# GOALS AND REQUIREMENTS FOR ADVANCED REACTOR CONCEPTS

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## Abstract

Economic problems and public concerns about safety have lead to a reassessment of current nuclear power plant designs and the development of improved designs or new reactor concepts to better meet the needs of United States utilities. This paper presents a set of goals and requirements, developed by the Idaho National Engineering Laboratory (INEL), to provide a means for evaluating the relative merits of alternate advanced reactor concepts. This set of requirements and goals is intended to be independent of any particular reactor concept, and is predicated on the assumption that nuclear power cannot become a viable option until the public is favorable to the use of nuclear power for electric power generation in the United States. Under this assumption, the top level requirements defined for new reactor concepts are (1) public acceptability, (2) acceptable investment risk, (3) competitive life cycle costs, and (4) early deployment. Each of these requirements is supported by several related lower level requirements and design goals that are necessary or desirable to meet the top level requirements.

## Background

Economic problems, slower than predicted electric growth rates, and public concern about the safety of current generation nuclear power plants have created a defacto moratorium on new orders of nuclear reactors in the United States. It is unlikely that there will be any new nuclear plant orders without a significant change in electrical generating plant economics, utility regulation, public (and Congressional) support, or electrical use growth rates.[1] This situation has effectively limited our national energy options to the use of fossil fuels or alternative energy sources such as solar and geothermal. For a variety of reasons these energy sources may not be sufficient to meet this country's long-term energy needs. For example, while alternative energy sources such as solar and geothermal have been successfully demonstrated on a limited scale, the economics and applicability of these technologies to large-scale power production are highly uncertain. Given the current state of alternative energy technologies, only the fossil-fuel and nuclear technologies are viable energy sources to meet near-term central station electric power generation requirements. Each of these energy sources, however, has certain inherent problems associated with its use.

Although there is presently an adequate supply of oil and gas on the world markets, the price of these commodities remains relatively high compared with nuclear and coal prices, and the current abundance of oil and gas will not continue indefinitely. Since a portion of the United States oil supplies are susceptible to international disruptions, we must not become overly dependent on foreign oil supplies.

The abundance of coal in the United States makes it an attractive energy source for production of electric power. However, increasing concerns about acid rain and the accumulation of carbon dioxide in the environment raise questions about the advisability of relying exclusively on coal-fired plants for the production of electric power in the United States. In addition, mining and transportation problems associated with coal will continue to increase as the use of coal for central station power generation increases.

Although there are issues associated with nuclear power relating to nuclear waste disposal, environmental impacts and public safety, solutions to these problems are being developed. Implementation of these solutions may ultimately prove easier than resolving the more complex environmental problems associated with effluent discharges from fossil-fuel plants.

Although the ultimate direction taken by U.S. utilities in the production of electric power will be influenced by the public's perception of the environmental risks associated with the various energy sources, there are many other technical, economic, and political factors that must be considered in the selection of a specific energy source. These factors include such things as energy generation needs, regulatory requirements, energy source economics, fuel availability, and national security. Until all of these factors can be adequately addressed, it is in the national interest to keep the nuclear option open.[2]

## Discussion

Several advanced reactor concepts have been proposed to address current and future energy needs. The new reactor concepts incorporate design improvements intended to reduce environmental impacts, enhance reactor safety, improve plant operations, and simplify the overall licensing process.

To provide a means for evaluating the relative merits of alternate reactor concepts, the Idaho National Engineering Laboratory (INEL) has developed a set of requirements and goals that are

* This work was conducted at the Idaho National Engineering Laboratory under DOE Contract No. DE-AC07-76ID01570.

intended to be independent of any particular reactor concept.[3] These requirements are predicated on the assumption that nuclear power cannot become a viable option until the public is favorable to its use for electric power generation in the United States. Under this assumption, as shown in Figure 1, four top-level requirements have been defined for new reactor concepts. These requirements are (1) public acceptability, (2) acceptable investment risk, (3) competitive life-cycle costs, and (4) early deployment. As indicated in Figure 1, each of these requirements are supported by several related lower-level requirements and design goals. This hierarchy of requirements and design goals is discussed in the following sections. Where possible, limited comparisons are made with the design goals of some current advanced reactor concepts.

