# Framework for Systematic Evaluation of Environmental Ship Design

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# Framework for Systematic Evaluation of Environmental Ship Design

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Submitted to the Department of Ocean Engineering on May 9, 1997 in Partial Fulfillment of the Requirements for the Degrees of Naval Engineer and Master of Engineering: Program in Marine Environmental Systems.

## Abstract

Increasing awareness of environmental issues related to product design, development, use and disposal is requiring that designers account for environmental issues that had previously been neglected. In the military, these requirements are being added at the same time budgets are being cut and performance expectations are being increased. A successful design must be able to incorporate a strategy that will satisfy cost, performance, quality, maintenance and legal criteria while also optimizing environmental objectives. To meet these objectives, a formal design approach or framework that considers a life-cycle evaluation of environmental requirements, cost and performance criteria is needed.

A framework is developed which considers both the engineering design requirements for the physical system, as well as the political constraints that often impact system design but are rarely formally considered. The New Attack Submarine program is used as a baseline for evaluating political constraints. Applications of the analytic hierarchy process and multiattribute utility functions are used to convey unspecified constraints to system design engineers. A case study of the approach recommended is developed using the air conditioning plants designed for the new attack submarine to eliminate the use of R-114 refrigerant.

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# 1. Introduction

## *1.1 Environmental Awareness in the Navy*

During the cold war, the U.S. Navy supported vital deterrence and presence missions around the globe. For the most part, mission requirements were met with little regard or analysis of the environmental impact Navy ships had during construction and operation. Government ships acted for the benefit of the country as a public good. In addition to providing a key element to national defense, the Navy kept thousands of skilled and well-paid shipbuilders employed across the country. The mission roles provided by the ships was believed to far outweigh any negative consequences of their operation. Very little effort was devoted to analyzing and correcting problems with Navy ships that did not affect mission readiness. This policy did not change even as environmental awareness became a key issue in politics and policy in the early 1970's. Military and government ships (Coast Guard ships as well as NOAA and other research vessels) were excluded from the provisions of laws such as the Clean Air Act (CAA), Clean Water Act (CWA) and other significant environmental laws. The governments right of eminent domain in the name of national security exempted the Navy from compliance.

In 1987 the cold war with the Soviet Union ended with the break up of the Eastern Block. Government defense policy priorities shifted rapidly from mission readiness to cost consciousness as the national security issues gave way to domestic policy issues. Defense budgets were cut drastically and the military came under intense scrutiny to cut costs. As the veil of national security was lifted, problems with defense policies relating to the environment were also opened to public scrutiny. By 1989, Defense Department [1] and Navy instructions began to seriously address hazardous material control and management.[2] Military awareness of environmental problems continued to improve through the early 1990's, culminating with Executive Order 12856 in August 1993. This Executive Order required federal compliance with various sections of the Emergency Planning and Community Right-To-Know Act (EPCRA).[3] The policy change effectively opened Defense Department operations to public scrutiny. Commanding

Officers of ships and naval bases are subject to personal liability and criminal prosecution for negligent acts relating to environmental pollution. Federal facilities have also been subjected to local laws, where practical, and required to document areas where compliance was not practical. Another significant change implemented in 1991 subjected all new government programs to environmental impact assessment requirements.[4]

In order to meet rapidly evolving environmental requirements, the Department of Defense and the Navy has integrated an environmental program manager into the procurement team for new systems. The first major Navy program with an environmental manager was the New Attack Submarine (NSSN). As the Navy's first major program considering environmental impacts at the procurement stage, the opportunities for improvements were dramatic while the policies, procedures and requirements were vague or non-existent. Thus the performance of the NSSN environmental program will have a major impact on the policies, practices and procedures used on subsequent system acquisitions throughout the Department of Defense. This thesis will examine possible environmental management policies that could be adopted in future programs and evaluate their potential effectiveness.

### *1.2 New Attack Submarine Environmental Program*

The fall of the Soviet Union and subsequent refocusing of defense mission planning and spending resulted in cancellation of the Seawolf class submarine program after 3 ships instead of the 30 ships planned during the Cold War.[5] The change in the Navy's defense policy required replacement of older submarines with a platform that is much less expensive than the *Seawolf* class submarines and capable of supporting ground forces in the littoral regions (ocean areas close to shore).[6] The new attack submarine program was quickly formed to develop a submarine to meet the new doctrine and fiscal requirements. For the first time in a major defense department acquisition program, environmental issues were openly addressed within the acquisition program team and incorporated into the preliminary design of the submarine.

The environmental management goals and objectives include completing an environmental analysis and addressing environmental compliance requirements. Formal control procedures are being developed to mitigate the cost and risk associated with environmental changes. The use and generation of hazardous materials are also being examined to eliminate or reduce pollution where possible. The program is not focused on the construction of the ship, but is looking at the entire life-cycle, including final disposal at the end of a 30 year life. The overall objective is to reduce the potential for environmental cleanup and remediation liability during the submarine's life-cycle.[7] This requires an estimation of the potential changes in pollution control requirements that will be implemented over the next 35 years! Both current and proposed environmental legislation and current program cost are being analyzed to incorporate necessary design changes in the ship before construction starts in 1997.

Pollution control methods for the ship are focusing on discharges during operation and hazardous materials generated during construction and operation. Discharges of various types are part of the routine operation of a submarine. Normally discharges are performed in the open ocean several miles offshore. While in port or transiting in or out of port, polluting discharges are kept onboard for shore or open ocean disposal. Some in port maintenance procedures, such as steam generator blowdowns, can result in discharging regulated items overboard while in port.

Potential pollution sources onboard submarines are numerous. Water seals and steam and feedwater leaks collect in bilge's along with oil from operating machinery. When onboard storage capacity is reached, the bilge water is pumped overboard. Operation of a pressurized water reactor (PWR) requires periodic steam generator flushing known as blowdowns. Steam Generator blowdowns discharge hot, phosphate water overboard. Liquids from sewage, showers and food preparation are also pumped overboard (black and grey water respectively). Trash is compressed, weighted and discharged overboard through the trash disposal unit (TDU). Sources of trash on a submarine are primarily food wastes and packaging materials, including non-biodegradable plastics and cans. Restrictions on discharging trash at sea have made sanitary storage facilities for items such as food contaminated plastic a major issue. Other discharge sources include lubricants used on external control surfaces such as the rudder and fairwater planes and radiation from nuclear ships.

Hazardous materials are being replaced in the design when possible. If hazardous materials can not be eliminated, the amount and location are being recorded. Components are being examined for hazardous materials they contain only, not for hazardous materials used during their construction. Vendors are expected to reflect environmental costs associated with producing components in their prices. The environmental management team is integrated into the procurement team. Methods for improving environmental performance are being directed from the environmental management team down to various contractors and Navy technical codes located in the Naval Sea Systems Command (NAVSEA).

### *1.3 Acquisition Design Considerations*

Incorporating environmental concerns into the military procurement system is much more complex and difficult to accomplish than it appears. Requirements are not always clearly spelled out and decisions are often made favoring less than optimum engineering considerations. The first step in establishing a framework for environmental design is to examine the major influences on the eventual design of the submarine. Important influences, even those not directly associated with the engineering aspects of the program must be considered in the framework for optimal results.

Considerations involved in developing the final design for a submarine are shown in Figure 1-1. Procurement cost limits are imposed by the federal budget. Increasingly, life cycle cost is also being considered in establishing program limits. Political influences come from the biases of the procurement team, previous designs, congress and congressional staffers. Regulations of the states where the ship will operate and federal regulations determine many of the environmental requirements that the ship must meet. International regulations such as the MARPOL 73/78, which bans dumping plastics at sea among other regulations, and the United Nations Convention on the Law of the Sea (UNCLOS) regulate ship operations with respect to the environment.

Bureaucratic momentum represents the nature of bureaucratic organizations to promote their own interests, survival and growth. Military industrial base considerations involve awarding contracts to specific companies in order to keep the production base capable of producing various systems which only have military applications. Performance specifications are criteria the design must meet to be approved. Individual performance specifications can be changed over the course of the project and are often traded off with cost and other specifications.

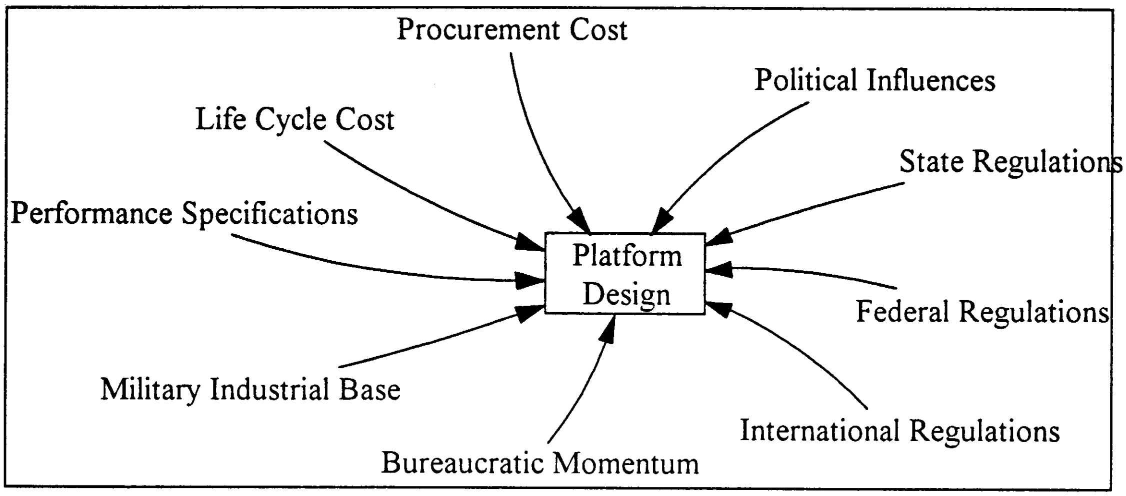


**Figure 1-1: Considerations in the Design Process**

# 2. Background

Deputy Under Secretary of Defense for Environmental Security Sherri Goodman has stated that 80 percent of DOD's pollution problems and concerns can be traced to some form of acquisition action or activity.[8] In order to reduce DOD pollution problems, environmental concerns must be addressed early and incorporated into the design and procurement of new systems. Government agencies and government actions in the environmental arena have also become a focus for environmental leadership. Federal activities that used to be exempt from environmental legislation such as the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA) and the Pollution Prevention Act of 1990 (PPA).[9] Awareness of Defense Department environmental performance has increased since the fall of the Soviet Union. Federal agencies and facilities are now leading the way in meeting and exceeding environmental requirements originally imposed on the private sector.[9] United States environmental leadership at the federal and local level is also being extended to the realm of international environmental agreements. President Clinton's Executive Order 12856 explicitly gives the federal government a leadership role in dealing with environmental issues in the following passage:

> "WHEREAS, the Federal Government should become a leader in the field of pollution prevention through the management of its facilities, its acquisition practices, and in supporting the development of innovative pollution prevention programs and technologies;..."[3]

## *2.1 Federal Compliance With Right-to-Know and Pollution Prevention Requirements*

Executive Order 12856, signed on August 3, 1993, signaled a major shift in the environmental policy of the Department of Defense (DOD). Practices kept secret under the guise of national security were opened to public scrutiny literally overnight. EO 12856 requires most federal activities to comply with all sections of the Emergency Planning and Community Right-to-Know Act and Pollution Prevention Act. Additionally EO 12856 requires each federal agency to reduce the amount of toxic chemicals released or transferred from the agency's activities by fifty percent.[9] The 50% reduction goal establishes federal agencies as leaders in industrial pollution prevention, beyond already established laws and regulations. An annual progress reporting requirement is also established in the executive order to monitor compliance.[3] Further emphasis on the Federal Government setting an example and become the leader in pollution prevention is contained in the EO; "Agencies should also set goals for reducing the acquisition, manufacturing, and use of products containing toxic substances, and revise specifications and standards to reduce the procurement of toxic substances."[10]

EPCRA gives the public access to information on hazardous and toxic chemicals at sites in their communities and promotes the establishment of emergency response plans and procedures. Hazardous material inventories, wastes and releases are required to be reported and the information gathered and plans generated as a result of EPCRA are required to be made available to the general public.[11] The PPA stresses source reduction in pollution prevention and control. It formally recognizes that most existing regulations focus on treatment and disposal rather than source reduction and that "source reduction is fundamentally different and more desirable than waste management and pollution control".[11] In essence, EO 12856 subjects the Federal Government to the same principles of public disclosure and accountability that have been enacted for application to the private sector and directs the Federal government to pursue pollution prevention at the source through substitution of less hazardous materials, improved maintenance, and more efficient production processes.[12]

Section 3-303 of the Executive Order addresses acquisition and procurement of toxic chemicals and hazardous substances and therefore applies directly to acquisition programs such as the NSSN. Reductions from the acquisition process have the potential to change items and systems bought and used, the processes by which they are manufactured, how they are maintained and operated and finally, how their disposal. Executive Order 12856 also directs DOD to review standardized documents, processes and procedures, including Military Specifications and Standards for opportunities to eliminate the use of toxic and hazardous materials. A key point is that the emphasis is to be on source reduction, not recycling, remediation or disposal. This requires consideration of pollution prevention opportunities in every area at the start of the acquisition process.[8]

Secretary of Defense Perry signed a memorandum on 11 August 1994, which detailed DOD's pollution prevention strategy. Pollution prevention and other environmental concerns are to be integrated into the entire life cycle of acquisition programs. Stated goals of the strategy include developing environmental life-cycle cost estimating tools, revising military standards, adopting a systems engineering approach, and changing environmental documentation including: specifications and standards, acquisition regulations and contract documentation.[8]

The Navy has fully adopted the precepts of EO 12856 and most notably the emphasis on source reduction. The following language from the Department of the Navy's *Environmental and Natural Resources Program Manual* emphasizes the priorities established for the Navy through Executive Order 12856.

> "Executive Order 12856 requires DOD to conduct its facility management and acquisition activities so that, to the maximum extent practicable, the quantity of toxic chemicals entering any waste stream, including releases to the environment, is reduced as expeditiously as possible through source reduction; that waste that is generated is recycled to the maximum extent practicable; and that any wastes remaining are stored, treated, or disposed of in a manner protective of public health and the environment."
>
> "...To the maximum extent practicable, such reductions will be achieved by implementation of source reduction practices."
>
> "...DOD will establish a plan and goals for eliminating or reducing the unnecessary acquisition of products containing extremely hazardous substances or toxic chemicals. Similarly, DOD will establish a plan and goal for voluntarily reducing its own manufacturing, processing, and use of extremely hazardous substances and toxic chemicals."[13]

## 2.2 International Marine Pollution Agreements and the Law of the Sea

The United States is also taking a leadership role in international environmental issues. Secretary of State Warren Christopher promised to "put environmental issues where they belong; in the mainstream of foreign policy." in an April 9, 1996 speech at Stanford University.[14] The major international pollution prevention regulations affecting ships are the International Convention for the Prevention of Pollution by Ships 1973 as modified by the Protocol of 1978 (MARPOL 73/78) and the United Nations Convention on the Law of the Sea 1982 (UNCLOS III). Secretary Christopher's comments seem to reflect the U.S. policy principle used to negotiate the convention to"...reflect and protect the stake of all states in the preservation of the global marine environment and the sustainable use of ocean resources wherever located."[15] Shipboard waste management practices in the design and construction of new ships must account for the baseline requirements set by international convention and be adaptable to future changes in these requirements.

### 2.2.1 MARPOL 73/78

MARPOL 73/78 regulates most discharges from ships at sea. The regulations are broken down into five annexes which contain specific regulations for a category of substances. These annexes cover the following topics: oil pollution, chemicals transported in bulk, harmful substances transported in packaged form, sewage and garbage. Regulated items of concern to military ships include oil, sewage and garbage which are covered in Annexes I, IV and V respectively . Each annex limits the quantity or concentration of discharges allowed and the locations where discharges are acceptable.[16] Annexes I and V have been fully ratified and are considered binding international agreements. Annex IV has yet to reach the required number of signatory countries, however most of the provisions are already included in national laws and regulations.[17]

### 2.2.2 UNCLOS III

Part XII of the convention addresses all sources of marine pollution, including pollution from land based sources, ocean dumping, vessels, seabed activities and atmospheric interaction. States are given the responsibility to enact and enforce environmental laws in their exclusive economic zones (EEZ). The EEZ can extend out 200 nautical miles from the coast. Since this region covers 30% of the world's oceans[15], enforcement of international environmental standards is expected to improve the overall environmental condition of the oceans. UNCLOS III does not set specific discharge limits, but requires signatories to conform to existing international standards such as MARPOL 73/78 and to create regulations for their own areas that must be at least as restrictive as existing requirements.

States are expected to control pollution from "any source" using "the best practicable means at their disposal and in accordance with their capabilities"[18]. They must ensure pollution in their jurisdiction does not spread outside "areas where they exercise sovereign rights."[18] Additionally, pollution must be reduced without transferring it from one area to another or transforming it from one type to another. States must not only prevent pollution from entering other states jurisdictions but must ensure pollution does not affect the open ocean as well. States are required to establish regulations for point sources pollution from vessels including pollution of the marine environment that comes from vessel air emissions.

States are encouraged to work together to develop general regional policies for control of pollution from all sources. Specific sources to be minimized include land based sources, atmospheric, dumping, vessels, and installations. Additionally, preventive measures through safe design, construction, operation and manning requirements are called out for vessels and installations at sea.[18]

It is important to note that under UNCLOS III, the minimum environmental standards are those set by MARPOL 73/78 and similar agreements and that local states are encouraged to develop more restrictive environmental standards for areas under their control. This may eventually extend MARPOL's limit of being at least 12 nautical miles from land for most discharges out to the 200 nautical mile limit of a country's EEZ.

### 2.2.3 Special Areas

Both MARPOL 73/78 and UNCLOS III provide for the designation of certain geographic areas of the world as "Special Areas" requiring particular care from ships operating in those areas.[16] [18] These areas have rare or fragile ecosystems which may be upset or destroyed by discharges from ships. As such, special areas are subjected to more restrictive environmental regulations.

Discharge limits for ships operating in special areas are much more restrictive to ensure greater protection of these environments. Special areas have been designated for the following locations: The Mediterranean Sea, the Baltic Sea, the Black Sea, the Red Sea, the Persian Gulf, the North Sea, the Antarctic area, the Arctic and the Caribbean.[17] Provisions are made for establishing special vessel regulations within a countries exclusive economic zone through the IMO. If the measures are required for "recognized technical reasons" a special area can be designated. Rules governing vessels in a special area must be approved by the appropriate international organization based on scientific and technical evidence. Once a special area has been designated, the local coastal states are responsible for establishing the discharge limits within the special area and enforcing these requirements.[18]

From a design standpoint, new ships need to incorporate storage capacity for expected discharge levels or develop waste management systems that meet the strictest special area requirements. Since requirements can change over the life of a ship, a means to operate without making discharges for a short time is needed. Operational predictions for the expected amount of time required to be spent in a special area and the corresponding discharge rates are used to size the storage capacity.

### 2.2.4 Military Exemption

A key provision of both MARPOL 73/78 and UNCLOS III is an exemption from compliance for military and other non-commercial government ships. States are supposed to comply with the measures as much as is "reasonably practicable."[16] [18] Individual states define what is reasonably practicable and how ,or if, changes will be made to existing ships and incorporated into new ship designs. Although MARPOL 73/78 allows nations to exempt their military vessels from compliance, domestic legislation requires U.S. ships to act "in a manner consistent with the MARPOL Protocol."[19] The policy of the United States as promulgated in the mission statement for the environmentally sound ship of the 21$^{st}$ century, is to comply with local, national and international laws and regulations on all military ships during peacetime.[20]

## *2.3 NSSN Environmental Compliance*

The Navy initiated the New Attack Submarine Program in 1992 as a more affordable alternative to the *Seawolf* class of submarines. The promulgation of Executive Order 12856 lead to a project objective to achieve maximum Environmental, Safety and Health (ESH) integration. A life-cycle approach, designed to ensure ESH integration over the 30+ year operational life-cycle of the ship, has been adopted.[21] The formal NSSN environmental policy is as follows:

> "The New Attack Submarine Program is fully committed to ensure that the next class of attack submarines will be designed and constructed so that the operation, deployment, maintenance, overhaul and ultimate disposal of the submarine will meet all applicable environmental requirements."[22]

In order to implement the new environmental strategy, a new management structure was needed. The new environmental strategies required to support the ship's readiness and operational requirements were formally identified. A program-level environmental management team was then established to incorporate the new environmental requirements into the ship's design. The environmental management team was made up of representatives with a vested interest in each of the submarine's life cycle phases (i.e., construction, supply, facilities, disposal, logistics, maintenance, etc.) and is responsible for pursuing the programs environmental management goals and objectives. Joint government / contractor teams ("design/build teams") have been formed to ensure "lessons learned" from prior submarine projects are utilized to reduce both cost and environmental impact of the final design. The objectives of the EMT are listed below:

- To conduct and implement management planning that addresses the environmental analysis (e.g. National Environmental Policy Act) and other environmental compliance requirements applicable to the New Attack Submarine Program and to provide adequate management oversight to mitigate environmental-related costs, schedule and performance risks.
- To be in compliance with applicable environmental requirements during all life cycle phases of the program. Applicable requirements include international treaties, federal, regional, state and local statutes, executive orders and other international conventions.
- To control the use and generation of hazardous and non-hazardous materials and waste during all New Attack Submarine life cycle phases through source reduction, pollution prevention and recycling efforts.
- To address environmental considerations in solicitation, source selection, contract award, and contract administration documents.
- To reduce the potential for environmental clean-up and remediation liabilities.[21]

The methods for achieving each objective are addressed in the NSSN's Environmental Management Plan and Pollution Prevention Strategy documents. The shipbuilder was also tasked to develop an implementation plan that embraced these objectives. There is no established precedent for the actions being taken by the New Attack Submarine Program, therefore, the methods of measurement comparison are not fully established. However, the *Seawolf* class design is being used as a baseline for comparison and the expected cost avoidance by the program are expected to be significant over the life of the program.[21]

### *2.4 Designing for Pollution Prevention*

Pollution prevention, as defined in the Pollution Prevention Act of 1990, is any practice that reduces the amount or the impacts of any pollutant released into the environment through source reduction. This includes modifications of equipment and processes; reformulation or redesign of products and processes; substitution or reductions in raw material usage; and improvements in the organizational activities associated with producing a good or providing a service. The focus of pollution prevention is on source reduction, which considers the release of any hazardous substance, pollutant or contaminant released to the environment. Source reduction is not limited to substances officially regarded as hazardous substances or pollutants, but extends to any waste stream released into the environment.[11]

By considering pollution prevention during design, the designer must extend the scope of analysis beyond normal operations to consider procurement and construction, operations and maintenance and subsequent disposal of the system. Thus designing a product for pollution prevention attempts to minimize not only wastes exiting the product throughout its' lifecycle, but materials going into and consumed by the product as well. This is a proactive approach for meeting both current regulatory requirements as well as potential future requirements imposed through national or international law.

### 2.4.1 Benefits of Designing for Pollution Prevention

The primary reason for designing for pollution prevention is an overall cost savings. Cost savings can be both direct and indirect, with benefits received immediately and over the life cycle of the system. Analyzing a systems waste streams tends to identify inefficiencies in the process which when corrected increase the overall efficiency of the system. This reduces both the energy used in production and operation, generating further cost savings.

The importance of considering pollution prevention issues at the start of the system design phase is directly related to the cost of implementing pollution prevention requirements. An estimated 70 percent of product system costs are fixed in the design stage. Activities associated with the design phase typically account for 5 to 15 percent of total product development costs, yet decisions made at this point can determine 50 to 80 percent of the life cycle cost of the entire project.[23],[24],[25]

The secondary reason for adopting a pollution prevention strategy is for improving the perception of regulators and the public. Exceeding current minimum regulatory requirements can prevent the need for costly end of pipe solutions if future environmental regulations become more restrictive. Eliminating waste streams also eases the burden of environmental management. With fewer waste streams to monitor, reporting, permitting, monitoring, environmental training, record keeping, treatment and storage time can be greatly reduced or eliminated. Also the opportunities for oversight or accidents related to various waste streams will be greatly reduced. Additionally, relationships with local and federal regulators, and the public will be improved.[26]

### 2.4.2 Barriers to Designing for Pollution Prevention

Although the benefits of adopting a pollution prevention strategy are expected to outweigh potential barriers, understanding the barriers will allow for accurate assessment of pollution prevention costs and benefits as well as the impediments to implementing a pollution prevention strategy.

The first significant barrier to designing for pollution prevention is a lack of information and experience. Design for pollution prevention places additional knowledge requirements on design engineers, requiring additional training outside their area of expertise. Design engineers must be cognizant of environmental regulations impacting the waste streams of their products; current and projected classification of materials as pollutants or hazardous materials; and understand the complete lifecycle of the entire system and the systems interactions between subsystems and components of the final product including operation, maintenance and final disposal. Few organizations have well established methods for pollution prevention design and data documenting the added costs and benefits received are not readily available. Additionally, the costs of analysis and project schedule impact are not easily quantified at the start of a project and therefore add an additional element of risk.[26]

The second significant barrier to designing for pollution prevention is quantifying the costs associated with making design changes up front for savings that will be realized in the future. Pollution prevention requires the design team to adopt a life cycle perspective, not only for environmental considerations, but also for cost savings considerations. Adopting a lifecycle prospective is especially difficult for long lived products such as Navy ships. The expected life of most ships is around 30 years, necessitating up front forecasts of economic considerations over this period for design decision making. Additionally, implementing a pollution prevention strategy carries up front administrative and design costs which must be offset against future cost savings. Unfortunately, capturing the true costs of environmental decisions and plans can be difficult and is not readily available in traditional accounting methods. Distorted cost information can obscure the positive aspects of beneficial changes and make them more difficult to implement.[27]

Support from senior management can also be a significant obstacle and is often closely related to the cost problems and concerns addressed above. Proactive environmental management requires a commitment to and an understanding of the potential returns from incorporating pollution prevention into system design. Environmental systems can be very large, complex, highly uncertain and involve long time frames (e.g. 35 years to disposal). Analysis methods that clearly present potential cost savings associated with pollution prevention design opportunities increase the likelihood of implementing successful pollution prevention strategies.[28]

### 2.4.3 Similar Design Concepts

The general themes associated with pollution prevention are already integrated into many system design strategies. Concepts such as 'good engineering practice', 'as low as reasonably achievable (ALARA)', 'total quality management (TQM)', 'design for environment (DfE)', 'concurrent engineering' and 'life cycle design' are very similar in many respects. Pollution prevention is simply an extension of these concepts to focus on a specific purpose and it is readily integrated into current design practices.[26]

Good engineering practice implies designing systems with maximum efficiency and inherent flexibility with a minimum use of natural resources. ALARA is intended to minimize or prevent, to the maximum extent practicable, a hazardous discharge or situation. Both these concepts are easily adapted to meet the objectives of pollution prevention design strategy.

Systems engineering, life cycle design and concurrent engineering emphasize proactive design approaches extended over the life cycle of a product to prevent shifting problems between life cycle stages. Process and product design are viewed from a systems perspective rather than as separate functions in a linear design sequence.[23] Concurrent design or concurrent engineering simultaneously develops product and process design and emphasizes incorporation of downstream criteria into the design process.[25] Again, use of these design strategies already includes or is readily adapted to a pollution prevention strategy.

Design for Environment is a strategy that evolved from a design for "X" approach developed by AT&T where X represents design objectives from manufacturing and disassembly to reliability or environment.[29] DfE emphasizes a life cycle approach to product design that considers all the environmental impacts and costs associated with the product. Multifunctional, integrated teams provide input in the design phase to improve products up front. Recyclability and overall environmental friendliness is designed into products without compromising the products functionality, quality or integrity.[25] DfE concepts are closely related to pollution prevention strategies and are an integral part of most environmental design methodologies.

