Modularization and Nuclear Power

Report by the Technology Transfer
Modularization Task Team

June 1985

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U.S. Department of Energy
Assistant Secretary for Nuclear Energy

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DOE/NE--0067

DE86 011393

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Modularization Task Team**

June 1985

**U.S. Department of Energy
Assistant Secretary for Nuclear Energy
Washington, D.C. 20545**

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MODULARIZATION AND NUCLEAR POWER

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I. SUMMARY AND FINDINGS

A. Mission Statement

1. Provide means for utilities to regain control over cost and schedule of constructing a nuclear power plant through:
 - o Fixed price contracts
 - o Reduction in capital cost and schedule by 10 to 15% below best performance to date
 - o Improve quality of construction through use of an experience, stable work force to minimize rework, thereby enhancing the licensability of the plant.
2. Reduce total power generation cost over the life of a nuclear plant by:
 - o Increased plant availability
 - o Reduction in cost of life extension
 - o Reduction in cost of decommissioning

B. Summary

This report describes the results of the work performed by the Technology Transfer Task Team on Modularization. This work was performed as part of the Technology Transfer work being performed under Department of Energy Contract 54-7WM-335406, between December, 1984 and February, 1985.

The purpose of this task team effort was to briefly survey the current use of modularization in the nuclear and non-nuclear industries and to assess and evaluate the techniques available for potential application to nuclear power. A key conclusion of the evaluation was that there was a need for a study to establish guidelines for the future development of Light Water

Reactor, High Temperature Gas Reactor and Liquid Metal Reactor plants. The guidelines should identify how modularization can improve construction, maintenance, life extension and decommissioning.

This study shows that modularization of an n^{th} of a kind of Pressurized Water Reactor nuclear power plant of about 600 MWe results in total capital costs which are 12 percent lower than n^{th} of a kind of plants built in a conventional manner. These cost savings are largely attributable to improvements in labor productivity by construction of most of the nuclear island and some of the balance of plant as prefabricated modules in offsite fabrication facilities, using an experienced, stable work force. Reduction in the overall schedule from 8 years to 6 years is considered achievable by the parallel construction of the modules with onsite construction work, which also contributes to the 12 percent cost savings.

The 12 percent cost saving identified in this brief survey is considered to be conservative. A greater savings may be achievable, since the effectiveness of modularization has previously been found to be greater as the labor intensiveness of the project increases. The nuclear power plants are more labor intensive than petrochemical plants, where the benefits of modularized plants have been determined to be in the range of 10 percent to 20 percent below conventionally constructed plants. These savings are generally attributable to one-of-a-kind petrochemical plants, with further savings possible due to n^{th} of a kind of plants. Further studies are needed to establish more definitive cost estimates for the n^{th} of a kind modular nuclear plants as well as for the n^{th} of a kind conventional nuclear plants to be used for comparison.

An important aspect of modularization is that the portion of the nuclear power plant which is constructed in an offsite facility can be built to more predictable schedules and costs. This is due largely to the stability of the labor force and management, and the fact that much of the work would be performed in a controlled environment of favorable working conditions. This predictability can facilitate fixed price contracts, which the nuclear utility industry would probably favor in the future.

Since the unpredictability of construction costs has been identified as a major problem in the nuclear power industry, improved predictability should contribute significantly to the revitalization of the industry. In summary, cost reduction and predictability of costs provide considerable incentives for further studies of modularization.

This study resulted in a determination that a generic study of modularization to reduce the cost of construction, maintenance, life-extension, and decommissioning of nuclear power plants of various sizes and types (Light Water Reactor, High Temperature Gas Reactor, and Liquid Metal Reactor) would be of significant value. This generic study could provide basic information to the organizations currently studying some specific forms of modularization so that their efforts can be guided, and subsequently evaluated, in terms of the broader aspects of modularization. Significant advances are being made in modularization technology to reduce capital and operating costs in other industries and the transfer of such technology to the nuclear power industry is an important task. The generic study could be performed as follows:

- o Evaluate technology transfer from other government agencies (such as the Maritime Administration, Navy Department, Department of Defense, and NASA) to the nuclear power plant industry.
- o Perform institutional studies to identify the role of DOE, NRC, and other agencies in the licensing and regulatory activities associated with modules built and tested at remote fabrication facilities and shipped to the plant site. This study could also describe the basic role of the contractors in terms of guidelines for all types of modular construction (nuclear and non-nuclear modules).
- o Perform a generic study which provides guidelines to designers of all sizes and types of nuclear plants (LWR, HTGR, and LMR) for the selection of sizes and basic contents of modules. These guidelines could provide a basis for the designer's selection of modules which are best suited for reducing the costs of construction (including start-up), maintenance, life-extension, and decommissioning.

A significant result of the current study was the identification of the extent to which modular construction has reduced the cost of process plants, offshore drill rigs, and ships. All of these products have been built in U.S. shipyards which are actively improving their productivity by the use of many of the manufacturing techniques that have been used in Japan since the end of World War II. These techniques, which were initially developed in the Japanese shipbuilding industry and quickly spread to the automobile and other industries in Japan, have reduced costs and improved quality. Many of these methods are now re-emerging into the U.S. to make many industries more competitive, such as shipbuilding, airplanes, automobiles. The key ingredients to success are Group Technology and Statistical Control Methods, both of which are used to make modular construction highly cost effective. Since the construction of ships and process plants is similar to the construction of nuclear power plants, cost reductions can also be achieved for the nuclear power plants. The construction of nuclear power plants has utilized very little modular construction to date, with the experience being limited to some skid mounted systems, rebar modules, pipe assemblies, condenser modules, and a few other applications. Basically, U.S. construction of nuclear power plants has been "stick-by-stick", using field labor, which has often resulted in very high construction costs. A considerably increased use of modular construction by properly motivated management and labor teams can reduce these costs and increase quality. Standard plant designs can achieve their cost savings potential by the fabrication of n^{th} of a kind modules in shipyards or other fabrication facilities.

Current modularization efforts in the U.S. are concentrating on the packaging of the Nuclear Steam Supply System (NSSS) into sizes which permit the reactor vessel (possibly with their associated coolant pumps, heat exchangers and steam generators) to be built in a shop, tested and shipped to the plant site on a truck, or rail car. These NSSS modules are being designed in the 100 MWe range for potential use in High Temperature Gas Reactor and Liquid Metal Reactor plants. Several NSSS modules would be connected together along with corresponding balance of plant (BOP) systems to provide the designed total plant output. Increasing the plant output

to match load growth would be achieved by adding NSSS modules and associated BOP equipment. The cost effectiveness of these schemes is currently being studied. Some intermediate size plants are also being evaluated in the 300 MWe range for HTGR and LMR plants, using one or more reactor vessels per plant, in conjunction with one BOP. Additional power at a site would be achieved by adding another NSSS and BOP package for this scheme also. Larger plants with a single reactor vessel and single BOP, such as a 600 MWe LWR (or larger), may be cost effective to an equal or greater degree as compared to the multiple reactor vessel/multiple BOP plants, if they are properly modularized. Studies are planned to begin in FY 1985. Selection of the size and type of nuclear plant (LWR, HTGR or LMR) which can provide electrical power at the lowest bus bar costs and can achieve a suitable level of safety is an unresolved issue in the U.S. Until it is resolved, the nuclear energy option will remain closed. Modularization, in its many forms, appears to have the potential for contributing to near term and long term solutions to the problem and needs to be vigorously studied at this time, including the relationship of modularization to economy of scale.

It is noted that while the shipyards represent an excellent, stable source of skilled labor, other established shop fabrication facilities can also be a viable source of some sizes and types of modules. The location of the plant size and means of access (barge, rail or truck), plus the distance to the fabrication facilities, influence the selection of the fabricator. In some cases, the fabrication of modules at the plant site may be a suitable method of construction, particularly if some elements of the Japanese methodology currently being used in shipyards and other industries are used to offset the otherwise high cost of field labor. The potential cost savings of n^{th} of a kind plants would not be fully achieved for site-constructed modules with these approaches, however. The selection of the fabrication facility and its staff is related not only to the base cost and schedule but to the risks of overrun, with the subsequent impact that such overruns can have on the entire nuclear industry.

The U.S. government has been supporting the transfer of many aspects of the Japanese production methods to U.S. shipyards for several years. The Maritime Administration, Navy Department, and Department of Defense are keenly interested in reducing the costs and construction schedules of naval vessels to reduce the costs to the taxpayer and maintain the country's defenses. Shipyards will remain in business and will be competitive, which makes them an excellent location for the construction of nuclear power plant modules. Relationships between the Department of Energy and these agencies could foster the transfer of technology to the nuclear industry. In return, by constructing nuclear plant modules in shipyards, the shipyards will be able to continue to optimize construction methods and reduce the costs of their products. This synergistic effect could be a significant factor in the economic viability of nuclear power in the U.S.

In addition to construction costs, the cost of maintaining, upgrading, or extending the life of any type of nuclear power plant can be potentially reduced by modularization. The U.S. Navy, NASA and the aircraft industry currently use this approach. The design of the replacement modules, as modules within larger modules, and the use of interchangeable modules between several types of reactors, may be feasible. The use of robotics to replace modules in high radiation areas should be considered, and modules should be designed for this application in the future. Decommissioning costs can be potentially lower through the use of modularization. There is considerable incentive to study how these aspects of modularization can also reduce the overall cost of generating electricity by nuclear power.

Modularization of nuclear power plants can be accomplished today by using proven technology during the past five years in the shipbuilding and process industries. No R&D is needed to apply the basic technology to the nuclear industry. The technology continues to be developed in these industries to utilize latest techniques. CAD/CAM has been used effectively in modular design and construction, but further use of these systems as they are continually being improved would be highly desirable. The future potential of the application of artificial intelligence (AI) to

modular design and construction appears to be worth evaluating at a future time. The proposed Center for Neutron Research (CNR), formerly HFIR-II, will provide opportunity to gain experience with AI. Robotics can potentially reduce the cost of construction of modular plants in the future. While all of the above subjects have been around for some time, their potentials for reducing the present costs of nuclear power are significant. Studies to determine how to best utilize these potentials are essential and should begin at this time so that the nuclear power option can be revived in the near future.

