic gains can be achieved by consolidation of equipment into fewer individual pieces before connections are made aboard ship. For certain consolidation features, an additional savings can be expected in the basic price of the components. With components combined, a shorter construction schedule and attendent cost reductions can be achieved. The objective of this work is to develop a plant arrangement in which the entire nuclear steam generating system is comprised of six to twelve factory assembled modules requiring limited interconnection. Concurrent fabrication and pre-testing, in addition to shipyard assembly, will be facilitated. Particular attention must be directed toward combining components, equipment, and systems without complication utilizing natural properties to achieve maximum effectiveness in over-all plant operation.

3. Once-Through Heat Exchangers

Once-through heat exchangers provide a saving because their use permits more compact arrangements, reduction in water inventory, and simplification of the secondary control system through elimination of valves and reduction in feed pump pressure. To realize their potential, a test of the performance of a once-through steam generator at relatively low pressures must be made. The tests should include a study of the effect of load changes on the stability of the system and quality of steam produced, investigations of control methods, various arrangements and segmentations, and determination of heat transfer coefficients. Water conditions must be determined and water treatment defined.

4. Core Heat Transfer Tests

One of the more effective ways of reducing costs is to develop a core from which design power can be obtained with minimum coolant flow rate and with the minimum number and complexity of fuel elements. Reduction in both coolant flow rate and physical size of the core permits reduction in system water volume holdup, containment size, shielding, and generally results in a compacted plant. One of the major parameters now limiting performance is the margin in maximum permissible heat flux set by burnout limitations. Tests are needed to reduce the level of uncertainty that is presently required to assure adequate design conservatism. Particular emphasis should be on low flow, high pressure, and coolant flow distribution.

5. Inherent Reactivity Control

This segment of the program is aimed at exploiting, to a degree not yet achieved, the inherent response to load demand which characterizes this type of plant. The results expected are reductions in capital cost through simplification and elimination of expensive control equipment and its installation as well as improved operating costs. Current reactor designs utilize imposed control, such as adjustable mechanical rods, a dissolved neutron absorber, or the more recent spectral shift concept with a variable mixture of light and heavy water moderator. However, spectral shift can be achieved by merely varying the temperature, thus the density, of the moderator in a light water reactor. The reactor will inherently respond properly by permitting its temperature to change thus maintaining criticality at the power level demanded by the turbine. Therefore, this work is directed toward improving the reactor system by substituting this inherent characteristic for controls imposed on the system by external means.

6. System Control and Protection Simplification

To obtain full advantage of the inherent load following characteristics of the reactor plant, it is necessary to examine and simplify the control and protection methods of the system. Reduction of instrumentation to essentials only is important, not only because of the effect on capital equipment costs, but also because the connecting and checking of instrument circuits appreciably influences the installation cost of the plant. Methods must be devised for simplifying the control of auxiliary systems through the use of a minimum number of reliable, direct acting, and less costly instruments. The only function of the reactor plant is to supply steam for ship propulsion and service upon demand. The fewer and simpler internal paths by which this function is controlled, the more reliable the system is likely to be. All of this must be done within the highest standards of safety for the plant.

7. Cladding Development

A major portion of fuel cycle costs is associated with that extra fuel enrichment required because of core structure neutron absorption. Over 90 percent of this is due to the stainless steel fuel element cladding in the current design. Therefore, it is quite important to minimize this parasitic absorption by use of thinner cladding or use of other lower cross section materials. The use of thin, hardened, free-standing cladding and the adequacy of even thinner cladding which uses the fuel for support should be evaluated for maritime service conditions. The use of UO_2 fuel in the form of ground and unground pellets and compacted powder should be compared for the various claddings. Manufacturing techniques require exploration from the standpoint of making the greatest use of the processes to achieve core design objectives.

8. Shielding Application Development

An expensive penalty paid by nuclear plants, particularly for shipboard use, is the cost of shielding, which amounts to over 10 percent of the cost of the steam supply plant. This percentage would be larger for a vessel which could not utilize cargo for much of the shielding. A major savings appears to be a consequence of consolidation of the primary loop since a more compact radiation source affords an opportunity to utilize local shielding. Placing biological shielding inside the containment would reduce the total surface area and cost. Greater use of water requires exploration. Since shielding requirements depend upon the reactor operating state, some of the water might serve a combined use for decay heat removal or vapor suppression containment.

9. Fuel Element Application Development

It is necessary to relate fuel element and core design objectives to those of a plant and ship in order to realize maximum over-all cost reduction. To realize the gains of a reactor plant which is compact and has low coolant and flow requirements, the nuclear, thermal, and structural factors influencing fuel element choice must be complementary. Core size might be reduced by peaking power near the bottom of the core. The fuel elements could vary in diameter over core length in a stepwise or continuously tapering manner. Multi-pass cores appear promising.

10. Reactor Vessel Radiation Damage Application Development

For a given size core, the minimum diameter of most reactor vessels of interest for maritime application is determined by radiation damage limitations. While little data is presently available from which firm conclusions can be drawn, there is evidence to indicate that radiation damage may be more of a problem than originally expected for reactor vessels operating around 400°F, but there is a reduction of the effect of radiation as the operating temperature of the reactor vessel comes into the 600°F range. The application development work necessary to make use of this information would include not only the evaluation of the beneficial influence of higher operating temperatures, but also the assessment of other means of reducing the effect of radiation exposure, such as special plant operational procedures and post-irradiation heat treatment. Should distance from the core prove to be the only satisfactory solution to the damage problem, it might be feasible to utilize this space and compact the plant by placing the heat exchangers in the annular space between core and reactor vessel.

B. EFFECT ON COST REDUCTION

Each of the ten research and development subtasks will supply a portion of the predicted reduction in annual operating costs for the tanker under consideration. A pictorial presentation of the cost areas to which each will most heavily contribute is given in Figure I-9, R & D Tasks Related to Cost Reductions, which is the pie chart previously shown as Figure I-8 with the research and development items added.

One of the most promising directions for improving capital costs appears to be in combining functions of the primary components and system so that the number of components can be reduced. Along with this, where possible, the principal and auxiliary systems should be modularized so that they can be assembled in a pre-packaged form. This consolidation leads to cost reduction through several avenues. Consolidated major components may share major pressure vessels. In some cases an entire functional system is eliminated. For example, in self-pressurization not only is the pressurizer included as a part of the reactor vessel, but also the separate pressure controlling function is eliminated. In the case of auxiliary systems, only slight modification of the components of one functional system permits the system to perform other functions and, hence, replace these as separate systems. It appears possible, for example, to modify the emergency cooling system so that it can perform the functions of the decay heat removal system, employed during core servicing, as well as provide back-up take-home power if a major difficulty necessitates isolation of both the steam generator and superheater.

If the auxiliary systems are modularized or packaged so that they can be installed as functional units, not only will savings result in installation costs but pre-installation testing can easily be performed and connection to the primary system made simply. It is clear, of course, that reduction of principal system components that require shipyard installation will reduce costs. By utilizing the inherent characteristics of the reactor system to reduce the need for complex control equipment and instrumentation, savings out of proportion to the cost of the equipment alone can be made by the elimination of its installation. An associated operating saving in servicing also results.

Fuel costs would be reduced measurably be decreasing the parasitic neutron absorption in the fuel element cladding and the core structurals. Recent developments give promise for use of thinner fuel supported cladding in the near future. Progressive development and increased use of newer materials, such as various zirconium or other alloys may bring their costs into a range where further improvements can be realized. Reduction of fuel costs will be speeded by information obtained through the broad use of low enrichment uranium dioxide fuels in other than maritime reactors. Still, application development to maritime service is required. Since cores are replaced in a three or four year period, advantage can be taken of new developments in subsequent cores.

Operation and maintenance costs depend heavily upon information developed from operating experience. However, design approach can help measurably in achieving cost reduction more rapidly. Inherent reactivity control as well as system control and protection simplification, all of which lead to less specialized crew training and a greater opportunity to program maintenance, are substantial steps in this direction.

VI. FUTURE NUCLEAR SHIP DEVELOPMENT

For the near future, the existence of an incremental capital investment for nuclear power must be accepted. However, this condition is a common one with many new developments. The important question in application is: can the ship, by utilizing the developed improvements, perform its intended function in such a manner that the return on the invested capital is greater than is now traditional? If a nuclear powered ship is identical with a conventionally powered ship except for the plant, and if it is operated under essentially the same conditions as a conventionally powered ship, then it is clear that nuclear power will simply not result in a significant break-through in the cost of shipping. In such a case, the new restrictions resulting from the utilization of nuclear power have only been added to the traditional constraints in design and operation. On the other hand, improvement will result if the nuclear plant characteristics can be utilized to operate the ship in a more effective manner. A reactor plant development program, no matter how successful, can supply only a contribution to improved ship operation. It must be integrated with improvements developed in other maritime areas. This integration is not a simple assembly of "good" features. The integration must consist of selecting features of ship and power plant that when taken together with intended service and method of operation produce the most economic transportation system.