### 2.4.4 Pollution Prevention and Quality Control

Pollution prevention must be considered at the earliest stages of design and recognized as another project constraint along with cost, schedule and function.[26] In order to fully integrate pollution prevention into a design process, it must be considered in terms understandable and achievable by each member of the design team, across each hierarchical level. Consideration of pollution prevention issues as an extension of system quality is a quick and straightforward way to accomplish these requirements. Companies already have quality control systems in place to ensure necessary quality levels are maintained. In Navy ship construction, military specifications (MilSpecs) or equivalent commercial standards are cited to ensure the platform meets acceptable standards for performance and quality. Considering environmental issues as defects in product or process quality may allow already established and in place quality infrastructures to be utilized for environmental design.

Similar to quality defects, the cost associated with making design changes to address environmental issues increases as products progress through the design phase to production and use. End of pipe treatment systems are similar to after market system repairs for quality oversights. Implementation costs are high and may have additional drawbacks. Since they were not considered in the initial systems requirements, add on systems are not easily adapted to existing performance requirements. Unintended effects of reduced efficiencies, shorter operating cycles and higher maintenance costs increase the life-cycle cost of operating the system and should be considered in assessing the cost of the treatment system. Developing and installing end of pipe waste treatment systems is not seen in the negative light of a product recall, yet the incurred costs are similar. Considering environmental issues as quality defects allows the synergism of existing systems and the cost accounting developed for quality issues to be readily applied to current design systems.

# 3. Procurement Process for Navy Ships

Before being able to establish a framework for implementing a life cycle pollution prevention strategy for Navy ships, the system that the framework will be developed for must be understood. Successfully engineered products that do not fully account for global system realities may not be implementable. Under these circumstances, the effort and expense spent on system design and development is wasted. As such, the non-engineering constraints imposed on, or at least the inputs to, the detailed design of a Navy ship and its' systems by the procurement process must be recognized in any design framework. The following example illustrates how a failure to account for non-engineering constraints can prevent otherwise successful environmental engineering designs from being adopted.

## *3.1 ARL's Synthetic Lubricating Oil*

In the early 1990's, Penn State's Applied Research Laboratory (ARL) conducted a research project into environmentally friendly lubricants for Navy ships. The research was directed to meet two different requirements. The first case was to develop an environmentally friendly replacement for the 2190 TEP oil currently used in Navy ships. The replacement was required to be fully compatible with all onboard systems and operating procedures and demonstrate an improvement, in both cost and environmental performance, over 2190 TEP. Additionally, the synthetic oil has demonstrated better wear characteristics. The second case was to develop additional lubricants that could be used in future systems, eliminating the backfit constraints of the first case. This class of lubricants was intended to produce significant improvements in environmental performance. Biodegradable and water soluble lubricants which could be designed into future propulsion system requirements were developed for this case.

The research into a 2190 compatible lubricant lead to the development of an interchangeable synthetic oil that lasted 4 times as long as 2190. The improved performance significantly reduces the amount of lubrication oil required per ship and therefore the associated disposal costs and environmental impacts. The synthetic oil is completely interchangeable with 2190, conforms to all certification standards, operates with onboard equipment without any modification and can even be mixed directly with 2190. The Navy has certified a producer and established the supply chain necessary to make it available to shipboard personnel. The oil costs about 3 times the price of 2190 to procure, but given that the life of the new oil is 4 times that of 2190, a quick life-cycle cost analysis shows that it is cheaper to use the new oil without even considering the cost savings from lower inventory requirements, improved performance and used oil disposal. From an engineering perspective, the synthetic 2190 oil is a successfully engineered, environmentally friendly alternative that should be used in all Navy ships. Unfortunately, because the procurement system was not analyzed as part of the project, the synthetic oil is available, but not often used in the fleet.[30]

Navy ships operate on annual budgets for operating and maintenance costs that are largely based on prior years expenditures of the ship and sister ships of the same class and the maintenance cycle of the ship. Budget performance is one criteria used to compare the performance of the ship's crew including the commanding officer and the supply officer. Normal tours of duty for ships officers are three years. This system does not support making large, unbudgeted outlays in a given year to generate savings in the future. The officers who get the benefit of having money budgeted for lube oil without having the need to purchase it are not the same as the officers who use their limited budget for future savings. There is no perceptible benefit to the current ship's company to purchase the synthetic oil and a significant penalty for doing so in the operating budget. The manning and budget system of the fleet effectively prevents the Navy and the environment from benefiting from ARL's synthetic 2190 oil. An up front understanding of the global system for Navy lubricants may have lead to a different engineering approach or at least a concerted effort to modify support systems to ensure an easily recognizable better alternative could be implemented.

### 3.2 Design and Acquisition Process

The ship design process is closely associated with the acquisition requirements for Department of Defense programs as shown in Figure 3-1. The acquisition requirements are set by Congress and implemented through DOD regulations and instructions.

Regulations differ for different programs based on the expected total expenditures of the program.[32] Ship acquisition programs are among the most expensive programs in DOD and are subject to the majority of the existing regulations, however the acquisition process for new systems and components is similar (including development and procurement of environmental systems). System level acquisition programs follow the same set of regulations and procedures, however most of the review and approval decisions are made at a lower level. [32] A basic understanding of the design requirements imposed by the acquisition process and the various interests that are represented is required before a framework to operate within the system can be developed.

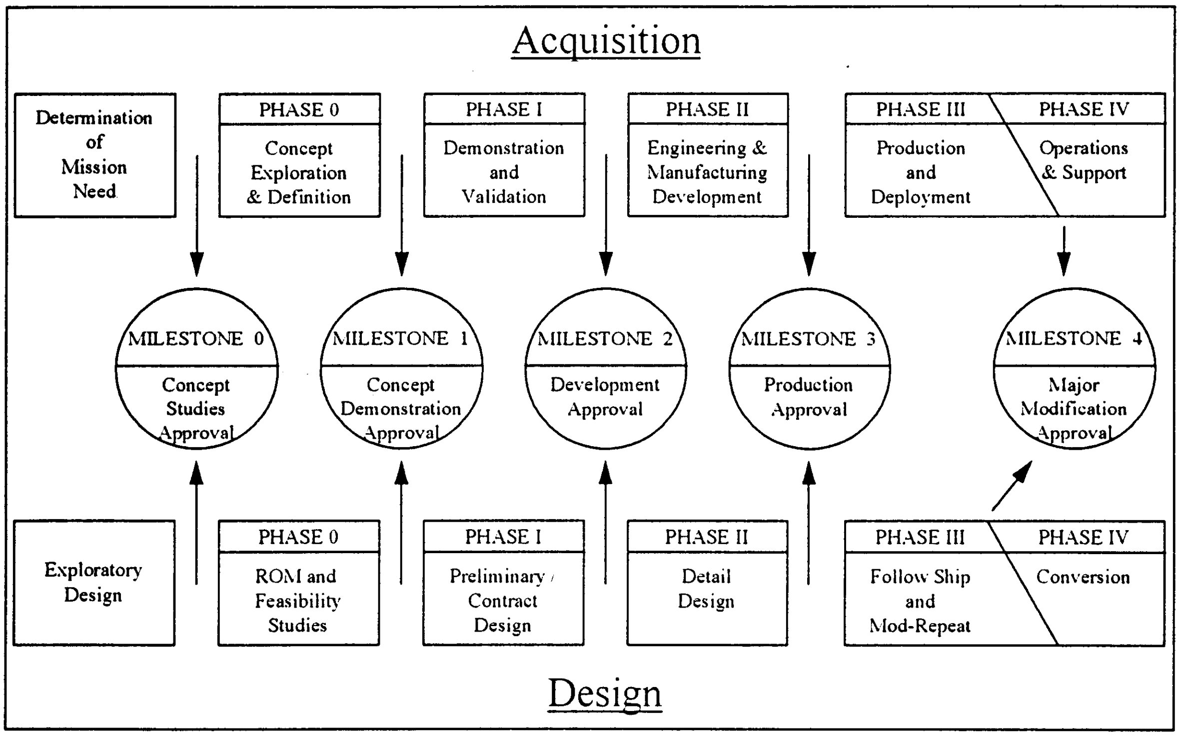


**Figure 3-1: USN Ship Design and Acquisition Process**

Acquisition programs start with the identification of a mission need. A mission need is identified by a DOD component with an operational deficiency which can not be overcome by changing tactics or procedures. A mission need statement (MNS) is developed which explains the deficiency and identifies potential material and non-material alternatives. The desired operational capabilities desired to correct the deficiency are also specified in broad, general terms. Mission need statements are generally developed by individual services (both active duty military and civilian personnel) with assistance from service and defense intelligence agencies.

Not all acquisition programs are initiated in response to a specific military threat. Economic benefits, new technological opportunities, environmental restrictions and other considerations may lead to the formation of a new acquisition program.[32] For example, the Deputy Chief of Naval Operations for Logistics developed the "Mission Need Statement for the Environmentally Sound Ship of the 21st Century". This MNS has been developed to ensure new ships eliminate or have the ability to process ship-board wastes to ensure freedom of operations in all waters and ports worldwide.[31] The waste stream problems encountered by Navy ships can be solved by many different alternatives including getting waivers through political channels, source reduction, onboard storage for eventual shore disposal and developing ship-board waste stream processing equipment. The component developing the MNS documents alternatives and recommends formation of an acquisition program to correct the deficiency. The MNS is then reviewed by the Joint Requirements Oversight Council (JROC) to determine the validity of the need and the potential for an acquisition program meeting joint service requirements. [32]

Once validated, the MNS is sent to the Under Secretary of Defense for Acquisition and Technology (USD(A&T)) who convenes a Milestone 0 Defense Acquisition Review Board (DAB) to review the mission needs statement (MNS), identify possible alternative solutions, and authorize concept studies. The DAB is made up of senior defense department acquisition officials including political appointees in the Department of Defense and senior military and civilian personnel from the military services. A favorable Milestone 0 decision authorizes Phase 0 concept level studies to begin. A favorable Milestone 0 decision does not yet mean that a new acquisition program has been initiated. At this point in the process USD(A&T) designates an individual to be the milestone decision authority (MDA). The MDA approves the transition of an acquisition program between phases through the milestone decision points.[32] Milestone approval must be received prior to proceeding with the next phase of the design. Environmental details are required at each milestone and are formally incorporated into each phase of the acquisition process.[12]

Phase 0 typically consists of several short-term concept studies in areas identified by the DAB. The concept studies define and evaluate the feasibility of a concept and provide a basis for comparing alternatives. The concept studies are both design and acquisition based and contain estimates for cost, schedule and performance, opportunities for subsequent tradeoffs and an overall acquisition strategy and test and evaluation strategy. For Navy ships and systems, phase 0 has inputs from a wide assortment of stakeholders. These include the Navy's engineering and technical staff (NAVSEA codes), assorted engineering design and manufacturing contractors and some input from the fleet or end users of the product. [32]

Once the concept studies are completed, a Milestone 1 decision is made to determine if an acquisition program is warranted based on the results of the concept studies. Approval to enter Phase I formally establishes an acquisition program. At this point, the MDA must also establish a formal acquisition strategy, cost objectives, a program baseline and the formal criteria required for the program to exit Phase I. The program baseline documents the cost, schedule, performance objectives and thresholds of the program. The life-cycle cost objectives for the program are based on consideration of the projected resources Congress will authorize. Recent unit procurement costs are used to make parametric cost estimates and technology and cost trends are also considered. Each milestone review reassesses the cost objectives and evaluates the program's progress towards achieving them. [32] Smaller programs and systems procurements in the Navy remain under the cognizance of NAVSEA.[39]

Phase I is the program definition and risk reduction phase. The program concepts are defined in a higher level of detail than in the Phase 0 concept studies. Assessments of the merits of alternatives are refined with the new information and, if practical, prototypes and technology demonstrations are conducted to quantify and reduce the risk associated with each concept. In ship design, prototypes are prohibited because of the high cost and lead time required, however individual systems and components are prototyped as warranted. Phase I also identifies cost drivers, sets preliminary life-cycle cost estimates, conducts tradeoffs between life-cycle cost and performance levels and develops alternative acquisition strategies and cost projections. [32]

DOD recognizes the importance of reducing life-cycle costs early in the design and focuses attention on making reduction during this phase of the program. Cost and performance tradeoff analyses must be conducted before the acquisition approach is finalized, which occurs at Milestone II. A cost/performance integrated process team (CPIPT) is formed with representation from users and industry if allowed by statute. [32]

The ship design is developed to the point where ship builders have the ability to submit construction bids on the project. The ship dimensions, general layout and systems to be included have been identified and planned, however the fine details of the ship are not yet completed.

At Milestone II, the MDA assesses the programs progress and performance to date and the projected costs. If the results of Phase I warrant continuation of the program, entry into the Engineering and Manufacturing Development phase is approved. At this point, the MDA approves the acquisition strategy of the program, the cost objectives, the program baseline and the Phase II exit criteria. A decision is also made on the initial production levels. The cost objective is based on considering cost as an independent variable (CAIV). The cost of any program must fit within approved and projected defense department budgets. [32] Expenditure levels authorized by Congress must be met for the program is to continue. Tradeoffs of current cost increases to support projected life-cycle savings must be approved in the annual budget appropriations for the program to proceed, regardless of the projected long term savings.

In Phase II the most promising design is refined. For ships, a detailed design is developed considering cost-effective design alternatives, the manufacturing and production processes of the selected manufacturer(s), and the projected system capabilities. Identification of the production base allows contractors to develop their production systems and process during this phase. The design is updated with test results and system upgrades as well as design fixes identified by completing the detailed design.[32]

Milestone III authorizes the programs final design entrance into production. Again, the acquisition strategy is reviewed with the baseline and refined cost projections. Congressional Defense Committees review the status of the program through several required reports and must allocate funds for production in the budget for authorization to proceed.[32]

For Navy ships, the acquisition and design process does not end with production. The program office is maintained, in some form, throughout the life-cycle of the ship class to oversee modifications and improvements in the design and the eventual demilitarization and disposal of the ship. The program manager is responsible for ensuring the disposal is carried out in a way that minimizes DOD liability for environmental, safety and health issues. This requires up front design considerations for disposal that will be conducted 30 to 40 years in the future with unknown technologies and environmental regulations.

### 3.2.1 Congressional Influence

Congress influences defense procurement programs through oversight committees and the budget process. The defense budget accounted for over 17% of federal outlays in 1995, and for many regions of the country military spending is a vital source of jobs and income. [33],[43] Because it is such a large purchaser of goods and services, Congress is concerned with defense as part of its constituency policy. How DOD spends money is subjected to social, economic and political judgments outside the realm of national security.[34] Most of these judgments are made through committee hearings, budget authorizations or public laws. Ten Senate committees and 11 House committees have formal jurisdiction over various parts of defense policy and other committees without formal jurisdiction also hold hearings on particular defense matters.[34]

Congressional influences can, and often do, affect the outcome of ship design and procurement decisions. The design of the DDG-51 class ship had arbitrary limits imposed on the size and design of the hull. The limits were based on keeping projected costs down by manipulating the parametrics of the cost models[35] and meeting arbitrary force structures related to ship classifications. This prevented optimizing the design for the mission requirements or for the procurement or life-cycle cost of the ship.[42] The Department of Defense Appropriations Act, 1996 (Public Law 104-61) contains requirements for the procurement of "an emergency generator set for the New Attack Submarine".[36] These requirements forced the program to use a larger, more expensive diesel generator than was required to meet the performance requirements of the submarine. Additionally, the submarine design is limited in the weight of equipment it can carry and the extra weight and space could have otherwise been used for other equipment.[45] The legal requirement for the NSSN emergency generator was the result of various congressional policy decisions on maintaining the military industrial base, "buy American" sentiment and lobbying by industry.

Congressional influences are principally wielded through annual Department of Defense Appropriations, corporate lobbying and the efforts of congressional staffers.

### *3.2.1.1 Congressional Budget Process*

The congressional budget process can result in legal requirements for ships or ship systems, as in Public Law 104-61. Congress annually sets the Department of Defense budget through the appropriations acts. Each appropriations act contains spending limits for each line item of the budget. Congress is not formally limited in how detailed a line item can be and utilizes the level of detail in the budget to exercise control over the executive branch and to carry out various constituency policies.[34] The size of the Defense Department budget also makes it a target for social policies not directly related to national defense. For example, Congress requires DOD to set aside contracts for small businesses and minority firms. In these instances, the contract and the business selected may limit the scope of a project beyond strictly engineering or cost efficiency concerns.[33]

The combination of set asides and the line-item budget can lead to Congressional determination of design parameters. Further, these decisions are often made to ensure the needs of a particular constituent are met rather than ensure the military gets the best designed system or product. House Armed Services Committee member Patricia Schroeder of Colorado pointed out that "If you want anything for your district, you're not going to get it in housing or any other place. The Balanced Budget Act and the deficits have knocked that out, [and so] the only place there is any money at all is the Armed Services Committee bill."[34]

Defense contractors create strong pressure on Congressmen and their staffs though lobbying. Large defense firms maintain full-time Washington staffs who assess and influence the political atmosphere surrounding their programs. Close relations with key officials in Congress, congressional staffers, DOD, Navy representatives and various technical codes are sought to protect corporate interests whenever possible. Smaller firms, without the ability to support full time lobbyists, can still exert influence through their congressional representatives and their staffs on politically sensitive issues.[33]

### *3.2.1.2 Congressional Staffs*

In addition to dealing with the many committees that have jurisdiction over DOD programs, each program must also deal with the interests and agenda of congressional staffers. The overall congressional staff has increased from 2,500 in 1947 to over 13,000 in 1979 to almost 20,000 in 1992.[33],[37]. As staffs, assigned to either standing committees or individual congressmen, have grown the level of detail considered in congressional actions such as bills and amendments and the number and length of hearings has also increased. "Annually, the congressional bureaucracy adjusts 1500 line items in the defense authorization and appropriations bills, mandates that DOD take some 700 specific actions, and enacts over 200 general provisions into law. In addition it deluges the department with about 600,000 telephone calls and written inquiries that demand responses—often in great detail."[37] It is beyond the scope of any single legislator to assimilate all the information he receives on the issues. As Senator William Cohen (R-ME) has explained: "We're not experts in the sense that we con devote our sole time to overseeing how we're spending money. We're all on four committees at least and about nine different subcommittees--all of which seem to meet at the same time."[33]

As members of Congress turn to their staffs for more assistance, the staffers have increased the oversight and attention focused on minor budgetary issues in defense appropriations. According to Richard Stubbing, author of *The Defense Game*:

> The staffers identify and investigate such issues, largely at their own discretion, and feed their findings to members for use in hearings and budget markup sessions. In many respects it is the staff members, and not the elected officials, who lead the defense deviate in Congress. Senator Barry Goldwater has put is most succinctly: "Staff runs Congress."[33]

The increasing influence of congressional staffers imposes problems for the management of defense department programs. In budget review, congress has a tendency to "micro-manage" program decisions through the details of the line-item budget. In addition, the hundreds of minute changes made in the defense budget by the Congress leads to program instability and increased managerial difficulties. As a prestigious panel of defense experts assembled by the Georgetown Center for Strategic and International Studies recently concluded: "Congressional procedures for review of the defense budget reflect and reinforce many of the obstacles to effective policy making and management in the Department of Defense."[33]

The power of congressional staffers is clearly seen in the NSSN program. The program office has a full time staff of 5 people dedicated to processing, tracking and answering inquiries from congressional staffers. Further, the program manager spends a significant amount of time formally responding to congressional inquiries.[45] Figure 3-2 shows the number of congressional inquiries submitted to the NSSN program over a 20 month period. A review of the programs database indicates that there is very little, if any, communication between the different committee staffs. The same or similar questions are often submitted repeatedly by different staffers, each asking the same question for a different purpose.

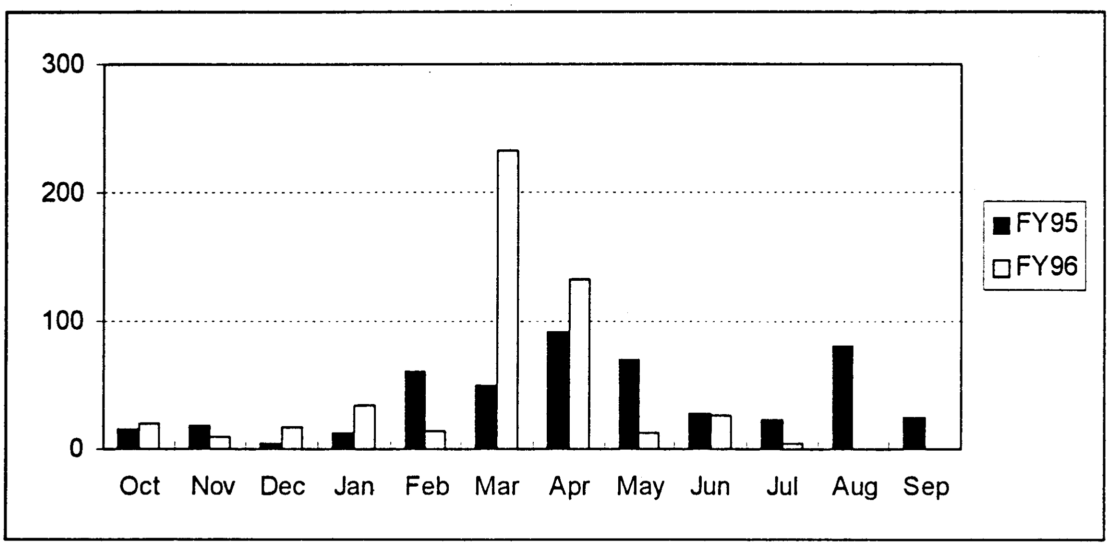


**Figure 3-2: NSSN Congressional Inquiries Oct 94 - Jul 96**

The influence carried by staffers is indicated by the efforts the program takes to answer their inquiries. There is no legal requirement for a DOD program to respond to the inquiries of a given staffer however the trouble a staffer can cause a program management team is not worth the effort saved by neglecting an inquiry. A quote from *The New Politics of the Budgetary Process* reveals the extent of their influence:

> "...asked if they would consider refusing to talk to committee staff, agency officials uniformly declared that such a stance would be tantamount to cutting their own throats. A staff person whose nose is out of joint can do harm to an agency by expressing distrust of its competence or integrity."[34]

Many of the questions submitted to the NSSN program do not directly concern the design and procurement of the NSSN. Questions such as "What is the Navy's position on the claim by Battista that the *Seawolf* will only be as quiet as a 688I? Do exercise results exist that support the claim?" do not have anything to do with the NSSN yet the NSSN program is responsible for tracking the question and ensuring the staffer gets an answer to his question.[1] Other questions like "What contractor(s) is involved and in which states?--What has been the contractor's performance to date, in terms of product and cost/schedule?" have strong political overtones and the answers require careful consideration of potential program impacts.[38]

### 3.2.2 System and Component Development in NAVSEA

System level procurements also impose constraints on ship designs. The procurement and design of system components falls under the guise of both the ship design team and a technical code within the Naval Sea Systems Command (NAVSEA) responsible for a particular aspect of ship systems engineering. NAVSEA's mission is to provide life cycle support to ships, including research and development, design, construction, maintenance, repair and modernization, and finally disposal.[39] NAVSEA technical codes are the program management team for systems under their cognizance. They develop the general specifications, requirements and constraints that are required to

[1] This question was actually submitted to the NSSN program while the *Seawolf* submarine was still under construction. Since the ship had not yet been to sea, there could not possibly be any exercise results.

be met in any ship design, perform and assess preliminary tradeoff studies and analysis, and are responsible for preliminary development of new ship projects up to the point where a ship acquisition program is formally established.[39]

Once a major program has been established, a program manager is designated by, and responsible to, the Assistant Secretary of the Navy for Research, Development and Acquisition (ASN(RD&A)). The acquisition program organization is a matrix organization directly under the ASN(RD&A), which is located at and supported by NAVSEA.[39] Project team members drawn from NAVSEA technical codes have a vested interest in validating the technical codes research and development efforts by having their particular systems incorporated into the new ship's design. For example, the Environmental Engineering Group (SEA 03V) is formally responsible for systems such as: "shipboard waste pulpers, compactors, plastic waste processors, oil water separators..."[39] As such, having these specific systems installed onboard all new ships increases the scope, influence, budget size and thus importance of SEA 03V. They have a vested interest in pushing the ship design team to accept these specific systems as solutions to environmental problems. Alternatives such as onboard storage for land disposal of trash and supply system strategies to eliminate the need for plastic waste processors do not support the mission of the SEA 03V organization.

NAVSEA technical codes are also influenced by corporate lobbying and congressional influences. Corporations regularly make sales presentations to NAVSEA codes explaining new ideas or new projects. Similarly, congressional staffers question specific NAVSEA policies and processes with political intentions in mind.[40]

#### *3.2.2.1 System Evolution*

NAVSEA technical codes develop individual ship systems which are integrated in to the overall ship design by the program design team. When budget constraints were not as prominent, individual systems from previous designs were modified or upgraded as necessary to meet the operational requirements of the new ship class. Over time, incremental modifications to the baseline design result in less than optimal performance of the entire system. For example, a submarine's torpedo ejection system must be capable of firing a torpedo under various speed and inclination angle constraints. The constraints are based on the performance characteristics of the submarine and therefore advance with each new class of submarine. The ejection system design for U.S. submarines has changed only incrementally from class to class since World War II. In order to meet the constraints of the *Seawolf* class submarine, the torpedo ejection pump design is one of the most complex and expensive pumps ever built.[41] The complexity and scope of the systems components finally drove research and development into a new method optimized for the current constraints to be developed for the NSSN.[41]

In an effort to reduce the cost of incremental development and logistics support for specialized equipment on each individual ship class, the Navy is pursuing initiatives in the development of Navy Standard Designs (NSD) and the use of Commercial off the shelf equipment (COTS). These initiatives use commonality between ship systems to reduce procurement and logistics costs. They have recently gained favor because budget cutbacks have precluded development of new systems except where the need is imperative.[35] Navy Standard Designs are complete systems common to most ships which are contained in a module. The most common NSD is a fire fighting station. The ship designer provides the space and the necessary connections to the ship's power and water systems at predetermined locations on the module. Use of Navy Standard Designs allows the Navy to procure large numbers of identical components usable across all ship classes. Commercial equipment can be used on ships if the cabinet and foundation of the equipment is designed to handle military shock requirements. Use of commercially available equipment eliminates concern for maintaining military only production capabilities and the need to maintain large inventories.

It should be noted that these two initiatives can be contradictory. Navy Standard Designs are military only procurements designed specifically for Navy ships. Ideally they are developed in areas where the technology is changing slowly, such as a pump, and establishing a Navy design significantly simplifies logistics issues. COTS equipment is well suited to rapidly changing technologies such as electronics where components can quickly become obsolete. Using COTS equipment allows the Navy to upgrade quickly without funding new development. Between these two ideal situations the trade-of between NSD and COTS equipment is not as clear and political and organizational issues tend to influence decisions between the two alternatives.[40]

### *3.3 Program Management 'Ship Design'*

In the vocabulary of major program management in the Navy, ship design has two definitions. The first definition, known as 'sd', refers to the engineering and naval architecture design that meets the platform's requirements and specifications. The second definition, known as 'SD', is everything required to design a ship as a system and keep the program alive. 'SD' captures the political aspects of getting a ship designed and developed to satisfy requirements of various stakeholders and policy makers and their unwritten agenda's.[42] The politics of acquisition are reflected in design decisions that can be as significant as overall dimensions and displacement or as minor as determining the appropriate supplier of a part or system.