It is suggested that studies also be performed on elimination of as many valves as possible in the plants to facilitate construction and maintenance. The Atomic Energy of Canada, Limited (AECL) recently did a valve reduction study for CANDU and successfully eliminated many valves.

C. Findings

The findings of this study led to the determination that further studies of modularization for nuclear power plants are warranted. These studies would consist of the following:

Task 1--Technology Transfer Study

Task 2--Institutional Study

Task 3--Module Sizing Study

It is noted that these studies would define how to apply existing technologies from other industries to the nuclear industry. No specific R&D work is required to achieve the objectives stated in the mission of this task force.

Task 1--Technology Transfer Study

This task would establish methods for the transfer of advanced construction technology from government agencies supporting the shipbuilding industry (such as the Maritime Administration, Navy Department, and

Department of Defense) to the Department of Energy for support of the nuclear power industry. The application of this technology to the construction of nuclear power plant modules in shipyards (or at plant sites) would be evaluated. This would include the zone-oriented approach to design, procurement, construction, quality management, etc. Methods for transferring technology from other government agencies, such as NASA for modular design for logistical support, would be identified.

Task 2--Institutional Study

This task would describe the role of the RM, AE, offsite fabricator, on-site constructor, and utility during design, construction, and startup. The role of the government agencies (DOE, NRC, and others) in the licensing and regulatory process will be defined. Labor related problems will be discussed, in terms of offsite labor and onsite labor, on subjects such as productivity, jurisdictional problems, wage rates, etc. The objective of this task is to define an organization that would appropriately plan and manage a modularized plant system to achieve an adequately integrated plant.

Task 3--Module Sizing Study

The overall purpose of this study is to identify a balance between modules sized for construction and modules sized for maintenance, life extension, and decommissioning. The information developed in this study will be published in the form of guidelines to the designers of advanced LWR, HTGR, and LMR plants in the current DOE and EPRI sponsored programs. These guidelines will aid in the ultimate evaluation of the alternative reactor types, since it is important that the approach to modularization is consistent between these alternatives. This study will be performed as follows:

Task 3A--Modularization for Construction

- o Identify systems and subsystems suitable for modularizing for generic LWR, HTGR and LMR plants.

- o Determine module sizes for offsite construction, various modes of transportation (barge, truck, rail, plane), and various installation configurations (nuclear island building only, nuclear island plus turbine buildings modules as inserts into concrete buildings, etc.)
- o Outline basic steps to develop a modular design.
- o Determine module sizes for on-site construction and installation, including establishment of fabrication shops.
- o Identify methods for limiting stress and corrosion of module during shipping and installation.
- o Develop schedule and costs for offsite versus on-site modularization and compare to conventional plant schedule and costs. This will be based on various module sizes and transportation modes. Design, licensing, procurement, fabrication, transportation and field construction will be included. First-of-a-kind and nth of a kind costs will be estimated for LWRs, HTGRs, and LMRs.
- o Evaluate risks of schedule and cost overruns.
- o Identify fixed price bidding potential and alternate methods of contracting.

Task 3B--Modularization for Maintenance

- o Identify how modularization reduces maintenance time and costs in other industries, based on identified items and frequency of replacement.
- o Describe how modularization can reduce maintenance time and costs in nuclear plants based on identified items and frequency of replacement (LWR, HTGR, LMR).
- o Determine how modularization can be applied to maintenance and upgrade of existing plants.

- o Describe how modularization reduces radiation exposure, including use of robots.
- o Compare schedule and costs of module replacement with schedule and costs of separate component replacements.
- o Identify cost impact on spare parts inventories, warehousing space, etc.
- o Identify size of replacement modules versus construction module.

Task 3C--Modularization for Life Extension

- o Identify items which need replacement after 40 years (LWR, HTGR, LMR).
- o Identify size of modules best suited for replacement to facilitate life extension.
- o Describe how modularization reduces radiation exposure.
- o Compare schedule and costs of module replacement versus piece-by-piece replacement.
- o Identify size of replacement modules versus construction module.

Task 3D--Modularization for Decommissioning

- o Identify components and system to be removed for various types of decommission (prompt dismantling, etc.) (Light Water Reactor, High Temperature Gas Reactor, Liquid Metal Reactor).
- o Describe how modularization reduces decommissioning schedule and cost.
- o Compare schedule and costs with conventional plant decommissioning.
- o Identify size of decommissioning modules versus construction modules.

D. Sponsorship and Implementation of Further Studies

The Modularization Task Team determined that future studies could be effectively implemented under the sponsorship of various organizations, as follows:

Task 1 Technology Transfer Study

This study could be sponsored by a study team comprised of architect engineers, reactor manufacturers, module fabricators (including shipyards) and constructors. The Department of Energy could take a lead role in coordinating meetings with the Maritime Administration, Navy Department, Department of Defense, and NASA and establish means to transfer modularization technology being developed by those government agencies (at taxpayers' expense) to the nuclear energy industry. This would make advances in this technology directly available to the nuclear power industry and provide information which can help to restore the economic viability of this energy option. Information could be placed into the Nuclear Energy Data Base being developed at Oak Ridge National Laboratory.

Task 2 Institutional Study

This study could be sponsored by the Department of Energy and implemented by a study team comprised of architect engineers, reactor manufacturers, module fabricators (including shipyards) and constructors. The Department of Energy could take a lead role in coordinating meetings with NRC to determine how modular construction with a stable experienced work force producing high quality products in an off-site facility could impact the licensing and regulatory process. The potential for getting NRC approval of modules before shipment to the site would be discussed.

Task 3 Module Sizing Study

Based on the results of the brief investigation performed by the Modularization Task Team, as described in this report, it was determined that modularization offers the potential to significantly reduce the costs of

a nuclear power plant. Further studies are needed to confirm these findings. The module sizing studies include the development of costs for constructing modular LWR, HTGR, and LMR plants, plus the costs associated with modularization for maintenance, life extension, and decommissioning. These studies could be sponsored by the Electric Power Research Institute (EPRI) and implemented by a study team comprised of architect engineers, reactor manufacturers, module fabricators (including shipyards) and constructors. These studies could utilize the results of the work performed in Task 1 and Task 2, so that all three tasks provide a source of closely related information which can be used to reduce the total costs of nuclear power in the U.S.

The modularization program needs to be supported by both DOE and the utilities (through EPRI). The current Advanced Light Water Reactor program at EPRI provides a vehicle for implementing the modular approach. The DOE portion of the program should be integrated with the rest of the high technology program. Regarding the DOE sponsored LMR Innovative Design Program, the contractors should be urged to explore steps to further modularize their designs at this time, since these designs are just now evolving.

II. TASK TEAM CHARTER AND MEMBERSHIP

A. Charter

Evaluate the modularization of systems, subsystems, and structures for nuclear power plants for the purpose of:

- Making possible essentially unlimited plant life by module replacement
- Facilitating retrofitting and modernization
- Developing concept-independent approaches to modularization
- Reducing maintenance costs
- Simplifying licensing process through use of standardized modules
- Reducing capital costs by substitution of shop labor for field labor to permit development of skills to be used for multiple plants
- Reducing decommissioning costs
- Reducing overall plant construction schedule
- Improving quality management
- Reducing social and environment impacts at the construction site
- Improving labor relations

The task force will evaluate modularization with maximum use of recent experience in nuclear and non-nuclear industries. The non-nuclear industries will include the petroleum, chemical, aircraft, space, and shipbuilding industries.

The task force will identify specific modules to be standardized for use on various types of plants for new construction, and for potential upgrading of old plants.

B. Membership of the Modularization Task Team

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III. TECHNOLOGY EVALUATION

A. Current Considerations of Modularization in the Nuclear Industry

1. General

Modularization has been used in the nuclear industry for many years to reduce plant construction costs. Methods to increase modularization in light water reactor (LWR) plants have been studied and put into practice on an increasing basis. Many small subsystems have been modularized by combining pumps, pipes valves, and instruments on skids which are placed within the plant. Pretesting of the equipment on these skids is often performed to reduce the in-plant testing efforts. Pipeways which contain many pipes have been prefabricated and installed into a few plants. Piping subassembly fabrication is a common practice. Rebar subassemblies have been used on many plants and prefabrication of turbine-generator pedestal legs and heavy beam rebar in walls is common practice. Preassembled pool liner assemblies have also been utilized. Steel containment rings are preassembled and lifted into place to reduce construction time. Condenser units are being constructed off site and installed as modules. The reactor vessel and other large components are in themselves modules which are constructed off site (Reference 1). Overall, modularization has been done on a moderate scale to date, and has been done within the context of the basic design of massive concrete and rebar structures containing many systems and subsystems. Some schedule and cost savings have resulted from these approaches.

Transportation of large, heavy components to plant sites has been improved in recent years. For example, schnabel cars permit moving components which weigh up to 880 tons along rail lines. Barge transportation of heavy components has been effective at many sites. At the site, a new generation of large-size heavy-lift cranes provides the capability to lift and accurately position heavy loads in the 900 to 1,000 ton range. These techniques are amenable to the

transportation of modules (Reference 1). If a waterway site is not available, the size of the module will be governed by the transportation mode.

The incentives to increase modularization become evident when one considers that in 1981 a study by the Atomic Industrial Forum (AIF) (Reference 2) showed that the construction phase of a nuclear power plant project accounted for more than 50% of the total capital costs of the project. These costs have been increasingly due, in part, to decreasing labor effectiveness at the job site. This is largely attributed to congestion, complexity and degree of required modifications. Compared to fossil plants, craft man hours per cubic yard of concrete are 2 to 3 times greater for nuclear plants, craft man hours per foot of pipe installed are 3 to 4 times greater, craft man hours per foot of installed conduit, cable tray and cable are 1.5 to 2 times greater and craft man hours for support of pipe and electrical raceway hangers are about 5 times greater. Modularization is recognized as a significant way to reduce congestion during construction. Effective use of modularization requires stability of requirements, a high degree of design completion, and purchase of components before bulk construction activities commence. Access to the modules during construction is the key factor in reducing their cost. Changes to the module after delivery to the field must be minimal.

The factors which drive the cost of nuclear power plants have been under study for several years. A detailed study was performed by United Engineers and Constructors for the Department of Energy to identify the trends in the cost of engineering and construction of nuclear power plants (Reference 3). While this study does not identify how modularization could effectively reduce costs, it provides a good basis for further evaluations of the potential cost advantages of modularization.