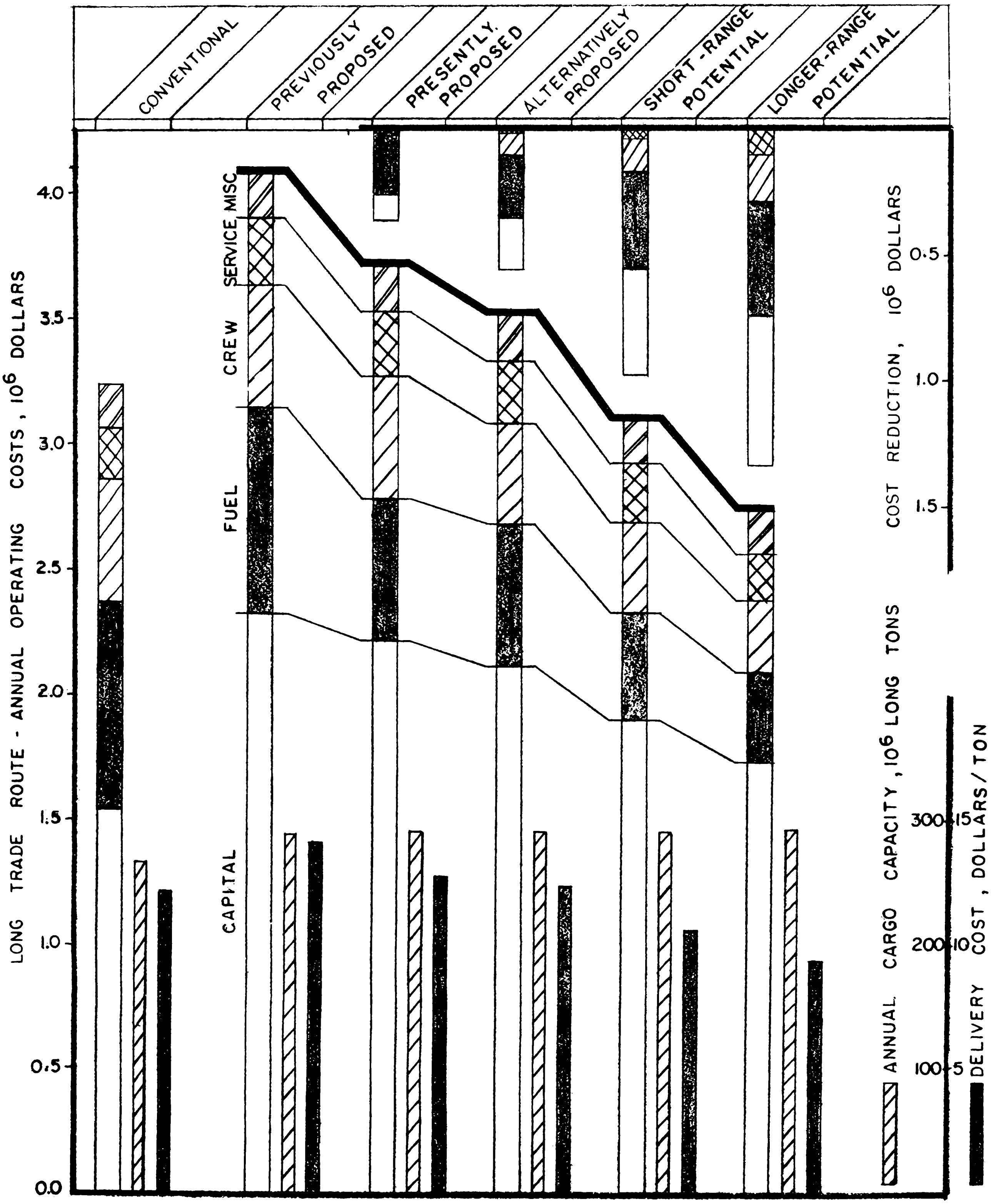


FIGURE I-1

LONG TRADE ROUTE ANNUAL OPERATING COST SUMMARY

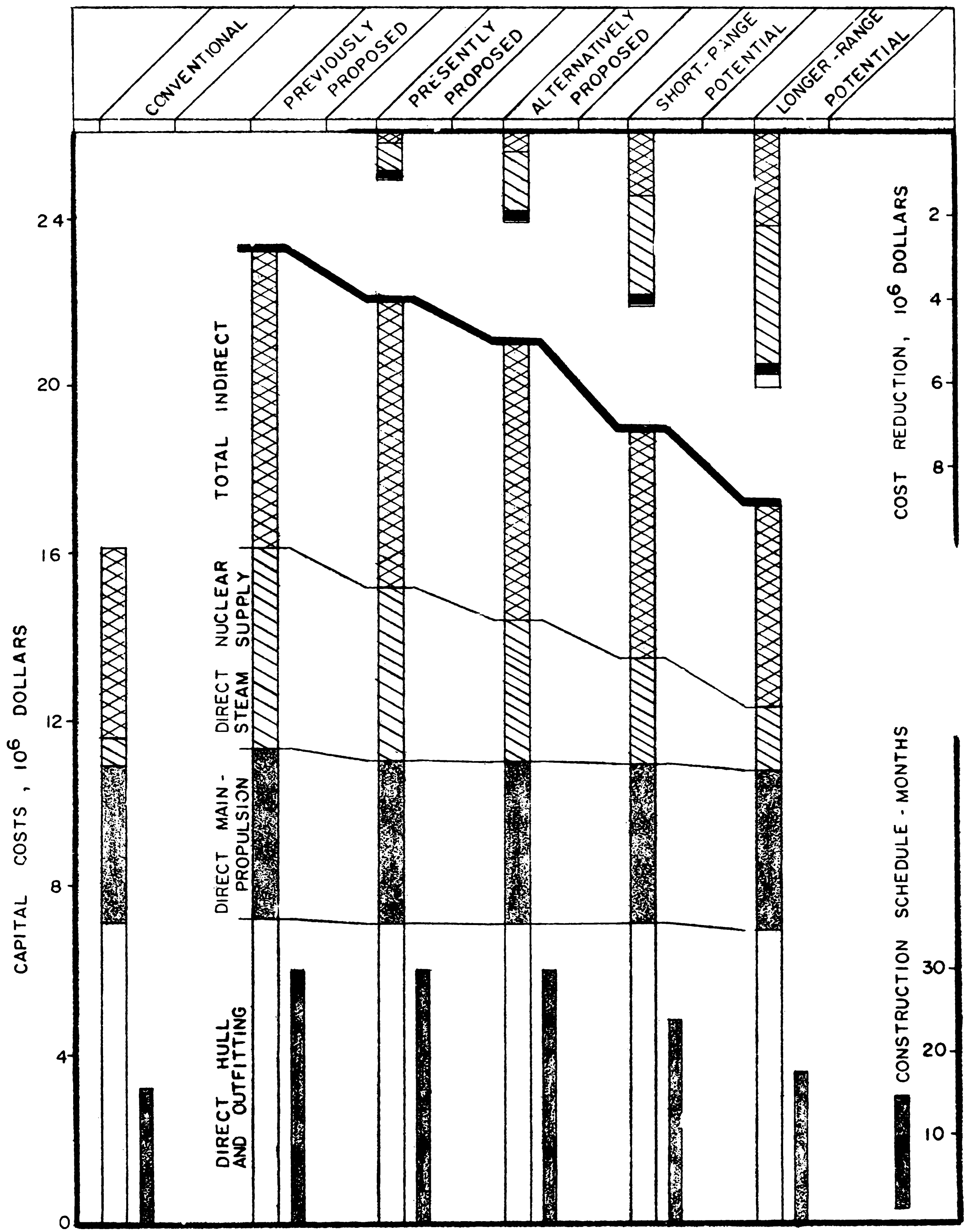


FIGURE I-2

CAPITAL COSTS SUMMARY

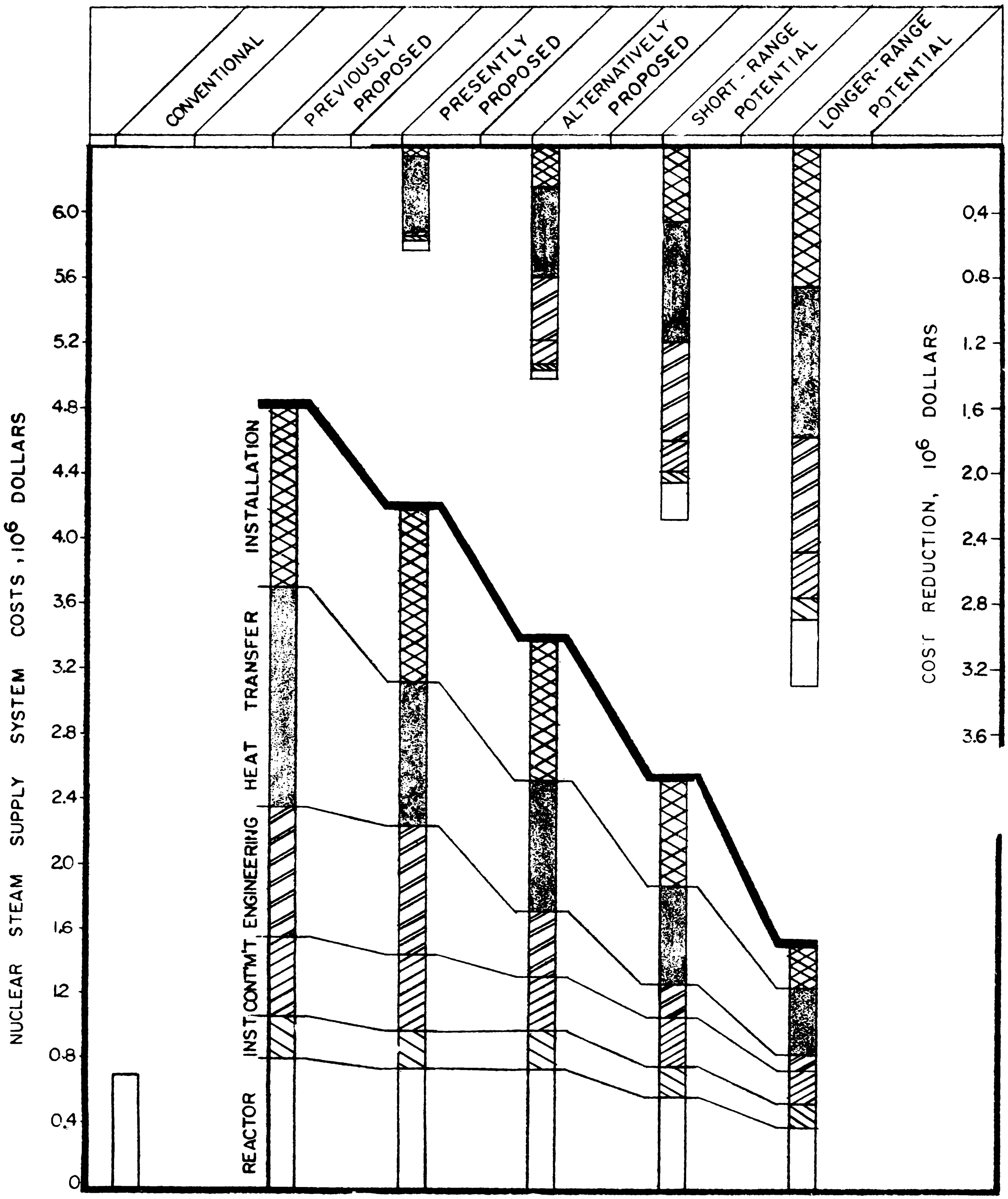


FIGURE I-3

NUCLEAR STEAM SUPPLY SYSTEM CAPITAL COSTS

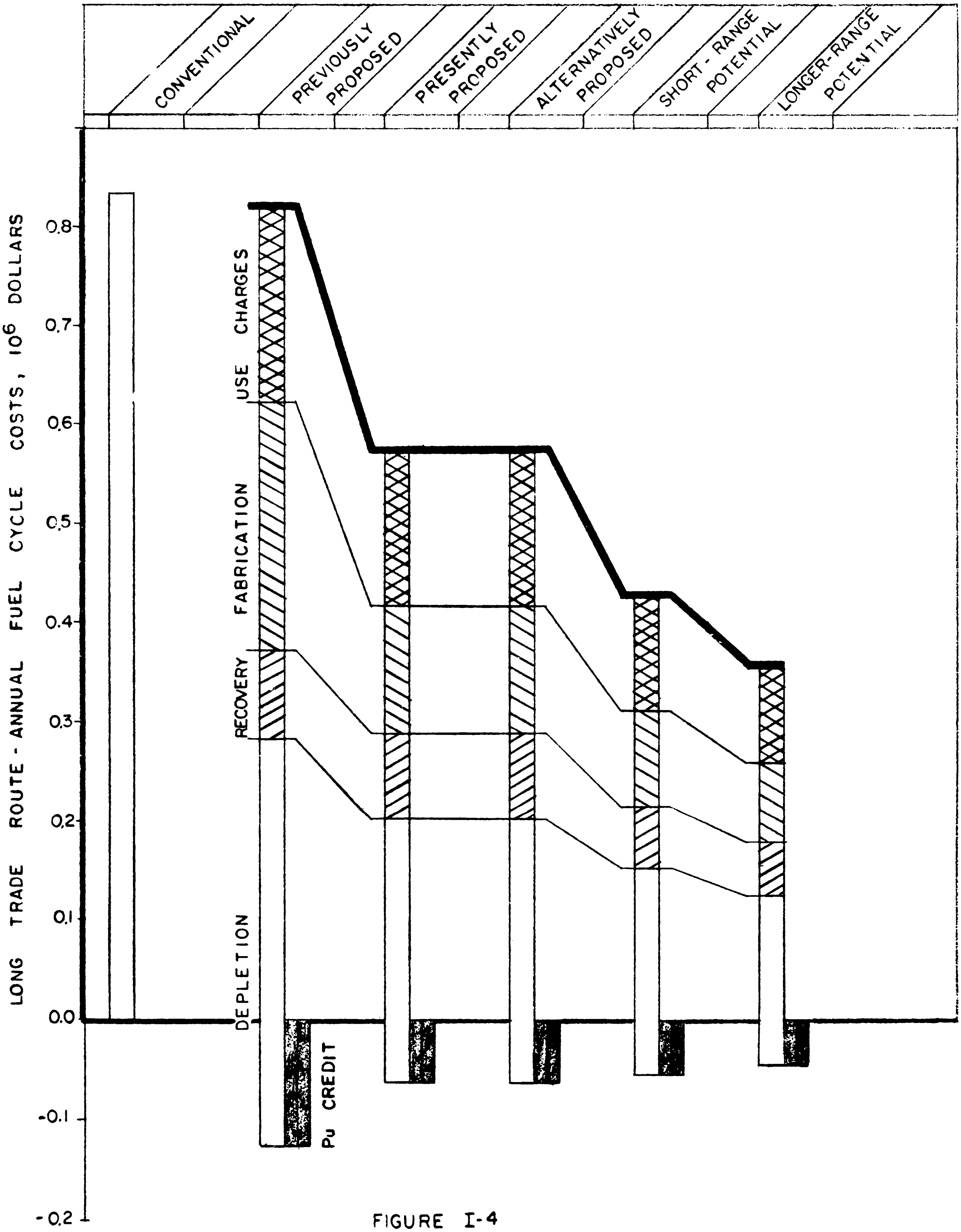


FIGURE I-4

LONG TRADE ROUTE - ANNUAL FUEL CYCLE COSTS

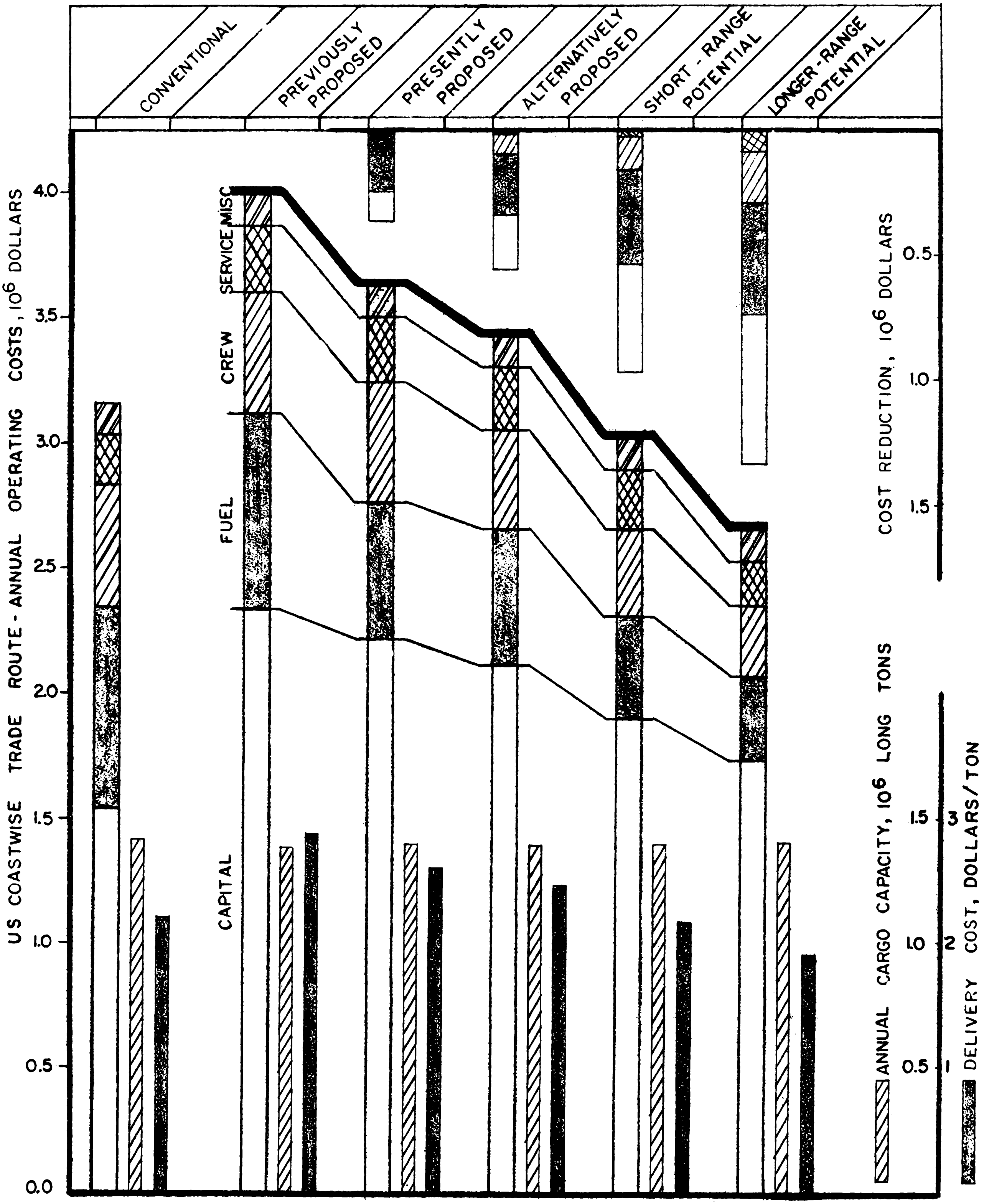


FIGURE I-5

US COASTWISE TRADE ROUTE - ANNUAL OPERATING COST SUMMARY

REDUCTION IN ANNUAL OPERATING COSTS

—— LONG TRADE ROUTE

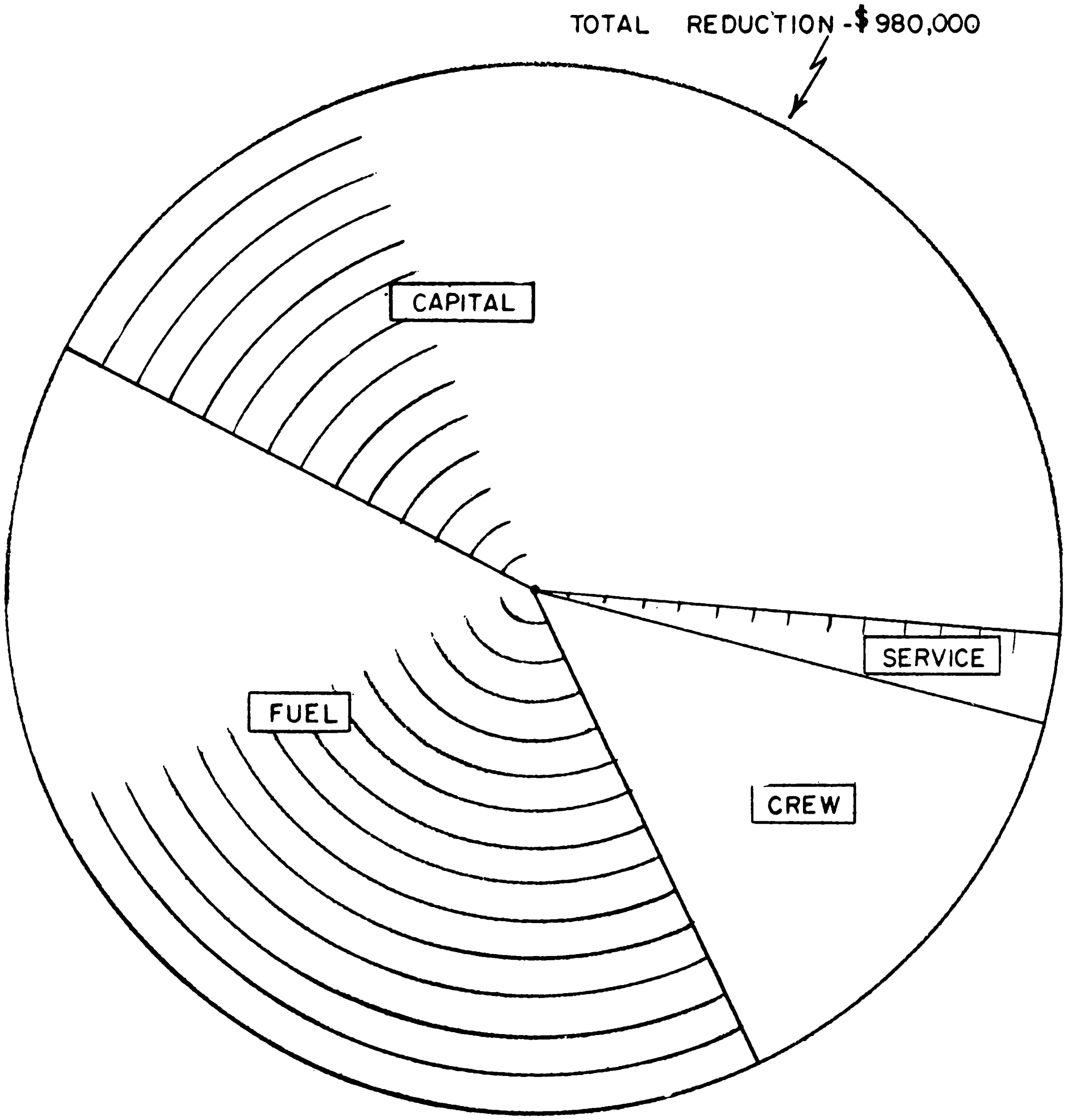
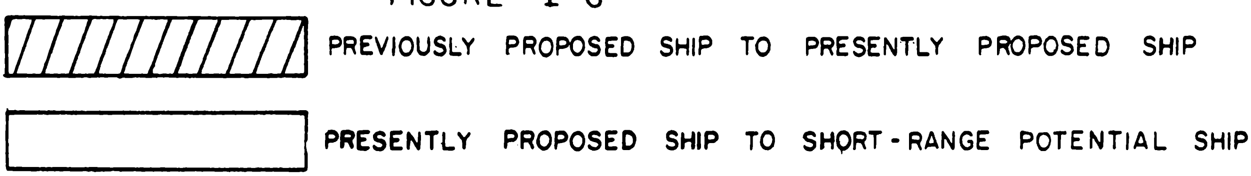


