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Nuclear Power Options Viability Study

Volume III, Nuclear Discipline Topics

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NUCLEAR POWER OPTIONS VIABILITY STUDY

VOLUME III, NUCLEAR DISCIPLINE TOPICS

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PREFACE

Systematic development of the information presented in this report was completed in September 1985. Delays in funding and review have prevented timely publication. An attempt has been made to include new information where substantial changes in programs or designs have occurred, but it has not been possible to bring the report fully up to date. Subsequent developments and events, particularly the Chernobyl accident, may alter some of the findings.

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ABSTRACT

Innovative reactor concepts are described and evaluated in accordance with criteria established in the study. The reactors to be studied were chosen on the basis of three ground rules: (1) the potential for commercialization between 2000-2010, (2) economic competitiveness with coal-fired plants, and (3) the degree of passive safety in the design. The concepts, classified by coolants, were light water reactors, liquid metal reactors, and high temperature reactors, and most were of modular design. All the concepts appear to be potentially viable in the time frame selected, but the information available is not adequate for a definitive evaluation of their economic competitiveness. This volume primarily reports in greater detail on several topics from the study. These are: Construction, Economics, Regulation, Safety and Economic Risk, Nuclear Waste Transportation and Disposal, and Market Acceptance. Although treated generically, the topics are presented in the context of the reactor concepts of the study.

1. INTRODUCTION

1.1 BACKGROUND

The Nuclear Power Options Viability Study (NPOVS) study was begun at Oak Ridge National Laboratory (ORNL) in January 1984. The objectives of NPOVS have been to assess selected nuclear power options with respect to viability and to identify new directions for industry, regulation, and research. Initially, the study was funded through the ORNL Director's discretionary fund. Since June of 1984, the U.S. Department of Energy (DOE) has funded the program directly. The Tennessee Valley Authority (TVA) and The University of Tennessee (UT) were added as partners to the study and have participated extensively; TVA has used its own funds, while UT has been funded by ORNL through subcontracts. The material on which this report is based has been obtained from reactor design organizations, vendors, research and development (R&D) institutions, the U.S. Nuclear Regulatory Commission (NRC), utility companies, public interest organizations, DOE, and the open literature. Proprietary information or other information received in confidence has been considered in the assessment but is not displayed per se.

This study has emphasized technical detail in the evaluation of the specific designs. Institutional factors are recognized as very important, even as overshadowing the technical issues, and are therefore included in the criteria chosen for the evaluation of concepts. However, the principal thrust of the report is on technical issues that have merit in their own right and particularly on those which may help to alleviate institutional problems; for example, enhanced passive safety may simplify regulation. Significant new design concepts have been generated in recent years through nuclear programs involved with innovative approaches. These designs constitute a substantial portion of the subjects considered. In the study attention was given to safety and reliability, cost, licensing, and development needs, as well as to the special features of each concept.

The NPOVS program proceeded in steps: (1) a literature search and development of a bibliography; (2) development of criteria for evaluation of nuclear plant designs and plans; (3) evaluation of selected design concepts using these criteria as a guide; and (4) recommendations for areas of research and development (R&D) needed to reduce uncertainties in the viabilities of options. The approach used in evaluation was to compile detailed information on the various reactor concepts of interest, synthesize that information in accordance with specific technical areas, develop an understanding of how design features influence the overall cost of generating power, and consider how changes in the design might accomplish improved economic performance and acceptance by regulators and the public. In addition to technical evaluations, assessments were made of other factors that influence commercial use, for example, regulatory requirements, industry perspectives on future technologies, market acceptance, electric power growth needs, and economic conditions.

1.2 REPORT ORGANIZATION

The overall report is organized into four volumes, as follows:

- Volume I is the Executive Summary.[1]
- Volume II (Reactor Concepts)[2] primarily describes and evaluates the selected concepts according to a chosen methodology based on the criteria. The advantages and disadvantages of each concept as well as needs for further R&D are described.
- Volume III, Nuclear Discipline Topics (this volume), deals with generic disciplinary issues relevant to nuclear viability and provides a more detailed discussion of these issues. It consists of five chapters that relate to, amplify, and support the findings of Volume II. These chapters (Construction, Economics, Regulation, Safety and Economic Risk, Nuclear Waste Transportation and Disposal, and Market Acceptance) were written to stand alone as well as to serve a supporting role. Each provides more detail, analysis, data, and references to related work than has been included in Volumes I and II. However, the chapters of Volume III largely have been written in the context of the evaluation criteria and the essential and desirable characteristics described in Volume II. Sections 1.3 and 1.4 of Volume III provide this background in abbreviated form.
- Volume IV is a comprehensive bibliography.[3]

1.3 CRITERIA AND CHARACTERISTICS

As a convenience to the reader, the evaluative criteria and the essential and desirable characteristics are reported here. For more detailed study, please consult the corresponding sections of Volume II.