2. Plant Size

The high costs for many nuclear power plants built in the U.S. in recent years has often been attributed to their large size and complexity. Some of these large plants were constructed within reasonable schedules and costs, such as St. Lucie 2 and River Bend. While many factors contributed to the big differences in the schedules and costs of these plants and many other recent nuclear plants, the ability to manage and control these large projects has become a key issue. Small-sized plants are currently under evaluation to determine if reductions in schedule and costs due to their reduced complexity and size can sufficiently offset the economy of scale which seems achievable, but is obviously difficult to obtain, in larger plants. Smaller plants may offer a significant advantage of being brought on line in a shorter time after the plant is ordered to better match load growth requirements. Smaller reactors also offer the potential for simplifying the safety related systems associated with larger cores, in particular, the decay heat removal systems.

The Electrical Power Research Institute (EPRI) has initiated a study of Advanced Light Water Plants, which is to be based on a plant of about 600 MWe. In addition to incorporating advanced technology features, this study is to consider the advantages which can be achieved by modularization of LWR's.

At the ASME Joint Power Generation Conference in Indianapolis, Indiana, in September, 1983, a session on small nuclear plants received considerable interest. At this meeting, Westinghouse discussed its two-loop 665 MWe light water nuclear plant (2LN), General Electric outlined its interests in a modular 130 MWe breeder reactor, and GA Technologies described a small (100 MWe) modular HTGR. Papers were also presented on a small CANDU reactor and IAEA interest in small reactors was discussed. The thrust of the meeting was for small modular-type reactors for international applications, with little discussion about U.S. applications.

For liquid metal reactors (LMR's), the Department of Energy awarded contracts in November, 1984, to General Electric and Rockwell International to study advanced LMR's. General Electric is evaluating the use of three 130 MWe modular nuclear steam supply systems (NSSSs) connected to one steam turbine. Their PRISM reactor concept is intended to permit shop fabrication of a closely coupled NSSS, and to demonstrate its operation and safety before going into production. The cost effectiveness of connecting many small NSSSs together to produce larger quantities of power at a site are being studied. Rockwell International is evaluating a 330 MWe pool plant design, which is to use extensive shop fabrication of the NSSS. In both of these studies, the extent to which the non-NSSS portions will be modularized is being studied.

For the high temperature gas reactors (HTGRs), it is of interest that the previous studies of a large (1100 MWe) HTGR were put on hold in the spring of 1984 to permit evaluation of small HTGRs of several types. These alternate designs were discussed at the annual HTGR Conference in San Diego in September, 1984. Concepts being studied are: (1) In-line steel vessel (100 MWe), (2) Side-by-side steel vessel (80 MWe) for cluster installation, (3) Annular core in multi-cavity PCRV (460 MWe). (4) Conventional core in multi-cavity PCRV (830 MWe). Studies of small HTGRs were also reported by KWU in Germany. The simplification of the safety related aspects of these plants is a key factor in reducing plant capital costs and improving the licensability of the plants.

At a National Science Foundation Conference entitled "Nuclear Power Plant Innovation," held at MIT on January 9 and 10, 1985, papers on small modular reactors were presented. These included U.S. and German perspective on modular HTGRs.

3. Recent Large Breeder Modular Design Experience

The Large Scale Prototype Breeder (LSPB) project, sponsored by DOE and coordinated by EPRI's Consolidated Management Office (CoMO) made a specific effort to improve the plant design by modularization. In

March, 1983, Bechtel completed a modularization study for this plant which established some basic guidelines for designing modules for use in a conventionally constructed concrete and rebar building (Reference 5). The building layout was developed by Burns and Roe, Bechtel, and Stone and Webster to facilitate the installation of modules. For example, simplification of the decay heat removal system by eliminating the safety grade functions of the steam generator system permitted the option of fabricating the steam generator cells as steel framed modules. Subsystems of auxiliary liquid metal systems and the inert gas receiving and processing systems were designed for assembly at vendor shops or on-site preassembly shops. The main condenser was designed for modular pre-assembly.

In September, 1984, Stone and Webster issued a Plant Constructibility Analysis Report for the LSPB project (Reference 6) which states that "modules or preassemblies that can be constructed by one or two craft disciplines are more adaptable to nuclear power construction." The following modular and pre-assembly construction techniques were recommended for the LSPB design:

- o Modularization of reinforcing steel
- o Preassembly of Condenser
- o Preassembly of containment liner
- o Preassembly of cell liners
- o Piping subassembly fabrication

In the LSPB report (Reference 6), Stone and Webster states with regard to more complex, composite modules, "modular construction offers the constructor the opportunity to reduce both cost and schedule while improving quality. However, these objectives are not always obtainable. For example --

- The cost of temporary structures to support a composite module may be more expensive than in-place installation costs. Unless a schedule improvement can be attained to achieve the additional expense, this "composite" module concept should be discarded.

- Composite modules require early engineering and material procurement, including many disciplines that are difficult for the engineer and fabricator to support.
- The constant revisions common for a nuclear project being designed and constructed in parallel would cause difficulties for composite module construction.

As a result, the large composite module construction techniques becoming commonplace for process plants and shipbuilding are not always suitable for the construction of a prototype nuclear power plant."

It is noted that Stone and Webster's report for the LSPB project was based on a prototype nuclear power plant designed for conventional concrete and rebar construction methods. The recommendations do not reflect the potential for construction methods that are less conventional in the nuclear power field but have been used for many years in the process and shipbuilding fields, as discussed further in this report.

4. Recent PWR Modular Design Experience

A recent example of a different approach to nuclear power plant construction which may be cost effective is the Westinghouse 600 MWe NUPACK design (Reference 7). This concept is based on fabricating a total nuclear island, and possibly other power plant buildings, in a shipyard and transporting them to a plant site for ultimate installation on a conventional foundation. Schedule advantages appear achievable by permitting parallel construction of the modules while site construction work is underway. Pretest of systems in the modules is suggested. Total plant costs and schedules should be more controllable, which is a key problem in the current U.S. nuclear power plant industry.

It is apparent that there are many ways to modularize a nuclear power plant and that further study is needed to determine the overall cost effectiveness of the various modularization schemes. Modularization will require more front-end engineering and design for the first plant, but considerable reductions should occur in the cost of follow-on plants built to the same standard design. Modularized construction will impact the current RM, AE Constructor relationships, but overall benefits to the industry should result.

5. Reference LWR Plant for Comparison With Other Nuclear Plants

As discussed in the AIF report entitled "Nuclear Power in America's Future," June, 1984 (Reference 4), the question has been raised of whether renewed utilization of the nuclear option should not be based on some system other than the light water reactor. According to the AIF report, these discussions "have failed to:

- a. Acknowledge the extensive research, development, and demonstration effort that went into alternative systems in the late '50s and early '60s.
- b. Recall the deliberative reasoning that went into the selection of the LWR, not only in the U.S. but subsequently in Europe and the Far East.
- c. Recognize improvements that have been incorporated into the LWR as a result of 25 years of design and operating experience.
- d. Specify how the LWR system is flawed or why alternative systems could be expected to perform better."

The AIF report does not suggest that "R&D on the LWR as well as other alternative reactor designs should not be vigorously pursued." The report notes that "design work on advanced versions of LWR's is being undertaken by the industry on a basis that supports the installed LWR

base...Included in these efforts are projects directed at refining small plant size, performance and economics to meet the utilities' needs for smaller incremental growth additions."

A question exists regarding the difference between small modular LWR plants and large modular LWR plants. The emphasis on small modular liquid metal reactors (LMRs) and small modular HTGRs is in the packaging of the NSSS for shop fabrication and the simplification of decay heat removal systems to the point where passive, inherently safe systems are used. These features are intended to offset the loss of economy of scale. It is possible that increased modularization of the LWR balance of plant beyond the NSSS package can provide cost and schedule reductions for larger LWR plants and that these modularized larger LWR plants should be the reference plant for comparison with the smaller LWR plants. The modularized larger LWR plants may also be a more realistic reference plant for comparison with the LMRs and HTGRs in terms of power generation costs (\$/Kwe). Modularization of a large LWR plant, since it requires only the new application of existing technologies, as opposed to the R&D and demonstration of new technologies, may result in low capital costs, shorter schedules to match load growth, and higher reliability due to use of established data bases. These factors require further study.

6. Modularization for Life Extension and Decommissioning

Life extension has been evaluated recently in an EPRI report entitled "Extended Life Operation of Light Water Reactors: Economic and Technological Review" (Reference 8). This report concludes that "the extended life option appears feasible and attractive for three basic reasons:

- a. The break-even costs are quite large.
- b. Major elements of the original plant cost (in items such as the site, concrete construction and engineered construction) appear preservable through extendable life.

- c. Current experience in major replacements, such as steam generators, suggests that target replacement times can be achieved."

It would seem reasonable to assume that if these conclusions are applicable to the current generation of LWRs, which are not specifically designed for ready replacement of all components and systems, then a plant which is designed to facilitate replacement would make life extension even more economically attractive. Modularization of systems and subsystems, and a building layout which permits good access for removal and replacement of such modules as well as the major components (reactor vessel, steam generators, etc.). should be a basic design requirement in future plants. A generic study of how modularization can facilitate life extension would provide useful guidance to plant designers in the future. The modules which facilitate construction may or may not be compatible with the modules that are best suited to life extension.

Decommissioning costs could be reduced by installing systems and components that are more readily replaceable than in current plant designs. Since the electrical power generation costs passed on to the ratepayer are influenced by decommissioning costs (as well as capital costs and life extension costs), a study to determine how all these factors influence the ratepayer and the utility would be useful.

7. Summary of Current Considerations

Most of the work on modularization has concentrated on reducing the construction costs of nuclear power plants. Minimal effort has been done to evaluate modules to enhance maintenance and repair over the life of the plant, to facilitate life extension, or to reduce decommissioning costs. Since these factors can also influence the rate base, they need to be considered.