FIGURE I-6



REDUCTION IN CAPITAL COSTS

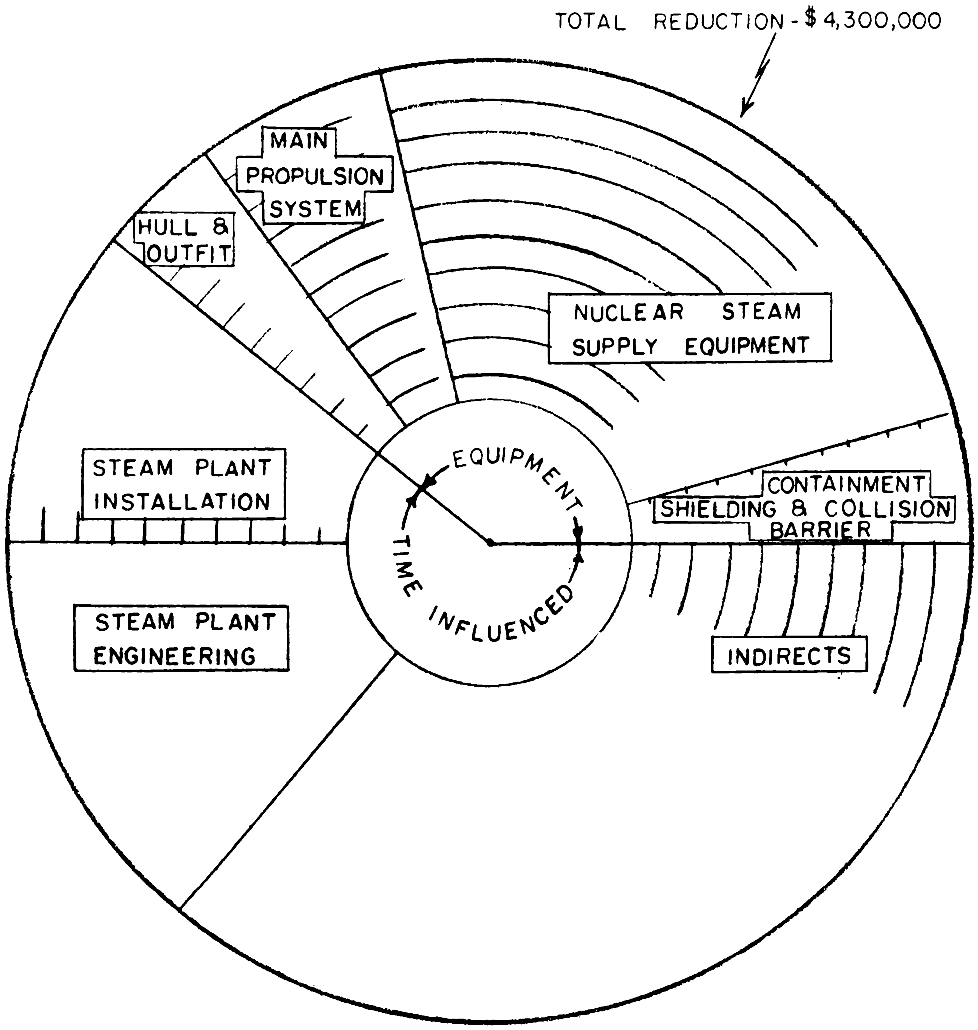
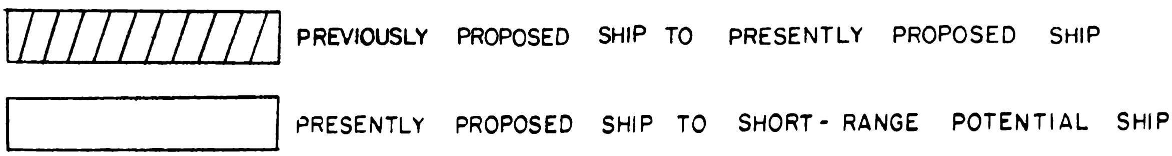


FIGURE I-7



REDUCTION IN FUEL CYCLE COSTS

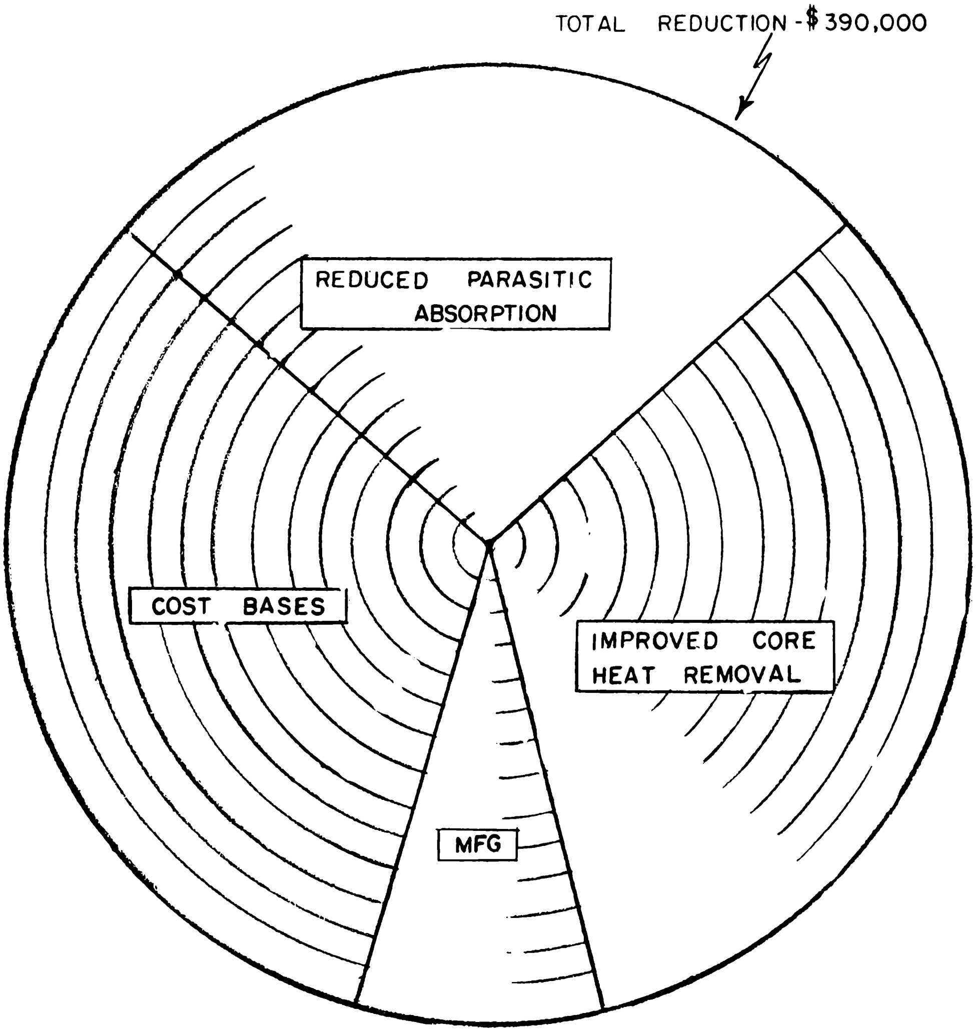
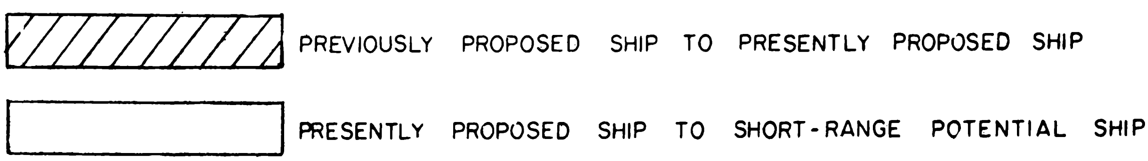


FIGURE I-8



R & D TASKS RELATED TO COST REDUCTION

(REDUCTIONS IN LONG TRADE ROUTE OPERATING COSTS)

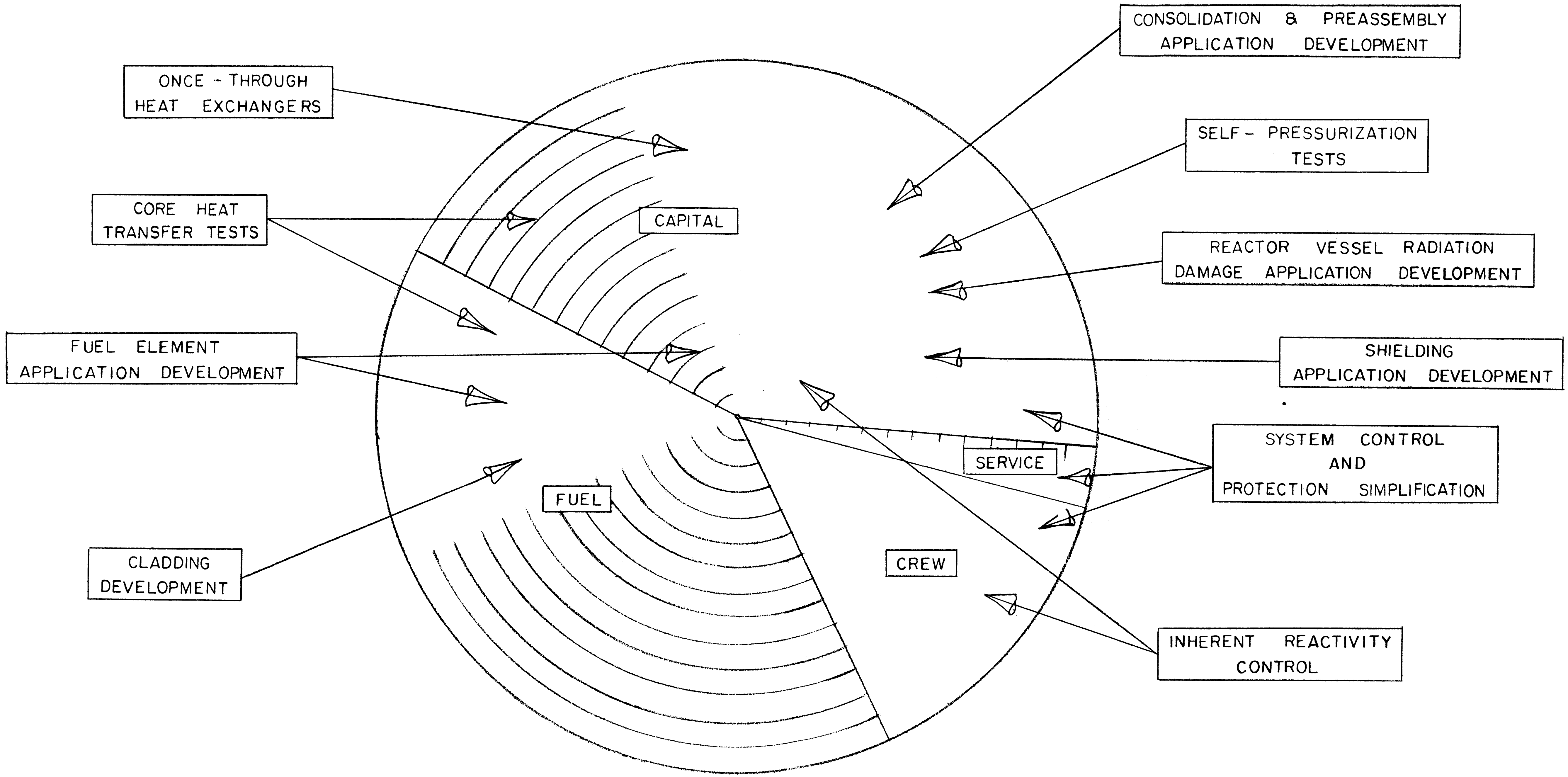


FIGURE I - 9

PREVIOUSLY PROPOSED SHIP TO PRESENTLY PROPOSED SHIP

PRESENTLY PROPOSED SHIP TO SHORT - RANGE POTENTIAL SHIP

APPENDIX A

PLANT DESCRIPTIONS

A. DESCRIPTION OF PRESENTLY PROPOSED PLANT

The presently proposed plant may be considered as consisting of two basic systems; the reactor system which develops and transforms nuclear energy into a useful form; and the propulsion system which utilizes this developed energy for ship propulsion and associated functions. The over-all objective in the plant design is to have the efficiency and reliability of both the reactor and propulsion system so adjusted as to produce the maximum efficiency and reliability for the entire plant.

The self-pressurized indirect cycle reactor system has one primary loop consisting of the reactor, a steam generator, a superheater, and two main coolant pumps as shown in Figure A-1, Presently Proposed Reactor System Flow Diagram. Since the system is self-pressurized, there is no need for a pressurizer. Saturated water at 2100 psia flows from the reactor through a single 18 inch pipe to the superheater, where approximately 10 percent of its energy is removed. The primary water then flows to the steam generator, where the remainder of the energy which it absorbed in the reactor core is removed. After leaving the steam generator, the primary coolant is split and returns to the reactor via two parallel 12 inch pipe legs, each of which contains one 5800 gpm centrifugal pump. The piping attached to the reactor vessel is arranged as a fluid trap in such a manner that any component of the primary system can be drained without draining the coolant from the reactor core. All material in contact with the primary coolant is austenitic stainless steel. The entire primary loop is enclosed in a sealed containment vessel. The self-pressurized reactor supplies steam for the ship's main propulsion unit, auxiliary turbine generator units, and auxiliary ship's services. The three-zoned single pass reactor utilizes uranium dioxide fuel clad with stainless steel. Maximum thermal output of the core is 80 megawatts. The reactor system is capable of delivering to the main turbine a maximum steam flow of 271,000 pounds per hour at a pressure of 600 psig and a temperature of 600°F.

The principal components of the propulsion system are the main turbine and condenser, the auxiliary turbine-generator units, the feedwater heaters and associated system pumps. Feedwater is pumped into the steam generator where it is heated sufficiently by the primary water to convert the feedwater into saturated steam. At normal power with normal service, 268,350 pounds per hour of saturated steam at 820 psia are produced from feedwater entering at 402°F. This steam then passes through a throttling valve to a superheater where it absorbs more energy from the primary water and is superheated 115°F. Superheated steam at 605°F and 615 psia is supplied at the rate of 234,200 pounds per hour to the main propulsion turbine, which is a cross-compound geared steam turbine driving a single shaft. Normal shaft horsepower is 27,300 and the maximum is 30,000. After expansion through the turbine, the steam is condensed and then passed through four feedwater heaters where the condensate is heated before returning to the steam generator. The feedwater heaters operate using steam bled from various stages of the turbine during expansion. In addition, some of the turbine throttle steam is bypassed to operate two 600 KW auxiliary turbo-generator units that are used to supply the plant electric requirements. Steam from the system is also used for the water evaporators, cargo pumping, quarters heating and other ship needs.

The reactor is designed so that all heat is transferred to the steam generator and superheater as sensible heat although some boiling is permitted in the core. The flow rate is four million pounds per hour and the temperature rise across the core at maximum core power is 42°F. Since it is a self-pressurized system, the coolant leaves the core saturated. The core is made up of 61 hexagonal clusters of stainless steel tubes containing uranium dioxide pellets. There are 49 stationary clusters and 12 that are movable for control purposes. The active length of the core is 60 inches and the equivalent diameter is 55 inches. The core loading is 6.67 metric tons of uranium. Under the conditions of service specified for the study, the core will have a lifetime of 4 years.

