SYSTEMS SELECTION METHODOLOGY
FOR CIVIL NUCLEAR POWER APPLICATIONS

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ABSTRACT

A methodology for evaluation and selection of a preferred Advanced Small or Medium Power Reactor (SMPR) for commercial electric power generation is discussed, and an illustrative example is presented with five U.S. Advanced SMPR power plants. The evaluation procedure was developed from a methodology for ranking small, advanced nuclear power plant designs under development by the U.S. Department of Energy (DOE) and Department of Defense (DOD). The methodology involves establishing numerical probability distributions for each of fifteen evaluation criteria for each Advanced SMPR plant. A resultant single probability distribution with its associated numerical mean value is then developed for each Advanced SMPR plant by Monte Carlo sampling techniques in order that each plant may be ranked with an associated statement of certainty. The selection methodology is intended as a screening procedure for commercial offerings to preclude detailed technical and commercial assessments from being conducted for those offerings which do not meet the initial screening criteria.

INTRODUCTION

Results of an IAEA study assessing the potential market for Small or Medium Sized Power Reactors (SMPRs) have indicated that prospects for smaller commercial reactors have improved in recent years and that both buyers in developing countries and suppliers in developed countries have expressed greater interest in their introduction within the coming decades.(1) Renewed interest in SMPRs has also extended to the United States for a number of reasons.(2) Among the reasons are anticipated improvements in plant safety, economics, operability and availability, and reduced plant complexity.(3) A difficulty posed, however, is the number and variety of advanced nuclear power plants being developed for the year 2000 to 2010 time frame. They include Advanced Light Water Reactors (ALWRs), Small Heavy Water Reactors (SHWRs), Modular High Temperature Gas-cooled Reactors (MHTGRs), and Modular Liquid Metal-cooled Reactors (MLMRs). Some incorporate passive safety systems to varying degree; most include modular design and a high content of shop fabrication of the nuclear island. Moreover, user requirements proposed for their development vary, and specific regulatory requirements for most remain to be established. Most Advanced SMPRs have yet to be constructed and demonstrated, though features in some designs have been demonstrated in operating plants.

Given the conceptual design state of these "second generation" Advanced SMPRs, one asks how they are to be evaluated by foreign Investors when mature. The well known International Atomic Energy Agency (IAEA) Guidebooks(4) for this purpose may not be adequate owing to the new innovative concepts involved. This paper explores the application of a method which has been used in the United States to evaluate and rank advanced nuclear reactor power systems against specified user criteria.(5)

DESCRIPTION OF WORK

The civil nuclear power applications evaluation procedure was developed from a disciplined methodology for ranking different nuclear power plant designs under development by U.S. Industry, the U.S. Department of Energy (DOE), and U.S. Department of Defense (DOD). These included designs proposed by industry for the DOE small ALWR, MHTGR, and MLMR programs and the DOD Multimegawatt Terrestrial Power program (MTP).

The fifteen evaluation criteria proposed for civil applications are similar to those developed for the DOE and DOD energy systems evaluation except that the weighting factors applied to each individual criterion reflect their perceived importance to civil applications in developing countries. The criteria and their weighting (importance) factors are presented in Table 1. Each criterion is characterized by a histogram or probability distribution of the numerical value assigned, which represents the evaluator's subjective

TABLE 1: EVALUATION CRITERIA FOR ADVANCED SMPRs

Two-Multiplier Criteria (6 criteria)

1. Demonstrated improved safety characteristics, including "intrinsic" safety.
2. Plant availability factor.
3. Plant cost index as a composite of Nth of a kind (NOAK) capital and 30-year NOAK levelized life cycle costs.
4. Plant systems complexity as reflected in plant operations and maintenance crew sizes, required skill levels and maintenance hours to achieve availability criteria.
5. Existence of an international competitive industrial infrastructure to supply and service major nuclear plant equipment (number and experience of companies).
6. Assurance of an international competitive fuel supply and related fuel cycle services (number of qualified commercial fuel fabricators for each Advanced SMPR).