The program management team ensures the design meets the formal requirements of each milestone as well as the 'SD' program requirements. At the highest levels, these requirements have recently been reflected in budget cuts and concern for maintaining the military industrial base of the country as procurements drop.

#### 3.3.1 Current Fiscal Environment

Defense budgets in general, and military procurement budgets in particular have been cut significantly since the fall of the Soviet Union in the late 1980's. In real terms, the defense budget was cut 40% between 1985 and 1997 and defense procurement funds have been cut over 40% since 1990. Figure 3-3 and Figure 3-4 show the annual appropriations for the Department of Defense and DOD procurements.[43] Significant cut backs coupled with approving Defense budgets on an annual basis has focused congressional attention on current procurement costs of major programs.

The shift in focus from the cold war arms race to cost and schedule overruns lead to the cancellation of the Navy's A-12 program in January 1991. The A-12 program cancellation, the largest, most expensive program ever canceled, embarrassed Navy officials running the program as well as DOD and Congress.[44] The A-12 program cancellation and the aforementioned reduction in the *Seawolf* class submarine program due to excessive costs has focused more attention on program costs.[2] Keeping the initial procurement cost of a ship below the levels expected by congress has become one of the most important 'SD' considerations in program management. Changes or improvements to the ship's design that add to procurement costs or that have a significant risk are rejected in the early design stages.[45]

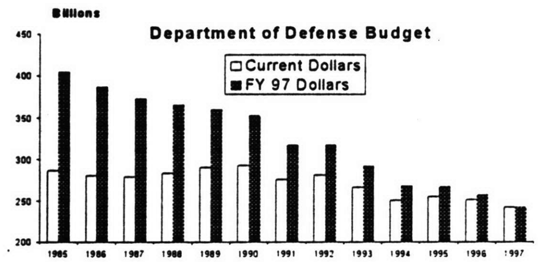


**Figure 3-3: DOD Budget 1985-1997**

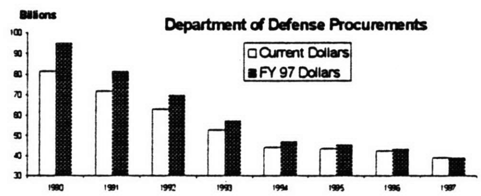


**Figure 3-4: DOD Procurement Budget 1990-1997**

The budget cycle and the intense scrutiny on procurement costs minimizes the importance of the life cycle costs of alternative designs. In new system development, the cost projections are risky until development is complete. This is a major incentive for designers to rely on previously deployed technologies and systems with predictable procurement costs.

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[2] The history of Navy procurement program problems did not start in the 1980's. According to Aaron Wildavsky in *The New Politics of the Budgetary Process* problems began with the first procurement program. "On March 27, 1794, Congress approved the creation of a sea-going navy by appropriating funds to build six frigates. The work was contracted to six private shipyards geographically spread in order to distribute the benefits of federal spending and to garner political support for the program. War in Europe prevented the purchase of necessary supplies and the keels were not laid until the end of 1795. Shortly thereafter, due to mismanagement, delays, and cost overruns, the number of frigates to be purchased was cut to three."

### 3.3.2 Military Industrial Base

The budget constraints described above resulted in a 35% reduction in the number of Battle Force Navy ships between 1990 and 1996 (546 to 359 ships).[43] The large and rapid draw down affected military suppliers in both procurement and maintenance activities for ships. Several defense related companies have gone out of business or been consolidated in large defense firms. Questions about managing the military-industrial complex have become both a political and security concern for the government. In the early 1990's the defense department conducted a Bottom-Up Review (BUR) to determine the appropriate size of the military in the post Cold War era. Part of the review focused on U.S. military industrial capabilities and concluded that defense related industries should be supported even if there were no immediate mission needs for their products.[46] Additionally, the U.S. government has restricted sales to foreign firms in an attempt to preserve the U.S. industrial base.

Industrial base policies have not been conducted without difficulty and official policy is under continuous review. Air Force Secretary Donald B. Rice expressed concern that reduced competition in the defense industry will deteriorate the ability to arm the county in the future: "It's not just the ability to apply the technology. It's the ability to invent the technology."[47] Additionally, the smaller number of suppliers has brought up anti-trust concerns about the way companies are dealing with smaller contracts.[48] Industrial base policy is currently handled on a case by case basis, making design decisions more difficult.[53]

Maintaining a ship building industrial base in the U.S. has changed the nature of competition for major ship construction contracts. By law, the Secretary of Defense "shall prescribe regulations requiring consideration of the national technology and industrial base in the development and implementation of acquisition plans for each major defense acquisition program".[49] The Secretary of Defense has issued guidelines for evaluating the need for Government action to preserve industrial capabilities based on the technology in question and the funding available.[50] Most U.S. shipbuilders rely on military contracts for their survival and awarding contracts without considering the effects on the industrial base would lead to further consolidation in the industry.

Recent industrial policy has been to award contracts based on maintaining the military industrial base rather than competitive designs and bids. In 1994, the Navy stopped the competitive bid process for destroyers for at least two years, instead allocating contracts between two rival yards involved in destroyer construction. According to Navy Secretary John Dalton:

> "This is a departure from the past practice of competitively procuring DDG-51 class ships and is the first step in a smart business strategy to determine and implement actions the Navy needs to take in order to maintain a healthy industrial base"[51]

Another highly visible example of industrial base policy was the contract for the third *Seawolf* submarine and the NSSN. The third *Seawolf* was awarded to Electric Boat to maintain the industrial capacity to build nuclear submarines. The contract was awarded even though there was no military need for the submarine.[51]

The contracts for the NSSN program have been handled in a similar fashion. In 1992, DOD and the Navy selected General Dynamics Electric Boat Division as the designing and building contractor. Electric Boat, which builds only nuclear submarines, would be out of business when the last *Seawolf* class submarine was completed without a new submarine construction contract. Newport News Shipbuilding is capable of building both nuclear submarines and nuclear aircraft carriers and would be the sole source supplier for nuclear ships if Electric Boat went out of business. In an effort to maintain the industrial base, Electric Boat was awarded the initial NSSN contract while Newport News was awarded a new aircraft carrier.[46],[51],[52] Political pressure from Virginia resulted in contracts for later NSSN submarines to be competitively bid rather than awarded to Electric Boat.[46]

Smaller contracts for parts and system components, although not as visible, require considerations for industrial capabilities and are being awarded in a similar manner.[53] The result is that the political pressure to support certain firms buy using their designs or equipment is strong and may be contrary to decisions made solely on engineering and cost criteria. As such, it must be given consideration in the design and procurement process.

### 3.3.3 Procurement costs vs. Life-cycle costs

Procurement cost and life-cycle cost are both required to be considered in the Milestone reviews of a program. DOD procurement instructions require detailed life-cycle costs of a program to be calculated. Additionally, design trade-off analysis are expected to be based on life-cycle cost estimates.[32] However, the relationship between major procurement programs and Congressionally authorized budgets places cost emphasis on short term projections. The defense department budget is projected on a five year cycle called the Future Years Defense Plan (FYDP). The current year is the plan being presented to Congress for authorization and the out years are projections based on current plans.[54] The entire FYDP is approved by the Secretary of Defense, however the out years are not officially presented to Congress and are therefore not binding.

The two tiered system in the budget process is reflected in the overall importance of program costs. A program must legally keep current costs within the amounts allocated by Congress. Further, a program must justify cost projections over the next five years to have them included in the FYDP to justify appropriate funding levels in future Congressional authorizations. Cost considerations beyond the FYDP, such as the life-cycle costs of a ship expected to last a 30 plus year lifetime, do not directly influence the budgetary process.

The line item defense budget system also limits the potential for life-cycle costs to influence design decisions over short term costs. Procurement, manning, maintenance and operation of a ship each fall into different categories of the Navy's budget. The acquisition program and the efforts to design and build a ship are paid for by procurement funds. The programs procurement cost is visible and open to congressional and DOD review long before the maintenance and operation line items enter the FYDP. As a result, there is tremendous pressure to keep procurement costs down, regardless of the impact on the life-cycle cost of the ship. As a result, life-cycle cost estimates are of secondary importance in the 'SD' aspects of an acquisition program.

### 3.4 Political Realities of Program Decision Making

Ignoring the realities of politics in engineering decision making does not make it go away. Worse, ignoring it implies the impact is negligible, which is not the case! The procurement process tends to operate back to front. "New weapons might well be inspired by the demands of the battlefield, but the pace of their evolution--not to mention their final form--is determined by the bureaucratic imperatives of those responsible for their development."[55] In order to effectively design Navy ships to meet environmental requirements, the influences of non-engineering based criteria must be recognized. Supplier selections often determine system capabilities because of political connections and location. The annual budget cycle may preclude spending more now for future savings. Sunk costs compel organizations to support past decisions and strategies, even if they do not appear in formal cost figures. Organizational power and influence drives system decisions for reasons other than life-cycle effectiveness. All these items must at least be recognized as part of the environment a ship design framework must work in for it to be effective.

# 4. Environmental Requirements for Navy Ships

There is a myriad of environmental legal requirements imposed on Navy ships. International, Federal, State and local governments restrict discharges from operations and maintenance through protocols and laws which are constantly under review and subject to revision at any time. In the design process for Navy ships, current requirements must be met and allowance made for future requirements that may develop over the projected life-cycle of the ship. It is not possible to perform detailed trade-off analyses with engineering solutions that may or may not meet unknown future requirements. Designers must be aware of all potential waste streams caused by the ship, from its initial construction through its eventual deactivation and disposal, and evaluate design changes against the legal requirements, both current and projected.

## *4.1 International*

The international environmental requirements for ships are primarily contained in the UNCLOS III and MARPOL 73/78 conventions mentioned in Chapter 2. Warships are exempted from MARPOL 73/78 convention requirements with the condition that they comply to the standards "to the extent practicable". The only regulations that are specifically applicable to US Navy ships are contained in Annexes I (oil), IV (sewage) and V (garbage). Annex V is invoked on US warships by the Act to Prevent Pollution from Ships. The U.S. Navy's current plan is to seek legislative relief from Annex V. Surface ships have been granted approval, so long as they pulp and shred waste first, and submarines are in the process of obtaining relief to continue shooting TDU Cans.[56]

Annex I generally prohibits oil discharges of any kind within 12 nautical miles of land and whenever water depth is less than 25 meters deep.[16] Ships over 400 tonnes must have an oily-water separator or oil filtering equipment to handle bilge water and oily sludge. The discharge limit for filtering equipment is 15 PPM for new ships and will be 15 PPM for all ships in 1998.[17] Sludge and bilge water kept onboard must also be handled properly and pumped to an appropriate facility when in port. Appendix I of Annex I provides a comprehensive list of substances classified as "oil" for regulatory purposes.

Annex IV limits discharges of sewage including drainage from toilets, water closets, medical premises and scuppers. Sewage discharges are prohibited within 12 nautical miles of land.[16]

Annex V regulates the disposal of garbage at sea. Garbage is defined as "all kinds of victual, domestic and operational waste...generated during the normal operation of the ship and liable to be disposed of continuously or periodically...". The discharge of plastics at sea is specifically prohibited at all times. Discharge of any garbage that may float is limited to ships outside 25 nautical miles from land. Other garbage discharges are limited to ships at least 12 nautical miles from land unless comminuted or ground such that it is capable of being passed through a screen with openings less than 25 millimeters across. Garbage ground to these specifications may be discharged as close as 3 nautical miles from land. When located in special areas, ships are prohibited from disposing of all garbage except food wastes, which may only be discharged outside the 12 nautical mile limit.[16]

Annex V currently has three special areas in effect where only food wastes can be discharged: the North Sea, the Baltic Sea, and the Antarctic Region.[57] Additionally, the Caribbean region is pursuing the establishment of special area classification for enforcement of Annex V.[17] Although military ships are exempt from complying with MARPOL 73/78 requirements, Section 1003 of the National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, established deadlines for compliance by U.S. Navy ships with the Annex V special area requirements. Surface ships must comply by December 31, 2000 and submarines must comply by December 31, 2008. In this instance, the MARPOL standard has become U.S. law specifically applicable to Navy ships.

### 4.1.1 MARPOL Changes

Special area designations under other MARPOL 73/78 annexes may further limit discharges from ships in the future. Stricter limits on routine discharges such as oily bilge water and sewage will force ships to drastically change current operating procedures and associated ship designs. For example, reducing the allowable concentration of oil in bilge water discharges below 15 PPM is beyond the current capabilities of shipboard oily water separators. To meet lower limits may require ship engineering spaces to be redesigned for biodegradable lubricants. Sewage discharge restrictions could greatly increase the onboard storage space required or possibly require segregation and treatment of black and gray water beyond current requirements. These potential changes could drastically alter current ship designs and operations or force the Navy to rely on military exemption clauses in the convention.

In addition to potential modifications of current annexes, the Marine Environmental Protection Committee of the International Maritime Organization is currently working on drafting a new MARPOL 73/78 Annex on prevention of air pollution from ships. Items considered under the new annex include emissions from marine engines, use of Halons, Chlorofluorocarbons and volatile organic compounds and shipboard incinerator requirements.[58] As a MARPOL 73/78 Annex, the requirements are subject to designation of special areas with additional and more restrictive requirements. This Annex will almost certainly be adopted in one form or another during the expected lifetime of ships currently being designed today. Although the specifics of the regulation are not currently known, designers need to consider the potential impacts applicable to new ships.

### *4.2 Federal Legislation*

Federal environmental legislation has increased drastically in both scope and quantity over the last 20 years as shown in Figure 4-1. Federal environmental constraints affect the construction and operation of Navy ships and should be considered in the design process to minimize their effects on cost and mission performance. By designing for legal environmental constraints at the outset of the program, subsequent back fitting of end of pipe treatments can be avoided. Back fitting ships is inherently more expensive than initial construction and weight and volume added to mature designs reduces the space available to upgrade other mission capabilities. A summary of some of the major federal environmental laws impacting new ship designs is provided below.

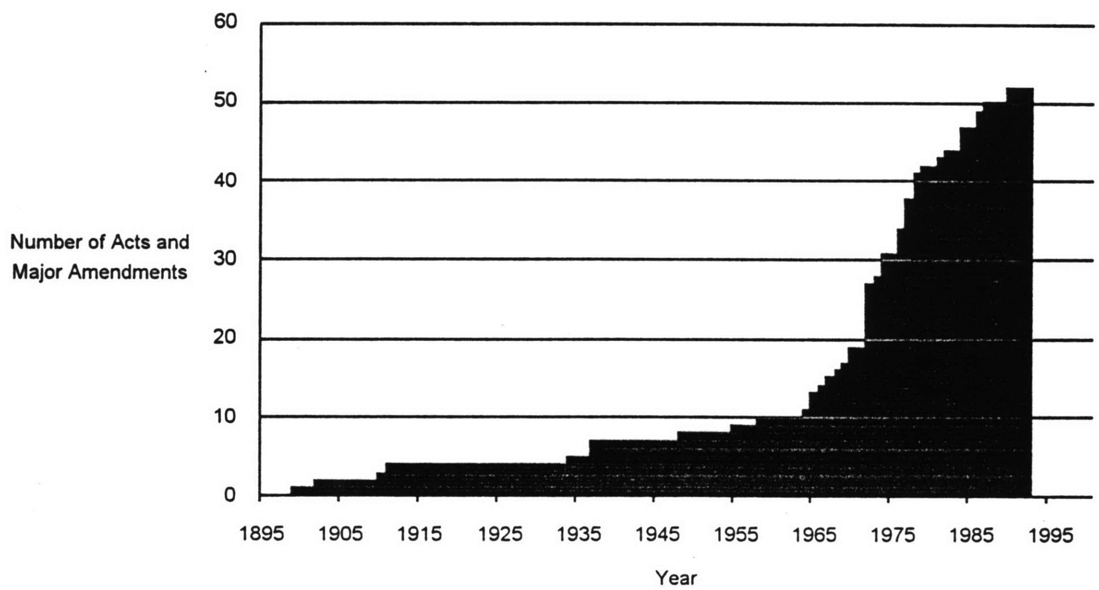
### 4.2.1 Clean Air Act (CAA)

The Clean Air Act, passed in 1955 and amended in 1970, 1977 and 1990, is intended to "protect and enhance the quality of the Nation's air resources so as to promote public health and welfare and the productive capacity of its population." It limits and controls volatile organic compounds, hazardous air pollutants, ozone depleting substances, sulfates, nitrous oxides and other chemicals. Hazardous air pollutants "may reasonably be anticipated to result in an increase in mortality, or an increase in serious irreversible, or incapacitating reversible illness." Standards for hazardous air pollutants are imposed on both new and existing sources for a detailed list of substances that currently contains 189 pollutants or categories of pollutants. The ozone protection section requires the phase out of CFCs and other substances thought to deplete the ozone. Shipbuilding processes such as welding, painting, surface cleaning and degreasing are regulated as well as the emissions from shipboard systems including diesel and gas turbine engines, refrigerators and air conditioners. Shipbuilders pay fees to obtain discharge permits under the CAA which are part of the construction costs of the ship.[59],[11]

### 4.2.2 Clean Water Act (CWA)

The Clean Water Act, passed in 1948 and amended in 1972, 1977 and 1987, is intended to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." It prohibits pollutant discharges to navigable waters and the discharge of toxic pollutants in quantities that may adversely affect the environment. It sets limits on pollutant quantities discharged in waste streams and controls storm water run-off. Discharge of any pollutant from public or private point sources requires a permit. Additionally, all dischargers must disclose the volume and nature of their discharges and report on compliance with mandated limitations. Shipbuilding processes affected include hydrostatic testing, water blasting, painting with anti-fouling paints and drydock operations. Regulated operational processes include boiler blowdowns and bilge water disposal.[59],[11]

## GROWTH OF FEDERAL ENVIRONMENTAL LEGISLATION




| | |
|---|---|
| 1899 | River & Harbor Act |
| 1902 | Reclamation Act |
| 1910 | Insecticide Act |
| 1911 | Weeks Law |
| 1934 | Taylor Graring Act |
| 1937 | Flood Control Act |
| 1937 | Wildlife Restoration Act |
| 1948 | Clean Water Act (Water Pollution Control Act) |
| 1955 | Clean Air Act |
| 1958 | Fish and Wildlife Coordination Act |
| 1964 | Wilderness Act |
| 1965 | Solid Waste Disposal Act |
| 1965 | Water Resources Planning Act |
| 1966 | National Historic Preservation Act |
| 1967 | Air Quality Act |
| 1968 | Wild and Scenic Rivers Act |
| 1969 | National Environmental Policy Act |
| 1970 | Clean Air Act Amendments |
| 1970 | Occupational Safety & Health Act |
| 1972 | Clean Water Act Amendments |
| 1972 | Marine Protection, Research & Sanctuaries Act |
| 1972 | Coastal Zone Management Act |
| 1972 | Home Control Act |
| 1972 | Fed Insecticide, Fungicide & Rodenticide Act |
| 1972 | Parks and Waterways Safety Act |
| 1972 | Marine Mammal Protection Act |
| 1972 | Noise Control Act |
| 1973 | Endangered Species Act |
| 1974 | Deepwater Port Act |
| 1974 | Safe Drinking Water Act |
| 1976 | Toxic Substances Control Act |
| 1976 | Federal Land Policy & Management Act |
| 1976 | Resource Conservation & Recovery Act |
| 1977 | Clean Air Act Amendments |
| 1977 | Clean Water Act Amendments |
| 1977 | Surface Mining Control & Reclamation Act |
| 1977 | Soil and Water Resources Conservation Act |
| 1978 | Endangered Species Act Amendments |
| 1978 | Environmental Education Act |
| 1978 | Quiet Communities Act |
| 1980 | Comprehensive Env. Response, Comp. & Liability Act |
| 1980 | Resource Conservation & Recovery Act Amendments |
| 1981 | Clean Water Act Amendments |
| 1982 | Nuclear Waste Policy Act |
| 1984 | Resource Conservation & Recovery Act Amendments |
| 1984 | Environmental Programs & Assistance Act |
| 1986 | Safe Drinking Water Act Amendments |
| 1986 | Superfund Amendments & Reauthorization Act |
| 1987 | Water Quality Act |
| 1990 | Clean Air Act Amendments |
| 1990 | Pollution Prevention Act |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(a) Balzhiser, R.E. in J. Ausubel & Sladovich (eds.) "Technology and Environment", National Academy Press, Washington, DC., 1989

(b) Corbitt, Robert A., "Standard Handbook of Environmental Engineering", McGraw-Hill Publishing Company, New York, 1990

(c) The Guide to American Law, Volume 4, West Publishing Company, New York, 1984

(d) Stoloff, Neil, "Regulating the Environment: An Overview of Federal Environmental Laws", Oceana's Legal Almanacs, Second Series, Oceana Publications, Inc., Dobbs Ferry, New York, 1991


**Figure 4-1: Growth of Federal Environmental Legislation**

### 4.2.3 Act to Prevent Pollution From Ships

In 1987 and again in 1992, Congress directed that US Navy ships comply with the requirements of MARPOL 73/78 Annex V for disposal of trash at sea. Disposal of plastics by U.S. Navy ships is prohibited in Special Areas and all aspects of Annex V are to be met by specified dates for ships and submarines. The 1972 Act to Prevent Pollution from Ships specifies that Navy ship's are to comply with Annex I oily waste discharge limits to the extent practicable. Program managers are expected to ensure ships are designed to meet Annex V requirements and have oily waste management systems which meet the Annex I limit of 15 ppm discharge oil concentration.[12]

### 4.2.4 Resource Conservation and Recovery Act (RCRA)

The Resource Conservation And Recovery Act, passed in 1976 and amended in 1984, was enacted to protect human health and the environment and to reduce or eliminate the generation of hazardous waste. All hazardous waste produced is to be treated, stored, and disposed of so as to minimize the present and future threat to human health and the environment. States are required to develop and implement waste management plans and a permit system for hazardous waste including "cradle-to-grave" tracking of hazardous substances. Additionally, states are encouraged to take over responsibility for program implementation and enforcement from the Federal Government. Hazardous substances used during the construction process and on ships must be tracked and accounted for through manufacture, processing, use and disposal.[59],[11]

### 4.2.5 Toxic Substances Control Act (TSCA)

The Toxic Substances Control Act was enacted in 1976 to "regulate chemical substances and mixtures which present an unreasonable risk of injury to health or the environment." It authorizes EPA to require industry to test certain chemicals for adverse health and environmental effects and limit or prohibit the import, export, production, use or disposal of certain materials. Manufacturers must notify the EPA 90 days before producing a new chemical substance and submit any required test data and information about prospective uses. Manufacturers and processors are required to keep inventories and maintain records of significant adverse reactions caused by their substances. The TSCA inventory currently contains approximately 80,000 chemicals, many of which are used in ship construction process or shipboard components.[59],[11]

### 4.2.6 Superfund Amendments and Reauthorization Act (SARA)

The Superfund Amendments and Reauthorization Act is a 1986 amendment to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) which established a Hazardous Substance Superfund. Title III of SARA is known as the Emergency Planning and Community right-to-Know Act (EPCRA) which identifies 402 Extremely Hazardous Substances and 322 (to be expanded to over 600) toxic chemicals or compounds. Each substance identified requires a Toxic Release Inventory to be maintained and requires state and local governments to establish emergency response plans in the event of a release. Inventories and site specific information on chemicals considered physical or health hazards must be provided to state and local authorities, including fire departments, through material safety data sheets.[59],[11]

### 4.2.7 Pollution Prevention Act (PPA)

The Pollution Prevention Act, enacted in 1990, shifts the focus of environmental legislation from "end-of-pipe" waste treatment solutions to reduction or elimination of pollution at the source. The act addresses the historical lack of attention to source reduction and states that "source reduction is fundamentally different and more desirable than waste management and pollution control." A priority system among pollution prevention alternatives is established with source reduction at the top followed by recycling and waste treatment. Disposal or release to the environment is considered a last resort. Under PPA, a voluntary program aimed at producers of 17 high priority chemicals, including shipbuilders, was established to reduce by 1995, the levels produced by 50% of 1988 levels.[59],[11]

### 4.2.8 National Environmental Policy Act (NEPA)

The National Environmental Policy Act of 1969 requires Federal departments and agencies to give the same consideration to environmental factors as is given to other decision making factors. All reasonable alternatives are to be considered, and all practical means are to be employed to avoid or minimize adverse effects on the environment.[59],[11]

### 4.2.9 Federal Facilities Compliance Act

The Federal Facilities Compliance Act waives government agency immunity to federal, state and local environmental regulations, and allows federal employees to be held personally liable for criminal penalties. The law impacts navy bases and homeports, however public vessels are generally exempt from its provisions.[59]

### 4.2.10 Marine Mammal Protection Act & Endangered Species Act

The Marine Mammal Protection Act (MMPA) was enacted in 1972 to protect marine mammals and establish a marine mammal commission. The Endangered Species Act (ESA) provides for the identification and protection of threatened and endangered species of animals and plants and their critical habitats. The "taking" of marine mammals incidental to marine activities is regulated by the MMPA and similar requirements apply under the ESA. When an activity which may harm or harass marine mammals is conducted, the potential for a "take" is considered to exist and requirements to mitigate the potential for a "take" are required. Shock testing vessels and conducting explosive weapons tests are examples of ship operational requirements where the procedures of these Acts must be followed.

### 4.2.11 Occupational Safety and Health Act

The Occupational Safety and Health Act became effective in 1971 and was amended in 1986. The act authorizes the development of standards to assure both safety and health of workers by setting standards for exposure to various chemicals, listing permissible exposure limits for airborne contaminants and informing employees of the dangers posed by substances in the work place. Minimum standards are set for labeling hazardous material containers, making inventory information available to employees and the conduct of employee training about hazardous chemicals. Companies are required to maintain material safety data sheets for all products containing hazardous materials as defined by CAA, CWA, RCRA, EPCRA, or TSCA.[59],[11]

### 4.2.12 Executive Orders

In addition to legal restrictions imposed by Congress, Navy ship design is subject to compliance with Executive Orders. A summary of some of the most significant Executive Orders relating to environmental issues in the Federal Government is provided below.

#### *4.2.12.1 Executive Order 12114*

Executive Order 12114, 4 Jan 1979, Environmental Effects Aboard of Major Federal Actions requires an evaluation of federal government actions taken outside the geographic boundary of the U.S. which may impact the environment of other countries or "the global commons outside the jurisdiction of any nation (e.g., the oceans or Antarctica)." Evaluations are in the form of environmental impact statements or similar documents developed by the federal agency involved, multinational group or joint federal agency and foreign government. The Department of State is responsible for coordinating all communications "with foreign governments concerning environmental agreements and other arrangements".[60]

#### *4.2.12.2 Executive Order 12843*

Executive Order 12843, 23 April 1993, Procurement Requirements and Policies for Federal Agencies for Ozone Depleting Substances mandates Federal agency use of non-ozone-depleting substances where economically practicable, and demonstration of leadership to phase out ozone depleting substances.[12]

#### *4.2.12.3 Executive Order 12856*

Executive Order 12856, 3 August 1993, Federal Compliance with Right-to-Know Laws and Pollution Prevention Requirements directs the federal government to pursue pollution prevention at the source through substitution of less hazardous materials, improved maintenance and more efficient production processes. It is discussed in greater detail in Section 2.1.

#### *4.2.12.4 Executive Order 12873*

Executive Order 12873, 20 Oct 1993, Federal Acquisition, Recycling and Waste Prevention requires federal agencies to promote waste prevention, to recycle, and to expand markets for recovered materials. This executive order places the Federal Government in the role of "an enlightened, environmentally conscious and concerned consumer" whose efforts "can spur private sector development of new technologies and use of such products, thereby creating business and employment opportunities and enhancing regional and local economies and the national economy".