The core is divided into three zones of enrichment with an average enrichment of 4.3 percent. The outer zone has an initial enrichment of 5.5 weight percent U-235; the middle zone, 3.9 weight percent; and the inner zone, 3.2 weight percent. Zoning the core flattens the radial power distribution. This reduces the maximum power peak in the core permitting a higher average core temperature and allows a higher average burnup without exceeding the upper limit on local burnup. Within the clusters, the 0.594 inch diameter rods are arranged on a triangular pitch to yield a water-to-uranium oxide ratio of 1.75. The high core temperature and the relatively low water-to-fuel ratio cause a small temperature change in the moderator to have a large effect on the core reactivity. The average moderator temperature coefficient in the operating range is -6×10^{-4} $\delta k/k/^{\circ}F$. This large coefficient becomes the dominant factor during transients and permits the reactor to be self-regulating for ship maneuvering.

For startup and shimming during lifetime, the reactor is controlled by 12 neutron rectifier control assemblies. The neutron absorber is a hollow cylinder of silver-indium-cadmium alloy clad in stainless steel. This absorber is attached to a movable fuel cluster which is drawn into the core as the absorber unit is removed. These assemblies provide a large amount of reactivity control in a few moving parts and eliminate water gaps when the control element has been removed. The elimination of water gaps reduces local power peaks. The control assemblies are moved by rack and pinion control drives penetrating the head.

The steam generator is a verticul U-tube heat exchanger with primary flow on the tube side. The reference steam generator is small when compared with an ordinary pressurized water reactor because some of the reactor energy is transferred in the superheater and because the steam generator temperature difference is large as compared with plants operating at lower temperature.

The superheater is a vertical, single pass heat exchanger with the primary coolant on the shell side. This arrangement with secondary side entrance on the bottom permits the superheater to be used as a once-through steam generator in an emergency if a major tube failure has occurred in the regular steam generator. The piping is arranged so that the necessary valving for bypassing can be done in the secondary side piping, where the pipe sizes are smaller and carbon steel is used. Under these conditions, the entire steam generator is permitted to fill with primary water. Therefore, the use of a single loop is justified and large, expensive stainless steel block valves can be eliminated from the primary system. These features considerably reduce the capital cost, lighten the weight of propulsion machinery, reduce primary loop size and simplify the over-all system.

All of the equipment in the plant is designed to operate satisfactorily with a momentary roll of 30° or a permanent list of 15° to either side, and a pitch of 7° or a permanent inclination of 5° fore or aft.

Control of this plant is very simple because of its inherent load following characteristics. When the turbine throttle is closed, the steam pressure at the superheater exit starts to rise. However, a pressure sensing device at this point actuates a throttling valve between the steam generator and superheater. Thus, at reduced load, the steam pressure at the turbine throttle does not rise as is common in pressurized water reactor plants even though the pressure is permitted to rise in the steam generator. The rising pressure in the steam generator and concurrent rise in boiling temperature reduce the amount of steam produced. The temperature of the primary water returning to the core rises, and the core power is cut back by the change in reactivity. Thus, this plant takes advantage of the inherent self control characteristics of the pressurized water reactor without making any special demands on the steam turbine. Also, small maneuvering transients may be met without movement of the control rods, while larger transients can be taken with limited and slow movement of rods.

A primary shield containing lead and borated water surrounds the reactor. This reduces the activity outside of this shield to a level equal to that due to the primary loop activity during operation. Oil or ballast tanks are used as secondary shielding around the sides of the reactor compartment, while lead and polyethylene are used over the reactor. Ship personnel have unlimited access to all regions immediately outside of the secondary shielding. Limited access to the containment vessel is possible 15 to 30 minutes after reactor shutdown. Limited access to some of the auxiliary systems outside the containment vessel is possible, if necessary.

All major components of the reactor system and any minor components containing high pressure, high temperature primary water are in a sealed containment vessel. This vessel is comprised of a short steel cylindrical section with two hemispherical heads. The containment vessel is 34 feet in diameter and 50 feet in over-all height, including the main hatch. In case of a major break in the primary system, all radioactive steam would be contained in this vessel.

The auxiliary systems of the steam generating plant provide the hydraulic, chemical, and heat removal service functions needed for the operation, maintenance, and safety of the primary system. The auxiliary equipment has been designed and located to serve multiple functions where possible, and it has been consolidated and arranged on factory-fabricated skids in order to reduce installation costs and simplify the mounting of the equipment in the ship.

A coolant storage and supply system receives water from the ship's sea water distillation unit, after it has been deionized, and stores it for use throughout the nuclear steam generating plant. It is of sufficient size to supply water for dêcay heat removal by natural circulation for a period of four days with the ship listing by 70°.

A fluid charging skid contains the equipment for the coolant charging, buffer seal water, corrosion control, poison injection, and decontamination systems. The equipment on this skid serves multiple functions. It provides high pressure primary water to fill the primary loop and to maintain a constant liquid level in the reactor during steady-state operation. It supplies the buffer seals on the pumps and control rod drives with high pressure water; it injects boric acid for reactor shutdown under certain abnormal conditions; it pumps decontamination solutions to the primary loop; and it is used to dissolve hydrogen gas into the primary coolant for corrosion control purposes.

A coolant discharge system cools and depressurizes primary water before sending it to the purification system, the quench drum, or the waste tanks. A continuous discharge flow is maintained in order to remove the water that leaks in through the buffer seals and to satisfy the flow requirements for the purification system.

A decay heat removal system, which is a multiple function system, removes heat from the primary coolant (a) during the normal depressurizing procedure, (b) during shutdown, even with the reactor vessel head removed for refueling or maintenance of the primary components, (c) during shutdown situations with the primary heat transfer system intact but out-of-commission, and (d) during the latter situation when, in addition, no pumps can be operated and the ship is listing by 70°.

A safety injection system on the decay heat removal skid supplies water to cool the reactor core in the improbable event of a major primary loop rupture. A cold water accident cannot occur since the system's low head pump is incapable of charging the low pressure water into the pressurized primary system.

A pressure relief system protects the primary system from an overpressure situation in accordance with the requirements of the ASME Boiler and Pressure Vessel Code, Section I. The self-actuated safety valves, which are attached to the reactor vessel dome, are capable of discharging steam at the rate that it would be produced by the reactor at the overpower scram point.

A waste handling system receives and stores gaseous, liquid, and solid radioactive waste for subsequent discharge into the sea or atmosphere as prescribed by Federal regulations.

A component cooling water system removes heat from the various reactor plant components during normal operation, removes heat from the main coolant and the plant components during shutdown, and transfers this absorbed energy to sea water. The component cooling water maintains the reactor plant components below their maximum permissible operating temperatures and services various heat exchangers.

This presently proposed plant provides a simple design which incorporates improvements that tend to increase plant reliability and decrease control requirements. The use of self-pressurization coupled with the higher allowable operating pressure for this type of system provides higher temperature primary water for the production of superheated steam. In addition to reducing the required size of the main heat exchanger, this consolidation eliminates the need for a separate pressurizer and its associated control and instrumentation. The over-all effect of using self-pressurization is to reduce capital costs while improving the favorable control and transient response characteristics of a sub-cooled pressurized water plant. The inclusion of the superheater permits the use of a single loop while still providing an emergency steam generator. The capital costs are reduced further by eliminating block valves, specifying conventional turbines, and utilizing steam driven primary pumps. The throttling between the steam generator and the superheater adds to the capital cost but simplifies the system control. The fuel costs are reduced by increasing the core size and hence reducing enrichment requirements. Due to the negative temperature coefficient of reactivity, the plant tends toward self-regulation in the operating range with limited control rod motion.

B. DESCRIPTION OF ALTERNATIVELY PROPOSED PLANT

The alternative plant described below is similar to the presently proposed system in both its theory of operation and its function. This plant, however, employs a modification in its equipment arrangement which makes its application as a propulsion unit for a ship more economical. Namely, the superheater is situated in the reactor head. This improvement in component arrangement is basically confined to a consolidation in the reactor system, however, the effect of it is also reflected in appreciable reductions in the costs for the reactor containment structure, and for the adjacent ship's structure.

The reactor system of this alternative plant, which is designed to produce a maximum of 80 MW, has one primary loop which consists of a reactor, a steam generator, a superheater, and two main coolant pumps as shown in Figure A-2, Alternatively Proposed Reactor System Flow Diagram. The superheater, however, instead of being a separate component, is incorporated within the reactor vessel. This is accomplished by slightly lengthening the vessel top head and coiling the superheater tubes around the inside periphery of the head. Thus, this reactor system not only eliminates the pressurizer by operating as a self-pressurized unit, but also reduces its capital costs by eliminating the need for a high pressure superheater shell.

As in the presently proposed plant, primary water leaves the core saturated at 2100 psia but in this system it flows directly to the steam generator instead of the superheater. Approximately 10 percent of core power is removed as steam which releases its absorbed energy by condensing on the superheater tube surfaces. The condensed fluid from the superheater combines with the primary flow to the steam generator. The entire primary flow of 4.4×10^6 lbs per hour emerges from the steam generator, passes through two centrifugal pumps, and returns to the reactor. It should be pointed out that the alternative plant utilizes a primary flow rate which is 10 percent greater than the flow rate for the presently proposed system. This increased flow is required to maintain the same thermal margin of safety for the two systems. The higher primary flow is required in the alternatively proposed system since the energy used in the superheater is obtained from steam formed in the reactor core.

Feedwater is pumped into the steam generator where it is heated by the primary water to generate saturated steam. This steam, which at maximum power is produced at the rate of 291,200 lbs per hour, then passes through a throttling valve to the superheater unit within the reactor vessel, where it absorbs energy from the condensing reactor steam and becomes superheated.

Several advantages are achieved by consolidating the superheater into the reactor vessel and utilizing primary steam as the superheater source of energy. One that has already been mentioned is a considerable capital cost savings by elimination of the necessity for a separate high pressure superheater shell. This is not a clear over-all gain since there is a small increase in reactor vessel cost due to the space requirements for the superheater tubes in the vessel head; also the decay heat removal heat exchanger is sized slightly larger to serve as an auxiliary steam generator in case the main steam generator becomes inoperable. The reduction in capital costs by the elimination of the superheater shell, however, more than offsets the cost increases due to the increased size of the reactor vessel and decay heat removal exchanger.

Another major advantage of this alternative plant is the reduction of primary pressure drop. This occurs in spite of the increased flow rate and is due to the elimination of the superheater from the primary water flow path. This pressure drop reduction is reflected as increased plant efficiency and, therefore, reduced fuel costs.

A very considerable additional advantage to incorporating both the pressurizer and superheater within the reactor vessel is the reduction in total primary water within the system. The amount of energy that would be released from the system water to the containment atmosphere subsequent to a major rupture in the primary loop plays a governing role in the required size of the containment shell. By reducing the amount of water in the system, the containment requirements are reduced. This is reflected in lower requirements on the amount of secondary shielding and a smaller collision barrier around the containment shell, thus appreciably reducing the over-all plant costs.

The propulsion system and auxiliary systems for the alternative plant are essentially the same as those described for the presently proposed plant. It is perhaps important to emphasize at this point that the control characteristics of the two plants are identical. The alternative plant completely maintains the inherent load following capabilities of the presently proposed plant, thus maintaining a high level of plant reliability while decreasing plant control requirements. To summarize briefly, it appears that the alternative plant with its consolidation of reactor, pressurizer and superheater into one shell leads toward a more economical system and maintains a high level of reliability with good control characteristics.