One-Multiplier Criteria (7 criteria)

7. Capability of commercial deployment by the year 2000.
8. Low gaseous, liquid, and solid radioactive waste generation and emission rates (expressed in Ci/year of specific nuclides).
9. Minimum "black startup" (without offsite power) time requirements.
10. Capability of an extended reactor plant lifetime.
11. Minimum reactor plant consumables required with low utilization rates (expressed as consumables total cost per year).
12. Extent to which designs meet current U.S. licensing criteria for advanced reactors, identified unresolved and generic safety issues, and NRC policies on standardization, safety goals, and severe accident criteria.
13. Maximum plant net thermodynamic cycle efficiency.

One-Half Multiplier Criteria (2 criteria)

14. Minimum plant construction schedule from initial concrete pour to initial operation (in months).
15. Capability of sustained operation by owner-operator without foreign or domestic industry support for an 18 month period.

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assessment of its certainty since the designs are presently in a conceptual phase and deployment is more than a decade away. A deployment period of 2000 to 2010 was selected since studies have shown that the need in the U.S. for increased base load capacity will be sufficiently high to justify this time frame,(6) although a significant need may arise before the year 2000.(7)

RATIONALE FOR CRITERIA

The rationale for the criteria selection is discussed below, although other criteria of importance to a developing country could be added or substituted for those presented. Similarly, the weighting factors could be changed to reflect the Investor's opinion of the importance of the set of criteria selected. Finally, the probability distributions associated with each criterion could be modified based upon the Investor's opinions and perceptions.

Improved Safety

Market acceptance of commercial nuclear power as a form of electric energy production in the U.S. and to varying degrees in other countries is conditioned by market apprehension over perceived operational safety problems and difficulties in regulation and radioactive waste management. These other problems are beginning to be addressed, and reactor concepts which feature intrinsic or inherent safety systems should instill greater public confidence and acceptance of a civil nuclear program. The Advanced SMPRs were formally evaluated against the safety attributes listed in Table 2.

Availability Factor

Plant availability factor, while primarily an economic factor, is also linked to maturity of reactor technology as reflected in the reliability of plant systems. High plant availability suggests an absence of operational problems with attendant possible safety implications. Advanced SMPR plant availabilities were evaluated over the range of 70 to 90 percent.

Plant Cost Index

A composite Plant Cost Index of the Nth of a kind (NOAK) plant capital cost and NOAK plant life cycle costs embraces the initial capital requirements for which the owner must arrange

TABLE 2: SAFETY ATTRIBUTES EVALUATED FOR ADVANCED SMPRs

1. Designs conform to the General Design Criteria in U.S. Code of Federal Regulations, Title 10, Part 50, Appendix A (as amended for non-LWR plants); NRC Policy on Future Reactor Designs-Decisions on Severe Accident Issues (NUREG-1070); NRC Policy Statement on Plant Standardization.
2. Designs comply with NRC proposed position requiring prototype testing module testing for design certification unless (1) the performance of each safety feature of the plant has been demonstrated via previous experience or full scale testing, (2) sufficient performance data exists on each safety feature of the plant to validate safety analysis analytical tools over a full range of operating and accident conditions including plant lifetime, and (3) system interaction effects among plant safety features have been properly accounted for.
3. Designs employ diverse, redundant, and inherent safe reactivity shutdown characteristics.
4. Designs employ diverse, redundant, and inherent decay heat removal characteristics.
5. Designs employ three or more separate physical barriers to fission product release to the environs.
6. Designs employ low primary system coolant pressures.
7. Designs employ primary coolants which are either single-phase fluids with good thermal conductivity or highly subcooled two-phase fluids with high thermal conductivity.
8. Designs empty fluids in primary, secondary, and auxiliary systems which are non-corrosive, non-combustible, and non-toxic.
9. Designs employ primary fluids having very low neutron activation potential.
10. Designs feature a long "grace period" for operator corrective action under system transients and faults.