As discussed in a June 1984 study by the Atomic Industrial Forum entitled "Nuclear Power in America's Future" (Reference 4), if nuclear power is to compete for new electrical generation, ways must be found

to reduce the uncertainties and financial risks associated with capital intensive and long lead construction. Increased assurances are needed that schedule delays and large cost increases to the utilities will not occur so that the financial community will want to support nuclear power. Fixed price bids from contractors, incentive contracts with financial bonuses and penalties for performance, or joint ventures by a group of utilities have been suggested as possible approaches in the future. It is possible that modular construction may provide better control over schedule and costs and permit fixed price bidding for large portions of the plant. In view of the large impact of AFUDC (allowance for funds used during construction) on the cost of the plant, reduction in the overall plant construction schedule due to parallel construction of modules and site facilities may significantly reduce the plant costs and the cost of electricity to the ratepayer. Another area where the ratepayer may benefit is where modularization could effectively increase the plant lifetime and reduce decommissioning costs.

Studies are needed to determine the appropriate balance between the degree of modularization needed to reduce construction costs and provide the assurances that these costs will not be overrun, the degree of modularization most desirable to increase plant availability by reducing plant downtime, and the degree of modularization that will increase plant life and facilitate decommissioning.

B. Preliminary Cost Survey

In order to identify a potential capital cost reduction which may be achieved by modularization of a nuclear power plant, a preliminary cost survey was performed. For this purpose, a 600 MWe PWR was used, with costs for a conventionally constructed plant obtained from a CONCEPT V code run consistent with the EEDB-6 data base and a 10-year overall schedule. These costs reflect recent industry average construction experience over many plants and were used as a base case for this study, as shown in the accompanying table, Column 1.

The CONCEPT V Code has a new feature in the form of a model which represents the best construction experience of several selected plants. The results of this run are shown in Column 2 of the attached table and are based on a 600 MWe plant located at a New Orleans site, a 1985 start date, and a 10 year overall schedule.

A preliminary cost estimate of a future conventionally constructed n^{th} of a kind plant was then developed to provide a basis for comparison with a modularly constructed n^{th} of a kind plant. As shown in Column 3 of the attached table, the total direct and indirect costs were conservatively reduced by only 11% to reflect reductions in accounts 91, 92, and 93 due to replication of designs and a reduced overall schedule (from 10 to 8 years). The 8 year schedule was based on a 5-1/2 year construction period, which is similar to the French experience on their n^{th} of a kind plants and is close to the U.S. experience on some of our best plants (St. Lucie 2 and River Bent). A 2-1/2 year period from project authorization to the Construction Permit was assumed, which anticipates improvements in the current licensing process. Project start was assumed to be 8 years before the 1995 date of commercial operation.

Preliminary costs for an n^{th} of a kind 600 MWe modular plant were developed for this study, as shown in Column 4 of the attached table. Selected portions of the cost of the conventional n^{th} of a kind plant, as shown in Column 3, were evaluated. A 15% cost reduction was assumed for fabricating the nuclear island modules in an offsite facility

PRELIMINARY PWR COST COMPARISON (10⁶\$)
(1985 Dollars, 1995 Commercial Operations)

Nuc Acct.	Title	Column 1	Column 2	Column 3	Column 4
		Conventional Construction (EEDB VI Average) Experience) 10 Years Total Schedule (Note 1)	Conventional Construction (EEDB VI Best) Experience) 10 Years Total Schedule (Note 2)	Conventional Construction (Future n th of a Kind) 8 Years Total Schedule (Note 3)	Modular Construction (n th of a Kind) 6 Years Total Schedule (Note 4)
20	Land and Land Rights	5	5	5	5
21	Structures and Improvements	196	124	124	105
22	Reactor Plant Equipment	233	195	195	166
23	Turbine Plant Equipment	161	139	139	125
24	Electric Plant Equipment	83	57	57	57
25	Miscellaneous Plant Equipment	49	35	35	35
26	Main Condensor and Heat Rejection System	30	25	25	25
91	Construction Services	178	112	105	95
92	Home Office Engineer and Support	328	179	100	90
93	Field Office Engineer	319	85	70	55
94	Owner's Costs	168	52	52	52
	Total Direct and Indirect	<u>1,749</u>	<u>1,008</u>	<u>907</u>	<u>810</u>
	Contingency	(15%) 262	(15%) 150	(10%) 91	(10%) 81
	Total Direct and Indirect (1)	2,011	1,158	998	891
	Escalation During Construction (2)	(7.9%) 1,172	(8.1%) 705	(7.8%) 705	
	Total (1) and (2) = 3	3,181	1,863	1,719	1,596
	AFUDC (10%/year) (4)	1,261	725	635	481
	Total Capital Investment ((3) and (4))	4,444	2,588	2,354	2,077

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NOTE 1 Concept V Code (Unmodified)

NOTE 2 Concept V Code (Unmodified)

NOTE 3 Judgmental Extrapolation of Col. 2; 2-1/2 Yrs. to CP, 5-1/2 Yrs Const. Period

NOTE 3 Judgmental Extrapolation of Col. 2; 2-1/2 Yrs. to CP, 5-1/2 Yrs Const. Period

and transporting them to the site (Accounts 21 and 22). A 10% cost reduction was assumed for fabricating the turbine island modules in an offsite facility and transporting them to the site (Account 23). The cost reductions are attributable to improved labor productivity by the stable work force, higher quality, less rework, and improved management control of schedule and costs, based on modular construction experience in the petrochemical and shipbuilding industries (which averaged 10 to 20%). All other portions of the plant were assumed to be built at the site in a conventional manner. Construction services, home office engineering, and field office engineering (Accounts 91, 92, and 93) were assumed to be reduced by a total of 13%, based on shorter schedules, less field construction with less need to make field modifications to correct installation problems, and learning curve improvements due to utilizing experienced procurement, planning, scheduling, and cost-estimating people, plus engineering and management personnel at offsite fabrication facilities. The total direct and indirect costs were a modest 11% below the n^{th} of a kind conventional plant.

A 10% contingency was used in lieu of the 15% shown for the conventional plants to reflect the ability to provide better control of the schedule and cost of the module construction at the offsite fabrication facilities.

A 6-year schedule was assumed for the n^{th} of a kind modular plant, based on a 2-year reduction in the construction period following receipt of the construction of the modules in an offsite fabrication facility in parallel with the onsite construction. The time from the start of the project to the construction permit was assumed to be 2-1/2 years. Project start was assumed to be 6 years before the 1995 date of commercial operation.

The net result is a cost reduction of 12% below the n^{th} of a kind conventional plant.

The 12% cost savings due to modular construction at offsite facilities is considered to be conservative from the following standpoints:

- The petrochemical industry has determined that 10 to 20% cost reductions are common on large one-of-a-kind projects where modules are built in offsite facilities and shipping to remote locations where labor costs are high. Even greater savings are achievable by n^{th} of a kind projects.
- A nuclear power plant is more labor intensive than a petrochemical plant, which means that offsite construction in an established facility with a stable experienced work force, such as a shipyard or other facility, has a large potential for reducing costs. Further study is needed to establish the full extent to which this potential exists. It is recognized that transportation modes and locations of power plant are also key elements in such studies.
- A short project schedule reduces the risk to the investors, which can reduce the interest rate during construction, or allowance for funds used during construction (AFUDC). This would reduce overall costs.
- A lower escalation rate would reduce the total cost.
- A larger percentage of the power plant may be modularized than assumed in this study.
- Equipment and material costs may be lower for n^{th} of a kind modular plants than assumed in this study.

In addition to the cost savings due to modularization, the ability to control the cost and schedule of the nuclear power plant is considerably enhanced. This is due largely to the stability of the labor force and management at the offsite facilities, such as shipyards or other large fabrication shops. Work can be performed at these locations in a controlled environment and under favorable working conditions. These same conditions currently permit such facilities to perform work in the petro-

chemical and shipbuilding industries for fixed price contracts. The nuclear utility industry would probably favor such an approach in the future.

Further studies are needed to develop the designs of a modular plant and determine how many plant structures should be prefabricated in offsite facilities, how large the modules should be, the alternate modes of transportation, the alternative of modular construction on the construction site, the design of the facilities for site construction, and the costs for all aspects of this approach based on detailed schedules. The cost of the first of a kind nuclear plant must also be developed. In view of the potential cost savings for the plant, the cost of future studies is readily justified. These studies should be initiated as soon as possible so that the economic viability of nuclear power in the U.S. can be established in the near future to keep the nuclear option open.

C. Potential Benefits and Risks of Modularization

1. Definition

One of the first tasks to do in a modularization study is to define specifically what is meant by the term modularization. Current usage spans quite different meanings. For example, the MHTGR (Modular High Temperature Gas-Cooled Reactor) refers to standardized reactor units in a range of 100-250 MWT per unit (Reference 9, 10). The extent of modularized contribution is not specified. On the other hand, Westinghouse has proposed Nupack, a 600 MWe modular PWR plant design in which the entire plant is made up of several large shipyard fabricated packages (Reference 7). Other meanings of modularized design include the concept of skid-mounted assemblies of systems and components which, when mounted and connected at the plant site, make up a large portion of reactor and auxiliary systems, and balance-of-plant systems.

A range of module concepts should be studied, from modules of systems and components that can be assembled at factories and shipped by barge, rail or truck, to modules which would be assembled at a plant site in a facility built solely for the purpose and then moved a short distance to be installed in the plant. Many factors will affect decisions on which concept to employ: labor rates, quality assurance, engineering, cost of required facilities for module fabrication, volume of projected module and plant business, etc. It is to be noted that no single modularization concept is likely to be optimal for all plant types and siting situations.

2. Costs, Risks and Benefits

Before discussing costs, risks and benefits, it is appropriate to identify the problems that we can expect modularization to solve or alleviate, and to distinguish between those and the nuclear power plant construction problems that modularization will not solve.

The problems of nuclear plant construction over the past ten years have been many. Problems have included public acceptance, plant financing, licensing problems such as the moving target of technical requirements mandated by the Nuclear Regulatory Commission, back-fitting of operating plants to requirements which have developed from the aftermath of Three Mile Island, the incorporation of new technological developments not mandated by the NRC, quality assurance problems, and failures in construction management leading to missed schedules and cost-overruns.

Modularization appears to have considerable potential for improving quality assurance and construction management. Modularization can address many quality assurance problems by shifting the place of fabrication from the plant site where controlling the environment is often very difficult, to a factory line where control of material flow, shop procedures, welding and quality assurance inspection and testing can be controlled to a greater degree.