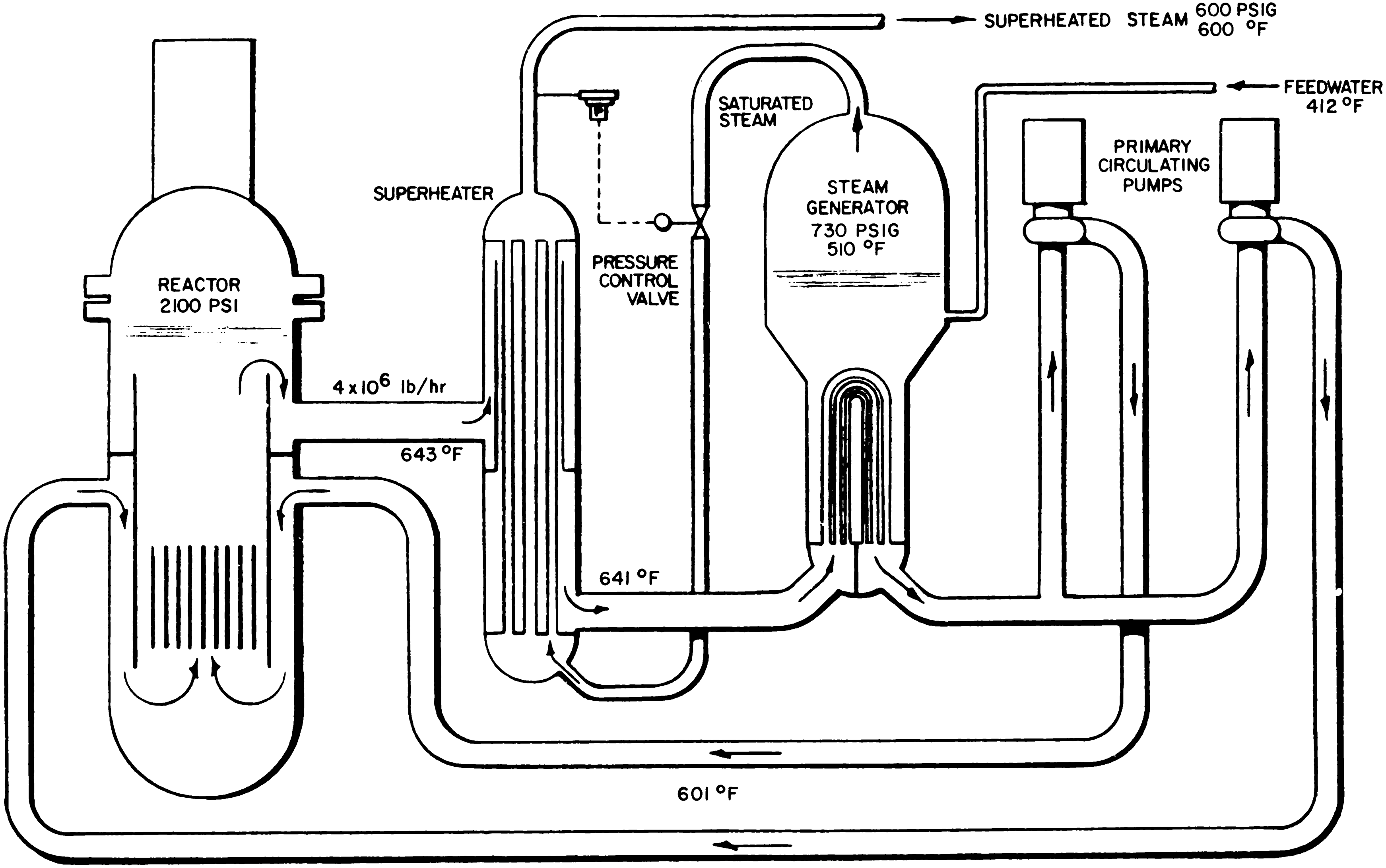


FIGURE A-1

PRESENTLY PROPOSED REACTOR SYSTEM FLOW DIAGRAM

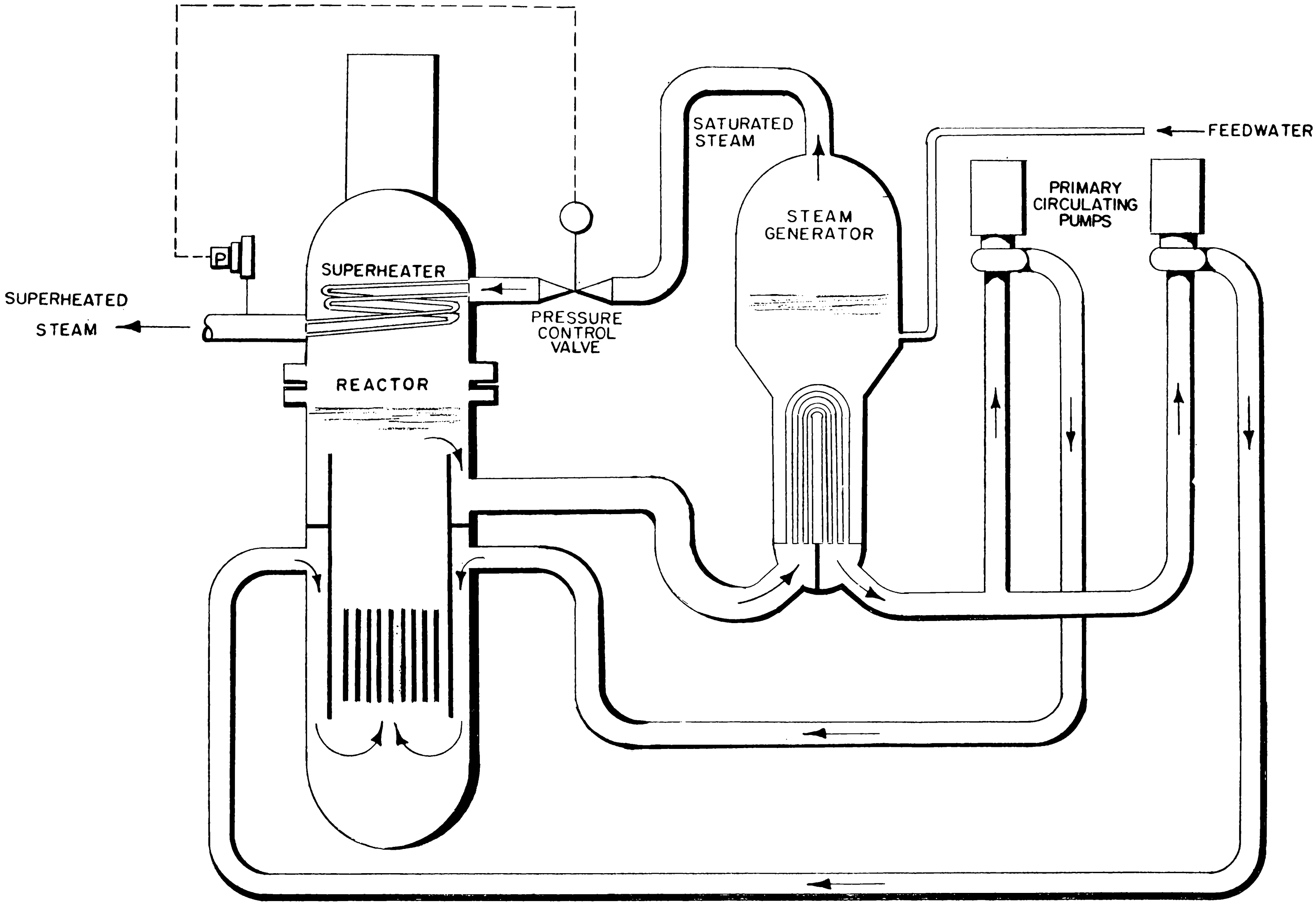


FIGURE A-2

ALTERNATIVELY PROPOSED REACTOR SYSTEM FLOW DIAGRAM

APPENDIX B

COSTS

Cost estimates were made for two presently-available second-of-a-kind nuclear plants for tanker use. Both systems are described briefly in Appendix A above, and the self-pressurized reference plant is more fully discussed in Part II, Plant Conceptual Studies of the current study report. The alternative plant, which is based on the combined energy, or C.E. Cycle, was included to show the gains presently available by adjustment of certain costs and contingencies as implied from given information or as dictated by a reassessment. In addition, forecasts were made to show the short-range and longer-range potentials for nuclear powered tankers of the 43,000 DWT class. For comparison, the cost tables presented below give these forecasted costs and the cost estimates made for the conventional and previously proposed plants.[1,2]

Operating costs were computed for two synthetic but typical trade routes for the tanker, which were specified by the Commission [2]. A long voyage to Kuwait in the Persian Gulf from the East Coast and a shorter U. S. Coastwise trip from the Gulf of Mexico to the East Coast were used. On the longer trip, the tanker would travel in ballast to Kuwait via the Suez Canal and return to Philadelphia, Pennsylvania loaded via the Cape of Good Hope. The total distance is 20,483 miles for this trade route and 1930 for the shorter U.S. coastwise route.

Current depressed-market costs for ships were not utilized in the comparative study since any gain available in the cost of bottoms for a conventional ship would also benefit a nuclear tanker, and the comparison is more realistic on more nearly normal market prices. Furthermore, the quoted depressed market cost is to a large extent explained by the difference between the construction schedules being used in the industry and the schedule originally assumed for the study.

A. COST BASES AND RULES

The following assumptions for use in computing the operating, capital, and fuel costs were established for earlier studies [1,2] by the Technical Program Branch of the Office of Maritime Reactors, Division of Reactor Development, U. S. Atomic Energy Commission. In general, they were adhered to in making the newer cost estimates and the forecasts. Exceptions are noted in the explanations.

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(1) NYO-2860, "Nuclear Powered Tanker Design and Economic Analysis - Pressurized Water Reactor.

(2) TID-8528, "Three Design Studies for Selecting a Prototype Reactor for a Nuclear Tanker."

1. Capital Costs

(a) Plans for the vessel and propulsion plant (including components) will be furnished by the government at no cost.

(b) The cost estimates will be based on a second-of-a-kind plant and ship, which would be a carbon-copy of a first that was built at a different shipyard.

(c) The design and construction period will be 40 months with 30 months needed for actual construction.

(d) The reactor plant components will be scheduled for a first-of-a-kind delivery, although they will be priced on a second-of-a kind basis.

(e) Each component of the nuclear steam-supply system will include the vendor's normal profit and overhead and the cost of freight and insurance for delivery to a shipyard in the New York City area.

(f) Reactor plant engineering costs will include the engineering and inspection necessary to insure delivery of an acceptable component and will include the required shipyard engineering for a carbon-copy second ship, but will not include first-of-a-kind engineering.

(g) Shipyard engineering, design and inspection for the carbon-copy tanker will be computed at 23.1% of direct shipyard labor for installing both the nuclear and propulsion plants, but only 11.6 percent of the direct labor will be used to obtain the engineering cost for the hull and outfitting.

(h) Indirect shipyard labor will be computed at 14 percent of the direct labor.

(i) Shipyard general and administrative costs will be assumed to be 70 percent of the sum of the shipyard direct and indirect labor and engineering costs.

(j) Escalation will be assigned a cost of 4 percent of one half of the direct costs per annum for the entire 40 month period.

(k) Shipyard profit will be computed as 5 percent of direct costs.

(l) A cost of 2 percent of direct costs will be used for changes.

(m) The following special indirect costs will be applied to the nuclear steam supply systems.

(1) Contingency and changes: 10 percent of plant construction costs.

(2) Reactor startup: $200,000

(n) A charge of $50,000 will be added for sea trials.

(o) The cost of construction funds will be computed at 6 percent per annum for the actual construction period of 30 months on one-half of the total ship capital cost.

2. Fuel Costs

(a) As specified in the Federal Register 26 FR 4765, the fuel use charge is 4.75 percent per year based on the value of the uranium, in the form of UF_6, that is givin in the same document. The fuel is evaluated at its initial enrichment during fabrication, its average enrichment during operation, and its final enrichment during processing.

(b) In accordance with the suggestion in the AEC Release D-138 of May 29, 1961, the plutonium recovered is credited at $9.50 per gram in order to maintain the same value relative to the current value of fully enriched uranium as when it was credited at $12.00 per gram and the older uranium price scale, which was specified in TID-4559, was in effect.

(c) As specified in the Federal Register 26 FR 4435, the loss of plutonium during reprocessing is assessed at one percent.

(d) In accordance with the Federal Register 23 FR 1707, the charge for converting plutonium salts to metal buttons is $1.50 per gram.

(e) The cost for shipping irradiated fuel to the reprocessing plant will be $12.45 per kilogram of uranium.

(f) As specified in the Federal Register 22 FR 1591 and 24 FR 10165, the use of the reprocessing plant costs $15,300 per day. For low enrichment fuel (less than 3.2 w/o) the reprocessing rate is 1000 kg of U/day; for higher enrichments (above 3.2 w/o) the rate is specified in WASH-743. The plant cleanup period for which charges are assessed varies from a minimum of two days for fuel batches of less than two metric tons of uranium, to the number of days equal to the number of tons for loadings between two and eight tons, with a maximum of eight days for loadings greater than eight tons.

(g) Conversion of uranium nitrates to UF_6 will be computed at $5.60 per kilogram of uranium, as specified in the Federal Register 23 FR 1707. A charge for a 0.3% loss of uranium nitrate is assessed in accordance with the specifications in the Federal Register 26 FR 4435.

(h) A loss of one percent of the uranium is assumed to occur during fission product removal, as specified in the Federal Register 24 FR 10165.

3. Annual Operating Costs

(a) Crew's wages and subsistence will be computed at the rate of $28.25 per man per day. A subsistence charge of $2.25 per man day will be made for each cadet.

(b) Stores-and-supplies cost for conventional equipment will be taken as $65,000.

(c) Maintenance-and-repairs cost for conventional equipment will be $140,000.

(d) The port-and-canal fees, radiation surveys, overhead, and miscellaneous will be $175,000 for the Long Trade Route and $125,000 for the U. S. Coastwise Trade Route.

(e) A factor of 10 percent of the total capital cost will be assigned for interest, depreciation, and insurance. A breakdown of this factor is as follows:

Basic insurance cost	1.578%
Nuclear Liability	0.589%
Depreciation (20 years less scrap value) and Interest	7.950%
Total	10.117%

(f) Refueling charges will be based on the assumption that the Savannah servicing barge will be available at no cost.

(g) The voyage time for the long trip will be 51.7 days.

(h) The tanker will operate 350 days per year, but sea days at normal power will be only 316 days per year.

B. COST SUMMARIES

The costs reported above are summarized in the following tables: Table B-1, Capital Cost Summaries; Table B-2, Fuel Cost Summaries; Table B-3, Long Trade Route Operating Cost Summaries; and Table B-4, U. S. Coastwise Trade Route Operating Cost Summaries. Each of the tables contains six columns of cost figures. The first column of each table is for the conventional tanker as reported in TID-8528, "Three Design Studies for Selecting a Prototype Reactor for a Nuclear Tanker," with the exception that an adjustment for a reduction in construction schedule to 16 months has been made. The second column is for the previously proposed plant, a second-of-a-kind carbon-copy plant of the pressurized water type described in NYO-2860. The costs for the present self-pressurized plant are given in the third column; while in the fourth, the costs are shown for the alternative present plant, a modified self- pressurized plant for which certain costs and contingencies have been adjusted.

TABLE B-1 - CAPITAL COST SUMMARIES

Item	Conventional	Previously Proposed	Presently Proposed	Alternatively Proposed	Short-Range Potential	Longer-Range Potential
NUCLEAR STEAM-SUPPLY SYSTEMS						
Reactor	$ 556,300	$ 739,400	$ 685,800	$ 700,800	$ 523,000	$ 350,000
Nuclear Heat-Transfer System		1,136,700	744,900	645,300	493,000	350,000
Radioactive Waste System		64,700	49,200	49,200	49,000	40,000
Instrumentation & Control		260,200	227,500	227,500	188,000	130,000
Containment, Shielding & Collision Barrier		486,500	473,500	336,700	299,000	200,000
Spare Parts		205,000	136,900	136,900	114,000	100,000
Engineering, Design & Inspection	21,200	800,000	800,000	418,100	200,000	100,000
Installation	104,700	1,100,600	1,048,700	857,400	648,000	250,000
Total Direct Cost	$ 682,200	$ 4,793,100	$ 4,166,500	$ 3,371,900	$ 2,514,000	$ 1,520,000
Indirect Costs	59,100	984,000	894,600	762,100	401,000	150,000
Total Steam Supply Systems Cost	$ 741,300	$ 5,777,100	$ 5,061,100	$ 4,134,000	$ 2,915,000	$ 1,670,000
MAIN PROPULSION AND AUXILIARY MACHINERY SYSTEMS						
Main Propulsion System	$ 1,903,600	$ 2,002,300	$ 1,976,200	$ 1,976,200	$ 1,934,000	$ 1,930,000
Electrical System	480,000	692,800	582,800	582,800	583,000	580,000
Auxiliary Systems & Piping	745,500	764,400	721,900	721,900	722,000	720,000
Instrumentation & Controls	24,700	35,000	35,000	35,000	25,000	20,000
Engineering, Design & Inspection	108,100	111,400	105,800	105,800	104,000	100,000
Installation	533,300	549,700	520,600	520,600	512,000	510,000
Total Direct Cost	$ 3,795,200	$ 4,155,600	$ 3,942,300	$ 3,942,300	$ 3,880,000	$ 3,860,000
Indirect Costs	825,500	1,111,700	1,026,500	1,026,500	907,000	860,000
Total Main Propulsion and Auxiliary Systems Cost	$ 4,620,700	$ 5,267,300	$ 4,968,800	$ 4,968,800	$ 4,787,000	$ 4,720,000
HULL AND OUTFITTING						
Direct Hull & Outfitting Costs	$ 7,148,900	$ 7,246,800	$ 7,181,800	$ 7,181,800	$ 7,067,000	$ 6,950,000
Indirect Hull & Outfitting Costs	3,075,200	3,357,500	3,349,900	3,349,900	3,146,000	3,060,000
Total Hull & Outfitting Cost	$10,224,100	$10,604,300	$10,531,700	$10,531,700	$10,213,000	$10,010,000
Total Ship Capital Cost	$15,586,100	$21,648,700	$20,561,600	$19,634,500	$17,915,000	$16,400,000
Cost of Construction Funds	623,400	1,617,000	1,542,100	1,472,600	1,075,000	740,000
Total Capital Cost	$16,209,500	$23,265,700	$22,103,700	$21,107,100	$18,990,000	$17,140,000

TABLE B-2

FUEL COST SUMMARIES

Item	Conventional	Previously Proposed	Presently Proposed	Alternatively Proposed	Short-Range Potential	Longer-Range Potential
LONG TRADE ROUTE						
Use Charge		$ 195,000	$ 154,300	$ 154,300	$ 116,000	
Fabrication Costs		229,000	120,800	120,800	91,000	
Depletion Costs		421,700	281,100	281,100	211,000	
Recovery Costs		-38,400	9,500	9,500	7,000	
Control Rod Costs		11,700	6,300	6,300	5,000	
Total	$ 832,400	$ 819,000	$ 572,000	$ 572,000	$ 430,000	$ 358,000
U.S. COASTWISE TRADE ROUTE						
Use Charge			$ 151,900	$ 151,900	$ 115,000	
Fabrication Costs			113,000	113,000	85,000	
Depletion Costs			262,800	262,800	197,000	
Recovery Costs			8,900	8,900	6,500	
Control Rod Costs			5,900	5,900	4,500	
Total	$ 801,000	$ 786,000	$ 542,500	$ 542,500	$ 408,000	$ 341,000

TABLE B-3

LONG TRADE ROUTE ANNUAL OPERATING COST SUMMARIES
(Persian Gulf to North of Hatteras: 20,483 Miles Round Trip)