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financing and the economic viability of the project in comparison with other electric generation technologies. For imported equipment the capital costs would include import duties and fees and reflect prevailing currency exchange rates. The Advanced SMPRs were evaluated on the basis of NOAK capital and NOAK life cycle costs.

Plant Complexity

This attribute is reflected in NOAK plant capital costs and annual operation and maintenance costs. It is linked to plant availability since the reliability of more complex components, systems and structures is less. In addition, for plants of greater complexity operator and maintenance staff skills must be greater with increased recurring training costs. Plant transient behavior under normal, upset, or fault conditions may also be less predictable, requiring greater safety margins. Advanced SMPR complexity was evaluated in terms of operator and maintenance manpower requirements, automatic load following capability, and plant availability.

Existence of International Equipment Supply Infrastructure

Unless imported major nuclear plant equipment is available in developing countries through domestic licensees, the Investor would seek assurance of a competitive international infrastructure of major equipment suppliers to service, repair or replace major nuclear components, systems and structures. The Advanced SMPRs were evaluated against the number and experience of known or prospective licensees of the vendor organizations.

Existence of International Fuel Supply and Fuel Cycle Services

Unless imported nuclear fuel and related fuel cycle services (interim storage, transportation, and spent fuel processing or final disposition) are available domestically, the Investor would seek assurance of a competitive international supply infrastructure to provide nuclear fuel and fuel cycle services. Reprocessing is expected to become important in the 21st century for LMRs reoptimized for breeding and may be desirable for optimum converters (ALWRs, MHTGRs, SHWRs). For an interim period, extended life (high burnup) fuel may make once-through fuel cycles economically more attractive. The number of international fuel suppliers for each of the Advanced SMPRs was evaluated.

Commercial Availability Date

The developing country would seek assurance that the Advanced SMPR had been licensed or type-certified in its country of origin and had been tested or operated successfully for a period of time to confirm its technical design, operational reliability, and economic performance prior to ordering. By the turn of the century it is expected that the Advanced SMPRs should have been demonstrated and replica plants would be available for commercial deployment. Construction of a commercial Advanced SMPR plant appreciably in advance of the year 2000, however, would entail potential risk in varying degree. The Advanced SMPRs were evaluated as to the likely date of type certification or commercial availability.

Low Radioactive Waste Generation and Emission Rates

The Advanced SMPRs considered differ in their gaseous, liquid, and solid radioactive waste generation rates and normal plant emission rates. The emissions (Ci/MWe-Yr) in Table 3 for each Advanced SMPR were used to evaluate occupational exposure to workers and offsite exposure to the public. The values are a function of fuel quality, chemical corrosivity of reactor system materials and coolant, reactor system material activation rates, and emission pathways from the reactor system and containment. Annual quantities of low level solid wastes generated for offsite shipment or on-site storage for each advanced SMPR were also evaluated, but radioactive wastes from decommissioning and dismantlement of plant structures at end of life were not considered.