Modularization can also avoid some of the problems resulting from inadequate construction management by shifting the responsibility for managing much of the field fabrication to a controlled factory fabrication and engineering environment. The field responsibility then would reduce to organizing the flow of modules to the reactor site, mounting, connecting and assuring that these jobs have been correctly done. The net result would be greater predictability in meeting construction schedules and costs.

Modular construction at offsite facilities can potentially reduce costs by substituting factory wage rates and productivity for field craft wages and the associated productivity. Modular construction at the plant site can also be cost effective by improving access to multiple modules constructed on parallel schedules, although not all of the advantages of offsite fabrication, such as a stable work force with high productivity, will be achieved.

The concept of shifting responsibilities from the field to earlier stages in the process of fabrication/construction can be far-reaching in bringing about fundamental changes in the structure and organization of the nuclear industry. The relationships between the reactor manufacturer (RM), the architect-engineer (AE), and the constructor (C), all working for a utility company project manager, could be altered in some very significant ways. Interaction with the NRC and the overall licensing process will be influential during design, fabrication, construction and pre-operational testing of the plant. The potential exists for certifying the modules in the fabrication shop, similar to the aircraft industry.

By constructing the plant in an offsite facility with experienced workers who are motivated to do a high quality job by virtue of the stability of the work environment, (i.e., they will have jobs after they complete the nuclear plant by working on other projects constructed at the facility), the amount of rework will be reduced. Quality management techniques can be effectively used, wherein the worker is accountable for the quality of his work and the number of inspectors are reduced. The overall effect will improve the product and should facilitate the licensing of the plant. By performing the inspections and system tests at this facility, it is anticipated that full (or partial) NRC acceptance of the modules prior to shipment may be achievable. This would minimize the extent of NRC acceptance required at the plant site, and would reduce the risk of schedule delays due to NRC acceptance late in the construction schedule. Integrated system tests and NRC acceptance will, of course, be done at the plant site.

The effect of modularization will be to commit final design of the specific assembly at an earlier stage of the total design/construction process. This will be necessary to obtain the full advantages of factory production. Modularization will achieve its full potential with standard designs which already have licensing approval, so that the only outstanding questions are in the categories of (1) does the

module meet all specifications? and (2) has the module been properly connected at its interfaces and checked for proper, expected operation? It is possible that modifications might be easier to accomplish on modules before they are shipped to the site than making modifications in a conventionally constructed plant but this requires further study.

Modular construction is well suited to plants with an established technology base, such as the Light Water Reactor, since changes during construction of the prototype and follow-on plants should be minimal. For newer technologies, such as the High Temperature Gas Reactor or Liquid Metal Reactor, with a smaller experience base, the incentives for extensive modularization in the first few plants may be less. Flexibility may be desirable in construction schedules, and possibly during early operation, to make changes as experience is gained in first-of-a-kind plants. Further study is needed on the advantages of modularization for first-of-a-kind plants.

The overall plant design must receive additional and early attention. For example, integration of the modules into the plant and assurances that the system will be entirely compatible may be even more important for a modular system than for one which may be considered somewhat more in its entirety. Also, provisions for maintenance and particularly for appropriate access to accommodate robots should be considered in both the overall design and for each module. Although modularization improves the possibility of removing components, in-place maintenance will continue to be a very important consideration. Modular plant designs should be aimed at grouping systems into the least number of modules so that systems within modules can be tested before leaving the off-site fabricator's shop. Module sizing relates to the method of transportation but several small modules could be tested as a unit before shipping, cut apart, then reassembled at the site. Standardization of designs greatly enhances the benefits of modular designs and permits the full benefits of offsite fabrication to be achieved.

A standard plant, when built at various locations throughout the U.S. using local labor forces, may not result in large cost savings due to the inexperience of the local labor force. The variations in productivity of local labor forces throughout the U.S., and variations in the experience and expertise of the construction management team, lead to widely varying plant costs for standard plant designs.

Construction of standard plants in the same off-site facility permits cost savings and consistency of costs to be achieved. This will facilitate construction of plants in off-site facilities on a fixed price basis.

Modularization will change the way in which engineering is done for first-of-a-kind plants, as well as sequences and schedules. Design drawings and the associated bills of material for modules will of necessity become final when the assembly is committed to manufacture which is early in the project.

Interconnecting modules will have to fit together, including piping and electrical connections. "As built" drawings, to record how a system was actually built in the field, will become less prevalent. As previously stated, design decisions will be made earlier for the first-of-a-kind plant.

A large part of the variability of nuclear power plant cost is attributable to differences in the experience and ability of utility and construction managers. Construction of modules in offsite fabrication facilities with experienced managers will provide more consistency in the overall construction schedule and cost performance. Considerable interaction will occur between management procedures and the zone outfitting or modular erection procedures to provide considerable control on the project.

Modularization facilitates the maintenance of detailed design and performance records of all aspects of a systems module, including tracking the bill of material, and recording the QA tests and inspections from initiation of the procurement, through installation and testing at the nuclear plant, and through operation as well. The

complete package of information could be maintained for the plant owner's use, for rapid recall in the banks of a computer memory. Where a complete system is provided in one module, a performance measurement and diagnostic system might be incorporated to facilitate functional checks when it is installed in the plant.

Modules can be provided to improve maintenance and reduce the downtime of a plant where components that are difficult to service and maintain could be provided in modules which are easy to disconnect and replace. The design of such modules is different than the design of modules intended to reduce construction costs. A good design of a maintenance module would avoid a configuration which makes it necessary to remove a number of modules, breaking piping connections, etc., to get at the removal of a particular module which requires repair or maintenance. What this suggests is that the approach to modular design should begin with a rethinking of layout and configuration, rather than cutting up the drawings of an existing non-modularized standard design and sorting these into the modules for the new design. The subject of component replacement versus module replacement requires considerable study from the standpoint of turnaround time, cost of components versus modules, warehousing, etc.

3. A Summary of Costs, Risks and Benefits

Modularization appears to have potential impact on how nuclear plants will be sold, committed, designed, built and put into operation in the future. Careful evaluation is required at an early stage to quantify costs and benefits so as to pick the most promising approach to modularization. Factors to be evaluated include risk in licensing, construction lead time, management of design and construction information, plant performance, maintainability, life-extension, decommissioning or some combination of the above.

4. Summary of Costs

a. Cost of Modular Design

Additional costs for engineering and design are required for modular construction. For a first of a kind plant, the engineering costs, which represent about 15% of a job, may be increased by a factor of up to 2. However, hardware assembly costs may be cut by 30%, with a net savings of 15 to 20%. Additional detailed planning and scheduling is also necessary. The first-of-a-kind plant costs will be increased. Benefits will be gained from n^{th} of a kind plants, built to the same standard designs. Future nuclear plants should be built to standard designs which are suitable for modular construction in offsite facilities or at the plant site.

b. Investment Cost of Modularization Facilities

It appears to be most cost effective for modules to be fabricated at existing factories already equipped, such as at a shipyard or other fabrication facility. If new factories are built, then the investment costs would be charged to the modules planned for, and the unit cost would depend on the factory loading. This latter situation may exist for onsite modular construction facilities for a two or three unit station, for example.

c. Variable Cost of Module Fabrication

This cost would include materials, labor, engineering follow, quality assurance, testing, manufacturing management overhead, etc.

d. Cost of Special Module Features

Modules are likely to include additional features for purposes of performance monitoring, troubleshooting, and the like. These may

replace, or may be additional to, similar features in conventional plant designs.

e. Cost of Transportation

Depending on the size and weight of the modules, transportation from the factory to the plant site may entail special problems and associated costs. Barge transportation appears to be desirable where feasible, and is likely to be relatively inexpensive.

f. Mounting, Interconnection, and System Check-out

These are costs that will be considered with modularization, which will displace some of the costs of field installation and system check-out.

g. Module Information Records Costs

These costs would include the records of module materials and fabrication history, which would become part of the plant data bank. They may substitute for substantial parts of field records costs; for example, in the case of weld inspection and records.

5. Summary of Benefits

a. Transfer of Field Fabrication to a Factory

A primary benefit of modularization will be to transfer field fabrication of systems to a factory where the environment can be greatly improved; i.e., material flows, assembly and fabrication procedures, etc. The benefit realized will depend on the extent of modularization that is achieved and the size of module units.

b. Shortened Construction Schedules

Provided that standardization accompanies modularization, the ability to make early commitment of modules, to separate civil works construction and field assembly of systems, and to schedule the arrival of modules at the plant site with civil works milestones should make it possible to significantly reduce U.S. construction plant schedules, making them competitive with foreign schedules or better.

c. Licensing

The conjunction of standardization and modularization offers a substantive change in the way plants are constructed, which could make it possible to restore predictability of licensing approvals which are not on the critical path of plant construction. The scope of public hearings could then center on and be confined to site-specific issues. The question of licensing modules containing complete systems (such as NSSS modules or auxiliary systems modules) relative to the process of licensing the entire plant requires further study, but may offer some interesting advantages in the licensing process.

d. Construction Project Management

The introduction of modularization would make it possible to improve construction project management by delegating substantial parts of the scope of fabrication flow to module contractors, allowing the construction management team to concentrate on the management of civil works, project oversight and troubleshooting.

e. System Fabrication Hours and Wage Rates

To the extent that module fabrication can be done at factories separated from the plant construction site, it will be possible to reduce the labor hours for fabrication, and possibly the wage

rates, by bringing the process under established factory industrial practice. Substantial savings in plant construction costs are expected.

f. Quality Assurance and Record-keeping

Quality assurance of field fabrication, assembly and welding is a major problem because of the difficulty of controlling conditions at the construction site and the need to train craft workers almost on a site basis. Modularization can greatly improve this situation. It can also improve the accuracy and storage of the records of fabrication processes for speedy recall and use during the plant life.

g. Maintenance and Repair

Although maintenance and repair costs are not part of construction cost, increasing utility management attention is being focused on them, because of their high cost, especially the cost of replacement power. The use of modules opens up interesting opportunities for reducing plant outage times through the use of replacement modules.