Public Acceptability

Public acceptability is probably the single most important requirement to be met before U.S. utilities will consider purchase of new nuclear power plants.[4] Although economic factors such as life cycle costs, capital costs, etc., are used by utility executives to select the technology on which new power plants are to be based, the public has a strong influence on the utilities' selection processes. Unfortunately, there is no simple measure of public acceptability. However, the public response to the Three Mile Island (TMI) and Chernobyl accidents have made it clear that safety and protection of the public and the environment are major concerns. In addition to public and environmental safety issues, other factors influencing the public perception of nuclear power include plant operations and maintenance, sabotage resistance, and fuel diversion resistance. Each of these factors is described in the following sections.

Demonstrated Inherently Safe Design. Safety has always been a prime consideration in the design and operation of nuclear power plants. Current plant designs rely on active safety systems to mitigate abnormal situations. Advanced reactor plants should incorporate passive systems into their designs that mitigate abnormal conditions using natural processes. These designs are inherently safe and require little or no action by the operator during an accident and significantly reduce the likelihood of plant damage. By adopting inherently safe designs, many problems associated with operator and safety equipment performance can be eliminated.

Environmental Impacts. Environmental impacts from different types of power plants are, in many cases, not easily understood by the general public. Although effluents such as $SO_x$, $NO_x$, $CO_x$, radioactive gases, and waste heat can be readily monitored, the effects of these pollutants on the biosphere are complex and not easily understood. As the

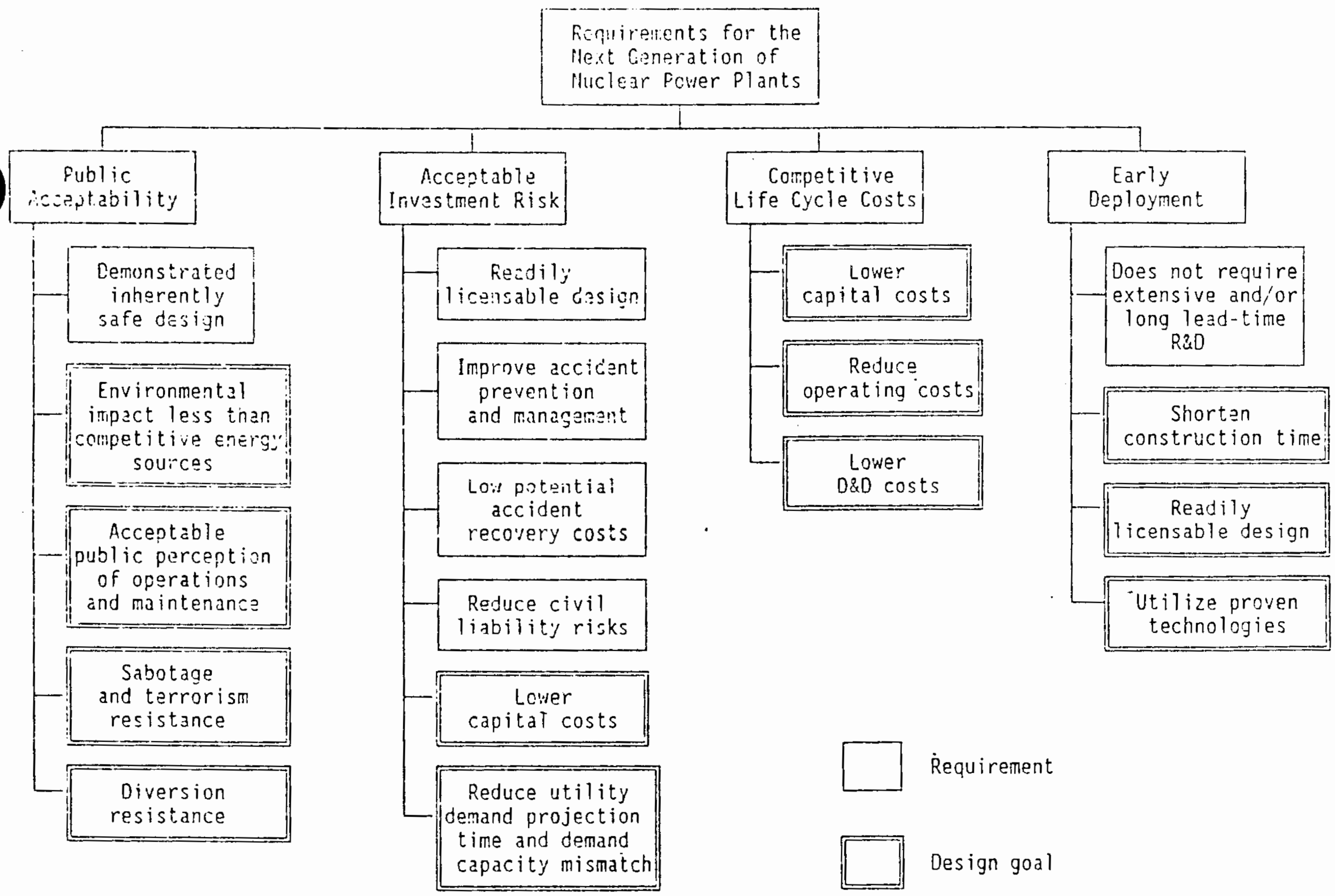


Figure 1. Requirements and design goals for new reactor concepts.

effects of these pollutants are better understood, the environmental restrictions and requirements imposed on central electric power generating plants may increase.