Agencies are required to develop procurement policies favoring the use of environmentally preferable products whenever possible. Specific requirements for recycled paper, re-refined lubrication oil and retread tires are provided and agencies are expected to facilitate the development of markets for recycled products and services in other applicable areas.[61]

## 4.3 State Requirements

State and local requirements for air and water discharges vary between states and locations. The different laws and requirements complicate compliance and confuses environmental design and management of ships that must operate under the jurisdiction of different coastal states. Each state has unique geography and coastal environments to protect different industrial goals and objectives to pursue. State laws, regulations and enforced compliance levels reflect these unique attributes within the structure set forth by federal laws such as the Clean Water Act and the Clean Air Act.

A typical regulatory and administrative structure for water and air quality controls are shown in Figure 4-2 and Figure 4-3.[62] State requirements are required to meet federal standards, however they may be more stringent. In many instances, federal laws encourage states to set their own standards and handle enforcement.

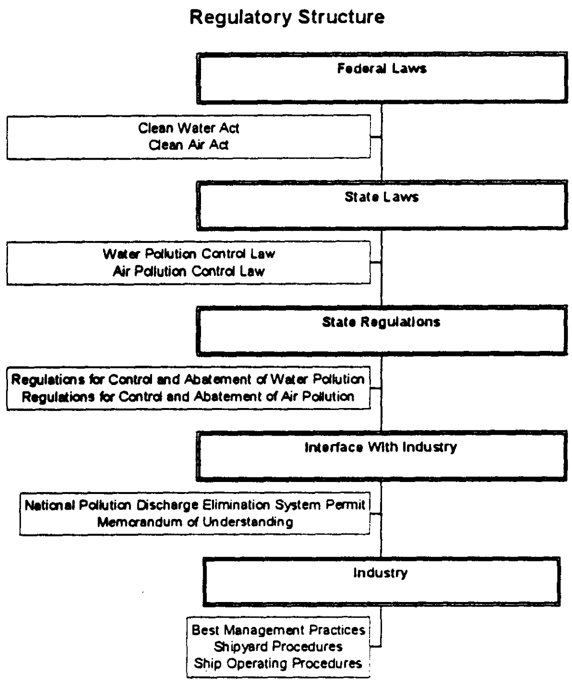


**Figure 4-2: Typical Environmental Regulatory Structure**

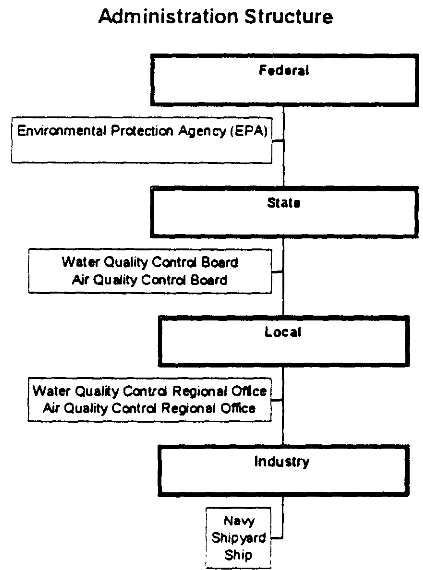


**Figure 4-3: Typical Environmental Regulatory Administration Structure**

This process encourages Navy ships to meet the most stringent state requirements, however predicting potential future requirements in several states is beyond the capability of the ship design process. A brief summary of the environmental requirements for a few Navy homeport states shows the difficulty associated with meeting state requirements in Navy ship design. Not only do the process requirements differ between states, but as shown in Table 4-1 the water quality standards and discharge limits also vary between states.

**Table 4-1: Selected State Water Quality Standards**

| Substance *: | **Connecticut** [63] | **Virginia** [64] | **California** [65] |
|---|---|---|---|
| Ammonia | pH 6.0 to 9.0 | 29 mg/liter ** | 26 mg/liter |
| Copper | 3.0 mg/liter | 2.9 ug/l | 2.9 mg/liter |
| Iron | 7.5 mg/liter | 300 ug/l | 300 mg/liter |
| Nickel | 3.0 mg/liter | 75 ug/l | 8.3 mg/liter |
| Zinc | 3.0 mg/liter | 95 ug/l | 20 mg/liter |

* Maximum allowable concentrations are listed when limits depend on circumstances present.
** Determined by temperature, pH and fish habitats of water body

### 4.3.1 Connecticut

Connecticut's water quality control program is based on established "Water Quality Standards" which set the overall policy for management of water quality under the General Statutes of Connecticut. The Water Quality Standards classify different water resources according to desired use, allowable types of discharges and principles of waste assimilation. They contain the allowable water quality goals for various pollution parameters for each water type and they classify each water resource in the state for application of the standards.

Connecticut's air quality program, also included in the General Statutes of Connecticut, covers registration of air discharge sources, regulations and civil penalties.[66]

### 4.3.2 Virginia

Virginia's State Water Control Law contains the state's requirements for discharges which are implemented by the Virginia Water Control Board. The Water Control Board is authorized by the EPA to administer the National Pollution Discharge Elimination System (NPDES) permitting program. Virginia issues Virginia Pollutant Discharge Elimination System permits which combine federal and state discharge limits. Virginia has developed a program for shipyard discharges which are detailed in a state document titled "Best Management Practices manual for the Shipbuilding and Repair Industry". This document contains 24 "Best Management Practices" (BMP) for controlling potential discharges to Virginia waters from shipyards. Shipyards are expected to comply with the detailed processes contained in BMP's under their discharge permits.

Virginia's air quality control requirements are contained in the Virginia Air Pollution Control Law which meets the state's responsibilities under the Clean Air Act. Under the law, the Virginia Department of Air Pollution Control has developed a memorandum of understanding with local shipyards. The memorandum stipulates shipyard process requirements for blasting and painting, similar to BMP's. Virginia has also established numerical ambient air quality standards.[66]

### 4.3.3 California

California water quality requirements are located in the Porter-Cologne Water Quality Control Act and the Water Quality Control Plan for Enclosed Bays and Estuaries of California. The State Water Resources Control Board is responsible for enforcing the provisions of the state's water quality control laws and is also authorized by the EPA to issue NPDES permits. Under the State Board are nine regional boards which implement the requirements at the local level. The water quality objectives include not degrading the estuarine communities and populations of marine life by discharging waste and not impairing the taste and odor of marine life used for human consumption. Toxic pollutants are not to be discharged at levels that will bioaccumulate in aquatic resources to levels which are harmful to human health or adversely affect beneficial uses. Both acute and chronic toxicity is prohibited in state waters and specific numerical water quality objectives are provided.

California air quality requirements are contained in Titles 13, 17 and 26 of the California Code of Regulations and are enforced by the Air Resources Board. California is divided into various air pollution control districts which have authority over permits, requirements, standards and prohibitions. In some areas permits are required to operate equipment that may pollute the air such as diesel engines and paint sprayers.[66]

## *4.4 Use of Exemptions*

In the past the Navy, through political channels, has been able to get waivers for environmental compliance with federal, state and local requirements. Executive Order 12856 and the Federal Facilities Compliance Act brought an end to this practice as a rule. Currently, Navy ships, shipyards and bases are expected to comply with all applicable environmental regulations. Waivers can still be obtained through administrative channels, however only as a last resort and after all reasonable alternatives have been examined. The NSSN environmental policy emphasizes compliance with all applicable environmental standards, with no mention of waivers.[22]

Although waivers are possible solutions to environmental discharge problems for Navy ships and they are specifically exempt from compliance with international conventions such as MARPOL 73/78 and UNCLOS III, there are several important policy problems with waivers that make them difficult to obtain. Internationally, the United States desires to set precedent in the waters of other nations to ensure reciprocal compliance with U.S. requirements by ships of other Navies. At the state level, processing waivers agitates state vs. federal conflicts over land use, environmental policies and national defense. Waivers are difficult to obtain politically and are currently sought only when there are no other reasonable alternatives.

In the NSSN program waivers are only granted if the project team has exhausted all practical resources and the requirement still can't be met. There is no formal DOD or Navy policy covering the requirements to process a waiver for environmental requirements however, the typical analysis for the NSSN is as follows:

1. What happens if the requirement is not met?
2. Who is affected if the requirement is not met?
3. What is the enforcement process for the requirement?
4. What is the penalty for non compliance compared to the cost of compliance?
5. Can the legislation/requirement be changed to be more practical?
6. How will the requirement or solution impact the crew or ship's mission capabilities?

The decision to process a waiver for an environmental requirement is complex and includes weighing the answers to the questions above with current political considerations.[67] The solution to this problem may come from the development of Uniform National Discharge Standards for Navy ships.

### *4.5 Uniform National Discharge Standards Act*

The Uniform National Discharge Standards for Armed Forces Vessels Act of 1995 (UNDS) is a proposed addition to Section 312 of the Federal Water Pollution Control Act. It is proposed "to establish uniform national discharge standards for the control of water pollution from vessels both domestically and internationally, stimulating development of innovative vessel pollution control technology, advancing the United States Navy's development of environmentally sound ships, and for other purposes." The Act would develop a set of discharge standards applicable to all Navy ships which, when established, would then exempt Navy ships from more stringent state and local requirements.[68]

EPA is tasked with the responsibility for promulgating the standards. However, the Navy has the lead in collecting much of the data, and will make recommendations to EPA regarding the technical approach to take regarding establishing the standards.

Under the proposed legislative amendment, the EPA would determine "the discharges incidental to the normal operation of a [Navy ship] for which it is reasonable and practicable to require treatment by a marine pollution control device in order to mitigate adverse impacts on the marine environment." In addition, for those discharges determined to require pollution control devices, the EPA would define federal standards of performance that would apply to Navy ships. Factors to be considered in the determination of whether to require pollution control devices and mandating of performance standards include: nature of the discharge, environmental effects, practicability of controlling the discharge, effect of the pollution control device on Navy operations and the costs of installation and operation.[69]

Adoption of UNDS would greatly facilitate the design and operation of environmentally responsible Navy ships. Incorporating goals for reduction of discharge levels in future ships would also ensure promising environmental technologies continue to be developed for shipboard use.

# 5. Environmental Ship Design Framework

The material presented in Chapters 1 through 4 outlined the environment in which a design framework for Navy ships must function to be effective. This chapter establishes the framework for incorporating environmental design considerations into Navy ships. A flow chart representation of the design framework is shown in Figure 5-1.

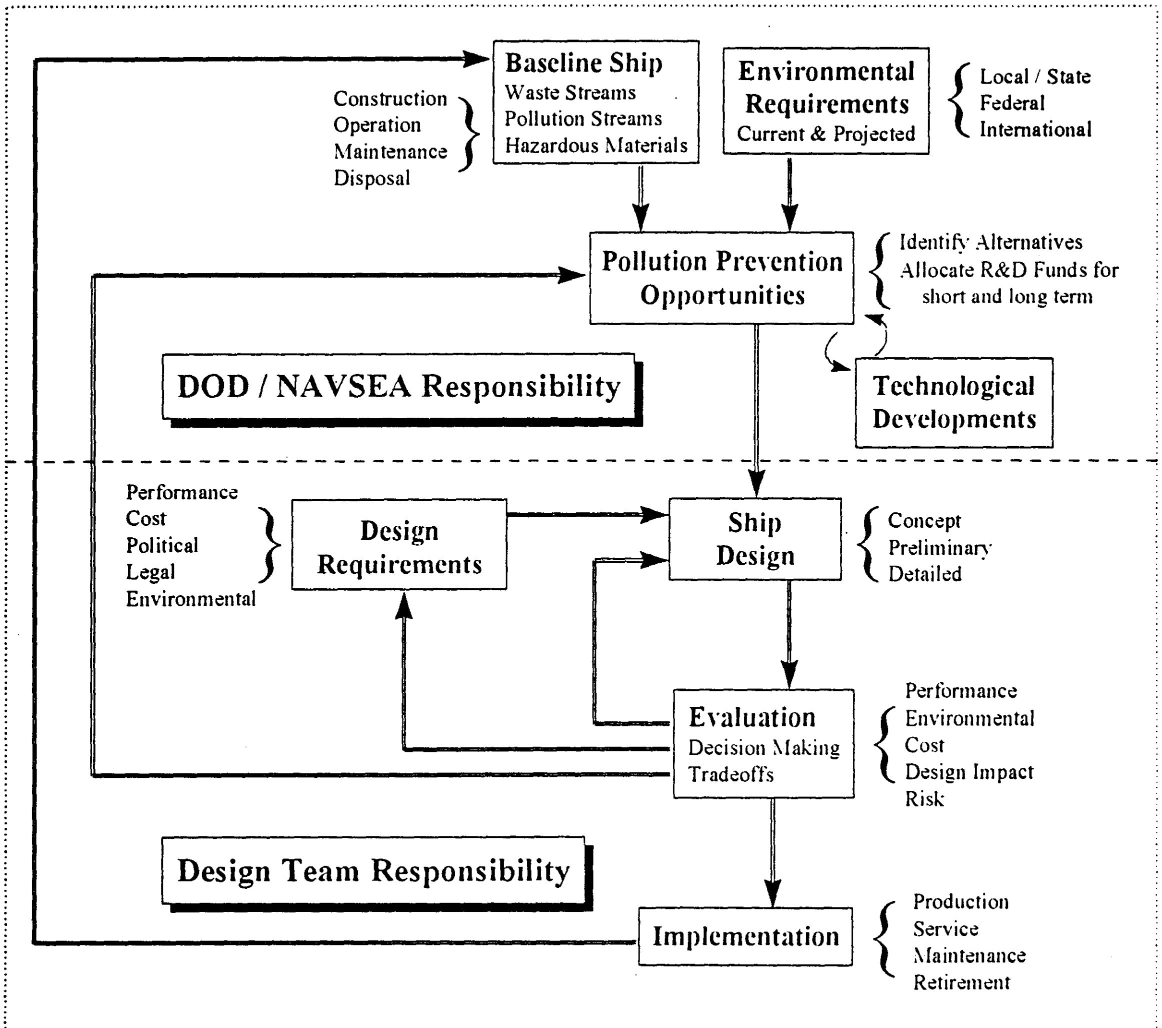


**Figure 5-1: Environmental Ship Design Flow Chart**

Incorporating environmental requirements into the early stages of design allows the most flexibility for undertaking environmental improvements without degrading performance characteristics. Additionally, the need for later corrective action can be reduced while enhancing the likelihood of developing a lower-impact design.[70] The framework presented integrates environmental requirements with traditional performance, cost and legal requirements.

Similar frameworks have been developed by designers in numerous fields including the EPA and Department of Energy.[70],[71] The most significant differences between the framework developed here and these other methods lies in the evaluation methods proposed and the basis on which decisions are made. Other approaches, such as the EPA's, focus decision making on a detailed inventory analysis and risk assessment.[70] Warships are built for political purposes which are not compromised by the results of an environmental impact study. As such, a practical approach for Navy ship design is to focus on improving the existing designs in the next generation of ships. The design framework utilizes this fundamental design approach to reduce the analysis and risk assessment burden without compromising incorporation of environmental considerations in the ship's design.

Implementing this framework within the currently existing design and engineering structure of Navy procurement programs and NAVSEA technical codes also facilitates use of this approach. The items in the top half of Figure 5-1 are continuously ongoing, independent of specific new ship designs. As such, they are the responsibility of the Department of Defense and NAVSEA (controlling operations of current ships, keeping up with legal developments, and funding and conducting short and long term research and development efforts). Higher level control over these items also helps to maintain continuity for long term efforts and prevents duplication by individual program office personnel. The process in the lower half of Figure 5-1 are specific to an individual ship design and best handled within the program office.

## *5.1 Establish Baseline Ship*

The first step in the process is to select a baseline ship similar to the ship being designed. The baseline ship provides waste stream and hazardous material inventory analysis data and serves as a benchmark for the environmental performance of the new design. Normally the baseline will be the previous class of the same ship type, however in some cases it may be different ships for the different life-cycle stages of the new design.

For example, the *Seawolf* class submarine would be the baseline for the NSSN, however since it was still under construction during most of the NSSN design phase, environmental data on *Seawolf* disposal is not available. In this case the NSSN baseline for disposal waste streams is the newest submarine that has completed the disposal process. For new ship types, where a prior class does not exist, the ship with the most similarities in design and mission type should be selected.

The baseline ship already has a waste stream and hazardous material inventory available and documented for its' life-cycle; including construction, maintenance, operation and disposal. Navy ships in general and submarines in particular are ideally suited for a control volume waste stream analysis using the outer hull as the control volume boundary during normal ship operations. The disposal process for submarines is also a tightly controlled process. Submarines are currently drydocked at Puget Sound Naval Shipyard and systematically disassembled. Much of the material is sold as scrap for recycling. The disposal process is integrated into the shipyard's management information system and waste stream and hazardous material information are well documented.

Setting the boundary for construction is much more difficult. Various components are built by numerous contractors and subcontractors with little, if any, direct environmental oversight by the Navy or shipbuilder. Subcontractors are often provided only with system specifications and performance standards and allowed to complete the design work and construction using their own expertise. It is not often clear from the Navy design teams position which specifications and requirements lead to unnecessary or excessive environmental difficulties.

Understanding waste stream and hazardous material impacts for detached construction efforts therefore becomes a more difficult administrative task than during the ship's other life-cycle stages. A readily implementable approach to this problem is to require contractors and subcontractors to identify the waste streams and hazardous materials required to produce a product, along with delivery of their product. Focusing on the problem areas identified by subcontractors allows the Navy to re-evaluate the specifications and requirements leading to the problem. Often changes can be made which eliminate the pollution problem without affecting the overall performance of the ship. For example, General Dynamics, Electric Boat Division has been working with first tier subcontractors to identify pollution problems imposed by Navy or EB specifications or requirements. One problem identified was the disposal of large quantities of acid required to acid etch submarine hull tiles. By re-examining the requirements for the tiles, mechanical etching methods using water or grit blasting are being evaluated as an alternative to acid etching. If successful, the mechanical methods will eliminate the need for acid etching, possibly with a net cost savings and with no impact on the performance of the tiles.[72]

Operational waste stream data for existing ships is readily available and problem areas are already identified. Records are kept on pollutant discharges from ships for both operational practice and permitting requirements. Additionally, the Navy has conducted numerous studies on operational discharges from all ship types including both solid wastes and wastewater discharges.[68],[73] A summary of significant operational discharges from submarines is provided in Table 5-1.

During construction and disposal, established procedures and processes are used to ensure quality and costs meet mission requirements. In these instances, the waste stream associated with construction and disposal are also readily available. By thoroughly documenting the environmental efforts of the new design team, the baseline for future ships is continuously refined. Once established, the data needed for producing environmentally friendly Navy ships will become easier to use and maintain, reducing the administrative and cost burden on later ship designs.

**Table 5-1: Submarine Discharges and Sources** [68]

| Effluent | Source or Requirement |
|---|---|
| Bilgewater: cleaners, solvents, oils and other discarded or leaking liquids in various concentrations | Water and other liquids collect in the ships bilges and are discharged overboard. |
| Boiler Blowdowns: includes phosphates, sulfates, sodium nitrate, hydrazine, pH additives, sodium chloride, oxides of iron, nickel, zinc and copper, manganese, lead and chromium. | Boiler Blowdowns are controlled discharges intended to change the water treatment chemical concentrations in boiler water and to discharge unwanted particulates from the boiler. |

| | |
|---|---|
| Clean Ballast: seawater containing trace amounts of zinc, corrosion by-products and paint leachate. | Clean ballast water is transferred into and out of dedicated tanks to control the ship's stability. |
| Graywater and Blackwater: Pollutants include suspended solids, biological and chemical oxygen demand, sulfate, nitrate, phosphates, copper, nickel, iron, zinc, lead, chlorate, calcium, oil, grease. | Water use dedicated to support human habitability. Includes sewage and water drainage from showers, sinks and messing facilities. |
| Compensated Fuel Ballast: oily water | Compensated fuel ballast is seawater that replaces fuel as it is consumed to aid ship stability. |
| Equipment Cooling Water: trace amounts of copper, nickel and zinc. | Seawater used in cooling systems and discharged overboard. |
| Evaporator Brine Solution: "Distiller Scale Preventive Treatment Formulations" and other anti-fouling agents. | Evaporators extract fresh water from seawater and discharge brine concentrate. Brine is treated with antifoulants to prevent organic growth in the evaporators and is normally discharge overboard. |
| Diesel Wet Exhaust: Diesel fuel combustion products | Seawater is injected into the diesel exhaust for exhaust cooling. The wastewater runs overboard. |
| Hull Paint Leachate: copper | Ship's underwater hulls are painted with anti-fouling paints to prevent organic growth that reduces ship speed. |
| Grease from Outboard Equipment | Periodic maintenance requires greasing of outboard equipment which is washed off external submerged systems. |
| Stern Shaft Seal Lubrication: shaft seal lubricants | Seawater is injected into the stern shaft seal to provide cooling and lubrication. The water is discharged overboard and to the bilge. |
| Cathodic Protection: Ionized zinc and aluminum | Sacrificial zinc or aluminum blocks bolted to ship's hulls minimize corrosion damage to external surfaces. |

### 5.2 Environmental Requirements

The next step in the process is to assess the legal environmental requirements for the ship's design. The legal requirements expected to be imposed over the life of the ship become the minimum acceptable standards for the environmental performance of the ship. Presumably, future ship compliance levels will be determined by the Uniform National Discharge Standards for the operational phase of the life-cycle. UNDS development, however, does not simplify environmental design issues in the construction, maintenance and disposal phases of the ship. Additionally, UNDS may run into conflicts with future international environmental developments. Issues such as the international acceptance of at sea incinerators needs to be thoroughly investigated before placing incinerators onboard all Navy surface ships. The potential for political strife exists if the Navy pursues technologies deemed unacceptable by international conventions.

Local state and federal environmental requirements can drastically affect the ability of a contractor to perform certain process used on prior ships. As an example, EPA is considering imposing strict new limits on worker exposure to hexavalent chromium. Hexavalent chromium is a by product of welding stainless steel and high yield steels used on submarine hulls. The new standards will drastically limit worker productivity in these areas by requiring protective suits, new ventilation procedures and worker training. The cost of performing ship construction and disposal process involving hexavalent chromium will be passed on to the Navy in both cost and construction time.[72] The new requirements are not currently in effect, however they are expected to be in place during the construction of the NSSN. By studying the effects of the requirements during the design phase the overall impact will be understood in advance for planning purposes and may allow design or process changes to take effect to reduce the impact.

### *5.3 Identify Pollution Prevention Design Opportunities*

Once the waste stream and hazardous material levels are established from the baseline ship and the minimum acceptable environmental performance levels are determined from legal requirements, the next step is to identify the pollution prevention opportunities that exist. Identifying opportunities before or separate from the new design team is important for allocation of research and development funds. Funds need to be allocated to areas showing promise from an environmental perspective but that are too expensive to be allocated to a single program or too far from fruition to be incorporated into current designs. For example, development of a nuclear propulsion system incorporating direct thermal to electric power conversion would eliminate the waste stream associated with boiler blowdowns and significantly reduce lube oil requirements on the ship, reducing bilge water contamination. Development of such a system is beyond the time horizon and financial constraints of current programs and would therefore be pursued by NAVSEA as a long term research and development project.

There is an opportunity to improve environmental performance of Navy ship's for every waste stream generated over the life-cycle of the ship. Alternative process and systems identified before the design starts allows new ship designs to balance the cost and risk of incorporating new technologies with the ship's design requirements, especially cost and schedule constraints. These opportunities are also influenced by technological developments; making new process possible or reducing the cost and risk associated with alternatives.

Pollution prevention alternatives can be broken down into two categories: material alternatives and non-material alternatives. Improvements in material alternatives involve using a systems approach to redesign the way a task is accomplished to eliminate the waste stream. Replacing existing systems with systems that reduce, but do not eliminate the waste stream and end of pipe treatment systems are also material alternatives.

Non-material pollution prevention opportunities consider changing operational procedures, deployment alternatives and required mission parameters to eliminate or reduce waste stream impacts. This approach includes removing packing materials from shipboard stores while in port to eliminate the need to dispose of the waste at sea. Additionally, onboard storage capacity for other waste streams can be sized to meet expected peacetime operational requirements eliminating the need for at sea disposal. Centralized shore based waste processing is cheaper and more efficient because it can be utilized for longer periods and higher capacity levels and does not have to operate under ship board conditions for shock and corrosion. Situational considerations for overboard discharges such as black and gray water may also be cost effective alternatives to onboard waste treatment systems. Onboard capacity and mission profiles that support periodic transit to less-sensitive environmental areas reduce the impact of designing a ship for worst case environmental requirements.

The pollution prevention opportunities pursued must attempt to integrate pollution prevention into the lowest possible level of system and component design to truly eliminate a waste stream. As alternatives are developed, care must be taken by the designer to ensure the production processes associated with new systems or components do not produce more pollution than the savings generated from final implementation on the ship. Finally, throughout the process the results of pursuing alternative approaches must be documented, especially for alternatives that do not prove to be beneficial. Problems encountered may be overcome by future technological developments and subsequent changes in economic conditions may make unattractive alternatives more attractive in the future. Documenting the process shows where shortcomings lie and provides insight into how they can be overcome.

### *5.4 Ship Design*

The ship design phase combines the design requirements for the platform and the pollution prevention opportunities available to improve on the environmental performance of the baseline ship. By the time a program office is established to work on the details of the ship several concept studies and an exploratory design have already been completed. The first step for environmental purposes is to update the waste stream data from the baseline ship to accommodate any changes imposed by the exploratory design. The concept design is then used to accommodate and evaluate the impacts of the design requirements and constraints.

The design requirements are determined by the missions the ship is expected to be able to fulfill. They can be determined as early in the design process as the mission need statement and are often exogenous to the program design team. Design requirements for systems already in place include cost weight and volume budgets for each system as well as functional and schedule requirements. Most often these requirements are viewed as constraints which must be met, although then can be modified somewhat as the design progresses. Tradeoffs between design requirements, such as reducing performance levels to develop an affordable design or obtaining waivers for environmental or legal requirements to reduce costs continue throughout the design process. New, better or more detailed information about the impacts of various requirements on the design can lead to a re-evaluation of the requirements. When warranted (as determined by the appropriate authority who established the requirement) the design requirements should be changed.

The program office continuously refines the design through concept, and preliminary design to the detailed design that is eventually built. Within this structure, alternatives are evaluated and the ship design and design requirements are re-evaluated in an iterative, spiraling process that eventually leads to the final design of the ship. Important tradeoffs are made throughout the design process that determine the level of environmental and mission performance that is achieved in the final design. The most difficult and often unappreciated aspect of the tradeoffs is evaluating the merits of different alternatives.

### *5.5 Evaluation*

The most important aspect of environmental design is the evaluation of the environmental merit of alternatives. Unfortunately, evaluation is also the most difficult aspect because important concepts and improvements can not be conveyed in terms of a single metric such as cost or net present value. A balanced analysis framework is needed to systematically allow the ship designers to make the best possible design decision balancing pollution prevention with cost, risk and mission performance. The decision process needs to balance diverse concepts such as procurement costs, life cycle costs, environmental impacts, performance and goodwill.