Modularization may be effectively used in the maintenance and upgrades of existing plants for mechanical and electrical systems. For example, radwaste system upgrades may be formed by replacing old systems with modularized packages. Auxiliary fluid systems throughout the plant may lend themselves to total or partial replacement with modularized packages containing pumps, pipes, instrument, controls, tanks, etc. The configuration of the replacement module, within the restrictions of the space envelope, may be different from the original configuration to improve plant operation and routine maintenance. Instrument and control panels and cabinets may be replaced with prewired modules containing state-of-the-art equipment. Cable replacement schemes may include the use of multiplexing systems. Modules designed for replacement

during routine maintenance must consider the balance between reduced maintenance time and increased costs for replacing more than one component, for the shipment and storage of modules versus components. Access limitations must be considered for each plant on a case-by-case basis. Specific studies are needed to determine the overall cost effectiveness of modules used for plant upgrades and maintenance.

In future plants, modular designs within radioactive areas can potentially reduce radiation exposure to workers by permitting replacement of several components as an assembly, such as several valves and their interconnecting piping. Modular designs should be developed to facilitate maintenance by the use of robotics, wherein such robotics may be guided by externally located people, or, at a future time, by artificial intelligence.

6. Summary of Risks

a. Labor Disputes

Modularization has the potential of increasing the frequency and level of labor disputes. The share of field craft labor would be reduced substantially. At the same time, the crafts might be involved in the task of interconnection of modules. The benefits of modularization obviously depend on the acceptance of this new mode of operations by the crafts, which would be in a position to resist the changes in the absence of a labor agreement. Extensive groundwork to set the basis for acceptance of the modularization concept is essential.

b. Design Changes

Design changes which require rework of the modules, and especially changes which have ripple effects in several modules, will rapidly dissipate the cost and schedule benefits of modularization. The

risks of such changes are considerable, and so too the incentives to establishing a final, standard design before the modules are committed.

c. Later Modification of Modules and Licensing

The conditions under which modules are accepted and reviewed in the licensing process is worthy of careful consideration and discussion in advance with the NRC in order to establish working rules. Licensing of modules and the relationship to the overall plant construction and operator license warrants further study.

d. Technology Development

Plant standardization will certainly alter the pace of nuclear plant technology development. The challenge will be to introduce new technology in discrete steps, so as not to void standardization by continuing to introduce changes as they occur to designers. The risk will be that standardization will crowd out innovation.

e. Technical Unknowns

Given a technology which has a sound experience base, the risk that modularization will pose unanticipated serious technical problems does not seem very great. Nonetheless, it appears appropriate to give close attention to the differences between modules and the conventional plant arrangements that they will displace. Mounting, interconnections, and interactions between modules are clearly areas requiring careful engineering review, so as to minimize the risk of plant outages to rework errors of oversight.

IV. DEVELOPMENTS UNDERWAY AND CONTACTS

A. Summary

Modularized construction has been used in virtually every U.S. industry where a product is built. The non-nuclear industries selected for survey in this study were the shipbuilding, petrochemical, aircraft, aerospace, and automobile industries. These industries were chosen on the basis of their potential for providing information which would be of value in the nuclear power industry.

The shipbuilding industry stands out as one which can potentially provide the greatest assistance to the nuclear power industry in terms of reducing the cost of the nuclear power plants. There are many reasons for this, but the main one is the incentive within this industry to reduce costs and increase quality. International competition in shipbuilding is extremely tight, and U.S. shipyards must make every possible effort to be competitive to stay in business. The methods which they have adopted in the past and which they continue to refine, such as modularization, are directly applicable to the construction of land-based nuclear power plants. Since the systems of both ships and land-based nuclear power plants are constructed to similar materials, such as pipe, cable, ductwork, components, instrumentation, controls and power distribution systems, the construction techniques and skills that are needed are similar.

Modules for many ships are currently constructed with equipment, piping, valves, instrumentation, etc. fully installed into the structural steel module. The modules are painted and subsystems are tested before attaching them to adjoining structures to make up the whole ship. Similar approaches can be used to construct nuclear power plant modules which can be shipped to the site for installation, with a minimum amount of concrete and rebar required and minimum use of site labor.

The U.S. government's Maritime Administration Office of Advanced Ship Development supervises the highly successful government/industry National Shipbuilding Research Program (NSRP), which is responsible for the

development of advanced construction techniques. The NSRP was described in a Rand Corporation report of Government-funded efforts as one of the five most effective research programs in terms of development and implementation achieved. Other government agencies have been urged to recognize these achievements, in related industries. The nuclear power program would appear to have much to gain from the NSRP activities. Other government agencies, such as the Navy Department, can also provide valuable information on methods of advanced ship construction and other end products. The Society of Naval Architects and Marine Engineers (SNAME) has a Ship Production Committee that is a useful source of information which is applicable to nuclear power plant construction.

There is a need to evaluate how several government agencies could collaborate on the application of advanced construction techniques in shipyards for the building of ships (naval and commercial), and nuclear power plants.

The petrochemical industry was selected for evaluation since it was recognized that large, complex process plants have been built at shipyard facilities and transported by barge to remote land-based sites for many years. This was done to eliminate the costs of providing skilled labor at such locations and of reducing overall construction schedules and costs while improving the quality of the product. Many of the process plants utilized large quantities of piping, often of stainless steel or other corrosion resistant material, considerable instrumentation and large components. Design conditions include corrosive and toxic materials, often at very high or very low temperatures, so that material selection and welding were critical factors. Large offshore drilling rigs were also fabricated in shipyards and transported to ocean sites. The water transportation methods and land-based installation schemes which were developed for this industry, as well as the modular construction of these plants in shipyards, are directly applicable to nuclear power industry. The American Institute of Chemical Engineers (AIChE) has recognized the significance of modular construction in the petrochemical industry, as evidence in their sponsoring of the 1983 "Modular Construction and Barge Mounted Plant Symposium".

Modular construction of automobiles, airplanes, and many other products built on an assembly line is also being done on an increasing basis to reduce construction costs. Some of the methodology may be applicable to the construction of nuclear power plant modules, such as robotics and electrical cable harness production. The overall production line approach is not as useful to the nuclear power plant module construction as the shipbuilding and petrochemical experience.

Modular design of space stations is based on the need for logistical support, not on the desire to reduce construction costs. The size and weight of these modules is based on the weight carrying limitations of the space shuttle which must transport the replacement modules to the space stations. The designs of the replacement modules are also based on the working environment, wherein the modules located outside the space craft are replaced as complex "black boxes" to reduce the time the astronaut spends in the dangerous environment. Inside the spacecraft, smaller, less expensive modules, are provided.

Modular designs of subsystems on naval vessels are also governed by logistical support requirements, since replacement parts must be flown or shipped to the vessels on station around the world.

Modular design of commercial aircraft permits replacement of engines, interiors and other equipment to facilitate the maintenance and extend the life of the airframe.

Modular design experience for logistical support, maintenance and life extension in the non-nuclear industries has some applicability to the design of nuclear power plant modules and should be evaluated further.

A brief survey of non-nuclear industries was made to identify the extent to which modularization is currently being used. The existing RECON data base at Oak Ridge National Laboratory was used as a source of information with regard to organizations which are using modularization techniques. In addition, technical societies such as the Society of Naval Architects and Marine Engineers (SNAME), the American Institute of Chemical Engineers

(AIChE), and the American Institute of Aeronautics and Astronautics (AIAA) were contacted to obtain the information related to these industries. Based on these leads, information from the following sources was obtained by personal contacts, meetings, and reports:

- o Shipbuilding Industry
- o Petrochemical Industry
- o Commercial Aircraft Industry
- o Military Aircraft Industry
- o Aerospace Industry
- o Automobile Industry
- o Heavy Lift Industry
- o Universities

A brief writeup reflecting the highlights of contacts made with these industries is attached.

B. Shipbuilding Industry Experience in Modularization

1. General

Henry Kaiser caused an industrial revolution in the shipbuilding business at the outbreak of World War II. By introducing Group Technology, he was able to achieve the benefits normally associated with production lines even while producing many different subassemblies in varying quantities, as required for building ships. Simplified welding techniques were possible because by turning the modules to facilitate access by the welders, he organized the work to fit the worker, instead of vice versa. Kaiser's methods reduced the costs of building ships 25 percent below traditional methods, in two-thirds the time.

Following World War II, Elmer Hann, a former Kaiser employee, took the Kaiser methods to Japan. He taught the Japanese how to organize the work in accordance with the basic principles of Group Technology, with emphasis on proper welding techniques. With these methods, the old

pre-World War II shipyards in Japan were able to produce 40 percent of the world's total ship-building tonnage by 1964.

During this period, Dr. W. Edwards Deming, Professor of Statistics at New York University, was also making a significant contribution. In 1946, Japanese products were of poor quality, and the Union of Japanese Scientists and Engineers (JUSE) determined that Statistical Control Methods (SCM) could significantly improve quality and productivity. Starting in 1950, Dr. Deming began to teach SCM to Japanese managers and engineers and laid the foundation of modern construction methods, including the development of automated and specialized welding. From this, workers began to be more sensitive to production issues and Quality Circles (QC) were developed. These methods are the basis of the advanced quality assurance/quality control/quality management systems being used throughout the world in all industries.

Dr. Hisashi Shinto, a pupil of Elmer Hann's, is the dean of shipbuilding in Japan. When he retired in 1979 as president of Ishikawajima-Harima Heavy Industries (IHI), he left behind a constantly improving system for building ships and other end products, including one-of-a-kind units, with the basic Kaiser logic still intact. At that time, the IHI system enabled a worker to achieve in one hour the work which required three man-hours to complete in a traditional U.S. shipyard.

This Japanese technology began to return to the U.S. with the Merchant Marine Act of 1970. The Act provided the authority for the establishment of the highly successful government/industry National Shipbuilding Research Program (NSRP). This is a defacto consortium which is cost shared and managed by a number of shipbuilders in behalf of the entire industry and supervised in behalf of the government by the Maritime Administrator's Office of Advanced Ship Development. Under NSRP sponsorship, shipbuilders, academicians and program managers toured shipyards in Europe and Japan looking for ways to improve productivity. However, it was not until 1976 that the real significance of the IHI shipbuilding system was recognized. In 1979 the NSRP published a book called "Outfit Planning" based on a research contract

between ISI and NSRP which showed that the Japanese success was mostly based on methods which enabled their managers to apply methods by which workers could work more effectively. Avondale Shipyards, Inc., of New Orleans, LA retained IHI consultants to accelerate their transition to these more effective methods.