Advanced reactor concepts should be designed with the ultimate goals of zero release of radioactive materials during normal operation and reduction of unplanned releases to the extent that off-site evacuation plans are not required. As a minimum, the designs should ensure that the total environmental impact, including release of radioactive material, is less than competitive energy sources.

Another aspect of environmental impact concerns the entire population rather than just those located near power plants. This aspect has to do with transportation, reprocessing, and storage of nuclear material. Although advanced nuclear reactor designs may have an influence on these potential environmental problems, through concepts such as on-site fuel reprocessing, these environmental issues normally involve factors beyond the specific reactor design goals and requirements. However, the public will include these environmental issues when judging the acceptability of advanced reactor technology.

Operations and Maintenance. The perception of poor operation and maintenance practices by some utilities has raised public concerns. Announcements of fines imposed on utilities by the Nuclear Regulatory Commission (NRC) for safety violations further heighten public apprehension of nuclear power. These fears can be allayed by designs that simplify reactor operation and maintenance and reduce forced reactor shutdowns. Designs that facilitate repairs and thereby decrease radiation exposure to plant personnel will also be beneficial to the public's perception of nuclear power.

Sabotage and Terrorism Resistance. The public views nuclear power plants as complex, high technology devices that are difficult to control under the best of operating conditions. Consequently, nuclear power plants are perceived as potential targets for sabotage or terrorism that could result in serious consequences to the utility, the operating staff, and the public. Advanced reactor systems must provide features to reduce the public's apprehension about the potential threat of sabotage or terrorism. Public acceptance can be improved by designing into the plant inherent safety features to significantly reduce or eliminate the potential consequences of sabotage or terrorism. Designs improving physical security, such as underground siting, and minimizing the number of external support systems would also improve the public's perception.

Materials Diversion Resistance. Diversion of materials in a form that can be used to assemble weapons has always been a governmental and public concern. Materials diversion resistance can be improved by advanced reactor designs that reduce the external flow of plutonium and highly enriched uranium. By utilizing low enriched fuel, high activity reprocessing, and on-site processing, the public's apprehension over diversion of weapons grade materials can be reduced. However, on-site reprocessing may raise public concern over possible radiation releases.

## Investment Risk

Any large project involving major construction entails some element of financial risk. Nuclear power plant construction in the 1970s and 1980s has demonstrated that forces outside the utility can have major impacts on the financial health of the utility. Utilities considering investment in advanced nuclear plants must have assurance that selection of the nuclear option will provide an acceptably low risk in comparison with other power generation technologies.

At the present time, nuclear construction is a high risk undertaking and has become an unacceptable option for utilities. Long construction times for large power plants, uncertainties in power forecasting, construction financing, licensing changes, and public utility commission (PUC) actions are issues that add risk to a utility investment. Plant availability, accidents, and accident recovery are also risks to the utility investment, as the TMI accident has demonstrated.

Clearly, utilities will not invest in a power plant based on advanced reactor concepts until there is some assurance that the plant can be constructed and licensed in a reasonable time frame and can be easily operated with little risk to their capital investment. This risk must be comparable to risks offered by competing power generation technologies.

To ensure that investment risks are at least comparable with other power generation technologies, advanced nuclear power plants must provide a readily licensable design, improved accident prevention and management, low accident recovery costs, reduced civil liability risk, lower capital cost, and improved demand/capacity matching.

Readily Licensable Design. Uncertainty in licensing due to changing requirements, licensing delays, litigation, etc., lead to investment risks that are unacceptably high for nuclear power plants. Therefore, advanced reactor plants must be easily licensable. Introduction of advanced reactors into the NRC licensing system presents an opportunity for simplification, streamlining, and improvement of the overall licensing process. One option being considered is licensing by test in which the safety features of inherently safe reactors are demonstrated by running a series of prescribed accidents. These tests would be designed to resolve uncertainties associated with licensing the plant.

Another option usually considered is design standardization. This option allows a single licensing review to be applied to numerous plants of the identical design.