True differences in procurement costs can only be measured by comparing the life-cycle cost of an entire design both with and without various pollution control strategies. This is the only way to capture the effects of adjusting weight and space requirements in a ship or submarine design and truly evaluate operational life cycle costs. Changing the design of various systems may change the total amount of maintenance and staffing requirements of the ship and repair parts needed. The extent of the change to the system may be significant, however if unintended effects degrade the overall ship's environmental performance the change should not be implemented. For example, if the propulsion system of a ship were changed to eliminate the need for lubricating oil for the same cost as current propulsion systems then on a systems evaluation the change would be worth implementing. However, if the change required adjusting the hull in such as way as to increase the ship's resistance as it passes though the water then the change has a detrimental effect of reducing the overall efficiency of the ship. A complete analysis of the proposed propulsion system must include differences in operational costs which can only be estimated using a holistic view of the entire ship's design.

An ideal evaluation method would evaluate the differences between completely designed ships based on a catalog of alternatives for each system. The catalog entry would include all important aspects of the system or component, including cost, performance and environmental merit. A computer algorithm could then determine a truly optimum ship design. Research into a system capable of executing this process using genetic algorithms to optimize the search parameters of the design optimization is in progress at MIT, but has not yet advanced to the point where it could be applied to Navy ships.[74],[75] Currently, the time and computational power required to completely design a ship to evaluating multiple alternatives is prohibitive.

Given that optimal evaluation methods are currently too expensive or time consuming to produce and are not accessible to designers at the system or component level, another approach is needed. A method to communicate project and ship design priorities to system designers that includes both cost and non-cost items would facilitate development of environmental ship designs. An overview of the considerations required for such an approach is shown in Figure 5-2. Each area can be evaluated separately and used as an evaluation input on its own or, preferably, the results of each area can be combined into a single metric reflecting the overall preference of various design alternatives.

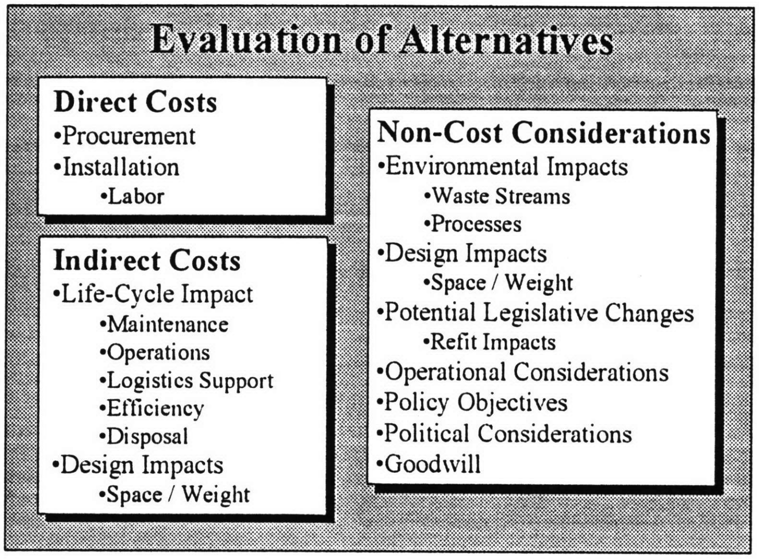


**Figure 5-2: Evaluation Considerations**

### 5.5.1 Cost Analysis

> "In the current vocabulary of condemnation there are few words as final and conclusive as the word 'uneconomic'," wrote British economist E.F. Schumacher in *Small Is Beautiful* (1973). "Call a thing immoral or ugly, soul-destroying or a degradation of man, a peril to the peace of the world or to the well-being of future generations; as long as you have not shown it to be 'uneconomic' you have not really questioned its right to exist, grow and prosper."[76].

This sentiment is well reflected in government and Navy procurements, as discussed in Chapter 3. Navy ship design is currently being conducted with cost as an independent variable (CAIV). Under this approach, the cost of the final design is fixed at a politically determined level. The final ship design cost reaches the target value by adjusting the performance capabilities of the platform. CAIV makes cost comparisons between alternatives in all aspects of ship performance paramount. Analyzing costs associated with pollution prevention alternatives involves evaluating direct costs associated with procurement, operation, maintenance and disposal as well as evaluating the indirect costs associated with preventing a waste stream from impacting the environment.

It is difficult, if not impossible, to quantify the effects of reducing pollution from Navy ships. Over 80% of ocean pollution originates from land sources.[77] Since Navy ships are only a small percentage of total world wide shipping, determining environmental savings from pollution control methods on a given ship is not realistic. Questions such as "How much savings is associated with not shooting a TDU load?" or "What is the financial benefit from reducing oil content in discharged water from 50 ppm to 15 ppm?" have no direct financial answers. Similarly, goodwill benefits from setting a performance standard for military ships under the UNCLOS or MARPOL 73/78 conventions are also unquantifiable. Yet, neglecting goodwill and pollution prevention benefits assumes their value is zero, which is clearly not the case! The decision support system used by the designer and other decision makers needs to consider these unquantifiable costs and benefits alongside direct cost calculations.

Market economic concepts can be used to evaluate alternative pollution control alternatives once the costs have been calculated and the benefits identified. Start with the assumption that the marginal benefits must be greater than the associated marginal costs to select a given alternative. The marginal cost values are known and can be compared to the list of marginal benefits. Instead of determining a value for marginal benefits, the design team only has to determine whether the marginal benefits are greater or less than the value of the marginal costs. If the marginal benefits exceed the marginal costs, the alternative is acceptable, although perhaps not optimal.

Each pollution problem should also consider operational and procedural alternatives to each design change. Ships and submarines are restricted from making discharges within 12 nautical miles of land. The restriction is enforced by operational procedures that have very low costs, if any, associated with them. Operational requirements can be based on marginal cost verses marginal benefit for each operational situation encountered. Marginal benefits for limiting discharges are greater in environmentally sensitive areas than they are for the open ocean. Modifying operational procedures and deployment scheduling to allow discharges only in particular areas where the marginal benefits are low need to be compared to the costs of designing the ship to operated unrestricted in environmentally sensitive areas. This approach does not increase the procurement cost and may have little effect on ship operations. Extending the economic framework further, during a war the marginal benefit of making a discharge where ever the ship may be is considered to outweigh the marginal costs.

Comparing costs and benefits of various design alternatives requires a decision analysis tool which can capture indirect and direct marginal costs in a quick, straightforward manner. Such a tool has to be capable of being utilized at the lowest levels of the design and ensure all important impacts are considered. The Analytic Hierarchy Process (AHP) and multi-attribute utility analysis allow decision makers to formally rank different alternatives based on various considerations that may not be quantifiable.[78] Using these and other decision tools allows designers to consider the merits of various design approaches and choose the best alternative.

#### *5.5.1.1 Direct Costs*

The first step in evaluating alternatives is to compare the direct costs associated with procuring and installing a new system. Direct cost also needs to consider the installation process required and the associated labor costs. In most instances installation costs for alternative systems will be close, if not the same. However, it is still necessary to verify that there are no significant changes in installation procedures and processes. Direct cost is usually readily available for ship systems because of the oversight requirements for procurement programs. It is often limited to a predetermined maximum limit by the acquisition authority and tradeoffs are made between performance levels and direct cost. Additionally, direct costs are readily calculated from generally accepted accounting principles and are supported by refined estimation techniques. Parametric cost estimation models based on previous procurement experience are used throughout DOD. In general, the inputs and outputs to the cost models used are shown in Figure 5-3. The overall parametric cost estimation process is diagrammed in Figure 5-4.[79]

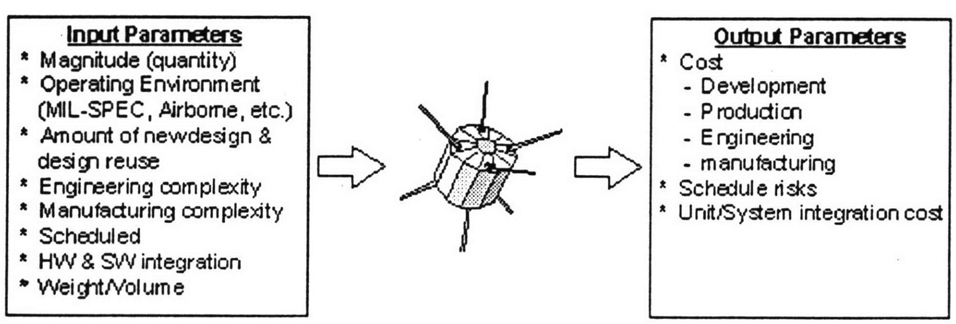


**Figure 5-3: Cost Model Parameters**

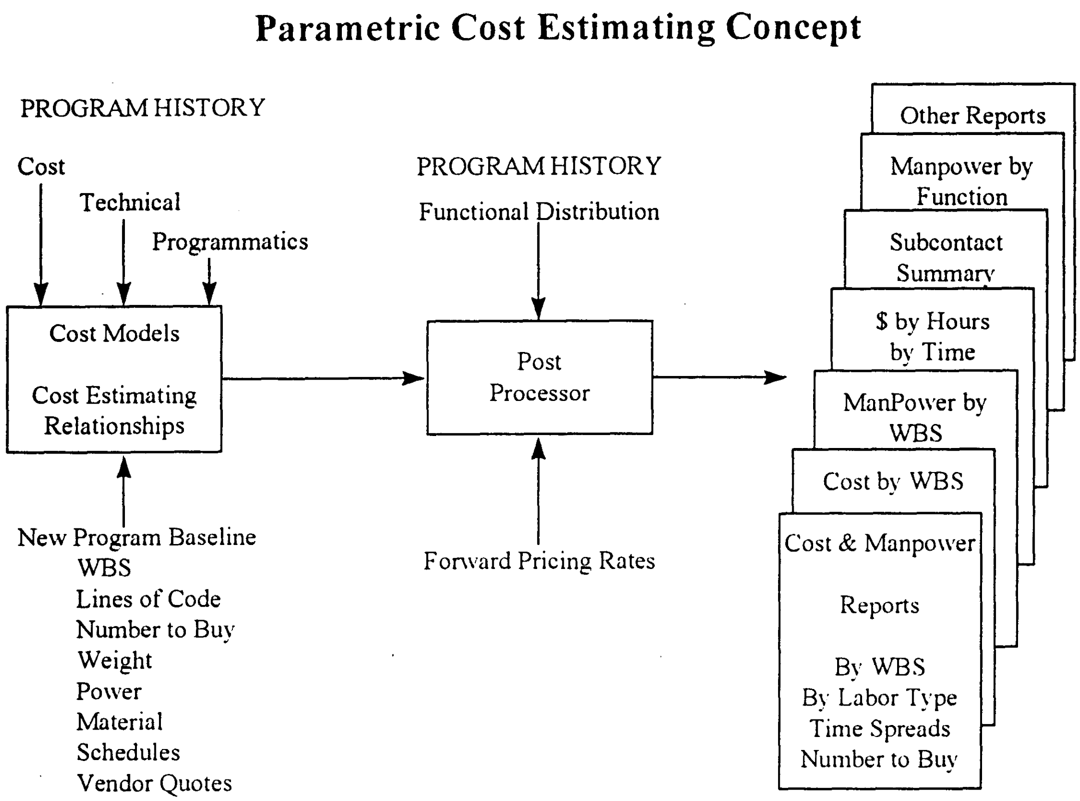


**Figure 5-4: Parametric Cost Estimating Process**

Unfortunately, many procurement decisions are made based on direct cost alone. It often meets program requirements for cost accounting and exploration of alternatives and focuses attention on the procurement cost and budget associated with the program. As discussed in Chapter 3, the procurement cost of a program determines the political acceptability of alternatives, not the life-cycle cost. The disadvantage of relying on direct cost alone is that it does not capture the holistic cost impacts on the ship. Indirect costs of changing the ship design to accommodate alternative systems may result in changing the direct procurement cost of the ship and also need to be considered in the evaluation process.

#### *5.5.1.2 Indirect Costs*

Indirect costs start by capturing the life-cycle cost items associated with alternatives. Life cycle cost is defined by the Department of Defense's *Parametric Cost Estimating Handbook* as the cost associated with all the phases of a program: design, development, prototype, production, and maintenance and operations. Life cycle cost studies are required to be performed as part of a system's acquisition studies, however;

> "Life Cycle costs may not be accumulated into the project's total costing structure. They must be kept track of separately; the reason for this is that the time frames over which Life Cycle costs would be realized always span a much greater period of time than other facets of the project." [79]

This practice is driven by budget cycle considerations discussed in Chapter 3 and reinforces the second class nature of life-cycle cost estimates within DOD. A realistic evaluation framework must consider life-cycle costs as part of an overall evaluation of alternatives.

The most significant inputs for life cycle cost estimating are the maintenance strategy to be used, the concept of operations and the logistics support structure needed to support the system.[79] When comparing alternatives, the basic design work has already been completed; is a sunk cost and should not be considered in further evaluation of the design. Life-cycle cost analysis also needs to consider final disposition of items including hazardous waste disposal costs and any associated potential for future liability as well as any demilitarization costs.

Another item to consider with traditional life-cycle cost estimates is any change in efficiency from the baseline. This includes accounting for a lower system operating efficiency as a result of design changes to improve environmental performance. Increasing fuel consumption by the ship for propulsion or auxiliary loads increases both the cost of operations as well as the environmental impact of an alternative. In cases where the system efficiencies of auxiliary systems are close to that of the baseline, the life-cycle cost can be neglected without significant impact. In many instances, the design of new systems for environmental purposes provides an opportunity for system design to update to more modern technology and the overall efficiencies are higher.[3] An impact on the final ship

[3] For example, the NSSN R-134a air conditioning plants are more efficient during shipboard operations than R-114 plants. The environmental requirement to eliminate CFC's such as R-114 allowed designers to optimize the air conditioning plants for the load requirements of the NSSN. As a result, the ship's normal air conditioning load can be handled by a single unit, rather than 2 or 3 smaller R-114 units. The operation of a single, larger unit improved the overall efficiency of the air conditioning ship set.

design affecting the overall ships operating efficiency is considered separately.

#### *5.5.1.3 Preliminary Evaluation*

At this point in the evaluation process, both direct and life-cycle costs of alternative designs can be determined using existing cost models. A standard engineering economic analysis can be used to combine the two costs to generate a net present value for each alternative. However, the cost of possible impacts to the ships overall design and the value of improving environmental performance have not yet been considered. If there is no ship impact associated with alternative designs and the environmental performance improves the baseline significantly, then a preliminary evaluation can be used to select the preferable design configuration. This evaluation combines the direct and life-cycle cost values in to a single cost figure representing the net present cost of the systems being considered. If the environmentally friendly alternative has the most preferable net present value, then it should be selected without wasting time and resources on further analysis.

In situations where the alternatives impose additional requirements on the overall ship design and/or where the merits of environmental performance levels are not clearly in favor of an alternative, then the evaluation process must account for the value of these impacts. The life-cycle cost figure can accommodate ship impacts as a dollar amount if the extent of the impacts can be assessed from the current stage of the ship design process.

If additional volume or weight must be added to the ship to accommodate alternative systems, the direct cost and life-cycle cost on the overall platform must also be considered. This requires use of a cost per ton or cost per cubic foot of ship space and knowledge of the effect on the ships operations in term of an efficiency per ton displacement or overall length. If these values can be determined easily, they should be added to the design alternatives direct and indirect costs. In most instances, however, an analysis of this type is not practical. Weight or volume considerations are normally included in design margins that are refined as the design progresses. As such they should be evaluated with environmental performance criteria as non-cost considerations. A flow chart depicting the requirements and process of the preliminary evaluation is shown in Figure 5-5.

# Preliminary Evaluation Flow Chart

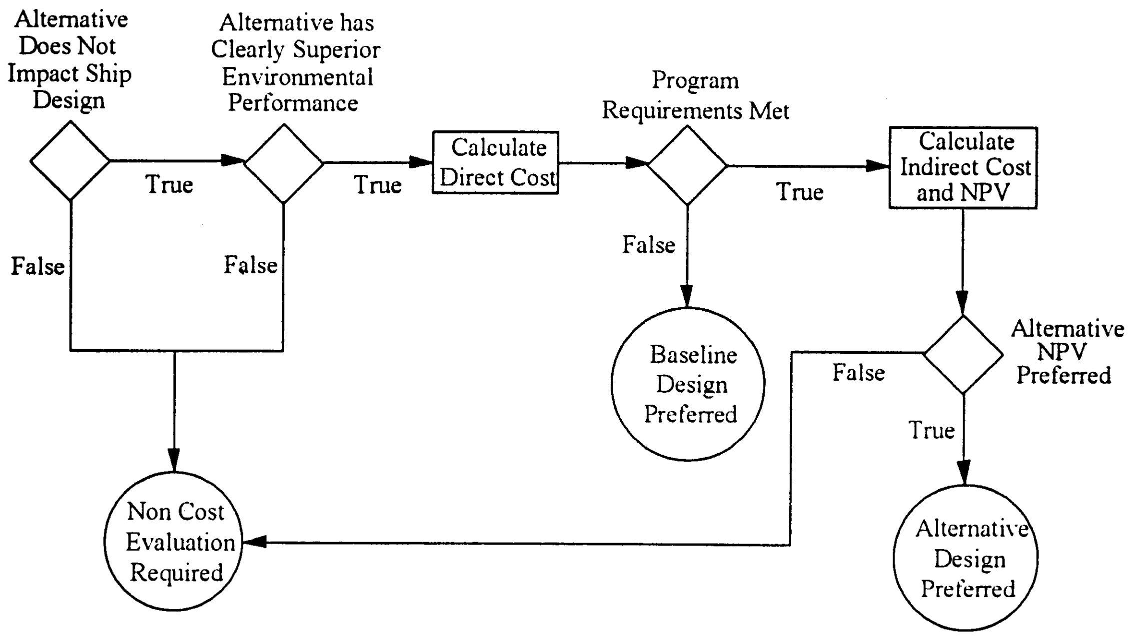


**Figure 5-5: Flow Chart for Preliminary Evaluation Criteria**

### 5.5.2 Non-Cost Analysis

Environmental attributes of various designs often can not be easily captured in financial terms. Environmental impacts can consider both chronic and acute effects, requiring different time scales to use for analyzing the effects of environmental damage. Additionally, ecosystem analysis can consider not only the direct impact on a species from a given waste stream, but also the secondary and tertiary effects on other species resulting from the initial impact. The cost value of recreational use of an ecosystem (swimming, fishing, natural beauty, etc.) are also necessary for a complete evaluation, yet do not lend themselves to a reasonable cost figure.[80] This is also a major shortcoming of traditional environmental impact assessments.

In addition to the "cost" associated with the environmental impact of a waste stream, items such as goodwill, policy objectives, politics and the impact on the overall ship design play a significant role in the decision process but are not captured in traditional cost figures. A straight forward method for discriminating between the different designs which includes these non-cost metrics is needed. The Analytic Hierarchy Process (AHP) and multi-attribute utility analysis (MAU) are decision support and analysis tools that can accomplish this task.

Both methods allow decision makers to formally rank different alternatives based on various considerations that are not formally quantified. The ranking process can be completed in general terms by the decision maker, allowing abstract concepts such as goodwill, and secondary considerations associated with various cost levels and impacts, to be implicitly included. Once the decision process structure has been established it can be used to guide the system designer in making tradeoffs during the formative stages of the design.

### 5.5.3 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), developed by Prof. Thomas L. Saaty of the University of Pittsburgh, provides a means to compare the relative merits of alternative designs. AHP makes it possible to deal with both tangible and intangible factors for multi-objective decision making, allowing a formal ranking to be developed which expresses the overall merits of each alternative under consideration.

The evaluation is formally structured into a hierarchy or decision tree structure which allows the decision maker to rationally examine the objectives of design. At the top of the structure is the goal of the process. In our case it is something like: "Select the best design alternative." Under the goal, criteria are listed in terms that measure the relative success of achieving the goal. Criteria for an environmental design framework might include cost, environmental performance, ship design impact and risk. A pairwise comparison between criteria is made to determine the weighting factor assigned to each criteria. Alternative designs are then compared, also in a pairwise manner, to establish a measure of overall preference. A symbolic representation of the AHP decision framework is shown in Figure 5-6. The pairwise comparisons allow the decision maker to fully factor in otherwise intangible factors. By comparing each new alternative to the baseline design, the merits of the intangible factors such as environmental performance can be incorporated with tangible factors such as cost.

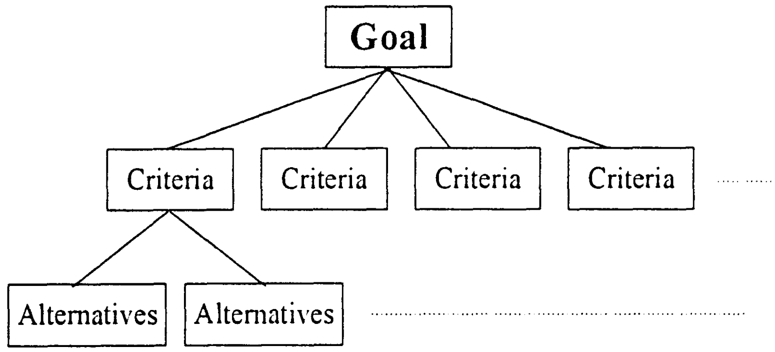


**Figure 5-6: AHP Decision Framework**

The primary advantage of AHP is the relative ease of use, especially through commercially available computer programs. The interview process is not very complicated and decisions are limited to straightforward comparisons of two alternatives. The decision maker only needs to chose which of the two alternatives or criteria are more important and by about how much. AHP is also adaptable to group decision making forums. Additionally, sensitivity analysis of the weighting of each variable in the decision process can be performed, allowing decision makers to have confidence in their selections.

The principle drawback is that the relative value of the inputs must vary linearly under each criteria. Additionally, the merits of each criteria are evaluated independently of the value of other variables. The assumptions of linearity and independence often do not hold, especially as the ends of the range of consideration is approached. This problem can be overcome by using another approach called multi-attribute utility analysis. AHP has been applied to the NSSN air conditioning selection described in Chapter 6 and the specific details of the analysis are presented in Appendix A.

### 5.5.4 Multi-attribute Utility Analysis (MAU)

Often, people's valuation of costs and benefits is nonlinear. In these circumstances, the accuracy of linear evaluation techniques such as reducing all dimensions to cost values and basing decisions on NPV or using AHP can lead to less than optimal design solutions. Utility functions are one method of capturing the nonlinear relationships between alternatives and consequences and are well suited to situations involving uncertainty, such as cost and risk estimates. For example, a tradeoff between acceptable levels of ship performance and cost depend on the actual values being considered.[81] It may be worthwhile to reduce the ship's speed by one knot for a savings of $20 million if the ship's speed is well above the threshold performance level and cost is near or above its limit. However, a knot reduction in speed may not be worth the same $20 million if the projected ship's speed is near its threshold value and costs are well under established limits. Utility analysis allows the decision maker to tradeoff alternatives between cost and speed across the whole spectrum of acceptable levels.

The first step in a utility analysis is to select the variables that the decision process will include. Practically, the number of variables is limited to 4 or 5, based on the amount of data that can be reasonably gathered from an interview with a decision maker. The next step is to establish the possible range of consideration for the variable. In ship design, a goal and threshold level for items such as performance and cost are often established early in the procurement process and serve as the range. For other design objectives, comparison with the baseline design can quickly establish a range. For example, the range of acceptable costs values for an environmentally friendly air conditioning plant design might be between 50% and 150% of the cost of the baseline air conditioning plant design. On the low end, this implies the decision maker does not feel a reasonable level of performance can be produced for less than 50% of the current design. On the high end, the decision maker is not willing to pay for the improvements in the design if the cost exceeds 150% of the baseline.

Once the range has been established for each variable, an interview is conducted with the decision maker which evaluates his preference or utility for the various levels of each variable. The ends of the range of interest are assigned a utility of 0 at the low end and 1 at the high end. Other points on the curve are then determined by asking the decision maker to compare two alternative designs in a lottery fashion. One option sets the value of the variable while the other sets the utility of that particular value. The probability associated with utility is adjusted until the decision maker has no preference for one option over the other. At the indifference point, the utility value can be determined. This process is repeated for each point determined on the utility curve. This is known as the one dimensional utility function for the variable.

Cross correlation between variables is then analyzed in a similar fashion to incorporate interactive affects between the variables. The final result is a multi-dimensional utility function which captures the tradeoffs for inputs of each variable under consideration. Specific details of setting up a multi-attribute utility analysis are available in reference 81. The use of multi-attribute utility analysis for the NSSN air conditioning plant is described in Chapter 6. The interview questionnaire and calculations supporting the utility function are provided in Appendix B.

MAU meets the needs of the design evaluation technique discussed, can be very accurate and overcomes the limitations of AHP. However there are some drawbacks. First, it is not as simple to set up as AHP. The interview process requires a working knowledge of utility theory to properly set up the questionnaire and evaluate the results. Additionally, the lotteries used in the interview process are taxing; limiting the number of questions, and thus variables and points on the utility function that can be determined. Practical interviews are limited by the accuracy the decision maker can maintain to about 30 questions. For a four dimensional utility function, four scaling factors are required, leaving a maximum of 6 internal single attribute utility points (the range locates the end points for 0 and 1.0 utility values). If additional variables are required in the analysis, the number of points is further reduced. In the limit only the end points are determined, the curves are linear, and a one level AHP result is generated. The interview complexity also makes it very difficult to use MAU for group decision making.

### 5.6 Implementation

The final step in the ship design framework is to implement the results of the decision process. This includes documenting the results for future evaluations, incorporating new system requirements into the overall ship design, updating the baseline to the latest design and procuring the system. Documenting the evaluation process to show where alternatives fall short of the baseline can provide valuable information to designers and contractors about the alternative. This information can then lead to more significant improvements to the new baseline without the need to "reinvent the wheel".

Updating the baseline ensures a continuous improvement process is in place for environmental design concerns.

The link between implementation and establishing a new baseline for environmental performance in Figure 5-1 passes from the project team back to NAVSEA. This is a critical link that is currently missing from the Navy's environmental policies. At the conclusion of a design, the design team has a good understanding of the environmental impacts associated with the ship. They know where they have been successful and where the largest potential for future improvements lie and they are familiar with areas that hold promise but were not pursued because of cost or schedule risk. These items are important focus areas for future pollution prevention opportunities and research and development programs. Formally closing this loop will ensure limited research funds are allocated where they can provide the most significant impacts to future ship designs. Unfortunately, pursuing these items for the next generation of ships is not part of NAVSEA's environmental code's mission.

Another key aspect of implementation is establishing the life-cycle support structure for the design. This entails ensuring the environmental consideration that were considered during the evaluation phase are carried out throughout the ships' service, maintenance and retirement. In most cases, the service and maintenance requirements are routinely incorporated into the ship's operating procedures and maintenance instructions. Part of this process is to ensure the administrative requirements for solvents, cleaning agents and other periodically or infrequently used substances required for long term operation meet applicable environmental guidelines and policy objectives. Review of standard specifications and maintenance requirements at this stage can reveal numerous additional opportunities for pollution prevention, especially where actual system requirements can be determined accurately. This has been a key area of focus for the NSSN environmental management team, resulting in significant improvement in the life-cycle environmental performance of the ship.[59]

### 5.6.1 Requirements for Contractors

The final aspect of implementation concerns extending improvements in environmental performance to the production or procurement of ships and ship systems. The Navy has very little control over the process and procedures used to produce components under contract with vendors. Generally, the contractor delivers a product meeting required performance specifications for a price. How the product was developed and produced is not part of this exchange. Often, however, the specifications for a product unnecessarily lead to environmental hazards, like the requirement to acid etch tiles discussed in Section 5.1. Encouraging contractors to use environmental accounting techniques or comply with commercial environmental standards would allow contractors to more easily identify environmental hazards associated with producing a product so that design changes or replacements can be identified. Currently, there are at least two formal approaches in place which would meet this objective: ISO 14000 certification and 'green' accounting practices.