Item	Conventional	Previously Proposed	Presently Proposed	Alternatively Proposed	Short-Range Potential	Longer-Range Potential
Crew's Wages and Subsistence	$ 486,600	$ 486,600	$ 486,600	$ 400,500	$ 348,500	$ 282,000
Stores and Supplies	65,000	68,000	68,000	57,500	49,200	40,000
Maintenance and Repair	140,000	190,000	190,000	190,000	190,000	140,000
Refueling Charge	---	9,100	2,500	2,500	2,500	2,500
Port and Canal Fees, Radiation Surveys, Overhead and Misc.	175,000	175,000	175,000	175,000	175,000	175,000
Interest, Depreciation and Insurance (including nuclear liability) 10% of capital costs (conventional 9-1/2%)	1,539,900	2,326,500	2,210,400	2,110,700	1,898,900	1,714,000
Fuel Costs	832,400	819,000	572,000	572,000	430,000	358,000
Total	$ 3,238,900	$ 4,074,200	$ 3,704,500	$ 3,508,200	$ 3,094,100	$ 2,711,500
Fuel Cost, Mills/SHP-Hr.	3.92	3.88	2.71	2.71	2.04	1.70
Annual Cargo Capacity, Long Tons	267,600	289,600	290,500	290,800	290,800	292,000
Delivery Cost, Dollars/Ton	12.10	14.07	12.76	12.40	10.64	9.28

TABLE B-4

U. S. COASTWISE TRADE ROUTE ANNUAL OPERATING COST SUMMARIES
(Gulf Coast to North of Hatteras: 1930 Miles One Way)

Item	Conventional	Previously Proposed	Presently Proposed	Alternatively Proposed	Short-Range Potential	Longer-Range Potential
Crew's Wages and Subsistence	$ 486,600	$ 486,600	$ 486,600	$ 400,500	$ 348,500	$ 282,000
Stores and Supplies	65,000	68,000	68,000	57,500	49,200	40,000
Maintenance and Repair	140,000	190,000	190,000	190,000	190,000	140,000
Refueling Charge	---	9,100	2,500	2,500	2,500	2,500
Port and Canal Fees, Radiation Surveys, Overhead and Misc.	125,000	125,000	125,000	125,000	125,000	125,000
Interest, Depreciation and Insurance (including nuclear liability) 10% of capital costs (conventional 9-1/2%)	1,539,900	2,326,500	2,210,400	2,110,700	1,898,900	1,714,000
Fuel Costs	801,000	786,000	542,500	542,500	408,000	341,000
Total	$ 3,157,500	$ 3,991,200	$ 3,625,000	$ 3,428,700	$ 3,022,100	$ 2,644,500
Fuel Cost, Mills/SHP-Hr.	3.92	3.93	2.74	2.74	2.07	1.73
Annual Cargo Capacity, Long Tons	1,421,000	1,388,000	1,392,200	1,392,200	1,392,200	1,397,900
Delivery Cost, Dollars/Ton	2.22	2.88	2.60	2.46	2.17	1.89

The fifth column is for a near future plant which would be a fourth or fifth-of-a-kind evolved from either of the two presently available plants as technology develops, or the second-of-a-kind if a complete research and development program is conducted prior to the initiation of any ship construction. Further in the future, as industrial participation becomes complete due to the economic incentive of the short-range potential plant, the cost of a nuclear tanker would continue to decrease. The forecast for the longer-range potential is presented in the sixth column of each table.

In making the bar charts shown in the text above, certain groupings were made. For the annual operating costs, the title "Service" was given to the sum of the costs for stores and supplies, maintenance and repair, and refueling. Port and canal fees, radiation surveys, and operating overhead are included in the Miscellaneous item. In the breakdown of the cost for the direct nuclear steam supply system, the radioactive waste system was included with the heat transfer system, and the costs for spare parts were distributed to their proper categories.

C. COST ESTIMATE EXPLANATIONS

The cost estimates for the two presently-available plants were made in the same detail as for the previously proposed plant [1,2]. As before, each plant was considered to be a second-of-a-kind, carbon-copy plant of one previously built. However, since there has been little or no actual cost data for second-of-a-kind, carbon-copy nuclear components, the costs reported in these estimates are the same as first-of-a-kind costs less design engineering.

The capital cost breakdown for the nuclear steam supply systems represented a complete analysis of all components, pipes and fittings, including installation, engineering and inspection and indirect costs. In determining the fuel costs, all aspects of the fuel cycle were examined, from the ordering of UF_6 through the manufacture of fuel clusters into a core and the reprocessing of spent fuel. The cost estimates were made by using commercial manufacturers' quotations, and/or interpolations of them, and generally-accepted estimating formulae for equipment and its installation, as well as by using the rules and cost bases established by governmental agencies, which are given in section A of this appendix. Only summaries of the results of this thorough investigation are presented.

In determining reactor costs, conceptual designs of the pressure vessels were made and costs established. The single reactor item reported reflects the total summation of costs of the pressure vessel, core supports, control rod mechanisms, neutron sources, primary shield and thermal shield.

The cost reported for the nuclear heat transfer system represents the largest area of investigation. Included under this item are costs of the primary circulation pumps, check valves, primary piping, superheater, steam generator, auxiliary systems, primary relief valves, insulation and the steam shut-off valves. Designs of the major components such as the steam generator and superheater were made. A general arrangement of the primary and secondary systems within the containment was drawn and the plant was optimized and priced. The supporting auxiliary systems were designed as consolidated packages and all components were individually estimated.

Radioactive waste treatment and disposal is reported as a separate item. The total cost includes the necessary heat exchangers, tanks, pumps, pipe, valves and fittings not already reported as part of other systems.

Instrumentation and control includes both nuclear and non-nuclear instrumentation for the reactor safety system. The detailed breakdown of instrumentation costs contains the rod drive control and panel, the nuclear and process instrumentation for reactor control and the operating consoles. In addition, the waste control and monitoring system, the radiation monitoring equipment and the auxiliary system instrumentation are included.

Containment, shielding and collision barrier is reported as a single item. The items embraced by this total are the containment structure, biological shield, the necessary hull modifications, auxiliary services and shield cooling.

Spare parts requirements for the nuclear components were established by the Commission and are the same as outlined in NYO-2860, "Nuclear Powered Tanker Design and Economic Analysis - Pressurized Water Reactor."

Installation costs are based on uniformly-applied average cost factors developed by the U. S. Maritime Administration for estimating the cost of ships. All installation costs attributed to the nuclear steam supply systems are included under this item.

As in the case of the nuclear steam-supply system, those items reported under main-propulsion and auxiliary machinery systems represent a summation of many items. Prices for these items consist of shipyard as-purchased costs and include spare parts in conformance with regulatory body requirements.

The main-propulsion system represents the total cost of those items that are considered the major propulsion components. These include the main turbine and throttle valve, the moisture separator, main condenser, main steam piping and valves and the propeller shaft system.

Under electrical system, the total cost contains the electric generating equipment such as the turbo-generators, the diesel generator and the emergency generator. Also included are the main and emergency switchboards, the power plant wiring and distribution panels, the motor generators and batteries.

The auxiliary systems and piping item encompasses all of the equipment associated with the main propulsion system that is not included in the preceeding items. The main areas covered under this item are the auxiliary steam system, the feed and condensate system, the blowdown evaporator and desuperheater, the lube oil system and the salt water circulation system. Equipment for the compressed air service, evaporators, pumps and engine room accessories such as the workshop, lifting and handling equipment and ladders and gratings are also included in the reported cost.

The engineering, design and inspection, the installation and the indirect costs are based on the guidelines given in section A of this appendix.

The hull and outfitting direct costs include both steel and outfit. Those items associated with the nuclear power plant such as containment vessel, biological shield and collision barrier are not included in the hull steel costs. The indirect costs were computed using the bases outlined in section A of this appendix. All hull-and-outfit, as well as shipyard installation costs, were estimated by the naval architects using common cost factors.

The fuel fabrication costs include all of the costs incurred in converting UF_6 to ceramic grade UO_2, sintering the UO_2 into pellets, and in manufacturing the fuel clusters, as well as the expenditures for all materials required in addition to the fuel. The irrecoverable uranium losses during fabrication and the cost of converting scrap UO_2 back to UF_6 are also included in the fabrication estimate. The use charge during fabrication of the core was assessed on an average fuel possession time estimated to be nine months. The cooling, shipping, and reprocessing time at the end of the core life was estimated to be six months. The fuel depletion cost was taken as the difference in the value of the uranium loaded into the reactor and its value after removal at the end of the core life. The uranium recovery costs include all of the costs incurred after removal of the fuel from the reactor to the return of UF_6 to the AEC.

1. Conventional Tanker

For comparative purposes, the Maritime Administration developed a design and prepared estimates for a conventional American ship using the same general rules as those used for this nuclear study. The bases of the cost assumptions and tabulated summaries of capital and operating costs are reported in TID-8528, "Three Design Studies for Selection of a Prototype Reactor for a Nuclear Tanker." No breakdown of the costs was published.

The total ship capital cost presented in Table B-1 is lower than the value previously given in the reference becuase a shorter construction schedule was used. A recent investigation revealed that conventionally-powered tankers of the class under consideration can be built in 16 rather than in 30 months, as originally specified. Accordingly, the cost for the conventional tanker is about one million dollars less due to the appreciable influence of this reduction in the purely time-dependent cost factors, such as escalation and cost of construction funds.

The fuel costs for the conventional tanker were calculated by using a bunker C fuel oil price of $2.70 per barrel. This value was established by guidelines(2). Although the price set for bunker C fuel oil is higher than the currently depressed market value, it is lower than the average fuel-oil price shown by price trends plotted using data from 1930 to the present time. Fuel and annual operating costs for the Long and U. S. Coastwise Trade Routes for the conventional tanker are shown in the first columns of Tables B-2, B-3 and B-4.

2. Previously Proposed Tanker

The previously proposed ship costs shown in the tables of this Appendix are those originally presented in NYO-2860, "Nuclear Powered Tanker Design and Economic Analysis," with adjustments as made in TID-8528, "Three Design Studies for Selecting a Prototype Reactor for a Nuclear Tanker." The schedule for this nuclear-powered tanker was not altered from the 30-month estimate, since the additional construction time at this phase of development may be needed. Although this sub-cooled pressurized water reactor plant contained certain advanced features for its time, it has become outdated by the feasibility of such concepts as self-pressurization, consolidation of primary and auxiliary components, the combined energy cycle, once-through steam generation and the like. Accordingly, the cost for this ship is no longer appropriate for assessing the present competitive situation of a nuclear tanker. The cost breakdown for this previously proposed tanker has been included because it provided the foundation for the presently available plants. The advantageous features of this safe, reliable plant, such as the production of superheated steam suitable for a conventional turbine, the single-loop design without block valves, the inherent response to load demands, and the reduced coolant flow and inventory of water have been preserved in the presently and alternatively proposed designs.

3. Presently Proposed Tanker

The evolution of the previously proposed plant into a self-pressurized system yields an appreciable $1,100,000 reduction in total ship capital cost. As can be ascertained from Table B-1, Capital Cost Summaries, the significant reductions are in the costs of the reactor, the heat transfer system, spare parts, installation, the electrical and auxiliary systems of the propulsion plant, and in the hull. None of the cost reduction was due to changes in the cost estimating rules.

The lower reactor cost is due mostly to a reduction in number of rod mechanisms needed. The unit price was adjusted upward but elimination of seven rod drives yielded a net reduction. Although a larger vessel is needed for the self-pressurized system, the cost is lower due to correction of the faulty bid made for the previous reactor vessel.

As would be expected, elimination of the pressurizer along with its heaters, sprays, and instrumentation and controls represents a major portion of the reductions in capital cost, and contributes to the lower installation charge. Consolidation of the auxiliary systems into more compact arrangements on skids, together with certain functional simplifications, resulted in another large capital cost savings, and also led to the reduction in installation costs by simplifying the mounting of the systems in the ship.

Another important factor that lowered the cost of the heat transfer system was a change to bent centrifugally cast pipe from forged piping with fittings for the primary loop.

In addition to the elimination of the pressurizer, self-pressurization has the advantage that the operating temperature can be higher for a given design pressure since the system is saturated. The increase in temperature between the primary and secondary fluids lowers costs by enabling a reduction in the required heat transfer surface. In the present design, this feature reduced the cost of the steam generator markedly.

The reduction noted in the electrical system of the propulsion plant is the result of a substitution of steam-driven pumps for the electrically-driven primary pumps. The resultant savings in required generating capacity was sufficient to permit the specification of 600 KW turbo-generators and a 600 KW diesel generator instead of 1000 KW units. The use of steam driven coolant pumps is discussed in detail in Part IV of this study.

The decrease in hull cost was obtained by eliminating the ballast and hull alterations originally needed to offset the reactor plant weight. The preliminary weight estimate was found to be too high and subsequently corrected.

Fuel costs for this plant are lower than those reported in NYO-2860. The use of a larger core with an increased moderator-to-fuel ratio and reduced stainless steel content results in a lower fuel enrichment requirement. A larger fuel rod diameter with increased power output per unit length permits a reduction in the number of fuel clusters and control assemblies, and, therefore, a decrease in the fuel fabrication costs and the number of control rod drives. The increased core size and fuel rod diameter improve the core thermal characteristics such that the primary system flow rate is appreciably lower. In addition to influencing the capital costs, the lower flow rate contributes to an increased plant efficiency. The reduced fuel costs reflect the improved over-all plant efficiency due to the reduced pumping power and the addition of a moisture separator at the cross over between the high and low pressure turbines. The recent reductions in the AEC uranium prices also contributed substantially to the lower fuel costs.

4. Alternatively Proposed Tanker

By taking advantage of certain cost adjustments by reason of a reassessment and by incorporating additional consolidation, which is offered by this modified self-pressurized system, an additional million-dollar reduction in capital costs can be obtained. Placement of the superheater in the steam dome of the reactor vessel, rather than external to it, leads to a tighter primary loop and reduces the inventory of water. Reductions in the costs of the containment structure, collision barrier, and biological shield, as well as the superheater itself, were thereby made possible.

As can be seen from Table B-1, Capital Cost Summaries, the installation cost for this smaller, more compact plant is also significantly lower. The reason this gain could be achieved is that different shielding arrangements could be utilized with the smaller containment vessel. For example, space was made available for situating the decay heat removal system's stored water in such a manner that some credit as shielding could be taken for it. Also, the containment vessel could be relocated within the reactor compartment for better shielding arrangements and for more advantageous use of the fuel oil as a radiation barrier.

The other major cost difference between this alternatively proposed plant and the present plant is in engineering, design, and inspection. After assessing the value of $800,000 assigned to this item for the subcooled, separately pressurized plant, it is believed that due to the technological developments included in this modified self-pressurized plant, a cost of $480,000 is conservatively reasonable.

Because of the savings made in direct capital costs, additional savings are made on the indirect costs, which as usual, are various percentages of the direct costs. Also, savings in construction funds costs are realized since this item is a fixed percentage of the total ship's capital costs.

No changes were made in the estimated costs either for the other items of the nuclear-propulsion plant or for the fuel costs.

D. COST FORECAST EXPLANATIONS

The same general format used in generating the cost estimates was followed in making the cost forecasts for nuclear tankers. That is, the formulae for such items as overhead, escalation, profit, changes, and construction funds were employed. The difference between the estimates and forecasts resides in the method for obtaining component costs. Since an estimate is by nature valid because misjudgements in overpricing are balanced by misjudgements in underpricing, special care must be exercised in reducing the cost in any particular item. The reasons for the changes must be well-justified, as they were in making the estimates for this study. Whereas the estimates are based on manufacturers' quotations, generally-accepted estimating formulae for equipment and its installation, and on more or less specific coneptual designs, the forecasts are a more qualitative evaluation of the effects of improvements in design, manufacture, and methods of accomplishing the job. In order to obtain the equivalent reliability for the capital and fuel cost forecasts, credit was not taken for all conceivable economic gains. This procedure compensates for the absence of the inherent averaging process in making a cost estimate. Accordingly, not all the individual predictions must be true for the over-all answer to be valid.

The projected costs for specific components, and other items in the breakdown, were based on expected evolutional developments from today's technology, including improvements in prices that usually occur as a new industrial product becomes a more familiar commodity. For the short range potential plant, the assessment was made item by item, whereas for the longer range forecast, predictions were made in terms of general groupings.