TABLE 3: ESTIMATES OF ADVANCED SMPR RADIOACTIVE WASTE GENERATION

	System	Nature of Waste	Specific Activity (Ci/MWe-Yr)
Small APWR:*	Primary coolant cleanup	Ion-exchange resins, cartridges	$5x10^{2}$ to $5x10^{3}$
	Liquid waste processing	Evaporator concentrates, sludges	10^{-1} to 1
	Off-gas and ventilation	HEPA filters, Charcoal filters	10^{-1} to 1
	General power plant operation	Paper, rags, clothing	$2x10^{-2}$ to $2x10^{-1}$
		Discarded hardware components	1 to 10^{2}
		Control rods and components	$3x10^{4}$
Small ABWR:**	Primary coolant cleanup	Ion-exchange resins, cartridges	$4x10^{-1}$ to $2x10^{2}$
	Liquid waste processing	Evaporator concentrates, sludges	$6x10^{-1}$ to 10
	Off-gas and ventilation	HEPA filters, Charcoal filters	60 to 300
	General power plant operation	Paper, rags, clothing	4
		Control rods and components	200 to $12x10^{5}$
Modular HTGR:	Primary coolant cleanup	Charcoal filters	$1.7x10^{-1}$ to $1.7x10^{1}$
		Titanium sponge (tritium)	1.3 to 3.3
		Dust	$1.7x10^{2}$ to $3.3x10^{2}$
	Liquid waste processing	Evaporator concentrates, driers	$3.3x10^{1}$ to $6.1x10^{2}$
	Off-gas and ventilation	HEPA filters, Charcoal filters	$1.7x10^{-1}$ to $1.2x10^{1}$
	General power plant operation	Paper, rags, clothing	$1.7x10^{-1}$ to 3
		Control rods and cables	$1.7x10^{2}$ to $1.7x10^{3}$
Modular LMR:	Primary coolant cleanup	Charcoal filters	$1.7x10^{-1}$ to $1.7x10^{1}$
	Liquid waste processing	Evaporator concentrates	$3.3x10^{1}$ to $3.3x10^{2}$
	Off-gas and ventilation	HEPA filters, Charcoal filters	$1.3x10^{-1}$ to $1.3x10^{1}$
	General power plant operation	Paper, rags, clothing	10^{-1} to 1
		Control rods and components	$2x10^{2}$ to $2x10^{3}$

NOTE: Data from Technical Report Series Numbers 198 and 236 (LWRs), 236 (HTGRs), and 246 (LMRs), International Atomic Energy Agency.

*6,000 m^3/yr average liquid waste volume assumed for a 600 MWe plant.
**12,000 m^3/yr average liquid waste volume assumed for a 600 MWe plant.

Minimum "Black Startup" Time

The potential for loss of offsite power and requirement for "black startups" without offsite power may be higher in developing countries where utility grid Loss of Load Probabilities are higher. Outage times associated with black starts may impose greater societal costs in developing countries due to the challenge presented to the electric grid and potential failure of other operating electric generation facilities. The Advanced SMPRs were evaluated in terms of black startup time requirements.

Reactor Plant Lifetime

The large capital investment and costs and difficulty of dismantling and disposing of reactor equipment offer incentive for increased reactor lifetimes through improved designs, greater modularity, and improved maintenance and repair techniques. New technologies for remote maintenance operations, the development of improved materials, and Advanced SMPR designs which reduce radiation damage to important structural materials, offer the potential for greatly extended lifetimes. There is a growing concensus within U.S. industry that a 60-year lifetime is feasible, and even longer lifetimes for Advanced SMPRs may be possible. The major nuclear equipment should be accessible for maintenance by robotic systems and designed for ease of replacement along with their associated instrumentation and electrical systems. Refurbishment of reactor systems would preserve the costly facility installation, site preparation, and environmental and social/demographic studies, minimize the requirements and costs of new suitable sites, and defer the costs of decommissioning and dismantlement. The potential lifetimes of the Advanced SMPRs were evaluated.

Minimum Consumables Requirement and Utilization

While the required inventory of reactor plant consumables and their utilization rate is an economic consideration, it may also present an importation difficulty unless local firms can provide the required commodities and products. Required consumables and utilization rates of the Advanced SMPRs were evaluated.

Conformance to U.S. Licensing Criteria

Prospective Investors in Advanced SMPRs of U.S. origin would seek assurance that these plants conform to current U.S. licensing criteria, including NRC's Proposed Policy for Regulation of Advanced Nuclear Power Plants (plant standardization); the "defense in depth" safety philosophy of General Design Criteria (10 CFR Part 50 Appendix A) and NRC Regulatory Guides; NRC's Policy on Future Reactor Designs-Decisions on Severe Accident Issues in Nuclear Power Plant Regulation (NUREG-1070); NRC's A Prioritization of Generic Safety Issues (NUREG-0933); and a manufacturing license for shop fabrication of modular plant systems and components (10 CFR Part 50 Appendix M). The extent to which the Advanced SMPRs may comply with these regulatory criteria was evaluated.