Improved Accident Prevention and Management. Advanced plants must incorporate design features that facilitate the prevention and management of accidents which pose significant financial risk to the utilities. Although major accidents are addressed by the public safety aspects of nuclear plant operation, minor accidents or failures that do not present a public safety threat may pose a financial risk to the utility through loss of on-line capacity and added risk to its plant investment. These accidents and their management must be considered in new plant designs. Inherently safe designs now under consideration should contribute significantly to accident prevention. However, improved diagnostic systems are also necessary to ensure that accident management capabilities are adequate to protect the utilities' capital investment.

Reduced Accident Recovery Costs. Advanced reactor plant designs should take into consideration plant cleanup, component repair, and component replacement. By integrating these items into the design, recovery time and the magnitude of the cleanup efforts can be reduced. Possible methods that can improve accident recovery include utilization of robotic cleanup devices, minimizing the use of materials that produce volatile or long-lived activation products, providing readily replaceable components, providing readily cleanable and accessible surfaces, minimizing the total number of systems and components, and minimizing the number of pathways for the spread of radiation.

Reduced Civil Liability Risk. Civil liability from operation of an advanced nuclear power plant can represent a substantial investment risk to the utility. Liability risk can be reduced by designs that ensure safe operations, minimize radiation releases, and reduce operational exposures to the public and operating staff.

Lower Capital Cost. An acceptable investment risk varies with the size of the investment and the assets of the utility. A higher risk is more acceptable for a small investment than for a large investment. Lower capital costs will reduce the utility's exposure to financial risk. Modular, factory-fabricated advanced nuclear plants are being considered as one option for reducing capital costs and investment risk. A suggested limit for capital cost is that the cost of new plants should represent less than 10% of the utility's assets.[5]

Improved Capacity Projection Time/Demand Capacity Matching. The further into the future electric growth demand projections must be forecasted, the larger are the uncertainties in the projected power plant construction requirements. One method to reduce the investment risk from either building too much capacity or from not building enough, is for the utility to incrementally add small amounts of capacity to their system. Ideally, the construction time for adding capacity should be consistent with the accuracy of the projection demands. Presently, advanced reactor power plants are being designed to provide one to three years of projected growth and construction times of approximately four years.[5,6]

Competitive Life-Cycle Costs

While reducing cost uncertainties is a current major concern of utilities, the nuclear option must also be cost competitive with alternate electric energy generation sources to ensure long-term viability.

The life-cycle cost of electricity can be divided into three primary cost categories. These categories are:

1. The capital cost for plant construction, including interest costs.
2. Operating costs, including fuel cycle costs.
3. The costs of decontaminating and decommissioning (D&D) the plant at its end of life.

Capital Costs. Of these three categories, capital cost for plant construction is generally the major cost item in the life-cycle cost of nuclear power. This is in contrast to the situation ten to fifteen years ago, when fuel and capital costs contributed about equally to the cost of nuclear power generation. Today, capital costs contribute three to four times as much as does the cost of fuel.[4] For this reason, reducing the capital costs for construction of new reactor plants have been a major objective in the design of most advanced reactor development efforts. Overnight capital costs in the range of $1000/kWe (1984 dollars) or less are representative of the required nuclear power plant construction costs necessary for nuclear plants to be competitive with fossil-fired electric power generation plants.[5,7]

A major factor influencing nuclear power plant construction costs has been the length and uncertainty of the required construction time, which has generally ranged from 10 to 15 years. The current goal of several advanced reactor concepts is to produce power within four years or less from the start of plant construction.[5,8] One approach to minimizing plant construction time has been to develop small, modular reactor designs that allow the reactor module and much of the balance of plant equipment to be factory fabricated and shipped to the construction site by rail or barge. This reduces the required field construction activities, which tend to be more costly and uncertain.

The above advantages of smaller plants, however, are dependent on demonstrating that there is no significant loss in economic performance for smaller plants when compared with the bus-bar energy costs of larger plants. Studies[5,6] performed to define the optimum balance between the advantages of smaller and larger plants indicate that powers between 300 and 600 MWe appear to be optimum for the small modular reactor concepts.

Operating Costs. The second major category in the nuclear power plant life-cycle costs is operating cost. Operating cost includes (1) capital amortization, including money costs, (2) fuel, including processing, transportation, and waste disposal, (3) operations, including maintenance and repair, and (4) technical and plant operations support staffs. To minimize these costs, the general approach has been to reduce the number and complexity of plant components and systems. In particular, emphasis is being placed on reducing the number of required plant protection systems and required operator actions in favor of inherent or natural plant processes to mitigate the consequences of plant accidents and ensure long-term decay heat removal.