1. Short Range Potential Tanker

Approximately one-half of the cost reduction shown for this ship over the alternatively proposed tanker is due to a modest change in construction schedule from 30 to 24 months, which demonstrates the importance of the time-dependent factors in the construction of a ship. The reduction is certainly reasonable considering that it has been assumed that either the necessary research and development has been performed so that the system is well established, or that this ship is the fourth-or-fifth-of-a-kind.

The reactor will be less expensive because control rod drive mechanisms will become cheaper as they become an industrially-produced item, and because improvements in the manufacture of reactor vessels will be realized once they are familiar enough to be removed from the exotic classification with respect to fabrication, cleaning, and inspection methods. Furthermore, since enough experience will have been obtained, true carbon-copy pricing of the components for this short range potential plant can be used.

The use of once-through heat exchangers in the primary loop will effect an appreciable change in the cost of the heat transfer system, as will the use of less expensive steels for the larger surface areas of the primary system, e.g. pump casings, piping and pressure vessels of the heat exchangers. The use of cheaper steels tends to increase the post-shutdown radioactivity of the primary loop and consequently, the radiation hazard to maintenance personnel, but the situation can be improved. Exposure to the radiation will be decreased when the need for access to the containment diminishes in accordance with an improved operational reliability, or when the economics permits more extensive shielding of the loop during maintenance. Alternatively, the activity of the system will be lowered when better methods have been acquired for decontamination and corrosion control.

Once-through steam generation will also lower the instrumentation cost by eliminating the need for the present large control valves between the steam generator and superheater.

For this plant, the engineering has been reduced to the amount required at the shipyard plus a special engineer for following the progress of the reactor plant. This should be sufficient since the reactor system will be pre-designed and specified in the same way that conventional systems, such as the propulsion plants are.

The use of less expensive materials throughout the reactor plant together with more favorable consolidated arrangements of the auxiliary systems will bring about the forecasted reduction in installation costs.

Since the reactor system will be more firmly established in all aspects, the contingency was changed from ten to six percent for this short range potential plant.

The propulsion system for use with this plant that produces superheated steam is conventional, except for the steam piping to the primary coolant pumps and a moisture separator. The cost shown reflects this characteristic. The remaining significant gain is in the outfitting cost, which is obtained via a reduction in the number of crew members. As experience is obtained with the favorable control characteristics of the indirect-cycle water reactor system, such crew members as the junior engineers and a special electronic technician will not be required.

The forecasted fuel costs reflect the trend of declining nuclear fuel cycle costs as the technology advances. Expected design improvements relative to increases in burnup limitations for uranium dioxide, reduction in cladding thickness, and improved heat output capabilities together with simplification in manufacturing processes and lower material costs will contribute to the reduction indicated. Conservative improvements were forecasted and then only a portion of the calculated cost reduction associated with them was taken as credit for the short range potential.

2. Longer-Range Potential Tanker

In the future, as industrial participation becomes extensive due to the competitive position of nuclear energy, standard methods for conducting the building of a nuclear ship will be utilized. The power plant will no longer be considered unique and the reactor and heat transfer system will fall into the class of normal vessels, heat exchangers, pumps and controls. Accordingly, the construction schedule can be reduced to nearly the time needed for building an oil-powered vessel, i.e. to 18 months compared with 16 months for the latter. Again, the time-dependent factors associated with this change materially affect the over-all ship cost.

Instrumentation will be decreased to the bare minimum needed for safe, reliable control by elimination of all those instruments provided only to supply information concerning system performance and of those serving as extra precautionary back-ups. Shielding concepts will be advanced to the extensive use of localized barriers, and "hot" spots will have been defined and over-protection in the other areas thereby removed. The containment structure, as well as the shielding, will be less expensive due to the decrease in size accompanying the consolidation of the nuclear system and the reduction in its inventory of water. In addition, the use of vapor suppression methods and newer fabrication concepts will contribute to a savings in the cost of containment.

Although the charge for engineering is still much greater for this steam supply system than for the conventional, it has been lowered to the value estimated for the installation of the propulsion plant, which entails about an equivalent effort in this area.

The anticipation that the nuclear plant can be preassembled into six to twelve packages with a minimum number of pipe and instrument connections leads to the large reduction shown for installation. It should be noted that the cost is assumed to be still appreciably larger than for a conventional boiler.

The fuel costs are lower due to the assumption that a larger fraction of the conservative improvements forecasted for the short range potential plants will be attained. Nothing revolutionary was predicted; prices and improvements were, in the main, extrapolated from current trends.

No changes were made in the forecast for the propulsion plant over the short-range potential plant (which will be about as expensive as present-day estimates). But credit was taken for another reduction in crew members consistent with developments in the direction of a minimum attention system and with the experience that will demonstrate that nuclear energy is a normal source of propulsive energy.

APPENDIX C

RESEARCH AND DEVELOPMENT PROGRAM FOR MARITIME REACTORS

For maritime application, the objective of nuclear reactor plant development is commercially competitive propulsion plants for a significant fraction of ship applications consistent with safe and reliable service. This means that the resources invested in nuclear powered ships must yield a greater return than alternative propulsion systems for the service intended.

In developing the cost analysis for present day and projected plants presented in this report, the importance of actual construction and in-service experience was continuously evident. This experience can be gained through step-by-step improvement in the various plant areas both through construction of successive ships and through modification of an existing ship. In the latter case, full value of a particular improvement cannot always be realized on that ship but, on the other hand, a larger number of steps can be made within a given time interval at a lower total expenditure. In either case, there is a demonstration of the improvement which provides a basis for the next step. This is development through evolution from experience which has proven in the past to be a fruitful development direction.

At best, however, this is a costly process since it involves the construction and operation of ships. In a commercial atmosphere each step must be large enough to realize an appreciable gain, and the first step must be sufficiently attractive to give reasonable assurance of achieving the goal in the near future. To provide this assurance, a vigorous research and development program is required. The key development areas have been outlined in the body of this report and are discussed in greater detail in this appendix. For the greatest gain, the program should be substantially completed before committing a next ship to construction. It can easily be seen from the computation of the capital costs that when ship construction is initiated, the major plant decisions must have been made and backed with sufficient information to insure that the construction schedule will not be compromised.

Before the key research and development areas are discussed in detail, it is well to identify in each of the traditional cost areas where the heavy contributions lie, and the possible means by which these costs might be reduced. Let us consider, in order, capital costs, fuel costs, and maintenance and operating costs.

One of the most promising directions for improving capital costs appears in combining functions of the primary components and systems so that the number of components can be reduced. Along with this, where possible, the principal and auxiliary systems should be modularized so that they can be assembled in a pre-packaged form. This consolidation leads to cost reduction through several avenues. Consolidated major components may share major pressure vessels. In some cases an entire functional system is eliminated. For example, in self-pressurization not only is the pressurizer included as a part of the reactor vessel, but also the separate pressure-controlling function is eliminated. In the case of auxiliary systems, only slight modification of the components of one functional system permits the system to perform other functions and, hence, replace these as separate systems. It appears possible, for example, to modify the emergency cooling system so that it can perform the functions of the decay heat removal system, employed during core servicing, as well as provide back-up take-home power if a major difficulty necessitates isolation of both the steam generator and superheater.

If the auxiliary systems are modularized or packaged so that they can be installed as functional units, not only will savings result in installation costs but pre-installation testing can easily be performed and connection to the primary system made simply. It is clear, of course, that reduction of principal system components that require shipyard installation will reduce costs. By utilizing the inherent characteristics of the reactor system to reduce the need for complex control equipment and instrumentation, savings out of proportion to the cost of the equipment alone can be made by the elimination of its installation. An associated operating saving in servicing also results.

It is important to recognize that these improvements can appear as cost savings only if the planned construction schedule is maintained, and a true competitive position established only if the schedule is comparable to those for conventionally powered ships.

Fuel costs would be reduced measurably by decreasing the parasitic neutron absorption in the fuel element cladding and the core structurals. Recent developments give promise for use of thinner fuel supported cladding in the near future. Progressive development and increased use of newer materials, such as various zirconium or other alloys, may bring their costs into a range where further improvements can be realized. Reduction of fuel costs will be speeded by information obtained through the broad use of low enrichment uranium dioxide fuels in other than maritime reactors. Still, application development to maritime service is required. Since cores are replaced in a three or four year period, advantage can be taken of new developments in subsequent cores.

Operating and maintenance costs depend heavily upon information developed from operation experience. However, design approach can help measurably in achieving cost reduction more rapidly. Inherent reactivity control as well as system control and protection simplification, all of which lead to less specialized crew training and a greater opportunity to program maintenance, are substantial steps in this direction.

A. KEY RESEARCH AND DEVELOPMENT AREAS

The research and development associated with the present or immediately available plant is presented in Part II, Conceptual Design Studies. It is directed toward obtaining certain information to better utilize the several advantageous features that have been incorporated in that plant. It could be performed concurrently with ship design and construction.

A program with broader objectives is discussed here. The key areas have been identified as having greatest potential for improvement of reactor systems for maritime application. A directed effort in these key areas performed before commitment to construction would permit the results to be factored into the initial ship design and construction planning. The development depth should be such that the features could be incorporated in a ship to be built on an initially established schedule with confidence that these features will result in the performance anticipated. With reasonably successful results from this program, it could be expected that the cost savings associated with the near term potential plant could be realized in a second ship.

1. Self-Pressurization Tests

A self-pressurized reactor system lowers both capital and fuel costs compared with a conventional pressurized water reactor with pressurizer. Lower capital costs result from the elimination of the pressurizer and associated instrumentation, and from simplification of reactivity control since it improves the load following characteristics of the reference plant. Lower fuel costs result from the higher net thermal efficiency obtained by using higher temperature superheated steam in the secondary system.

The principal uncertainty which has been encountered is the determination of the thermodynamic path followed by the steam conditions in the dome during a load change. The path followed by the steam conditions is important in that it determines, for a fixed steam dome volume, the pressure surge which will occur on a decrease in load or, for a given allowable pressure increase, the steam dome volume required. Analog computer studies of the change in steam demand transients have been run for a self-pressurized plant and the results are reported in Part III, Analog Simulation of Reactor Plant Transients. In these studies initial compression of the steam has been postulated either isentropic, along the saturation line, or in equilibrium with liquid below it. These studies indicate that a considerably larger steam dome is required if the process is isentropic. Since analog studies, by themselves, will never reveal the nature of the process followed by the steam, and since an understanding of the process followed is important in sizing the reactor vessel, a test loop embodying the self-pressurization feature should be designed, built, and tested to investigate the transient behavior of self-pressurized systems.

The loop would consist of a simulated reactor vessel containing an electrical heat source and steam dome, a heat exchanger for a heat sink, a circulating pump, piping, and instrumentation. Instrumentation would be provided to determine the pressure and temperature of the steam in the dome during changes in rate of heat removal from the heat sink. The system would be designed for an operating pressure of 1500 to 3000 psi, a power of up to 5000 kw, and a primary coolant flow rate of 20,000 lbs/hr. Load changes would be imposed on the experimental system and then analog computer runs of the same transient would be conducted using various assumptions about the thermodynamic behavior of the steam. Exact simulation of the nuclear feedback on power does not seem to be necessary; rather, the power would be varied in a simple manner approximating that following a load change. Comparison of experimental results with computed results would reveal the process followed by the steam.

2. Consolidation and Preassembly Application Development

Since installation costs constitute a major portion of the nuclear steam supply system capital cost, appreciable economic gains can be achieved by consolidation of equipment into fewer individual pieces before connections are made aboard ship. For certain consolidation features, an additional savings can be expected in the basic price of the components. Further, with components combined, a shorter construction schedule and attendent cost reductions can be achieved.

In the designs presented in Part II, Plant Conceptual Studies, the self-pressurized feature lowered costs by eliminating not only the separate pressurizer but also most of the pressure controlling equipment. An additional economic gain may be achieved by combining the two main heat exchangers into one unit. Other ideas of merit are to incorporate the superheater tubes into the head of the reactor vessel and to use a segmented once-through steam generator positioned around the reactor vessel. A further step in consolidation would be to locate the reactor core, the superheater, the boiler tubes, and perhaps even the primary coolant pumps within a single pressure vessel, which would be surrounded by the primary shield. Not only would capital and installation costs for the primary loop be reduced by these consolidations, but also there would be a savings in secondary shielding, containment vessel size, and ship's structure. The closer-packed array might enable more effective use of vapor suppression methods in containment.

Also included in this phase of the program is the development of factory-mounted skids for the consolidation of the many items comprising the auxiliary systems. Preassembly of this equipment into a few packages will appreciably reduce the installation cost.

In summary, the general objective of the work is to develop an arrangement for a unified modular plant in which the entire nuclear steam generating system is comprised of six to twelve factory-assembled modules. Particular attention should be directed toward:

Combining Functions -

> Combining components, equipment, and systems without complication utilizing natural properties to achieve maximum effectiveness in over-all plant operation.

Developing Pre-fabricated Modules -

> Developing a plant arrangement permitting components, equipment, and systems to be pre-fabricated into a few factory assembled modules, requiring limited interconnection, for ease of concurrent fabrication and pre-testing in addition to simplified and rapid shipyard assembly.

The merit of a particular functionally compact arrangement would be measured by the reduction of total plant costs including those associated with biological shielding, containment vessel size, and ship structure.

3. Once-Through Heat Exchangers

Once-through heat exchangers provide a large potential saving in nuclear plants because their use permits more compact arrangements, reduction in water inventory, and simplification of the secondary control system. Consolidation of equipment within the containment vessel permits a cost savings through a reduction in containment size and shielding requirements. Removal of the valves presently specified for control of the pressure of the superheated steam will yield a gain. Operating as well as capital savings result from feed pump pressure requirements never exceeding the low level associated with full load conditions.

A safeguard feature of the once-through steam generator associated with its low water holdup is not commonly recognized. In the event of a major break in secondary steam piping, the secondary coolant would be quickly expelled resulting in a rise in primary coolant temperature thus providing an inherent reactor power cutback rather than an initial excessive power demand.

In order to realize the potential, a test of the performance of a once-through steam generator at relatively low pressures must be made. Operation of conventional boilers with once-through flow at pressures above the critical point and down to 2000 psi is commercial practice. However, the effect of the greater volume change as water is converted into steam at lower pressures, in the range of about 700 psi, needs to be assessed. Instability problems could be encountered, and if so, specific schemes for damping or removing them must be developed. Although burnout of heat exchanger tubing is not of concern in a nuclear system that cannot exceed 650°F, the heat transfer coefficients should be known for design purposes. The tests should include a study of the effect of load changes on the stability of the system and quality of steam produced as well as investigations of control methods and various arrangements and segmentations. Operating water conditions must be determined and water treatment must be defined.

4. Core Heat Transfer Tests

One of the more effective ways of reducing costs is to develop a core from which design power can be obtained with minimum coolant flow rate requirements and with the minimum number and complexity of fuel elements. In doing this, not only can the capital costs directly associated with a smaller circulating pump and fuel cycle costs be significantly reduced, but even larger cost savings are possible due to cost reductions associated with coolant holdup and a compact plant.

Improved core heat removal will permit primary coolant flow reduction and thereby reduce system water volume holdup and containment size. Reduction in the physical size of the core permits further consolidation of the plant. The ability to more clearly identify permissible power levels will permit lower fuel costs due to use of fewer fuel rods. It will also increase operational flexibility, particularly at higher pressures where inherent control characteristics are further improved and additional reduction in control equipment can be made.

Recent developments in UO_2 technology have shown that a higher heat output per unit length of fuel element is possible without reaching centerline fuel condition restrictions. As a result, maximum heat flux is becoming a more important criterion for determining output limitations of fuel elements than maximum fuel temperature. One of the major parameters now limiting the performance of reactors under study for maritime application is that of maximum permissible heat flux set by burnout restrictions. Burnout information for the area of interest is very limited. This necessitates considerable extrapolation and use of uncertainty margins in order to insure adequate conservatism when using existing information for core geometries and system conditions of interest for maritime application. Discussion of one aspect of this situation is presented in Appendix B of Part II, Plant Conceptual Studies. While many burnout correlations exist, the data upon which they depend in regions of interest are small. In the high pressure range, which is of interest in connection with inherent reactivity control, the data on which design can be based are particularly sparse.