#### *5.6.1.1 ISO 14000*

ISO 14000 is a voluntary, international environmental management method developed by the International Organization for Standardization. The ISO 14000 series standards are intended to establish a common worldwide approach to management systems that will lead to the protection of the environment "while spurring international trade and commerce". The standards do not prescribe performance levels, but focus management attention on performance shortfalls and improvement methods. As a voluntary standard, the push for ISO 14000 certification comes from potential regulatory relief, requirements for international trade and requirements to do business with governments and companies in a manner similar to existing certification processes focusing on quality control.[82]

ISO 14000 certification requires a company to establish an environmental management system based on the "plan, implement, check and review" dynamic process advocated in quality improvement programs such as Total Quality Management. The process includes establishing an environmental policy; identifying the environmental aspects and impacts of its operation; identifying legal and regulatory requirements; setting priorities; providing an implementing structure; instituting monitoring and control procedures and reviewing overall policies for effectiveness. Topics covered include direct emissions, energy consumption, raw materials, supplier standards and product use and disposal.[83]

It is important to note that the certification process is performed by an independent organization for a companies' management system as it pertains to environmental issues. It is not a certification of environmental performance. The certification process determines if the procedures and accounting processes are in place, not the validity of data or what is being reported. Since there are no formal performance requirements other than improvement over time, it can not replace legal environmental regulations.[82]

Current DOD policy on ISO 14000 is that DOD already has life-cycle responsibility for its' products (weapon systems) and currently has an established environmental management system which conforms to the ISO 14000 requirements. DOD will not seek ISO 14000 certification. Additionally, certification will not be required for companies to do business with the DOD, however, certification will be encouraged. Encouragement may come in the form of a competitive advantage in contracting by being required to meet fewer DOD auditing and oversight requirements or preference in contracting where it is otherwise legally acceptable. DOD will not reimburse any costs associated with a companies implementation of ISO 14000.[84]

#### *5.6.1.2 Activity Based Costing*

Activity based costing or "Green Accounting" involves the implementation of a managerial cost accounting systems which includes environmental as well as other life-cycle costs of a product. Under currently required accounting practices corporations don't really know where pollution prevention and environmental costs are incurred and how high they might be. They are often incorporated into operating costs such as product specifications, process design and waste handling, or in administrative costs such as public relations and compliance monitoring.

Distorted cost information is the result of the evolution of accounting practices that made sense decades ago, but that no longer provides a clear cost picture for decision making. Current practice is based on companies producing a narrow range of products with direct labor and materials as the most important production factors. Distortions to these costs from non-production areas like overhead were minor and the expense of collecting and processing data made it difficult to justify more sophisticated allocation of indirect costs. As the fraction of corporate costs spent on direct labor decreased with increasing expenditures on support operations, engineering, research and development and environmental compliance and liability, this accounting cost system lost its ability to scrutinize cost drivers effectively.[85]

Activity based costing considers all the costs generated by a company as product costs of some type. This approach allows cost categories that vary with changes over a period of years to be captured by the product that requires them, rather than in traditional categories of overhead or administration. The activity based costing system focuses on expensive resources, whose demand patterns are uncorrelated with traditional allocation measures like direct labor, processing time, and materials; such as environmental compliance. Costs are traced from resources to activities and then from activities to products.[85]

By assigning pollution and environmental costs directly to a product, the environmental cost basis can be determined and used to pursue opportunities for pollution prevention. An Amoco study found the environmental costs associated with a refinery to actually be 22% of operations instead of the 3% assumed under traditional accounting methods. They had considered wastewater treatment to be the most significant single cost, but found that maintenance requirements had a higher environmental cost. The accounting change allowed Amoco to address issues in the most cost effective manner, subsequently reducing both the cost of operations and the environmental impact of the refinery.[86]

The Navy can not simply require contractors to implement activity based costing, however, similar to the approach being taken with ISO 14000, the Navy can encourage its use. Imposing contract requirements to report environmental costs associated with product development in an activity based manner would be a start. Preferences and competitive advantages for companies implementing such system would also further enhance the spread of activity based costing.

## 6. Evaluation of Design Alternatives

This Chapter demonstrates implementation of the evaluation process shown in Figure 5-1 and discussed in Section 5.5 for the use of an environmentally preferable air conditioning plant on the NSSN. All U.S. Submarines since the 688 class, designed in the 1970's, utilize chlorofluorocarbon (CFC) - 114 centrifugal compressor air conditioning plants for cooling components and for personnel comfort. CFC-114 or refrigerant - 114 (R-114) is considered to be an environmental hazard because it depletes the earth's protective stratospheric ozone layer. Under the 1990 amendments to the Montreal Protocol and United States Clean Air Act, the production of CFC-114 will be banned by the year 2000. Additionally, a Presidential announcement in February 1992 declared that the United States will end all CFC production by 31 December 1995.[87] This announcement was followed up by Executive Order 12843 in April 1993 which mandates Federal agency use of non-ozone-depleting substances where economically practicable, and demonstration of leadership to phase out ozone depleting substances.[12]

The Navy has accumulated a stockpile of R-114 for use in existing ships until the units are decommissioned, however new ships are not granted access to the stored R-114. As a result, a new air conditioning plant using a non-CFC refrigerant is required for the NSSN. HFC-134a was selected as the replacement refrigerant because it will be commercially available in time to support the NSSN, it has an ozone depleting potential of zero and it was the only alternative meeting these requirements at the time the decision had to be made.[87]

HFC-134a is a more dense compound than CFC-114 and is used at a much higher pressure. In centrifugal compressor applications, HFC-134a impellers must be considerably smaller than those for CFC-114 and operate at much higher speed. As a result, HFC-134a can not be backfit into existing CFC-114 designs.[87] A research and development program was initiated in 1991 to develop an HFC-134a shipboard air conditioning plant with a prototype available by 1996. The 1991 total development cost for a HFC-134a design and prototype was estimated to be about $8.4 million dollars.[88]

The air conditioning plant decision is used as an evaluation example because the change was mandated without a detailed analysis. As a result, pertinent data for both the baseline design and the new alternative are available and a hindsight analysis can be conducted. An interview with the NSSN environmental manager assessed the weighting of the criteria used in the decision process as well as the preferences between the air conditioning plant alternatives. The environmental manager's selection for the interview process is based on his knowledge of the environmental issues associated with the NSSN as well as knowledge of the other constraints the program is currently facing.

## *6.1 NSSN Air Conditioning Plant Alternatives*

A comparison of the alternative air conditioning plants for the NSSN is shown in Table 6-1. The evaluation process will determine which system is preferred assuming R-134a is not required. The R-114 system uses two plants to carry the ships load with two installed spares. The plants are arranged in pairs with each pair supplied by an independent power bus allowing the entire ship's load to be carried from a single bus. The R-134a plants are larger, allowing the ships load to be carried by a single plant. The other plant serves as an installed spare powered from a different bus.

**Table 6-1: Comparison of R-134a and R-114 Air Conditioning Plants**

| | R-114 | R-134a |
|---|---|---|
| **Capacity per Unit** | 225 tons | 450 tons |
| **Capacity per Ship Set** | 1000 tons (4 units) | 900 tons (2 units) |
| **Cost per Ship Set** | $5.2 M FY97 | $4.7 M FY97 |
| **Cost per Ton** | $5,200 FY97 | $5,222 FY97 |
| **Power per Ton** | 0.86 kw/ton | .96 kw/ton |
| **Horsepower** | 260 | 311 |
| **Weight** | 85,000 lbs | 60,000 lbs |
| **Environmental Concerns** | CFC | Decomposition in Burner to HF acid gas |
| **Ozone Depletion Potential** | 0.7 | 0 |
| **Global Warming Potential** | 3.7 | .25 |
| **Atmospheric Lifetime** | 200 years | 5 years |
| **Risk** | Field Proven Design | Untested Design |

The NSSN design is considered a weight limited design, meaning the weight of the components that go in the hull has been fully allocated. If any component exceeds its' weight budget, an equivalent weight must be removed from somewhere else in the design. There is some extra volume in the hull for components but no extra displacement to support added weight.

### *6.2 Evaluation Criteria*

The most significant criteria in making decisions concerning a ships' components are cost, risk and any impact the systems may have on the overall design.[89] In evaluating alternatives at the component level, each alternative must meet specified design requirements to be considered viable. Performance criteria are constrained by higher level design decisions, thus the level of performance provided is not an explicit evaluation criteria. Since the main concern here is to incorporate environmental considerations into the evaluation criteria, environmental performance of alternatives must also be considered.

Cost can be broken down into acquisition cost and life-cycle cost, however due to budget cycle considerations discussed in Chapter 3, direct cost is the most important. Within the NSSN program, life-cycle cost estimates are suspect and there are very few incentives to trade-off current dollars for potential future savings that may or may not materialize.[89] Therefore acquisition cost is used as the cost criteria for this evaluation.

Risk considerations at the program level include risk of cost estimates being understated, risk of a product being unable to deliver stated performance, risk a system or component can not be produced in time to support the ships' procurement schedule and industrial base associated with vendors being unable to meet future needs for replacement parts or service.[89] Of these considerations, the risk of impacting the program's schedule is the most significant. Cost risk can be included with the direct cost estimate for incorporation in the decision process. New product performance levels are subjected to rigorous engineering analysis by NAVSEA engineers and often prototype testing before being considered viable, thus this risk has already been minimized by this stage of the decision process. Industrial base risk is a consideration that parallels life-cycle cost estimates in that it concerns future projections which are suspect. Additionally, it also is addressed along with the viability of the product. Industrial base considerations are also incorporated into the political and performance inputs to the design requirements in Figure 5-1.

Schedule risk is therefore the most important factor to consider. Impacting the production schedule can cause significant disruption costs and impacts to the Navy which are unacceptable. In evaluating alternatives, the project team assesses the ability of the vendor to deliver the product as scheduled. The overall procurement schedule of the ship tends to slip to the right as the design matures, accommodating political, budgetary and design constraints. As such, there is some schedule flexibility for the delivery of systems and components which can be traded-off against other evaluation criteria.

Design impact in the NSSN program is a function of the weight of a system as compared to the weight allotted for it in the overall ship design. As the design matures the margins become strict allotments. Systems that end up weighing more than expected must be offset by weight reductions elsewhere. Since some estimates are inevitably exceeded and others reduced, it is possible for the design team to trade-off weight for other criteria.[89]

The final and most difficult criteria to evaluate is environmental performance. The considerations given to environmental performance in the NSSN program to ensure that decisions reflect "smart business". Investments are made to eliminate life-cycle problems of the baseline ships and to reduce, minimize or eliminate, by volume or quantity, the hazardous materials involved. The environmental design team has established a list of 70 hazardous materials targeted for reduction or elimination in the NSSN design. Each item on the list is considered equally undesirable in environmental performance. However, when a trade-off between environmental performance and other criteria is required, preference is given to substances which can be easily contained such that their use does not pose significant risk to the crew. For example, the design team would continue to use Cadmium electrical connectors if the cost of alternatives is too high. The connectors can be easily mapped to ensure proper disposal at the end of the life of the component. The connectors are generally inaccessible to the crew and do not pose a significant personnel hazard.[89]

## 6.3 Preliminary Evaluation

At the program level, the first step in the evaluation process is the preliminary evaluation shown in Figure 5-5. The weight of the R-134a plant is less than the baseline so that it does not impact the ship design and provides a clearly superior environmental performance. The direct cost is also below the baseline indicating that the R-134a plant can be chosen without further evaluation if the indirect costs and non-cost considerations described in Figure 5-2 are preferred over the baseline. Since the R-134a alternative uses 2 instead of 4 plants the life-cycle impacts listed in of the new design are lower than that of the R-114 baseline. Non-cost considerations also clearly favor the R-134a alternative because of its' environmental performance improvements without adversely impacting the overall ship design. As a result, the R-134a alternative could be selected without further analysis. For demonstration and analysis purposes, the evaluation process is continued using both the Analytic Hierarchy Process and Multiattribute Utility Analysis.

## 6.4 Analytic Hierarchy Process

An interview with the NSSN environmental manager based on the analytic hierarchy process determined the preference for air conditioning plants on the NSSN.[4] The interview started with a discussion of the criteria used for trade-off decisions and a definition of the terms used. The objective of the decision process is stated as: "Select the most preferred Air Conditioning plant for the NSSN".

### 6.4.1 General Prioritization of Evaluation Criteria

With the objective in mind, the first step in the process is to determine the weighting associated with the decision criteria. This was accomplished by a pairwise comparison of each of the criteria. The comparisons are made on a scale from 1 to 10. The decision maker starts by choosing which of the pair of criteria being considered is the most important. Next, the decision maker estimates how much more important that criteria is compared to the other. A value of one is assigned if the criteria are equally important, three is moderately more important, five is strongly more important, seven is

[4] The interview included Expert Choice™ software.

very strong and nine is extreme. The matrix determined through the interview process is shown in Table 6-2 and the resulting weighting factors assigned to each criteria are shown in Table 6-3. The arrows in Table 6-2 point towards the most important criteria.

**Table 6-2: Pairwise Criteria Weighting Matrix**

| | Risk | | Weight | | Env. Performance | |
|---|---|---|---|---|---|---|
| **Cost** | 5 | ⇐ | 2 | ⇐ | 6 | ⇐ |
| **Risk** | | | 4 | ⇑ | 4 | ⇐ |
| **Weight** | | | | | 5 | ⇐ |

**Table 6-3: Decision Criteria Weighting Factors**

| Criteria | Relative Weight (Sum = 1.0) |
|---|---|
| Cost | 0.499 |
| Risk | 0.125 |
| Weight | 0.320 |
| Environmental Performance | 0.056 |

The weighting factors in Table 6-3 provide a relative measure of importance for the evaluation criteria considered. These values can be used in several ways to facilitate developing new system designs. Design engineers can evaluate alternatives at the component level with the weighting factors as a guideline, discarding engineering solutions that have little chance of become ship design alternatives because of cost or weight considerations. Similarly, by assigning a goal and threshold to each of the criteria the design engineer can roughly determine the value of potential engineering solutions before investing a significant amount of research and development time and resources. The goal and threshold levels are established by comparing the value of each criteria of the new design to the baseline. The range of consideration for the NSSN program is provided in Table 6-4.

The goal or minimum values in Table 6-4 represent the minimum level the NSSN program considers reasonable for trade-off decisions. It includes considerations for design viability as well as the low end that a trade-off would be considered as reasonable. For risk and environmental performance the goal is also a minimum possible. For cost, a zero cost item could not be expected to fulfill the design requirements of the system and is therefore not considered. The 75% value indicates that a new system design proposal estimated to cost less than 75% of the baseline system while meeting the same engineering requirements is not likely to be viable. The cost and performance of the system would be carefully evaluated before being considered a viable alternative and the risk associated with the low cost estimate would also be included with the cost value used in the decision process.

**Table 6-4: Range of Consideration for Decision Criteria**

| Criteria | Goal or Minimum Conceivable Value | Threshold or Maximum Acceptable Value |
|---|---|---|
| Cost | 75% of Baseline | 150% of Baseline |
| Risk | Delivery will not impact current schedule. | 75% chance to impact current schedule by 9 months. |
| Weight | 85% of Baseline | 150% of Baseline |
| Env. Performance | No environmental Impacts | Impact of Baseline Design |

The low end of the weight estimate is different from cost in that it represents a point of minimal or no value to the decision maker. Since each system is allotted a weight budget based on the baseline design, there is no incentive to trade other criteria for weight reductions below about 85% of the baseline. The 15% reduction considered compensates for excess weight in other systems which has value. Lower weight in a design is still acceptable (the R-134a ship set weighs 71% of the baseline R-114 ship set) however, beyond the 15% reduction, this decision maker is not willing to compensate for a lighter system through increased costs or reduced environmental performance.

Combining the weighting of each criteria with the goal and threshold values allows designers to make trade-off decisions at the earliest stages of design. For example, an alternative that completely eliminates environmental concerns would raise the score of the new design by 0.056 points. This improvement is worth roughly 11% of the cost range or 45% of the risk range or 18% of the weight range or some combination of each accounting for the equivalent value.

A drawback to this approach is that it assumes the weight of each criteria is constant over the range allowing the trade-off to be made linearly. This assumption is rarely, if ever, true as is shown in Section 6.5. A decision that eliminates the environmental impact for a cost of 10% of the range will often depend on where in the range the actual cost lies. If cost is below baseline, the decision to make the change is acceptable, however if the cost is currently over the baseline by 30%, the decision to increase the cost further to improve environmental performance may not be acceptable.

Within AHP this assumption can be overcome at the decision makers level if the alternatives are compared to each other rather than scored on an absolute scale. This process allows the decision maker to determine which of several alternatives are preferred for incorporation in the design using the same pairwise comparison approach used to weight the decision alternatives. The pairwise approach eliminates the range requirement, allowing the actual values to be considered by the decision maker. Unfortunately, this approach is not readily transferable to design engineers and other decisions made early in the design process or outside the program office.

### 6.4.2 Evaluation of Alternatives

The air conditioning plant alternatives described in Table 6-1 are evaluated using the pairwise comparison approach with the weighting factors shown in Table 6-3. The scores generated by the AHP process are shown in Table 6-5. As expected, the R-134a plant is clearly preferred.

The magnitude of the difference in the final values has little meaning in itself since the scores are generated on a comparative basis and normalized to a total of 1.0. An examination of the sensitivity of the results to the various weighting factors and scores awarded during each comparison provides a measure of confidence in the results. The results and sensitivity analysis are included in Appendix A. Since the R-134a plant was preferred in all categories except risk, this is the only variable of interest for further analysis. The weighting factor for risk would have to be more than doubled to a value of 26% while reducing all other weighting factors proportionally for the R-134a system to be equal in preference to the R-114 system. Since a doubling is not a reasonable margin for error in setting up the weighting factors, the R-134a plant is certainly the preferred option.

An analysis of other design decisions where the preferred option is not as clear would make the sensitivity analysis more meaningful.

| Table 6-5: AHP Air Conditioning Plant Results | | | |
|---|---|---|---|
| **Criteria** | **Alternative** | **Level 1** | **Level 2** |
| Cost | | 0.49869 | |
| | R-114 | | 0.40860 |
| | R-134a | | 0.49869 |
| Risk | | 0.12530 | |
| | R-114 | | 0.12530 |
| | R-134a | | 0.02535 |
| Weight | | 0.32040 | |
| | R-114 | | 0.19845 |
| | R-134a | | 0.32040 |
| Env. Perf. | | 0.05561 | |
| | R-114 | | 0.02500 |
| | R-134a | | 0.05561 |
| **Final Results** | | | |
| R-114 | | 0.45695 | |
| R-134a | | 0.54305 | |

### *6.5 Multiattribute Utility*

Following the AHP interview with the NSSN environmental manager a second interview generated a multiattribute utility curve for the decision criteria. The utility analysis measures the utility of each function over the range of possible values rather than assuming it is linear as with AHP. The goal value is assigned a utility of 1.0 and the threshold value a utility of zero. A lottery process is then used to define points on the curve across the range. A weighting function for each criteria combines the individual curves into a five dimensional function (utility versus the four decision criteria) representing the overall preference of any combination of criteria values.

The advantage of the utility function is that it can be used by anyone in the design process to determine the decision makers preferences and the differences in scores between alternatives provide a direct measure of their overall preference. Break even points or the utility of various changes in a design can be directly determined. The disadvantage of this process is that the interview process is tedious, limiting the number of data points that can be collected in a single interview. This tends to limit the process to a few important considerations in the evaluation process. The questionnaire used for the interview and the calculations supporting the development of the utility function are included in Appendix B.

### 6.5.1 General Prioritization of Evaluation Criteria

The first step in the process is to determine the one dimensional utility functions for each curve. These function are shown in Figure 6-1 through Figure 6-4. The range of cost and risk, for practical purposes, is smaller than the interviewee originally surmised. The highest cost acceptable is around 1.4 times the baseline and the longest period of schedule risk acceptable is about 6 and a half months. Beyond these points, there is no appreciable utility to the design team.

The one dimensional utility functions provide significant insight into the decision process used by the program office. Figure 6-1 shows that reducing the overall cost by a significant amount is important. This is reflected in the large slope of the cost curve between 75% and 90% of the baseline. The lower slope from 95% to 125% reflects a standard or typical range for cost estimates which are expected. The increase in slope at about 125% reflects the concern estimates in this range are expected to generate. The slope at 75% indicates there is additional utility from costs lower than the range considered. Consideration of cost values outside this range requires a re-evaluation of the one dimensional utility function for cost.

The weight function in Figure 6-2 clearly reflects the weight budget and margin approach of the design. The flat portion of the curve between 95% and 115% implies that this is the acceptable range for system weights. Weights less than 95% increase utility at a rapid rate because they compensate for overruns elsewhere in the design. Weights above 115% decrease utility at about the same rate, reflecting the need to make up this weight in other systems. In this case, the decision maker is not willing to trade off other criteria for weight savings below 85% because of the weight budget approach used in the design. As the design progresses, deviations in weight from the target level have the potential to change the range of consideration and shape of this curve.

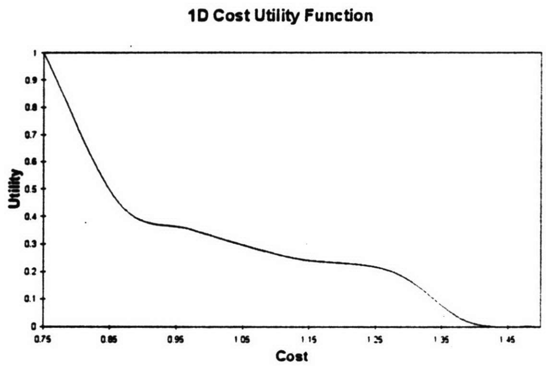


Figure 6-1: Cost Utility Function

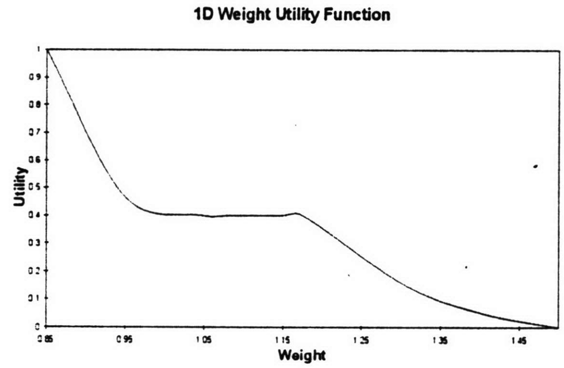


Figure 6-2: Weight Utility Function

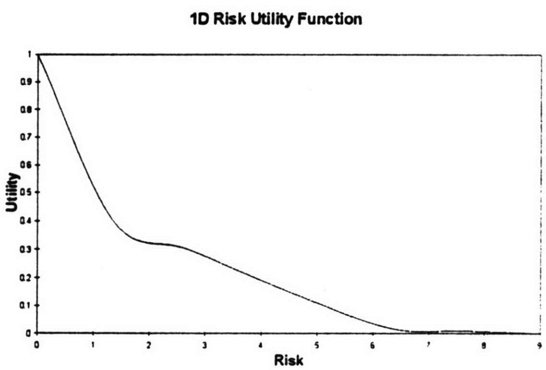


Figure 6-3: Risk Utility Function

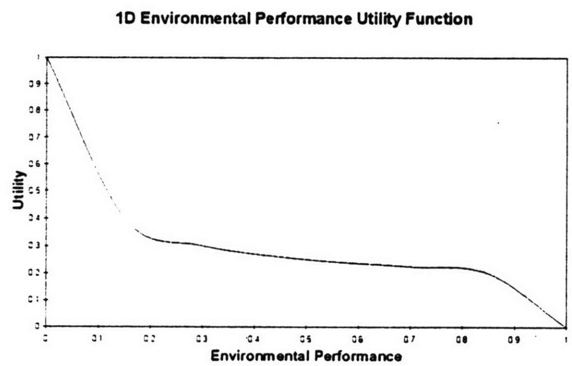


Figure 6-4: Environmental Performance Utility Function

Schedule risk in Figure 6-3 shows two distinct regions of concern. The first is the zero to two month range where there is a large drop in utility reflecting the initial concern over not meeting a desired date. Once the schedule date is missed, a little more or less makes little difference between 1.5 and 2.5 months. The period from 2.5 to six months reflects increasing concern over schedule impact. This time period is expected to be absorbed in overall procurement schedule delays. After about 6 months the delay is too long for comfort and there is no trade-off potential for other areas.

The environmental performance function shown in Figure 6-4 reveals how environmental improvements are valued. The large slope from 0 to 20% of the environmental impact of the baseline carries a significant amount of utility. This indicates that the priority of the environmental effort is to completely eliminate the environmental impact whenever possible. The utility of a system is cut in half if an alternative goes from no impact to only 10% of the impact of the baseline! Environmental impacts between 20% and 80% of the baseline are roughly indifferent. This indicates that once credit has been given for reducing the impact to this range there is little incentive to go further, unless the overall impact can be reduced below 20%. The increased slope between 80% and 100% of the baseline indicates that there is a perceived value of making an improvement, even if it is small.

Once the one dimensional utility functions are determined, the weighting factor of each criteria to combine the separate curves into a multiattribute utility function are determined. These weights are analogous to AHP weights and are also assumed constant over the function. A graphical representation of the 5 dimensional function is not possible, however two criteria can be simultaneously evaluated on a 3 dimensional plot. These curves comparing environmental performance to the other criteria are provided in Figure 6-5 through Figure 6-7. The slope of the curves across the page represents the utility of the first variable, the slope into the page represents the comparative utility of environmental performance and the height represents the combined utility. The matrix determination of the complete multiattribute utility function is included in Appendix B

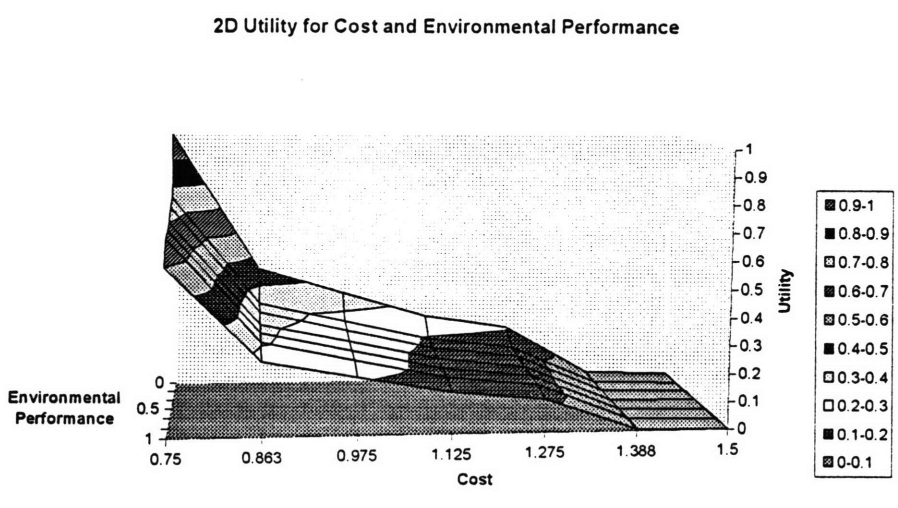


**Figure 6-5: Cost and Environmental Performance**

Figure 6-5 shows the relative trade-off potential between cost and environmental performance. For a given cost level, the relative value of environmental performance is reflected in the number of color changes in the curve moving back along the environmental performance axis. Each color change represents a 10% range of utility. If cost is above 1.275 times the baseline system there is very little room for environmental performance to change the overall utility (no color changes). Environmental performance does not affect utility significantly unless cost is below baseline (2 to 3 color changes). Further, significant gains in utility driven by environmental performance are not possible unless cost is reduced below about 90% of baseline (3 to 5 color changes).