IHI was also retained by NSRP to record the logic and principles which they applied to the organization of their work. This was published in a book entitled "Product Work Breakdown Structure (PWBS)", published in 1980 and again in 1982. This is based on the Kaiser/Shinto methodology which uses the Group Technology principle. Process lanes are organized by interim products, which are related by parts, subassemblies and assemblies. In addition, Statistical Control Methods (SCM) permits description and control of variations. This combination of process flow and statistical control is the key to advanced shipbuilding (or other end-product use). It "feels the pulse" of each process lane and provides for constant problem solving by all levels of the work force and management to permit constant improvement of the productivity and quality. The NSRP, in 1983, published two books, "Integrated Hull Construction, Outfitting and Painting" and "Design for Zone Outfitting". These books point out that designers and purchasing people cannot remain system oriented while production is zone oriented.

Because of the NSRP initiatives, an irreversible revolution in U.S. shipbuilding methods is now underway. Breakaway from traditional methods was first achieved by Avondale Shipyards, Inc. During October 1983, Avondale delivered "Exxon Charleston", a complex product carrier. This was the first ship built in North America from contract to delivery in accordance with the Group Technology methods that were highly refined in Japan. In addition to the Avondale Shipyard, Japanese consultants are now assisting six U.S. shipbuilding firms. (Reference 11).

It is noted that the SNAME Ship Production Committee (SPC) carries out the National Shipbuilding Research Program (NSRP) through cost share contracts between the Maritime Administration and shipyards which sponsor each of the committee panels. About 50% of the government funding is provided by the Navy Department.

The following U.S. shipyards are sponsors for specific SPC panels which coordinate the preparation studies and reports on the subjects noted (Reference 12).

Ship Production (SP)		
<u>Panel No.</u>	<u>Subject</u>	<u>Shipyard</u>
SP-1 and 3	Shipyard facilities, environmental effects	Avondale Shipyards Inc.
SP-2	Outfitting and production	Todd Pacific Shipyards Corporation
SP-4	Design/Production Integration	Newport News Shipbuilding Company
SP-5	Human Resources Innovation	Bethlehem Steel Corporation
SP-6	Standards and Specifications	Bath Iron Works
SP-7	Welding	Newport News Shipbuilding Company
SP-8	Industrial Engineering	Bath Iron Works
SP-9	Education	University of Michigan
SP-10	Flexible Automation	Todd Pacific Shipyards Corporation
Panel 023-1	Surface Preparation and Coating	Avondale Shipyards Inc.

The shipbuilding industry has been a leader in advanced construction technology since World War II. The initial advancements were made in the U.S., then shifted to Japan where they were dramatically applied and expanded to a very high level of sophistication. These techniques were applied to all Japanese industries (automobiles, television, etc.) and resulted in their current position as a world leader in productivity and quality. These techniques are actively being applied to U.S. industries, which had lost much of their previously held leadership position. Rapid comebacks in many industries, such as car manufacturing and shipbuilding, are occurring due to the efforts to adopt the Japanese methods. Since shipbuilding and nuclear power plant construction are similarly complex industries, with products that have similar costs and similar quality requirements, the current shipbuilding industry efforts to utilize advanced construction techniques are directly applicable to reducing the costs and improving the quality of nuclear power plants.

The U.S. shipyards need the opportunity to build more ships and other end products to achieve the full advantages of the advanced construction techniques currently being developed. A synergistic relationship can exist between ship construction and the construction of petrochemical plants and nuclear power plants. The more ships that are built to these methods, the more the technology will be perfected and the costs reduced for the petrochemical and nuclear plants. The opposite is also true. The shipbuilding industry obtains government aid when it builds naval ships and, in a different sense, when it builds commercial ships for U.S. operating companies with government subsidy money. In order to reduce the costs of naval and commercial ships, government aid (or subsidy to the utilities) for nuclear power plant construction may be worthy of future evaluation.

It is noted that the shipbuilding industry did not build smaller ships to be competitive, but instead developed methods of construction to be competitive on larger ships.

Reference 19 provides some examples of modular construction at Avondale Shipyards, Inc.

Discussions with representatives from Avondale Shipyards, Inc. and the Newport News Shipbuilding Company follow.

2. Avondale Shipyards, Inc. (Subsidiary of Ogden Corporation) New Orleans, Louisiana
 - o Avondale Shipyard has extensive experience with modular construction of process plants as well as ships. They have been highly successful in receiving fixed price contracts for their work and have completed the jobs on schedule and within budget.
 - o The size and complexity of modules envisioned for a nuclear power plant is well within the capability of Avondale, based on previous projects they have completed.
 - o Modules of process plants have been constructed for barge, rail and truck shipments.
 - o Quality assurance is currently covered by Military Specifications for naval ships they have built. It is noted that MIL-1-4528A and MIL-Q-9858A are very similar to 10CFR50, Appendix B. Material certifications and other paper trails are currently being applied. Some upgrading of the paperwork and some welder qualification work would be required. They have not built nuclear ships.
 - o Shipyards have built hulls by modular construction for many years, but piping, components, cable, instrumentation was installed piece by piece. This was similar to the current method of constructing a nuclear power plant in the sense that after the structure is built, the pieces must be carried into the plant one at a time. Shipyards have found that worker productivity goes down due to working in congested areas, costs go up, and schedules are longer. For this reason, Avondale has developed an advanced modular construction

technique for building ships. Worker's access during the construction of the modules is enhanced by turning the module several times during the installation of piping, conduit, cable, etc. The modules are painted before assembly.

- o Modularization requires that nearly all the engineering must be done before the construction begins. More drawings must be produced for modularized construction. Computer-aided design is used extensively.
- o Avondale has a stable work force in the area. The people are motivated to perform high quality work. Supervision of persons working on the modules is excellent, since all workers are highly visible to the supervisor.
- o Avondale's experience in modularization is generally described in a paper entitled "Modular Construction - Why Shipyards?" (Reference 13).
- o Avondale Shipyard has been selected as low bidder for the construction of a prefabricated plant structure (PPS) for the low-head hydroelectric power plant at Vidalia, Louisiana. The power plant will be fabricated in the shipyard of steel shapes and plates which will be backfilled with concrete at the construction site. The power plant will be outfitted at the shipyard with the bulb turbine generators, auxiliary equipment, emergency power supply, piping, cable, ductwork, cranes, etc. Subsystems will be tested at the shipyard. The PPS will be transported by barge to the site, where it will be lowered onto its foundation. This project is described in a paper entitled, "Prefabricated Hydroelectric Power Plant" presented at a December, 1984, meeting of the Society of Naval Architects and Marine Engineers.

3. Newport News Shipbuilding Company (A Tenneco Company), Newport News, VA

- o Newport News has built many nuclear-powered surface ships and submarines as well as conventional ships. Quality Assurance is covered by Military Specifications, which are very similar to 10 CFR 50, Appendix b requirements. Design, construction and testing functions have been performed for the naval nuclear plants and commercial vessels of all sizes and complexities, including aircraft carriers with eight plants.
- o The Department of Defense is urging the shipyards to do more modularization to reduce schedule and cost.
- o Modules are being constructed that are 130 feet long, 100 feet wide, and 12 feet deep, with the only constraint then being weight (900 ton lifts are maximum). The wiring and piping is included in these modules. The major concern is the fitup of the structure, pipes and cables. Theodolites assure alignment of the modules.
- o Analysis is performed for each module to be sure that deflection and alignment are acceptable during the lifting. Extra structure is sometimes added to limit stresses.
- o A new program is being initiated to do more extensive testing of systems in a submarine module before the module is installed as a part of the total ship.
- o Modularization reduces the time that a slipway is occupied, which decreases costs. Modularization provides for better access during construction. Nuclear-grade welding is better controlled in the shop, with less rework.
- o Non-essential modules are sometimes built by outside fabricators to reduce costs.

- o Future ship designs will be influenced more and more by modularized construction techniques.
- o Modularization of some systems on the ships is dictated by the Integrated Logistical Support Studies. These studies size the modules to facilitate repair and replacement.
- o Robotics may be used increasingly for welding and materials handling.

C. Petrochemical Industry Experience in Modularization

The petrochemical industry has utilized shipyards and other fabrication facilities for the modular construction of process plants and offshore drilling rigs for many years. There has been a large increase in the use of modularization in recent years, due primarily to the constantly improving economics. Between 1976 and 1980, an estimated total of 3000 modules went into process plant construction worldwide. From 1980 to 1985, an additional 9000 will have been installed. Many major engineering/construction contractors are offering some type of modular alternatives to conventional structures.

The technology of modularization and the number of applications now makes it possible to effectively evaluate the economics for new projects. Recent studies show that modularization is cost effective for not only the remote sites, but the closer sites as well.

Fluor Engineers, Inc. has been responsible for over 100 projects involving offsite construction (Reference 14). They have developed their Integrated Construction Approach to blend prefabrication, preassembly and modularization techniques. The major potential benefits are:

- o Cost savings
- o Schedule reduction
- o Reduced social and environmental impact

- o Improved labor relations
- o Reduced project use
- o Improved quality control

A proper balance of offsite construction and onsite construction must be determined by studies before a job begins. Key features of the studies are:

- o Identify modular construction concepts
- o Establish modular design criteria
- o Identify extent of modularization
- o Evaluate reduction site labor and support costs
- o Survey fabrication yards
- o Evaluate site labor agreements
- o Develop plan and costs for shipment and transfer of modules
- o Develop overall cost estimate and schedules of modular vs conventional construction
- o Identify risks

Another leader in the field of modular plants is C-E Lummus (Reference 15). A recent project was a refinery in Calgary which was completed in 1982. On this job, 62% of all equipment and 57% of all piping was located on 120 modules which were built in nearby shops. Sizes of modules were 6.7 meters wide, 5.6 meters high, and 12 meters long, weighing up to 40 tons. A 25% reduction in construction time was achieved. Engineering man-hours were about 10% higher for the modularization effort, but overall costs were not impacted. An overall consideration for modularization is that module fabrication is generally being accepted by organized labor in many regions, but it is necessary for the plant management to take firm steps to cope with it well in advance of the project.