A dramatic example of the unsatisfactory state of burnout knowledge, even in the area where the bulk of the work for the naval reactor program has been performed, has recently been displayed.(1) For the same flow rate and quality, 11 values of burnout heat flux ranging from 630,000 to 1,130,000 Btu/hr-ft^2 were predicted by as many correlations. Tests are needed to gain greater assurance in predicting burnout situations for those conditions of interest to reduce the level of uncertainty that is presently required to assure adequate design conservatism.

In this program burnout data and related information on coolant flow and steam distribution would be obtained for the geometries of interest at the present and higher operating pressures. Particular emphasis would be given to low flow burnout tests since this area appears to offer the greatest potential for plant cost reduction. The effects of axial flux distribution would also be investigated. Preliminary evaluation of the nature of burnout for this application indicates that a tapered axial power pattern, with the power peak at the bottom of the core, gives promise of increasing

(1) "DNB Correlations Disagree," Nucleonics, Vol. 20, No. 2, (Feb., 1962) page 70.

heat removal capability. Another area of interest is the partial film boiling range. Some evidence is available indicating there may be design regions where initiation of film boiling does not lead to unacceptably high fuel element temperatures. Investigations of heat transfer in the film boiling regime for various pressures may permit significant relaxation of criteria for thermal margin, particularly in the study of accidents and transients.

Since core heat removal potential affects so many important areas of design where significant cost savings may be made, it is particularly important that heat transfer tests be started early. Only by doing this can the knowledge of improved core heat removal capability be established early enough to obtain maximum cost reduction for various areas of design.

5. Inherent Reactivity Control

This segment of the program is aimed at exploiting, to a degree not yet achieved, the inherent response to load demand which characterizes the indirect-cycle water reactor plant. Analyses carried out over the past several years have consistently yielded results which indicate promise in the direction of employing the natural responses of the reactor to obtain desirable operating characteristics.

Current reactor designs depend upon costly controls which are imposed on the system to produce a specified set of operating and safety conditions in the reactor. These include mechanical rods with accurate position control, dissolved neutron absorbers, reactor pressure controls and the more recent spectral shift concept which requires a controlled mixture of light and heavy water. In addition, whenever a control function is imposed on a system, instrumentation and read-out equipment and safety devices as well as the control equipment must be purchased, installed and maintained.

The basic objective is to utilize operating conditions in the reactor to provide control rather than using imposed control devices to fix these conditions. The indirect-cycle water reactor has the property that it will adjust its power level through changes in the moderator-coolant density in the proper direction to meet changes in the power demand on the system. This feature suggests the evolutionary development of the water reactor such that this inherent characteristic rather than extra equipment is utilized to enable the system to perform its designated task with safety and convenience while realizing a cost savings from the resulting simplification.

The particular objective of this research and development program is to focus the ideas which can contribute to cost reductions clearly enough to achieve the savings on the short-range potential ship. This requires that the characteristics which can be exploited be defined with adequate certainty before construction is initiated. For example, it is clear that the range of operating temperature and pressure in a self-pressurized reactor will weigh heavily in the selection of the steam dome volume in the reactor vessel. Since the vessel is a long-lead item, the operating ranges to be used to attain cost advantages in control and instrumentation must be firmly established at the time construction starts.

In order to achieve this certainty, the program must accomplish two things. The first is the definition of the operating bands or ranges, within which the desired reactor performance can be expected, for various promising reactor design alternatives. The second involves an "error analysis", that is examination of the sensitivity of the results to uncertainties, to permit the selection of the most promising area for incorporation into a plant with a minimum of control and instrumentation equipment.

An important feature of development in this area is that there is no distinct threshold which must be reached before a cost advantage accrues. Rather, it is an evolutionary development in which any gain will yield savings proportional to the step taken. For instance, the comparison of reactivity control requirements with the control available by varying the reactor pressure shows that increasing the range of pressure variation permits control of larger increments of reactivity (1). A modest step is the control of maneuvering reactivity changes due to the Doppler effect and hot channel steam voids by allowing pressure to change to simplify plant operation without control rod motion. A further development might be to combine pressure variation with burnable poison in order to eliminate control rod motion requirements over long periods of time, possibly even for the life of a core. Such an advancement would considerably influence the control and instrumentation philosophy of the plant. The currently used positioning reactivity controls could be replaced by a much simpler device which functions only to start up and shut down the reactor, possibly only for refueling and planned maintenance. Plant reliability would be improved by eliminating sources of spurious scrams. Development along these lines may eventually eliminate the need for any scram signals.

There are a number of other possibilities for capitalizing on the inherent control characteristics of the water reactor. The basic concept provides reactivity control through variable water density by allowing changes in the moderator temperature and pressure. However, another improvement may be obtained by a proper combination of the core coolant temperature rise and the steam void content of the core to minimize the reactivity and hence the pressure change from zero to full power. As power is increased from zero, reactivity losses appear due to the Doppler effect and any steam voids generated in the core. However, if the inlet temperature of the core drops sufficiently, the lower average moderator temperature could provide enough positive reactivity to just balance the losses with the core outlet temperature and pressure remaining constant. The current plant design with a relatively low flow rate has a large enough core temperature rise to make this effect an interesting possibility. Further improvement can be expected if suitable methods for adjusting the moderator density coefficient of reactivity are developed. Initial studies of one method, the use of a central water hole in the core, indicate that such adjustment is attainable (2).

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(1) Graphically displayed in Fig. II-20, Part II, Plant Conceptual Studies.
(2) Fig. II-21, Part II, Plant Conceptual Studies.

The addition of a means of displacing water from the hole is a logical next step in the direction of controlling the reactivity coefficient. Another variation of interest is the use of a neutron absorbing boundary on the water hole. This should further extend the range of the reactivity coefficient adjustment. Displacement of water in a central hole will also change the reactivity as well as the coefficient, thus possibly providing a dual advantage. In addition to finding methods of influencing the coefficient through core design features, simple low cost methods for achieving reactivity control to augment moderator density changes will permit the reactor to operate with uniformly high outlet temperature to maintain good thermal efficiency over the load range. Burnable poison can be used to minimize the reactivity variation through core life.

6. System Control and Protection Simplification

To obtain full advantage of the inherent load following characteristics of the reactor plant, it is necessary to examine and simplify the control and protection methods of the system. Under the inherent reactivity control task of this key area research and development program, methods have been outlined by which the reactor proper can be developed to make full use of this property. These methods must be integrated with the entire plant control and protection for full realization of gains. All of this must be done within the highest standards of safety for the plant.

Reduction of instrumentation to only the essentials is important, not only because of the effect on capital equipment costs, but also because the connecting and checking of instrument circuits appreciably influences the installation cost of the plant. Further, plant operation is improved by focusing operator attention to a minimum of "action" information. The least restrictive specifications that can be given for accomplishing the plant control functions must be studied. Methods must be devised for simplifying the control of auxiliary systems through the use of a minimum number of reliable, direct acting, and less costly instruments.

The central feature that needs recognition is that the only function of the reactor plant is to supply steam for ship propulsion and service upon demand. The fewer and simpler the internal paths by which this function is controlled, the more reliable the system is likely to be. It appears that normal steam demand changes can be effected without control rod movement through coolant-moderator effects on reactivity without loss of design latitude. Abnormal, emergency, as well as maintenance situations must be explored. For example, power restrictions required upon loss of a coolant pump might be handled by limiting the steam demand through the use of the secondary system steam control valves rather than signaling for rod motion. This would adjust for abnormal operation directly without recourse to a rod control feed-back loop to prevent over-compensation.

7. Cladding Development

A major portion of fuel cycle costs is associated with the extra fuel enrichment required because of core structural neutron absorption. Over 90 percent of this is due to the stainless steel fuel element cladding in the current design. Therefore, it is quite important to minimize this parasitic absorption by use of thinner cladding or use of other materials of lower-cross section.

While the need for advancement in this area is shared by reactors for maritime service with other uranium dioxide fueled, water cooled reactors, it is well to review where work needs to be done. The fuel costs reported in the present plant evaluation were based on annealed, weld-drawn, nuclear grade type 347 stainless steel, self-supporting tubing containing centerless ground uranium dioxide pellets. This proven method of design and fabrication represents the most prudent approach for present day plants. However, for future cores or plants, fuel costs can be reduced if ways can be found to reduce the cladding tube wall thickness thus allowing a reduction in fuel enrichment, to reduce fuel element fabrication costs, and to increase the maximum allowable power output per unit length of fuel element. Some of the areas of investigation which embrace one or more of the above improvements are the use of fuel-supported tubing, hardened tubing, unground pellets, and vibratory-compacted UO_2 powder rather than sintered pellets.

The use of thin free-standing cladding made of hardened stainless steel and the adequacy of even thinner cladding which uses the fuel for support would be evaluated for maritime service conditions. For elements with fuel-supported cladding, the fraction of cladding in the core can be further decreased by increasing the fuel rod diameter. For this reason, particular emphasis would be given to the development of large diameter fuel elements. Because fuel element heat flux increases with rod diameter, the gains obtainable by rod diameter increase will be determined by maximum heat fluxes associated with available burnout heat transfer information. Data from burnout tests would support the program for obtaining fuel elements with minimum parasitic absorption as well as obtaining information to improve core heat removal capabilities.

The use of UO_2 fuel in the form of ground and unground pellets and compacted powder should be evaluated for the various claddings. The use of unground pellets, rather than pellets which have been centerless-ground to much smaller diametral tolerances, means that clearances between the pellet and cladding tube will be larger. Recent test data indicate that the effect of pellet-to-cladding clearance on allowable power output per unit length of fuel element may not be as significant beyond a certain range of clearances as has previously been expected. If it is possible to use unground pellets with fuel supported cladding, even greater fuel cost improvement may result. The use of vibratory-compacted UO_2 powder rather than sintered pellets gives promise of the use of less expensive, larger tolerance, commercial-grade tubing while providing an intimate contact between fuel and cladding. Manufacturing techniques such as swaging, vibratory compaction, stretch forming, and rolling as they influence use of various cladding materials, require evaluation from the standpoint of making greatest use of the process to achieve core design objectives.

8. Shielding Application Development

The development of shield concepts which are specifically oriented to the problems peculiar to maritime application is required in order to achieve capital cost reductions in this area. In the current tanker design, the biological shields amount to ten percent of the total nuclear steam supply system costs. This percentage would be greater for a vessel which does not have the advantage of utilizing cargo for much of the shielding.

It appears a major savings could be made by proper component arrangement in consolidation and compaction of the primary loop. Unfortunately, improved biological shielding arrangement is not the only condition imposed on the primary loop component arrangement. Possible methods of improving shielding, which take into consideration the other constraints, must be developed. With compacting of the nuclear steam supply system, placing the secondary shielding inside the containment would reduce the total surface area to be covered and so reduce costs. Greater use of water, not only as neutron shielding but also as gamma shielding, requires further exploration. Costs can be reduced measurably by this means if requirements imposed to insure that the water remains in place under all possible motion conditions do not impose costly design for the tankage. Emergency conditions must also be considered.

The fact that shielding requirements depend upon the operating state of the reactor suggests multiple use of shielding water. A conceivable method for reduction of shielding is to partially substitute water stored for decay heat removal purposes for solid shielding material. The large quantity of water could be located to serve as shielding for radiation produced during operation in excess of that emanating during decay heat removal. Another possibility is combining vapor suppression containment with shielding requirements.

In order to realize the maximum cost reduction benefits from the development of plant consolidation concepts, application data pertaining specifically to shipboard shielding problems must be available for the development of the most desirable plant layout. Particular shielding arrangements must be developed and analyzed in order to achieve a less expensive over-all protective structure.

9. Fuel Element Application

It is necessary to relate fuel element and core design objectives to those of a plant and ship in order to realize maximum over-all cost reduction. Resulting cost savings may be associated with either fuel cycle or capital costs.

There are various ways in which fuel element application development relates to particular plant or ship requirements. For example, a reactor plant which is quite compact and has extremely low coolant flow requirements has promise of significant over-all cost savings. System water volume and related containment requirements are lower. The potential for cost savings associated with preassembly and packaging is increased. Operating and capital costs associated with reduced pumping power are lower. At low coolant flow rates, core sizes may be reduced by having an axial power distribution with maximum power peaking near the bottom of the core. Such a power distribution might call for development of fuel elements with variation in rod diameter over core length in a stepwise or continuously tapering manner. Further coolant flow and core size reductions may be obtainable by using a two-pass core in which case development of mechanical, thermal, hydraulic, and nuclear aspects involved would be required.

10. Reactor Vessel Radiation Damage Application Development

Considerable cost savings are directly or indirectly related to plant consolidation. One of the key factors in determining the extent of such savings is the ability to minimize the reactor vessel diameter. Vessel diameter influences system water volume, containment and shielding, and the ability to take advantage of compaction.

For a given size core, the minimum diameter of most reactor vessels of interest for maritime application is determined by radiation damage limitations. While little data are presently available from which firm conclusions can be drawn, there is evidence to indicate that: radiation damage may be more of a problem than originally expected for reactor vessels operating around 400°F; higher reactor vessel operating temperatures (450-550°F) are beneficial in reducing the effect of radiation exposure; and further reduction of the effect of radiation exposure may be obtained as the operating temperature of the reactor vessel is increased to 600°F or more.

In order to take maximum advantage of the higher operating temperatures of the plants under consideration for maritime application, the latest data must be evaluated and applied to specific conditions and designs of interest. The full significance of existing radiation damage data, and associated changes in transition temperature, has not yet been fully evaluated. The application development work necessary to make use of this information would include not only the evaluation of the beneficial influence of our higher operating temperatures, but also must assess other means of reducing the effect of radiation exposure and minimizing vessel diameter as well. This would involve such areas as the evaluation of the gains to be obtained with special plant operational procedures, use of different vessel materials and the feasibility of using post-irradiation heat treatment of the reactor vessel. It is necessary to consider all of these factors in order to obtain maximum plant cost reduction without sacrificing operational safety. This synthesizing is particularly important in view of the trend indicated by data showing a strong interrelationship of radiation damage, the amount of radiation exposure, the vessel temperature during exposure, the post-irradiation heat treatment temperature, and the duration of this heat treatment. Should distance from the core prove to be the only satisfactory solution to the damage problem, this information would provide the basis for placing heat exchangers in the annular space between core and reactor vessel.

B. PROGRAM COST AND SCHEDULE

The key research and development areas just discussed are central to an orderly and expeditious program of maritime reactor plant improvement. By central it is meant that more must and will be learned in these areas if reactor plants are to be improved regardless of the emphasis on the particular course of this improvement. However, the next proper question is: to what depth should effort be expended in these key research and development areas? To answer this question the course of plant development must be established. The course which presently would appear to make the highest utilization of the resources invested is to do sufficient work to permit a construction start on the short-range potential plant and realize its gains without having to build the presently proposed plant as a development step. On this basis, dollar estimates have been associated with each of the key research and development areas. These are given in Table C-1. It is estimated the work could be completed within a 30 month period.

The relationship of the whole program to the individual key items calls for comment. Some of the tasks, such as Self-Pressurization Tests and Core Heat Transfer Tests, would yield full and useful information without the accompaniment of the program as a whole. Others such as System Control and Protection Simplification and Reactor Vessel Radiation Damage Application Development would not.

It is interesting to notice that the total program cost is less than the capital cost savings alone between the presently proposed and short-range potential plant even when compared on a second-of-a-kind ship basis. The essential requirement, however, is that the program results be available before ship construction is started.

TABLE C-1

KEY AREA RESEARCH AND DEVELOPMENT PROGRAM COST ESTIMATE

Self-Pressurization Tests	$ 180,000
Consolidation and Preassembly Application Development	250,000
Once-Through Heat Exchangers	200,000
Core Heat Transfer Tests	300,000
Inherent Reactivity Control	250,000
System Control and Protection Simplification	150,000
Cladding Development	250,000
Shielding Application Development	200,000
Fuel Element Application Development	200,000
Reactor Vessel Radiation Damage Application Development	50,000
Total	$ 2,030,000