Improved component reliability, along with fewer and less complex nuclear power plant components and systems, are projected to result in advanced reactor plant availabilities of 75-85%

based on realistic estimates of planned and forced outages.[5,6,8] The projected benefits of these design improvements are expected to result in levelized bus-bar costs in the range of \$.03-.05/kWh (1984 dollars).[5,6,7]

D&D Costs. The last cost category, D&D costs at the end of plant life, should be reduced by design approaches which include (1) fewer components and support systems, (2) less complex systems and interfaces, (3) easily accessible and cleanable surfaces, and (4) easily removable components and systems. Other possible means of reducing D&D costs include designing for low mobility fission products in the reactor primary coolant system, minimizing the use of long-lived activation coolants and materials, and development of plant designs that can readily utilize robotics for plant cleanup and decontamination.

## Early Deployment

The requirement for early deployment of an advanced reactor stems from two considerations. First, with no new construction, and at a projected electric growth rate of about 2% per year, a majority of utilities will begin to have power shortages by approximately the year 2000.[4] Therefore, if advanced reactor concepts are to make a significant contribution to the energy needs of this country, the availability of these plants by about the year 2005 is critical.

The second consideration in arriving at the requirement for early deployment of an advanced reactor is that, since construction of currently ordered nuclear reactors will be completed in the early 1990s, the nuclear construction talent will begin to disperse at that time. The design and nuclear component fabrication infrastructure will begin to erode even earlier unless there are new orders or other financial inducements to maintain the infrastructure. Since the current infrastructure is beginning to erode, a major technology development and deployment effort must start now--both to maintain the current infrastructure and to meet the anticipated electrical energy demand projected for the next century.

To achieve deployment by the year 2005, new advanced reactor concepts will require (1) minimal research and development, (2) shortened construction schedules, (3) readily licensable design, and (4) proven technology.

Minimal Research and Development. Although some research and development will inevitably be required for the different advanced reactor concepts, the designs should not require extensive long-lead time research and development support. For first-of-a-kind components, adequate time should be provided for performance testing under conditions that are at least equal to or more severe than their designed operating conditions. The need for extensive performance verification testing of first-of-a-kind components, therefore, limits the use of new technologies to those that can be developed and demonstrated in the very near term if a new reactor is to be deployable by the year 2005.

Shortened Construction Time. In addition to reducing capital costs and utility investment risks, as described earlier, a shortened construction time also contributes to early reactor deployment by allowing greater time for completion of engineering design work prior to the start of plant construction. As noted earlier, the current goal for the construction of advanced reactor concepts is about four years from the start of plant construction to power production.[5,6]

Readily Licensable Design. In addition to the economic advantages of a readily licensable design described earlier, a design that can be easily licensed will reduce the likelihood of delays during the plant construction phase. Aspects of current designs that are intended to improve reactor plant licensability are (1) inherent safety characteristics, (2) modularity, and (3) plant standardization. These novel design aspects are intended to simplify the overall licensing process by allowing NRC licensing by certification of a standardized design. The NRC certification could be obtained through analysis or a combination of analysis and prototype safety testing.

Utilize Proven Technologies. The final requirement for deployment of advanced reactors by the year 2005 is the need to utilize proven technologies, which also relates to the need to minimize long-lead-time research and development activities. Technologies utilized in the advanced reactor designs must be such that they can be incorporated into the design and fully tested and demonstrated at the component, subsystem, and integrated system level before incorporation into the final design concept.

## Conclusions

This paper is an attempt to define and categorize a set of requirements and design goals for advanced nuclear power plants that are independent of any particular reactor concept. These requirements and goals are predicated on the assumption that nuclear power cannot become a viable option until the public is favorable to the use of nuclear power for electric power generation in the United States.

It is expected that these requirements will be improved and expanded. The goal is to evolve the requirements until a national consensus is reached. In that way, new-initiative reactor development can proceed along a variety of technologies, but with common, understood requirements. Since most new reactor concepts are still in the development stages, detailed comparison of these requirements with specific reactor performance characteristics is not yet possible. With finalization of the requirements and goals, and further development of the advanced reactor performance capabilities, a more definitive evaluation of the ability of the different reactor concepts to meet the established requirements should be possible.

Limited comparison of the requirements and design goals presented in this paper with the general design goals of several new reactor concepts indicate general agreement and consistency in the overall requirements and design goals being pursued by the different advanced reactor concept developers.

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