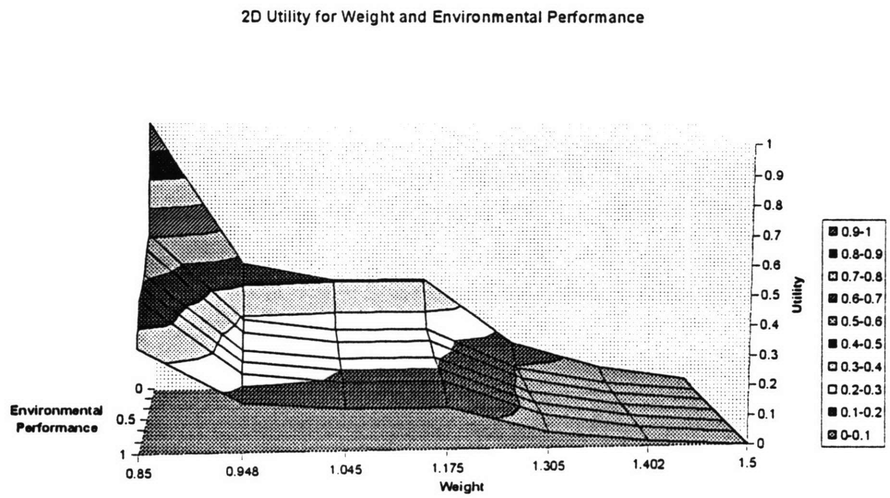


**Figure 6-6: Weight and Environmental Performance**

The weight comparison shown in Figure 6-6 reflects the underlying weight budgeting process discussed above. If the weight is outside the budgeted margin, environmental performance does not affect the overall utility much. If the system weight lies within the margin range, environmental performance considerations can impact utility and they make stronger impacts as weight is further reduced.

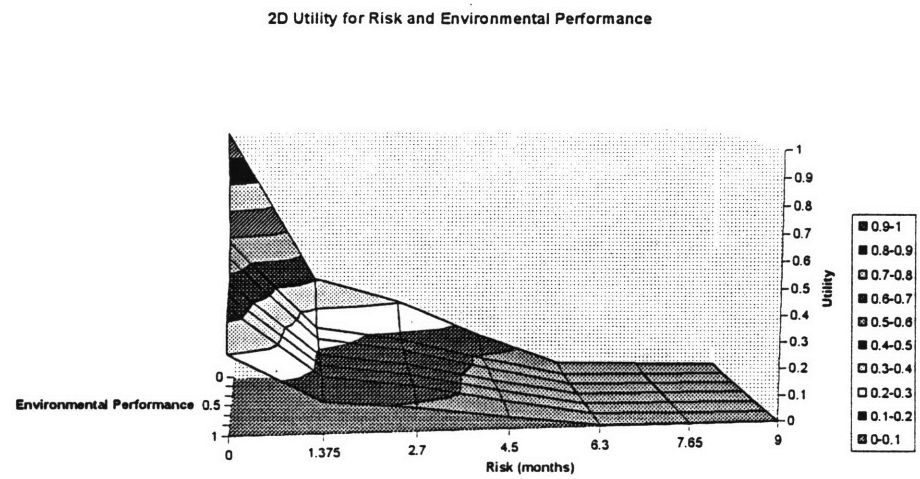


**Figure 6-7: Risk and Environmental Performance**

The risk comparison in Figure 6-7 reflects the same sentiment as the other comparisons. Environmental performance has very little effect when the risk of schedule impact is high. As the schedule risk is reduced to acceptable values environmental performance starts to influence decisions. Finally, as the negative consequences of risk are eliminated, environmental performance has the potential to significantly improve utility.

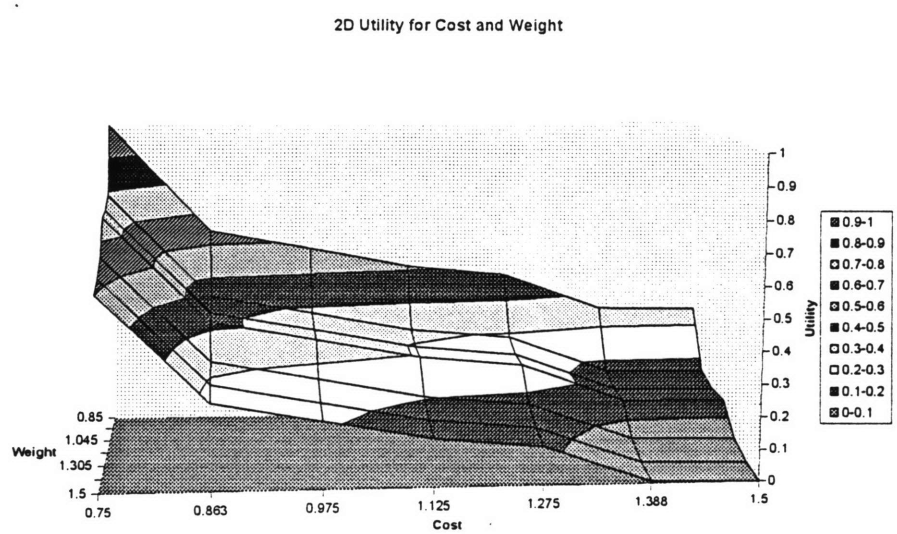


**Figure 6-8: Cost and Weight**

Figure 6-8 shows the utility function for the two most important criteria; cost and weight. The changes in utility across each axis are much more pronounced than for environmental performance. The potential for improvement is clearly dependent on where the design lies on the curve as utility contour line covers extends over a larger area. Starting from a design with 1.5 times the weight and cost, equal utility values can be achieved by reducing cost to about 0.85 without changing weight, reducing weight to about 0.90 without changing cost or any combination of weight and cost changes lying on the line joining these two points.

### 6.5.2 Evaluation of Alternatives

Continuing the non-cost analysis using the full multiattribute utility function with the air conditioning plant alternatives described in Table 6-1 produces the results shown in Table 6-6. As expected from the preliminary evaluation and the AHP results, the R-134a plant is clearly preferred. The calculations leading to these results are included in Appendix B.

**Table 6-6: Multiattribute Utility Results**

| Alternative | Utility |
|---|---|
| R-114 ship set | 0.579 |
| R-134a ship set | 0.609 |

Unlike with AHP, the magnitude of these values are meaningful. Evaluation of other alternatives can be made independently, without changing the values in Table 6-6. The expected utility of various alternative approaches within a design and break even points for improvements in criteria can also be determined. For example, at a cost of 0.972 or $5.05 million for a ship set, the utility of the R-134a plant is the same as that of the R-114 plant. At this value, the slightly reduced cost, improved environmental performance and lighter weight offset the schedule risk to produce the same utility to the design team as a similarly priced R-114 plant with no risk. The AHP approach indicates that the R-134a plant would have to cost more than the R-114 plant by an amount that can not be explicitly determined without a pairwise re-evaluation to be considered equal.

### 6.6 Comparison of AHP and MAU Results

AHP analysis provides an importance ranking between alternatives while a utility function is a substitution preference. The difference, although often subtle, can be important in determining the best method for decision analysis. Both evaluation methods selected the R-134a plant as expected. Setting up the decision framework through the interview took about an hour for AHP. The MAU interview took about 90 minutes and additional time was required to process the data and generate the curves and utility function. For both processes, the time required to set up decision framework is minimal compared to the potential returns.

There are, however, significant differences in the insight provided by each decision process. In AHP, the weighting factors for each criteria form the basis for subsequent decisions and the percent value assigned to each can be easily transferred and understood by stakeholders at all levels. The drawback is that the weighting factors do not account for differences in the weighting of criteria based on where in the range the criteria lie. Further, in order to account for differences in the range of criteria, a complete pairwise comparison must be repeated to determine the attractiveness of modifications to an alternative.

Multiattribute utility overcomes the problem associated with the value of each criteria changing across the acceptable range of values. Further, it more accurately determines the useful range of values for each criteria and allows designer to quickly evaluate the potential usefulness of conceptual changes. The one dimensional utility functions also provide insight to the actual decision process being used at the project level for making trade-off analyses. This allows stakeholders to be more certain that the results and decisions made with a MAU function will more closely correspond to those that the project team would make. Further, allocation of research and development resources can be more appropriately allocated to the areas with the greatest utility to the overall ship design. The drawback with MAU is that only two criteria can be shown on a graph at a time. This makes the process more complicated and the insights contained in the complete utility function more difficult to convey to stakeholders.

The potential uses for the multiattribute utility function and curve are far greater than that of the AHP matrix, making MAU the preferred decision approach for evaluation criteria in Navy ship design when the number of criteria is limited. In decisions involving a large number of important criteria the added complexity of the interview process must also be considered.

### 6.7 Value of Replacing R-114 Plants

The value of replacing the R-114 air conditioning plants with the R-134a design alternative was clear from the outset of the abbreviated evaluation process. Even without considering the environmental preference of the design, the benefits to the NSSN are significant; less ship impact (lower weight), lower procurement cost and potentially lower life-cycle cost (maintenance and logistics support improvements vs. increased power requirements). Further, once the R-134a plant is proven in the first ship, the risk associated with the design will be equivalent to the R-114, making it even more attractive.

In this instance, the impetus for environmental improvement forced the Navy to reexamine a baseline system design. Within the constraint for environmental improvement, a new system design better optimized for shipboard use was developed. The environmental requirement in this case served as a catalyst for a better engineering solution. Given the complexity of Navy ship and submarine systems and the incremental design process used, the potential for making similar improvements in other systems is tremendous.

# 7. Conclusions

An economic analysis of incorporating environmental design changes in Navy ships is a very complicated process. Accounting for the interaction of public goods, common property resources, goodwill and significant political forces makes developing a cost benefit analysis based solely on dollars almost impossible. A complete approach requires analysis of complete ship designs both with and without each new device or system solution. A relative comparison of associated benefits and costs can then be made and the appropriate alternative selected. Unfortunately, given the current design tools available to the Navy, this process is not feasible. Research into computerized design tools capable of quickly formulating and analyzing complete designs using genetic algorithms may eventually be able to generate optimal ship designs.[75] Until then, a simpler approach integrating decision analysis tools into a design framework based on the Navy's ship design environment provides the best opportunity for optimizing overall ship design. The framework developed in Chapter 5 and shown in Figure 5-1 meets this requirement.

## *7.1 Implementation*

Implementation of the design framework requires some modifications to the current structure. The functions depicted in the top section of Figure 5-1 need to become the formal responsibility of the environmental code in NAVSEA. NAVSEA 03V needs to change its' stated responsibilities from the following to something more in line with the ideals espoused in the Pollution Prevention Act.

> "Responsible for the life cycle engineering management of shipboard environmental protection systems and equipment including shipboard waste pulpers, compactors, plastic waste processors, oil water separators and related systems and equipment, sewage collection and processing systems and equipment, graywater collection systems and equipment and the introduction of refrigerants, firefighting agents and solvents which will eliminate the use of ozone depleting chemicals."[90]

Under current responsibilities, the NAVSEA 03V organization is actually threatened by pollution prevention developments. Pollution prevention efforts to reduce shipboard waste reduce the need for the devices under NAVSEA 03V's cognizance. In turn, this reduces the span of control of the organization and generates an internal conflict between pollution prevention efforts and self preservation. Changing the focus of NAVSEA environmental efforts away from a few very specific end-of pipe solutions to a broader approach espousing pollution prevention at the source facilitates incorporation of these principles into future Navy ship designs.

The environmental engineering directorate also needs to coordinate environmental activities within the other engineering directorates of NAVSEA. Knowledge of current and projected environmental requirements and close contact with current programs will allow the environmental engineering directorate to better identify pollution prevention opportunities. Using utility functions developed at the program level and feedback from project teams about where the next round of opportunities lie, research and development of new system alternatives can be focused on areas with the greatest potential for improving the overall design of future ships. Utility can be incorporated into the NAVSEA knowledge base and updated with technological developments. Finally, by tracking the progress of technological developments, program resources currently spent in this area will be saved and a greater continuity between subsequent designs provided.

Other functions depicted in Figure 5-1 are currently encompassed within the NSSN program team and can be readily adopted for use in other programs.

## 7.2 Results

The results of the R-134a air conditioning plant show how environmental improvements can become a catalyst for improving performance and cost of baseline systems used in Navy ships. Many baseline systems in current use in the Navy were designed decades ago; using different technological and political constraints then those currently in place. The current Navy ship design structure and incremental approach prevents optimizing system level designs if a "suitable" alternative is already available. Use of environmental considerations to redefine "suitable" allows designers to update and optimize systems to meet current constraints. In this process, benefits beyond environmental performance can readily be inserted.

By incorporating new technology into these systems, significant improvements in baseline systems, like that seen with the R-134a air conditioning system, should not be surprising. Further, the potential savings from re-engineering other systems to meet pollution prevention criteria in Navy ship design is tremendous. The NSSN won the 1996 Secretary of Defense Environmental Security Award in the area of pollution prevention for a weapons system acquisition team. An excerpt from the presentation ceremony shows just how significant the overall savings could be:

> "[NSSN] will avoid $300 million for each of its 30 nuclear-powered attack submarines, through the integration of a pollution prevention-related consideration in the ship's design. This $9 billion cost avoidance results from eliminating the mid-life refueling of the ship's nuclear reactor core, as current submarines require..."[91]

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# Appendix A: Analytic Hierarchy Process

## ***Select the most preferred system designs for the NSSN.***


| Abbreviation | Definition |
|---|---|
| GOAL | |
| Cost | Overall cost considering both procurement and LCC |
| Env Perf | Volume of hazardous materials used. |
| R-114 | Seawolf base R-114 Plant |
| R-134a | New Plant for NSSN |
| Risk | Schedule risk to overall ship deliver |
| Weight | Weight in pounds of the system. |

## *Select the most preferred system designs for the NSSN.*

Node: 0

Compare the relative IMPORTANCE with respect to: GOAL <

For each row, circle the more IMPORTANT element and indicate how many times more IMPORTANT it is in the intensity column (enter 1.0 for equality).

| | | Intensity | |
|---|---|---|---|
| 1 | Cost | | Risk |
| 2 | Cost | | Weight |
| 3 | Cost | | Env Perf |
| 4 | Risk | | Weight |
| 5 | Risk | | Env Perf |
| 6 | Weight | | Env Perf |

| Abbreviation | Definition |
|---|---|
| Cost | Overall cost considering both procurement and LCC |
| Risk | Schedule risk to overall ship deliver |
| Weight | Weight in pounds of the system. |
| Env Perf | Volume of hazardous materials used. |

## *Select the most preferred system designs for the NSSN.*

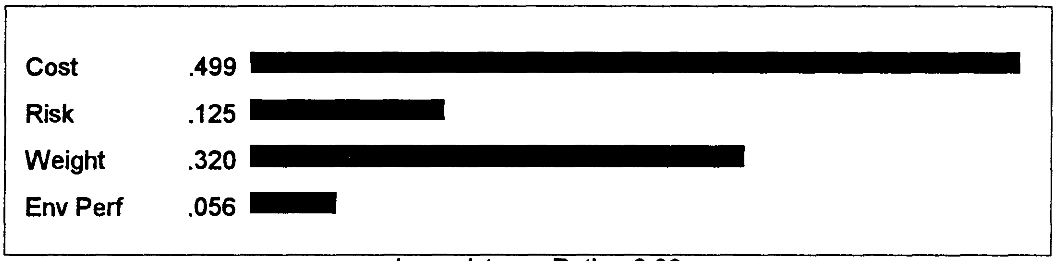
Node: 0

Compare the relative IMPORTANCE with respect to: GOAL <

| | Risk | Weight | Env Perf |
|---|---|---|---|
| Cost | 5.0 | 2.0 | 6.0 |
| Risk | | (4.0) | 4.0 |
| Weight | | | 5.0 |

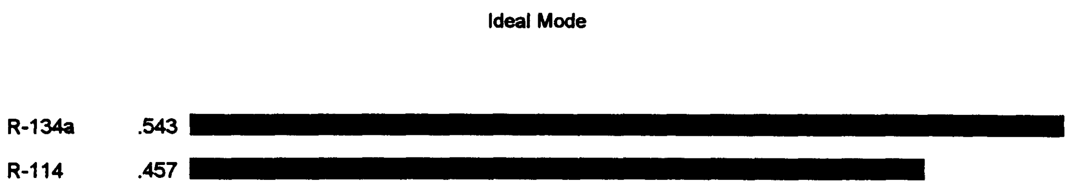
Row element is __ times more than column element unless enclosed in ()

| Abbreviation | Definition |
|---|---|
| Goal | Select the most preferred system designs for the NSSN. |
| Cost | |
| Risk | |
| Weight | |
| Env Perf | |



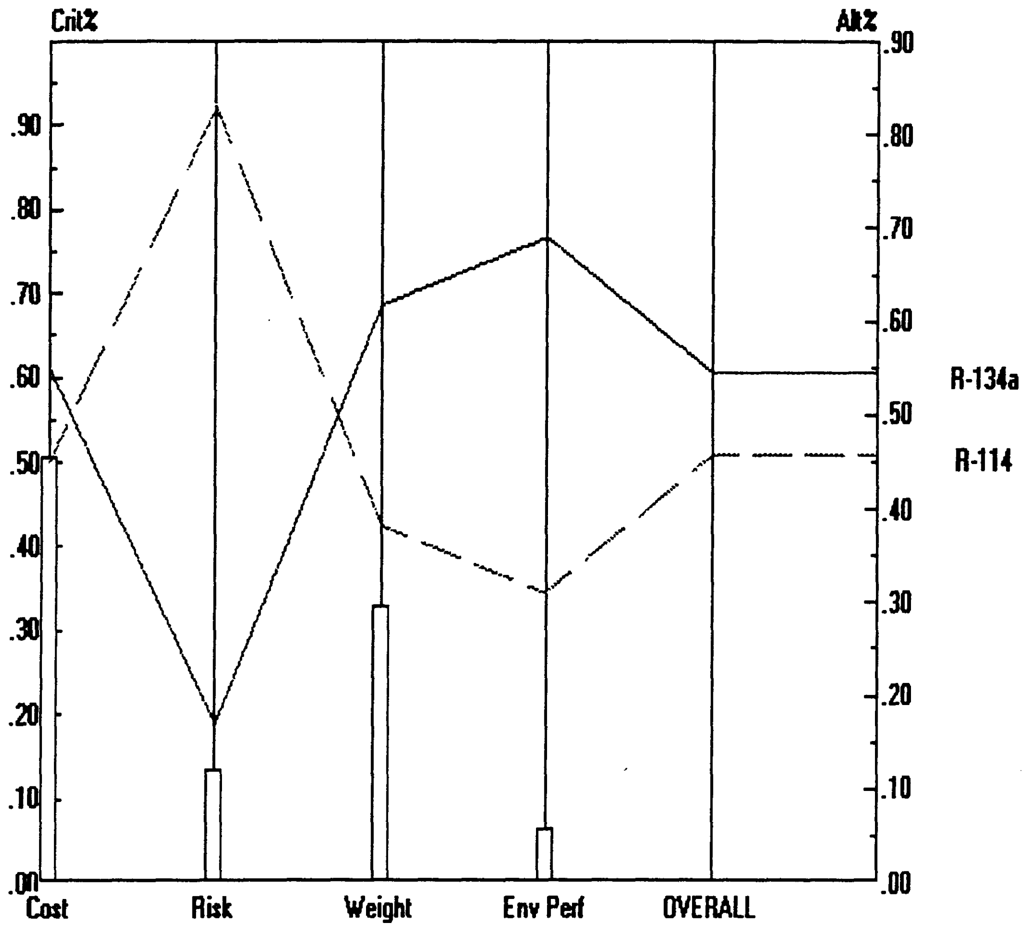

Inconsistency Ratio =0.08

## *Select the most preferred system designs for the NSSN.*




| Abbreviation | Definition |
| --- | --- |
| R-134a | New Plant for NSSN |
| R-114 | Seawolf base R-114 Plant |

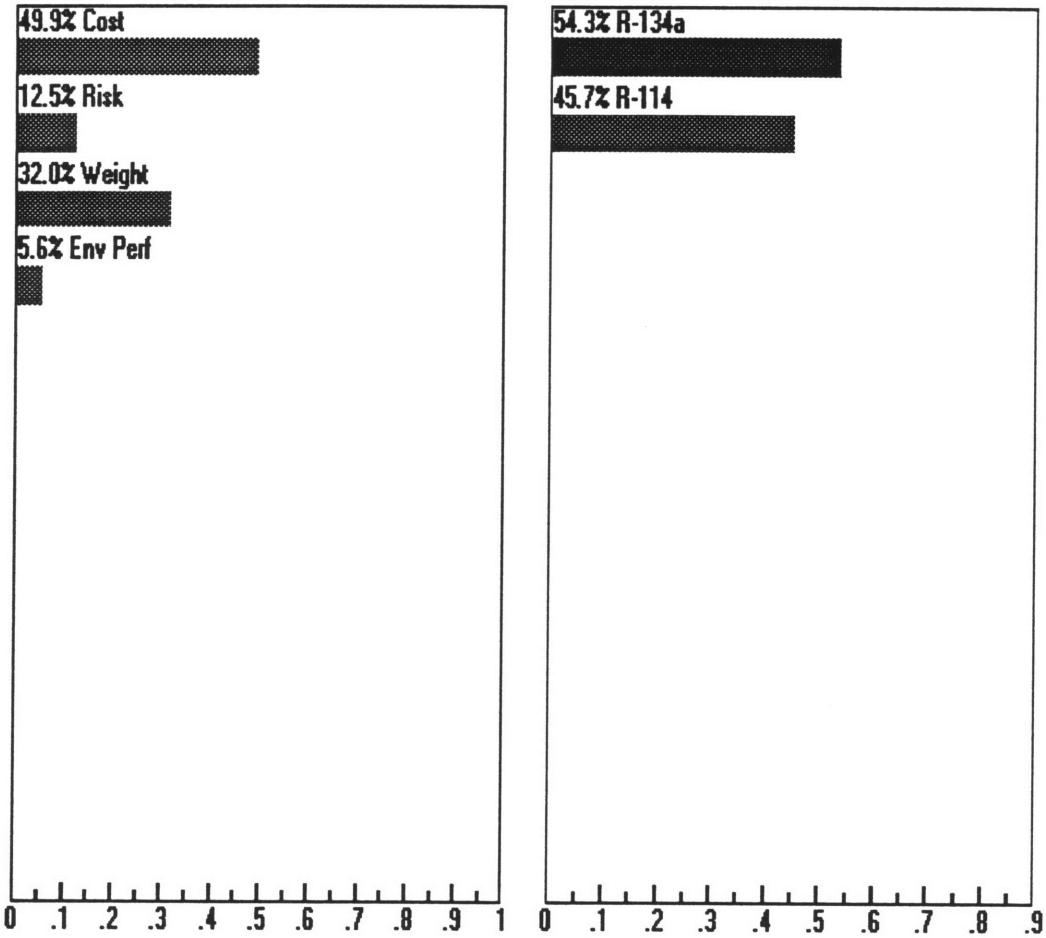
## *Performance Sensitivity w.r.t. GOAL for nodes below GOAL*




| Abbreviation | Definition |
|---|---|
| Cost | Overall cost considering both procurement and LCC |
| Risk | Schedule risk to overall ship deliver |
| Weight | Weight in pounds of the system. |
| Env Perf | Volume of hazardous materials used. |

| | |
|---|---|
| R-134a | New Plant for NSSN |
| R-114 | Seawolf base R-114 Plant |

**Gradient Sensitivity w.r.t. GOAL for nodes below GOAL**

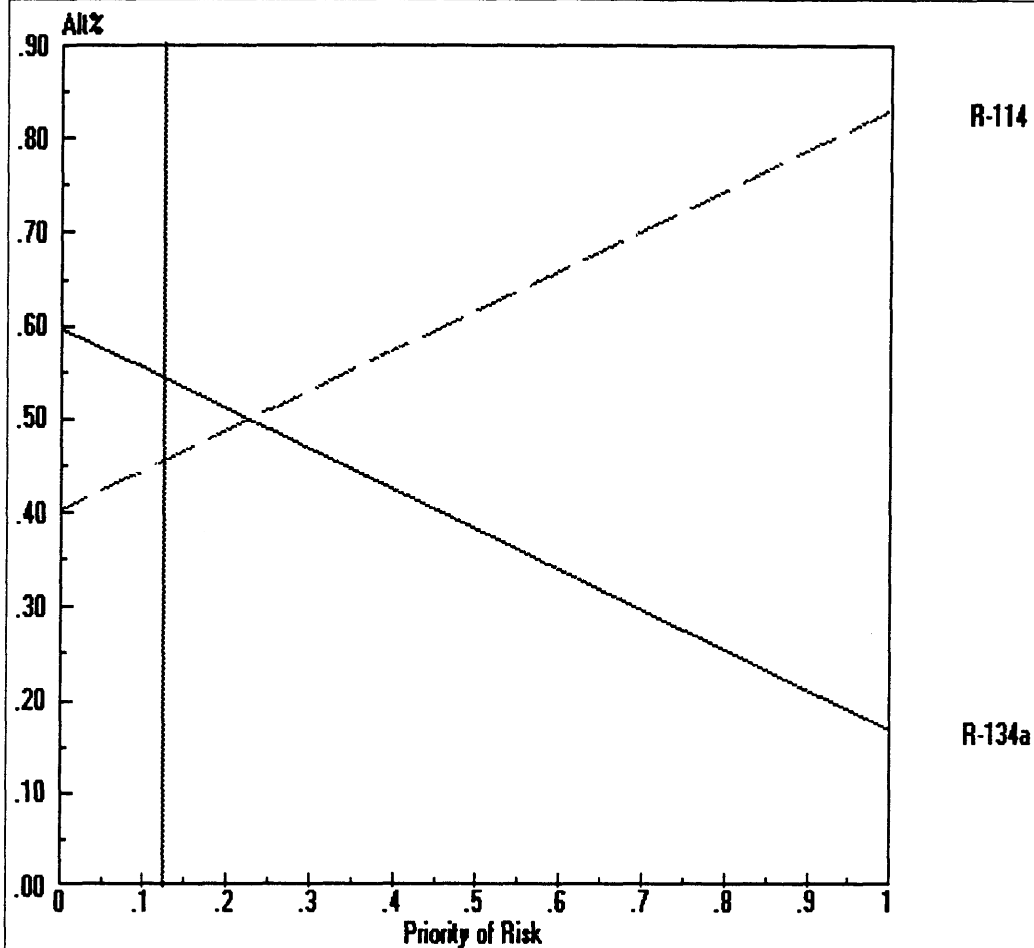



| Abbreviation | Definition |
|---|---|
| Cost | Overall cost considering both procurement and LCC |
| Risk | Schedule risk to overall ship deliver |
| Weight | Weight in pounds of the system. |
| Env Perf | Volume of hazardous materials used. |

| | |
|---|---|
| R-134a | New Plant for NSSN |
| R-114 | Seawolf base R-114 Plant |