Plant Thermodynamic Cycle Efficiency

While cycle efficiency is an operating economic issue, it may have an environmental impact and could affect plant layout and civil structural engineering requirements. Since certain of the Advanced SMPRs differ appreciably in thermal efficiency, this attribute was evaluated for each Advanced SMPR.

Minimum Plant Construction Schedule

The constructibility of Advanced SMPRs and the transportation of their modular shop fabricated reactor systems from factory to site are under extensive study. Parallel shop fabrication, Nuclear Island (NI) construction, and Balance of Plant (BOP) construction appear possible since all three activities are separable in varying degree. Parallel construction would be constrained by the interrelationships among the three activities: equipment delivery to the site, site readiness and availability of heavy-lift equipment to erect structures and install modular equipment, and management of the NI and BOP connections. Estimated construction periods for Advanced SMPRs vary from two to four years and require different types and numbers of construction equipment. The construction schedule was evaluated for each Advanced SMPR.

Capability of An Eighteen Month Sustained Operation Period

Most of the Advanced SMPRs operate on an eighteen month or longer fuel cycle. The requirement is that the plant be capable of sustained operation for this period in terms of major equipment reliability, availability of adequate supplies of consumables, and adequacy of plant maintenance staff. The intent is that the plant be capable of independent operation without undue reliance on non-domestic equipment suppliers, test and operational specialists, and spare parts or consumables from "third countries". Advanced SMPR capability for an eighteen month sustained operation period was evaluated.

ADVANCED SMPRs CONSIDERED

The U.S. Advanced SMPRs used to illustrate the selection methodology outlined in this paper include the small Advanced BWR,(8) the small Advanced PWR,(9) the modular HTGR,(10) the modular Power Reactor Inherently Safe Module (PRISM) LMR,(11) and the modular Sodium Advanced

Fast Reactor (SAFR) LMR.[12] These Advanced SMPRs are being designed under DOE, EPRI, and Industry-funded programs to meet specific goals of cost competitiveness, high availability, modularity and improved constructibility, and improved safety through passive or intrinsic safety features. The standardized Advanced SMPR designs have been presented to the NRC for consideration under its Advanced Reactors Policy. Performance data used in this evaluation is based on open literature descriptions, assessments performed by the Oak Ridge National Laboratory,[13] discussions with vendors, and information presented in briefings to NRC and Advisory Committee on Reactor Safeguards (ACRS) in October 1986 and February 1987. Statements of licensability (Preliminary Safety Evaluation Reports) of the U.S. Advanced SMPRs are expected from the NRC in 1988.

EVALUATION PROCEDURE

The uncertainty in the numerical score assigned to each criterion for each Advanced SMPR is handled by treating the numerical score as a random variable with an associated probability distribution; e.g., a histogram of various numerical scores each with its discrete estimate of probability over a given range of scores. Since there are fifteen evaluation criteria in the proposed selection methodology (the Investor or user could select any number of selection criteria), the uncertainties represented by each probability distribution or histogram must be combined into a single distribution. The method of combining probability distributions that has proved generally superior to other methods is Monte Carlo simulation.[14] The SPASM computer code developed under sponsorship of the U.S. Electric Power Research Institute (EPRI) uses several methods for generating random variables from as many as nine distributions, including discrete distributions with tabular representations of their cumulative distribution functions (histograms).[15]

Monte Carlo simulation can be used to obtain information about global system performance from component (individual criterion) data. The method has been referred to as "synthetic" or "empirical" sampling. It consists of "constructing" many systems by computer calculations and evaluating the performance of such synthesized systems. The technique has been applied to a wide range of problems, many of which require an extremely large number of samples. Several techniques have been developed to speed convergence and reduce the variability of Monte Carlo simulations. SPASM uses direct sampling to avoid these complications, and uncertainty propagation can usually be accomplished adequately within a few thousand samples.[15]