Modularization of process plants has been done by C. F. Braun and Company for many years (Reference 16). They have been developing modular engineering technology since the early 1970's. In 1977, a totally modular

ammonia-urea fertilization plant was completed in Alaska, with modules up to 55 feet wide, 70 feet high, 100 feet long, and weighing 650 tons, barged 1600 miles from the fabrication yard in Washington. They have done many larger plants since then, particularly on an international basis. The largest modules are 30 meters wide, 30 meters long, 30 meters high, and weight 1700 tons. Modular construction has been found to save time, reduce costs, and meet critical deadlines. A modularization feasibility study is performed for each project, based on site and fabrication aspects of location, labor, transportation, and productivity. From this study, module sizes and weights and modular criteria are developed, along with costs and schedules.

Imperial Chemical Industries of England has experience that shows that building process plants offsite in modules and transporting them to a job site reduces cost and construction time (Reference 17). This has been influenced by the rising costs of labor at the site, which has risen faster than material costs. Complete offsite preassembly of a process plant can save about 10% on the construction cost and 10% on the construction time.

Shipyards in the U.S., Japan, and other countries have constructed process plant modules for many years. Most of the process plant projects have been one-of-a-kind, with capital cost savings of 10% to 20% having been achieved in many cases. Considerably greater savings would be achieved for replicate plants, since the first-of-a-kind engineering costs for modularized plants are higher than for conventional plants. Once the engineering and detailed planning and scheduling is completed for a standard plant design, the plant can be constructed by the same construction personnel on a shorter schedule and for less cost. The use of skilled craft labor in shipyards reduces the cost of the first plant and subsequent plants. By using many of the construction techniques developed for the shipbuilding industry in Japan and now being used for the construction of ships and process plants in the U.S., the cost of modular construction of process plants is being reduced appreciably. One example of this experience is at Avondale Shipyards in New Orleans, LA., as described in a paper entitled "Modular Construction-Why Shipyards?" as presented at the AIChE meeting in Houston, Texas in 1983.

The construction of large process plant modules and offshore drilling rigs has required the development of special ocean-going transport ships. There are three basic categories of such ships: lift-on/lift-off, roll-on/roll-off, and float-on/float-off. Many of these ships exist in the world-wide fleet. Modules weighing 600 tons, 1000 tons, 3000 tons, 6000 tons have been shipped routinely on these vessels. Calculations are performed to determine the loads imposed on the components and piping within these modules and the entire module is designed for ocean transport. The technology and experience exists for transporting even larger modules (Reference 18).

D. Commercial Aircraft Industry Experience in Modularization

1. Boeing Aircraft Company, Seattle, Washington

- o Boeing developed a proprietary system for modular construction of their 757 and 767 commercial aircraft between 1980 and 1984. This is considered to represent the upper limit of aircraft modularization at this time. It is highly cost effective.
- o Jobs are divided up in a work breakdown structure. There are structural jobs, electrical jobs, etc. There are 1800 "jobs" on a 747 aircraft.
- o CAD is used extensively for all phases of the design. CAM is used mainly on structures.
- o Wire bundles are automatically assembled in lengths of 120 feet, using a special harness maker.
- o The modularization system provides a clear path of traceability to a worker, and high quality work is done. However, Boeing uses extensive QA and QC at all stages of construction and maintains a thorough paper trail. Boeing does not consider that Quality Management is appropriate for an aircraft, since public safety is at stake and failures cannot be tolerated. It may be acceptable for automobiles, but not aircraft.

- o Robots are being used on an increasing basis.

2. McDonnell Douglas, St. Louis, Missouri

- o With regard to commercial aircraft made by Douglas, they use a Work Breakdown Structure covering total systems, sub systems, and vendor parts. Separate work packages are developed with a person in charge of each.
- o Airplane modules come in from many places (Canada, Japan, Italy, etc.). Interface control is an essential part of modularization and much attention is spent in this area.
- o CAD/CAM is used for tubing and cabling.
- o People are often cheaper to use than robotics.
- o Modularization can increase weight due to the need to separately support the module. Weight is a major concern in aircraft.
- o Small plans use a unitized design.
- o Large planes are modularized, with the biggest modules being shipped by barge, which limits the number of suppliers.
- o Modularization is evolutionary more than revolutionary.

E. Military Aircraft Industry, Experience in Modularization

1. McDonnell Douglas, St. Louis, Missouri

- o While there has not been much modularization in military aircraft up to now, since cost has not been a key factor, more modularization will occur to minimize life cycle costs. For example, there is a keen interest in making all valves the same size and configuration, then use microprocessors to make the valves

perform certain functions (such as pressure regulator, flow regulator, etc). Digital computers will provide the functions with state-of-the-art sensors to provide the necessary signals to the advanced software packages. There were too many valve suppliers in the past, and not much valve reliability. With the new approach, there is only one valve specification needed.

- o Piping is not modularized, since space is tight on military aircraft and such items must be installed one at a time.
- o Tubing is designed and bent using CAD/CAM.
- o Cables are assembled on a "bundle board". Flat ribbon wiring and flat connectors are used to enhance maintenance, since a person can count the wires from the outer edge.
- o The cockpit on a fighter plane is not modularized, but data is presented on 3 to 5 CRTs. The F18 has a very advanced control computer for managing the data. The Grumman plan with the swept forward wings relies fully on the computer to fly. The NASA lunar lander also relied on the computer to maintain stability by the use of computer-controlled altitude rockets. Nuclear plants would require fail safe systems based on the laws of nature, making full reliability on computers for stability undesirable.
- o The engines have been modularized for 15 years. Pratt and Whitney engines have separate modules for the afterburner, compressor, etc.
- o A major consideration for modularization of military aircraft is their supportability to extend the life cycle.

F. Aerospace Industry Experience in Modularization

1. McDonnell Douglas, Huntington Beach California

- o Modularization must be done in a balanced manner to accommodate both initial assembly and maintenance. Some aircraft modules, such as during the DC-8 development, were designed too tightly packed. Access to the various parts was acceptable during the construction out in the open areas of the shop. However, if these modules were brought together to make up the total airplane, access to hydraulic lines would have been nearly impossible, making maintenance and repair very expensive. Maintainability engineers revised the design to enhance the accessibility for maintenance in the finished aircraft.
- o Modularization of space stations is undergoing an evolution. Modules were previously designed to be large to reduce construction costs. They are now tending to be designed smaller to facilitate maintenance, as the construction phase represents weeks or months and the operational phase represents years and decades of effort. Since a space shuttle must carry the replacement modules from earth to the space station, small modules permit optimum use of the space available and facilitate handling by astronauts in and around space stations. McDonnell Douglas uses analytical models to evaluate modularization concepts from a logistical support standpoint (the Logistic Support Analysis Model is an industry standard).
- o Modules for space stations will be based on two basic locations of equipment; inside the station and outside the station. For the modules inside the station where people can get at the modules, they want to use standard terrestrial practices, like exchange of computer cards. It is noted that the control room at the Southern California Edison Solar 1 Power Plant uses the type of modularization that will be applied within the space station. Outside the space station, there will be interchangeable "black boxes" with a considerable amount of equipment in them. They are exploring the

use of robots with intelligence to replace these modules to reduce the risk to personnel. The recent satellite rescue missions showed that a man can be more efficient, more flexible and less costly to use in these situations than a robot and that the risk is not so great. The cost of using the robot can be many times greater, and the robot itself can fail during its mission due to its own complexity.

Simple robots are good as an extension of man's capability, and keeping them simple has a tendency to make them more reliable. Modularized components and robotics should be designed to be compatible.

G. Automobile Industry Experience in Modularization

1. General Motors

- o For the first time since 1929, a new division has been formed at General Motors. A new factory is being built which will be highly automated, with many robots being used. Modularization will be done extensively. Quality management will be used in lieu of QA/QC. Car construction costs are expected to be much lower due to these innovative features.
- o On the other hand, while the car construction costs are less, the maintenance costs may be higher than normal. For example, on the GM "X" cars with front wheel drive, the engine and transmission are a complete module. To repair the transmission, the whole module must be removed resulting in a cost of \$1200 for the transmission repair. A standard cost for this job on other cars is \$400 to \$500.

2. Nissan, Tennessee

- o Nissan recently opened a plant in Tennessee using the latest Japanese techniques in auto production to reduce construction costs. Modularized construction techniques are used extensively. Quality management successfully eliminates inspection from the production line, yet quality is very high.

H. Heavy Lift Industry Experience in Modularization

1. Manitowoc Industries

- o There is no specific weight limit to the module, with regard to lifting it at the site. Multiple cranes have been used to lift process plant modules weighing several thousand tons.
- o Commercially available crawler cranes can lift up to 900 tons at close range. At further reaches, the load is reduced. Larger cranes have been designed and could be built in a relatively short period of time.
- o For barge-mounted modules that are transferred onto land, the crawler portion of several cranes can be placed on the barge and the modules placed on them. The crawlers can be synchronized and walk the module off the barge. After jacking the modules up and removing the crawler, the crane can be mounted on the crawlers to complete the erection process.

I. University Experience in Modularization

1. Massachusetts Institute of Technology (MIT)

- o The Nuclear Engineering Department at MIT has done considerable work over many years in the evaluation of current and future developments in the nuclear engineering field.

- o A significant effort was begun in 1983 to evaluate nuclear power plant innovation, and a multi-year research program has been developed. This program has three major elements:
 - o The Light Water Reactor (LWR) Innovation project
 - o The Modular High Temperature Gas Reactor (MHTGR) Project
 - o Nuclear Power Plant Innovation: Policy Analysis
- o The above projects include studies of design and construction improvements to reduce costs, including evaluations of offsite versus onsite fabrication of standard modules.

2. University of Michigan

- o The naval architecture program includes studies in advanced ship production concepts, including statistical methods.
- o Two elective courses in the College of Engineering focus specifically on ship production.
- o All courses use the publications of the National Shipbuilding Research Program (NSRP).

3. University of Washington

- o Elective courses in industrial engineering (IE) use the NSRP publications, Product Work Breakdown Structures (PWBS), Process Analysis via Accuracy Control (A/C) and other material related to advanced ship construction.
- o Students are taught how shipyard resources can be employed for end products other than ships.

4. Other Universities and Colleges

o Naval architecture and marine engineering for advanced ship design and construction is taught at the following locations:

- U.S. Navy Academy
- U.S. Merchant Marine Academy
- Webb Institute
- N.Y. State Maritime College
- Other State Maritime Schools

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