Ideal Mode

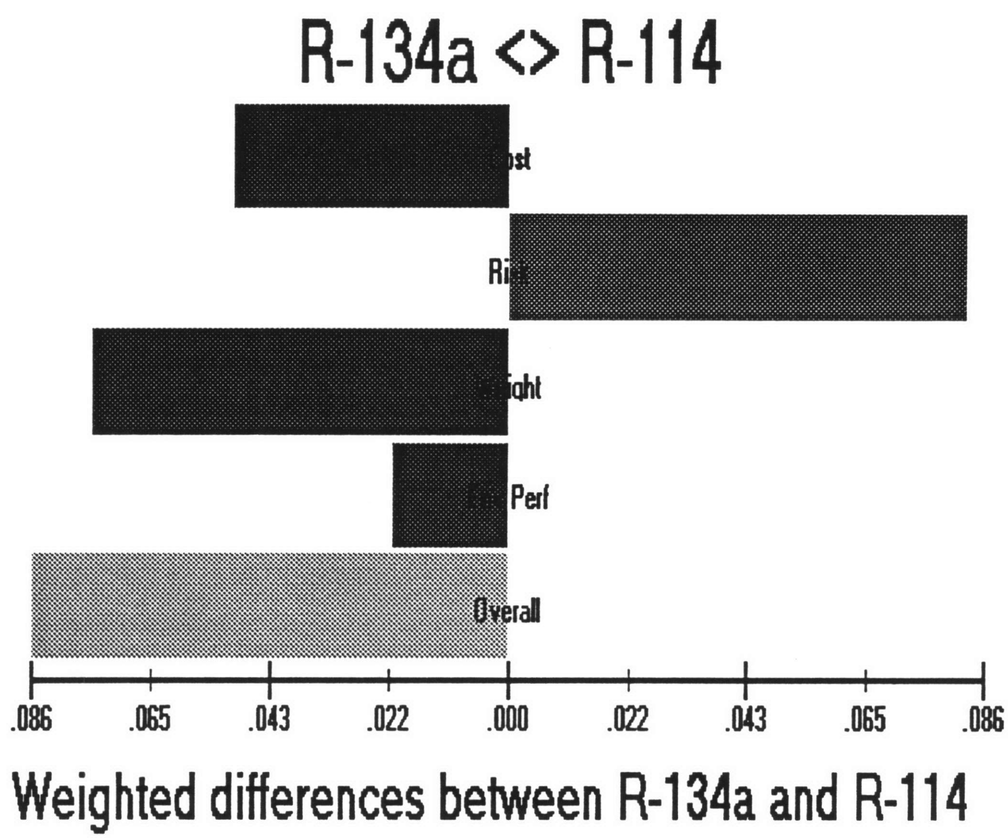
# *Dynamic Sensitivity w.r.t. GOAL for nodes below GOAL*




| Abbreviation | Definition |
|---|---|
| Cost | Overall cost considering both procurement and LCC |
| Risk | Schedule risk to overall ship deliver |
| Weight | Weight in pounds of the system. |
| Env Perf | Volume of hazardous materials used. |

| | |
|---|---|
| R-134a | New Plant for NSSN |
| R-114 | Seawolf base R-114 Plant |

***Differences Sensitivity w.r.t. GOAL for nodes below GOAL***




| Abbreviation | Definition |
|---|---|
| Cost | Overall cost considering both procurement and LCC |
| Risk | Schedule risk to overall ship deliver |
| Weight | Weight in pounds of the system. |
| Env Perf | Volume of hazardous materials used. |

| | |
|---|---|
| R-134a | New Plant for NSSN |
| R-114 | Seawolf base R-114 Plant |

Ideal Mode

# Appendix B: Multiattribute Utility Analysis

## Multi-attruibute Utility Function

**Single Attribute Utility Functions determined from the interview process are provided below. The first column for all variables except risk has been normalized to the baseline system. Risk is expressed in terms of potential schedule delay in months. The second column is the utility corresponding the the first column value.**

ORIGIN := 1

$$\text{cost} := \begin{bmatrix} .75 & 1 \\ .863 & .45 \\ .975 & .35 \\ 1.125 & .25 \\ 1.275 & .2 \\ 1.388 & .01 \\ 1.5 & 0 \end{bmatrix} \quad \text{risk} := \begin{bmatrix} 0 & 1 \\ 1.35 & .4 \\ 2.7 & .3 \\ 4.5 & .15 \\ 6.3 & .02 \\ 7.65 & .01 \\ 9 & 0 \end{bmatrix} \quad \text{weight} := \begin{bmatrix} .85 & 1 \\ .948 & .47 \\ 1.045 & .40 \\ 1.175 & .40 \\ 1.305 & .15 \\ 1.402 & .05 \\ 1.5 & 0 \end{bmatrix} \quad \text{env} := \begin{bmatrix} 0 & 1 \\ .15 & .40 \\ .30 & .35 \\ .50 & .25 \\ .70 & .225 \\ .85 & .2 \\ 1 & 0 \end{bmatrix}$$

**The $k_i$ values for each variable considered were also determined during the interview.**

$k_c := .6 \qquad k_r := .3 \qquad k_w := .35 \qquad k_e := .01$

**The next step is to determine the value of K. For graphical representations the value of K will be calculated in two dimensions, comparing each variable to environmental performance. K for the four dimensional case is also calculated.**

**Two dimensions; cost and environmental performance:**

$$0 = (K+1) - (K \cdot k_c + 1) \cdot (K \cdot k_e + 1) \qquad K_{2ce} := \frac{(1 - k_c - k_e)}{(k_c \cdot k_e)} \qquad K_{2ce} = 65$$

**Two dimensions; risk and environmental performance:**

$$0 = (K+1) - (K \cdot k_r + 1) \cdot (K \cdot k_e + 1) \qquad K_{2re} := \frac{(1 - k_r - k_e)}{(k_r \cdot k_e)} \qquad K_{2re} = 230$$

**Two dimensions; weight and environmental performance:**

$$0 = (K+1) - (K \cdot k_w + 1) \cdot (K \cdot k_e + 1) \qquad K_{2we} := \frac{(1 - k_w - k_e)}{(k_w \cdot k_e)} \qquad K_{2we} = 182.857$$

**Two dimensions; cost and weight:**

$$0 = (K+1) - (K \cdot k_c + 1) \cdot (K \cdot k_w + 1) \qquad K_{2cw} := \frac{(1 - k_c - k_w)}{(k_c \cdot k_w)} \qquad K_{2cw} = 0.238$$

**All four dimensions: in this case, there is not an explicit solution for K in closed form. An iterative solution is needed noting that -1 < K < 0 since Σki > 1.0 (see de Neufville).**

$K_{4D} := -.5530593$

$\text{Trial} := (K_{4D} + 1) - (K_{4D} \cdot k_c + 1) \cdot (K_{4D} \cdot k_r + 1) \cdot (K_{4D} \cdot k_w + 1) \cdot (K_{4D} \cdot k_e + 1) \quad \text{Trial} = 4.711 \cdot 10^{-9}$

**Calculate the Multi-attribute utility functions U(X) for each of the four cases of interest. Where the Multiattribute Utility Function is given by:**

$$KU(\mathbf{X}) + 1 = \Pi(Kk_i U(X_i) + 1)$$

$\text{COST}(C) := (K_{4D} \cdot k_c \cdot \text{cost}_{C,2} + 1) \qquad \text{RISK}(R) := (K_{4D} \cdot k_r \cdot \text{risk}_{R,2} + 1)$

$\text{WEIGHT}(W) := (K_{4D} \cdot k_w \cdot \text{weight}_{W,2} + 1) \qquad \text{ENV}(E) := (K_{4D} \cdot k_e \cdot \text{env}_{E,2} + 1)$

$$U_{4D}(C,R,W,E) := \frac{\text{COST}(C) \cdot \text{RISK}(R) \cdot \text{WEIGHT}(W) \cdot \text{ENV}(E) - 1}{K_{4D}}$$

**Verify the points corresponding to the $k_i$ values:**

$U_{4D}(1,1,1,1) = 1 \qquad U_{4D}(1,7,7,7) = 0.6 \qquad U_{4D}(7,1,7,7) = 0.3$

$U_{4D}(7,7,1,7) = 0.35 \qquad U_{4D}(7,7,7,1) = 0.01$

**Determine the Utility of the NSSN's R-134a AC plant and the Baseline Seawolf R-114 Plant:**

| | R-114 (baseline): | R-134a |
|---|---|---|
| Cost | 1.0 | 0.9 |
| Risk | 0 months | 3 months |
| Weight | 1.0 | .85 |
| Environmental Perf. | 1.0 | .15 |

**The cost and risk values for the R-134a system and the cost and weight values for the R-114 plant are not explicitly represented in the matrix. Interpolating for the actual values on the cost and weight single attribute utility curves gives the utility values of interest. These values are then entered into the Utility equation to compute the actual utility of each alternative.**

Determine the single attribute utility values of the points requiring interpolation:

$i := 1..7$ Decompose 1D utility functions into vectors for linterp function:

$costv_i := cost_{i,1}$ $riskv_i := risk_{i,1}$ $weightv_i := weight_{i,1}$ $envv_i := env_{i,1}$

$costu_i := cost_{i,2}$ $risku_i := risk_{i,2}$ $weightu_i := weight_{i,2}$ $envu_i := env_{i,2}$

$ucost_{134} := linterp(costv, costu, 0.9)$ $ucost_{134} = 0.417$

$urisk_{134} := linterp(riskv, risku, 3)$ $urisk_{134} = 0.275$

$ucost_{114} := linterp(costv, costu, 1.0)$ $ucost_{114} = 0.333$

$uweight_{114} := linterp(weightv, weightu, 1.0)$ $uweight_{114} = 0.432$

Check the values on the low and high end of interpolated values before modifying the utility function to verify results:

$U_{114low} := U_{4D}(4,1,3,7)$ $U_{114low} = 0.532$ $U_{134low} := U_{4D}(3,4,1,2)$ $U_{134low} = 0.554$

$U_{114high} := U_{4D}(3,1,2,7)$ $U_{114high} = 0.596$ $U_{134high} := U_{4D}(2,3,1,2)$ $U_{134high} = 0.632$

Update the utility function and determine the utility of the R-114 plant:

$COST(C) := (K_{4D} \cdot k_c \cdot ucost_{114} + 1)$ $WEIGHT(W) := (K_{4D} \cdot k_w \cdot uweight_{114} + 1)$

$$U_{4D}(C,R,W,E) := \frac{COST(C) \cdot RISK(R) \cdot WEIGHT(W) \cdot ENV(E) - 1}{K_{4D}}$$

$U_{114} := U_{4D}(ucost_{114}, 1, uweight_{114}, 7)$ $U_{114} = 0.579$

Update the utility function and determine the utility of the R-134a plant:

$COST(C) := (K_{4D} \cdot k_c \cdot ucost_{134} + 1)$

$RISK(R) := (K_{4D} \cdot k_r \cdot urisk_{134} + 1)$

$WEIGHT(W) := (K_{4D} \cdot k_w \cdot weight_{W,2} + 1)$

$$U_{4D}(C,R,W,E) := \frac{COST(C) \cdot RISK(R) \cdot WEIGHT(W) \cdot ENV(E) - 1}{K_{4D}}$$

$U_{134a} := U_{4D}(ucost_{134}, urisk_{134}, 1, 7)$ $U_{134a} = 0.609$

Check that the values for each system lie between the high and low values predicted.

**Determine the Cost of the R-134a plant which would make both plants have the same utility value:**

$$COST_{equal}(R,W,E) := \frac{U_{114} \cdot K_{4D} + 1}{RISK(R) \cdot WEIGHT(W) \cdot ENV(E)} \qquad COST_{equal}(urisk_{134}, 1, 7) = 0.883$$

$$Ucost_{equal} := \frac{COST_{equal}(urisk_{134}, 1, 7) - 1}{K_{4D} \cdot k_c} \qquad Ucost_{equal} = 0.352$$

$$costur_i := cost_{8-i,2} \qquad costvr_i := cost_{8-i,1}$$

$$cost_{134eq} := linterp(costur, costvr, Ucost_{equal}) \qquad cost_{134eq} = 0.973$$

**Calculate the three 2-dimensional utility functions to graphically show the value of environmental performance compared to cost, risk and weight.**

**2-D; cost and environmental performance:**

$$U_{ce}(C,E) := \frac{(K_{2ce} \cdot k_c \cdot cost_{C,2} + 1) \cdot (K_{2ce} \cdot k_e \cdot env_{E,2} + 1) - 1}{K_{2ce}}$$

$U_{ce}(1,1) = 1 \qquad U_{ce}(7,7) = 0 \qquad U_{ce}(1,7) = 0.6 \qquad U_{ce}(7,1) = 0.01$

$i := 1..7 \qquad j := 1..7$

$U_{2ce_{i,j}} := U_{ce}(i,j)$ $\qquad U_{2ce} =$

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 0.76 | 0.74 | 0.7 | 0.69 | 0.68 | 0. |
| 0.455 | 0.344 | 0.335 | 0.316 | 0.312 | 0.307 | 0. |
| 0.356 | 0.269 | 0.261 | 0.247 | 0.243 | 0.239 | 0. |
| 0.258 | 0.193 | 0.188 | 0.177 | 0.174 | 0.171 | 0. |
| 0.208 | 0.155 | 0.151 | 0.142 | 0.14 | 0.138 | 0. |
| 0.02 | 0.012 | 0.011 | $9.475 \cdot 10^{-3}$ | $9.128 \cdot 10^{-3}$ | $8.78 \cdot 10^{-3}$ | 6• |
| 0.01 | $4 \cdot 10^{-3}$ | $3.5 \cdot 10^{-3}$ | $2.5 \cdot 10^{-3}$ | $2.25 \cdot 10^{-3}$ | $2 \cdot 10^{-3}$ | 0 |

**2-D; risk and environmental performance:**

$$U_{re}(R,E) := \frac{\left(K_{2re} \cdot k_r \cdot risk_{R,2} + 1\right) \cdot \left(K_{2re} \cdot k_e \cdot env_{E,2} + 1\right) - 1}{K_{2re}}$$

$U_{re}(1,1) = 1$ $U_{re}(7,7) = 0$ $U_{re}(1,7) = 0.3$ $U_{re}(7,1) = 0.01$

$U_{2re_{i,j}} := U_{re}(i,j)$

$$U_{2re} = \begin{bmatrix} 1 & 0.58 & 0.545 & 0.475 & 0.457 & 0.44 \\ 0.406 & 0.234 & 0.22 & 0.191 & 0.184 & 0.177 \\ 0.307 & 0.177 & 0.166 & 0.144 & 0.139 & 0.133 \\ 0.158 & 0.09 & 0.085 & 0.073 & 0.071 & 0.068 \\ 0.03 & 0.016 & 0.014 & 0.012 & 0.011 & 0.011 \\ 0.02 & 9.76 \cdot 10^{-3} & 8.915 \cdot 10^{-3} & 7.225 \cdot 10^{-3} & 6.803 \cdot 10^{-3} & 6.38 \cdot 10^{-3} \\ 0.01 & 4 \cdot 10^{-3} & 3.5 \cdot 10^{-3} & 2.5 \cdot 10^{-3} & 2.25 \cdot 10^{-3} & 2 \cdot 10^{-3} \end{bmatrix}$$

**2-D; weight and environmental performance:**

$$U_{we}(W,E) := \frac{\left(K_{2we} \cdot k_w \cdot weight_{W,2} + 1\right) \cdot \left(K_{2we} \cdot k_e \cdot env_{E,2} + 1\right) - 1}{K_{2we}}$$

$U_{we}(1,1) = 1$ $U_{we}(7,7) = 0$ $U_{we}(1,7) = 0.35$ $U_{we}(7,1) = 0.01$

$U_{2we_{i,j}} := U_{we}(i,j)$

$$U_{2we} = \begin{bmatrix} 1 & 0.61 & 0.578 & 0.513 & 0.496 & 0.48 & 0.35 \\ 0.475 & 0.289 & 0.273 & 0.242 & 0.234 & 0.227 & 0.165 \\ 0.406 & 0.246 & 0.233 & 0.207 & 0.2 & 0.193 & 0.14 \\ 0.406 & 0.246 & 0.233 & 0.207 & 0.2 & 0.193 & 0.14 \\ 0.159 & 0.095 & 0.09 & 0.079 & 0.076 & 0.074 & 0.052 \\ 0.06 & 0.034 & 0.032 & 0.028 & 0.027 & 0.026 & 0.018 \\ 0.01 & 4 \cdot 10^{-3} & 3.5 \cdot 10^{-3} & 2.5 \cdot 10^{-3} & 2.25 \cdot 10^{-3} & 2 \cdot 10^{-3} & 0 \end{bmatrix}$$

**2-D; cost and weight :**

$$U_{cw}(C,W) := \frac{\left(K_{2cw} \cdot k_c \cdot cost_{C,2} + 1\right) \cdot \left(K_{2cw} \cdot k_w \cdot weight_{W,2} + 1\right) - 1}{K_{2cw}}$$

$U_{cw}(1,1) = 1$ $\quad$ $U_{cw}(7,7) = 0$ $\quad$ $U_{cw}(1,7) = 0.6$ $\quad$ $U_{cw}(7,1) = 0.35$

$U_{2cw_{i,j}} := U_{cw}(i,j)$

$$U_{2cw} = \begin{bmatrix} 1 & 0.788 & 0.76 & 0.76 & 0.66 & 0.62 & 0.6 \\ 0.642 & 0.445 & 0.419 & 0.419 & 0.326 & 0.289 & 0.27 \\ 0.578 & 0.383 & 0.357 & 0.357 & 0.265 & 0.228 & 0.21 \\ 0.513 & 0.32 & 0.295 & 0.295 & 0.204 & 0.168 & 0.15 \\ 0.48 & 0.289 & 0.264 & 0.264 & 0.174 & 0.138 & 0.12 \\ 0.356 & 0.171 & 0.146 & 0.146 & 0.059 & 0.024 & 6 \cdot 10^{-3} \\ 0.35 & 0.165 & 0.14 & 0.14 & 0.052 & 0.017 & 0 \end{bmatrix}$$

## NSSN R-114 Replacement Interview Guide

Jimmy Smith, NSSN Environmental Program Manager

Variables Considered:

1. Cost
2. Risk
3. Weight
4. Environmental Performance

### *MAU*

1. Determine upper and lower ranges for the four variables if not already appropriately determined by the AHP analysis.
2. Verify preferential independence of variables.
3. Measure one dimensional utility functions for each variable.
4. Measure scaling factors of variables.

Based on deNuefvill's recommendation, the maximum number of points in a utility function that can be reasonably determined in an interview is about 30. Four scaling factors are required, leaving a maximum number of internal SAU points of 6 (the range locates the end points for 0 and 1.0 utility values). For ease of understanding in the interview, points at 15, 30, 50, 70 and 85% of the range will be used for a total of 24 points.

## Preferential Independence:

The first set of questions verify the ranking of preferences over any pair of attributes is independent of the other attributes. Preferential independence only implies that the order of ranking between two attributes does not change because of changes in the level -- and value -- of the other attributes.

Example: Given two designs, one with a medium cost, medium risk and high weight and the other with high cost, low risk and high weight. Assume the first design is preferable. If preferential independence exists, then given the choice between a design with medium cost, medium risk and low weight would be preferred over a design with high cost, low risk and low weight. In this instance preferential independence exists for cost and risk versus weight.

The following questions are arranged in pairs, accounting for the four variables being considered in the interview. Select the preferred alternative in each row. If the middle column of each pair does not match, care must be taken to establish the bounds of preferential independence. Alternatives with levels of an attribute that fall outside the realm of preferential independence will then be eliminated.

| **Option A** | | | | | **Option B** | | | |
|---|---|---|---|---|---|---|---|---|
| *Cost* | *Risk* | *Weight* | *Env. Perf* | | *Cost* | *Risk* | *Weight* | *Env. Perf* |
| med. | med. | med. | good | > ? < | high | high | low | good |
| med. | med. | med. | fair | > ? < | high | high | low | fair |
| | | | | | | | | |
| med. | med. | high | fair | > ? < | low | high | low | good |
| med. | med. | low | fair | > ? < | low | high | low | good |
| | | | | | | | | |
| med. | high | low | good | > ? < | low | high | med. | fair |
| med. | low | low | good | > ? < | low | low | med. | fair |
| | | | | | | | | |
| high | low | med. | fair | > ? < | high | med. | high | good |
| low | low | med. | fair | > ? < | low | med. | high | good |

Verify that changing the value of any one variable in both columns of a pair would not change the results.

## Single Attribute Utility of Cost:

1. What is the highest feasible cost that could be considered for a replacement R-114 plant?
   __________% of the cost of an R-114 plant. (FY96 $4.4 Million for a ship set)

2. What is the lowest feasible cost conceivable for a replacement R-114 plant?

   __________% of the cost of an R-114 plant. (FY96 $4.4 Million for a ship set)

3. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
| --- | --- |
| A 50:50 chance that the ***cost*** is ____ (best + 15% of difference between best & worst) or ____ (worst). | A 45%$_{(p)}$ probability that the ***cost*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***cost*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
| --- | --- | --- |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

4. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***cost*** is ____ (best + 30% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***cost*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***cost*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

5. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***cost*** is ____ (best + 50% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***cost*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***cost*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |
| **Probability:** ____% | **A** | **B** |

6. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***cost*** is ____ (best + 70% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***cost*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***cost*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

7. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***cost*** is ____ (best + 85% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***cost*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***cost*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

8. **Utility Independence:** Would your indifference points change if any of the other variables (risk, weight, environmental performance) changed?

**Yes** **No**

## Single Attribute Utility of Risk:

1. What is the highest feasible risk that could be considered for a replacement R-114 plant?

   __________% of chance of impacting the programs schedule by ____ amount of time.

2. What is the lowest conceivable risk for a replacement R-114 plant?

   __________% of chance of impacting the programs schedule by ____ amount of time.

3. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***risk*** is ____ (best + 15% of difference between best & worst) or ____ (worst). | A 45%$_{(p)}$ probability that the ***risk*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***risk*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

4. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***risk*** is ____ (best + 30% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***risk*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***risk*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

5. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

**Option A:**

A 50:50 chance that the ***risk*** is ____ (best + 50% of difference between best & worst) or ____ (worst).

**Option B:**

A 45%(p) probability that the ***risk*** is ____ (best) and a 55% probability it is ____ (worst).

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***risk*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

6. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***risk*** is ____ (best + 70% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***risk*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***risk*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

7. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **<u>Option A:</u>** | **<u>Option B:</u>** |
| --- | --- |
| A 50:50 chance that the ***risk*** is ____ (best + 85% of difference between best & worst) or ____ (worst). | A <u>45%</u>(p) probability that the ***risk*** is ____ (best) and a <u>55%</u> probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**<u>Rule:</u>** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***risk*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
| --- | --- | --- |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

8. **<u>Utility Independence:</u>** Would your indifference points change if any of the other variables (cost, weight, environmental performance) changed?

**Yes** **No**

## Single Attribute Utility of Weight:

1. What is the largest weight that could be considered for a replacement R-114 plant?

__________% of the weight of an R-114 plant. (90,000 lb. for a ship set)

2. What is the lowest conceivable weight for a replacement R-114 plant?

__________% of the weight of an R-114 plant. (90,000 lb. for a ship set)

3. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***weight*** is ____ (best + 15% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***weight*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***weight*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

4. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***weight*** is ____ (best + 30% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***weight*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***weight*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

5. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
| --- | --- |
| A 50:50 chance that the ***weight*** is ____ (best + 50% of difference between best & worst) or ____ (worst). | A 45%$_{(p)}$ probability that the ***weight*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***weight*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
| --- | --- | --- |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

6. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***weight*** is ____ (best + 70% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***weight*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***weight*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

7. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***weight*** is ____ (best + 85% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***weight*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***weight*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

8. **Utility Independence:** Would your indifference points change if any of the other variables (cost, weight, environmental performance) changed?

**Yes** **No**

## Single Attribute Utility of Environmental Performance:

1. What is the environmental impact that could be considered for a replacement R-114 plant?

   A waste stream that has __________% of the environmental impact of an R-114 plant's CFC's.

2. What is the least conceivable environmental impact for a replacement R-114 plant?

   A waste stream that has __________% of the environmental impact of an R-114 plant's CFC's.

3. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| Option A: | Option B: |
|---|---|
| A 50:50 chance that the ***environmental performance*** is ____ (best + 15% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***environmental performance*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***environmental performance*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

4. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***environmental performance*** is ____ (best + 30% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***environmental performance*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***environmental performance*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

5. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

**Option A:**
A 50:50 chance that the ***environmental performance*** is ____ (best + 50% of difference between best & worst) or ____ (worst).

**Option B:**
A 45%(p) probability that the ***environmental performance*** is ____ (best) and a 55% probability it is ____ (worst).

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***environmental performance*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

6. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
|---|---|
| A 50:50 chance that the ***environmental performance*** is ____ (best + 70% of difference between best & worst) or ____ (worst). | A 45%$_{(p)}$ probability that the ***environmental performance*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***environmental performance*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

7. Suppose you have a pair of alternatives to the R-114 plant design. Given a choice between the following alternatives:

| **Option A:** | **Option B:** |
| --- | --- |
| A 50:50 chance that the ***environmental performance*** is ____ (best + 85% of difference between best & worst) or ____ (worst). | A 45%(p) probability that the ***environmental performance*** is ____ (best) and a 55% probability it is ____ (worst). |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 45% chance of having the ***environmental performance*** of ____ (best) you have a ____**% probability**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
| --- | --- | --- |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

8. **Utility Independence:** Would your indifference points change if any of the other variables (cost, risk, weight,) changed?

**Yes** **No**

# Assessing the K Values

The next 4 questions assesses the utility for each variable as compared to the other three. First, consider the extreme possibilities for an air conditioning plant design:

| **Best Design** | | **Worst Design** | |
|---|---|---|---|
| Cost | (best) | Cost | (worst) |
| Risk | (best) | Risk | (worst) |
| Weight | (best) | Weight | (worst) |
| Env. Performance: | (best) | Env. Performance: | (worst) |

1. ***Cost***: Suppose you can choose to use a new design. Given the choice between Option A, below, or **Option B:** a **10%**$_{(p)}$ chance of having the **Best Design** or a **90%** chance of having the **Worst Design**.

| **Option A:** | |
|---|---|
| Cost: | (best) |
| Risk: | (worst) |
| Weight: | (worst) |
| Env. Performance: | (worst) |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 10% chance, you have a _____% chance of having the **Best Design**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

2. ***Risk***: Suppose you can choose to use a new design. Given the choice between Option A, below, or **Option B:** a **10%**$_{(p)}$ chance of having the **Best Design** or a **90%** chance of having the **Worst Design**.

**Option A:**

| | |
|---|---|
| Cost: | (worst) |
| Risk: | (best) |
| Weight: | (worst) |
| Env. Performance: | (worst) |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 10% chance, you have a _____% chance of having the **Best Design**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

3. ***Weight***: Suppose you can choose to use a new design. Given the choice between Option A, below, or **Option B:** a **10%**$_{(p)}$ chance of having the **Best Design** or a **90%** chance of having the **Worst Design**.

**Option A:**

| | |
|---|---|
| Cost: | (worst) |
| Risk: | (worst) |
| Weight: | (best) |
| Env. Performance: | (worst) |

Which Option do you prefer? **A** **B**

**Rule:** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 10% chance, you have a _____% chance of having the **Best Design**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |

4. ***Environmental Performance***: Suppose you can choose to use a new design. Given the choice between Option A, below, or **<u>Option B:</u>** a **<u>10%</u>**$_{(p)}$ chance of having the **Best Design** or a **<u>90%</u>** chance of having the **Worst Design**.

**<u>Option A:</u>**

| | |
|---|---|
| Cost: | (worst) |
| Risk: | (worst) |
| Weight: | (worst) |
| Env. Performance: | (best) |

Which Option do you prefer? **A** **B**

**<u>Rule:</u>** **If A:** Raise p
**If B:** Lower p

Now suppose that with option B, instead of a 10% chance, you have a _____% chance of having the **Best Design**.

Which Option do you prefer? **A** **B**

**Repeat until indifference results:** **Indifference Point (P) = _____%**

| | | |
|---|---|---|
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |
| **Probability: ____%** | **A** | **B** |