The procedure involves constructing histograms of numerical values versus probability over some portion of a scale from 1 (poor) to 5 (excellent) for each Advanced SMPR case for each of the fifteen criteria of Table 1. Appropriate weighting factors for each criterion are then applied to yield resultant weighted histograms. The weighted score for an Advanced SMPR with a numerical score of 5 for each of the fifteen criteria and complete certainty would be 100. In most instances, the non-weighted mean score is less than 5 and the 90 percentiles are plus or minus approximately 1 or more from the mean value. Whatever the shape of the histogram, SPASM computes the empirical cumulative distribution function and the 99 percent confidence intervals for the sample mean and median. These intervals, specified by their end points, represent the range in which the true score of the distribution statistic lies with a probability of 0.99, permitting the Advanced SMPRs to be rank ordered. The probabilistic approach caters to the uncertainty associated with each attribute and could, for example, reflect the subjective opinions of experts for each Advanced SMPR or for each criterion.

RESULTS

In this paper point estimates of the means of the histograms have been used to illustrate the evaluation methodology for the five conceptual U.S. Advanced SMPRs in Table 4. The evaluations of each advanced concept are necessarily rudimentary since the designs are still conceptual and the extent to which each individual criterion is met for each Advanced SMPR can only be approximately estimated at present; i.e., the probability distributions are fairly broad. Once the concepts are further along in the preliminary design stage, the procedure described could be more rigorously applied.

Even in the rudimentary illustration, the evaluated global score for each Advanced SMPR may be affected by the importance weighting of the fifteen attributes. For example, if all of the initial six criteria in Table 4 had a multiplier of one assigned and criteria 7 through 12 had a multiplier of two assigned (the remainder unchanged), the relative ranking of the Advanced SMPRs would change. The Investor's opinion of the relative importance of attributes can affect the resultant rank order of the plants since individual attribute values differ for the various Advanced SMPRs.

The advantage of the procedure described is that the uncertainty in the individual attribute ratings can be quantified through subjective probability distributions so that the uncertainty in the resultant total ranking of each Advanced SMPR is known. A difficulty with

TABLE 4: ILLUSTRATION OF METHODOLOGY FOR ADVANCED SMPR EVALUATION

Criterion	Multi-plier	APWR	ABWR	MHTGR	SAFR	PRISM
1. Safety	2	7.8	8.0	8.8	8.0	8.0
2. Availability Factor	2	8.8	8.8	8.8	8.0	8.8
3. Plant Cost Index	2	3.8	3.8	6.2	8.0	7.1
4. Plant Complexity	2	4.0	4.0	7.4	10.0	8.0
5. International Equipment Supply	2	8.0	6.0	4.0	2.0	4.0
6. International Fuel Supply	2	7.0	6.0	4.0	5.0	5.0
7. Commercial Availability	1	5.0	5.0	3.0	1.0	1.0
8. Radioactive Waste Effluent	1	3.0	2.0	5.0	5.0	5.0
9. Black Start Time	1	4.0	4.0	3.5	3.0	3.0
10. Extended Plant Lifetime	1	5.0	5.0	4.0	5.0	3.0
11. Plant Consumables	1	3.0	3.0	4.0	4.0	4.0
12. Licensability	1	5.0	5.0	5.0	5.0	5.0
13. Cycle Efficiency	1	2.2	2.2	4.8	3.7	2.0
14. Construction Schedule	0.5	1.0	1.0	1.4	1.8	1.5
15. Operating Cycle Length	0.5	2.5	2.5	2.5	2.5	2.5
		70.1	66.3	72.4	72.0	67.9

NOTE: Values shown are point estimates of attribute probability distributions.

the procedure is the comparison of multi-module versus single module plants of different thermal ratings. For the Plant Cost Index criterion, the Advanced SMPR cost data must be normalized to a common electrical power rating. In an actual plant bid evaluation process it is intended that the methodology outlined be used to screen the commercial offerings against Investor preferences for selection of a preferred subset of offerings for detailed conventional engineering and economic analyses. The methodology described in this paper is not intended to replace conventional bid analysis practices.

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