The criteria were chosen to provide the important quantifiable requirements that are deemed necessary for a reactor concept to become viable in the future. In assessments of Volume II, these seven criteria were used as a guide to evaluate the concepts. The criteria are augmented by a list of characteristics that provide further guidance for properties and characteristics of importance to nuclear power viability. The characteristics chosen are not readily quantifiable but include features that complement and amplify the criteria. All are considered important, but some do not apply to certain of the concepts studied.

The criteria are as follows:

1. The calculated risk to the public due to accidents is less than or equal to the calculated risk associated with the best modern Light Water Reactors (LWRs).
2. The probability of events leading to loss of investment is less than or equal to 10^{-4} per year (based on plant costs).
3. The economic performance of the nuclear plant is at least equivalent to that for coal-fired plants. (Financial goals for the utility are met, and busbar costs are acceptable to the public utility commissions.)

4. The design of each plant is complete enough for analysis to show that the probability of significant cost/schedule overruns is acceptably low.

5. Official approval of a plant design must be given by the U.S. Nuclear Regulatory Commission (NRC) to assure the investor and the public of a high probability that the plant will be licensed on a timely basis if constructed in accordance with the approved design.

6. For a new concept to become attractive in the marketplace, demonstration of its readiness to be designed, built, and licensed and to begin operations on time and at projected cost is necessary.

7. The design should include only those nuclear technologies for which the prospective owner/operator has demonstrated competence or can acquire competent managers and operators.

These criteria obviously are not independent since criteria 1 and 2 deal with the probabilities for successful operation or failure, criteria 3 to 6 are primarily economic, and criterion 7 relates to operation. However, we deem each criterion to have sufficient stand-alone merits to justify its separate consideration.

The following four essential characteristics in large measure amplify the criteria. The desirable characteristics that follow are more peripheral and, in some instances, are applicable to all concepts. They provide a useful checklist for evaluation purposes. The essential characteristics are as follows.

- Acceptable front-end costs and risks
  - Construction economics
    - Low and controllable capital costs (utilizing, for example, shop fabrication, a minimum of nuclear grade components, and standardization)
    - Designed for long lifetime
  - Investment economics, including risk
    - Low costs associated with accidents
    - Low costs associated with construction delays
    - Low costs associated with delayed or unanticipated actions by regulatory bodies
    - Low costs associated with delayed or unanticipated actions for environmental protection
    - Unit sizes to match load growth
    - Uncertainties in technology and experience not likely to negate investment economics

- Minimum cost for reliable and safe operation

  - High availability
  - Minimum requirements for operating and security staffs
  - Designed for ease of access to facilitate maintenance
  - Simple and effective modern control system
  - Low fuel cycle costs
  - Adequate seismic design

- Practical ability to construct

  - Availability of financing
  - Availability of qualified vendors
  - Availability of needed technology
  - Adequately developed licensing regulations applicable to the concept
  - Ease of construction enhanced by design

- Public acceptance

  - Operational safety of power plants
  - Safe transportation and disposal of nuclear waste
  - Low radioactive effluent
  - Low effect on rates of construction and operation
  - Adequate management controls on construction and operation
  - Utility and regulatory credibility.

The related desirable characteristics are as follows:

1. practical RD&D requirements,
2. ease of siting,
3. load-following capability,
4. resistance to sabotage,
5. ease of waste handling and disposal,
6. good fuel utilization,
7. ease of fuel recycle,
8. technology applicable to breeder reactors,
9. high thermal efficiency,
10. low radiation exposure to workers,
11. high versatility relative to applications,
12. resistance to nuclear fuel diversion and proliferation,
13. on-line refueling,
14. ease of decommissioning, and
15. low visual profile.

Several of these characteristics are not readily determined quantitatively and therefore are applied primarily by judgment. They indicate areas and issues of interest and importance. As a rule, an individual characteristic should not determine the fate or viability of a concept.

1.4 CONCEPT SELECTION AND CLASSIFICATION

The ground rules for selection of the concepts studied are as follows:

1. The nuclear plant design option should be developed sufficiently that an order could be placed in the 2000-2010 time period.

2. The design option should be economically competitive with environmentally acceptable coal-fired plants.

3. The design option should possess a high degree of passive safety to protect the public health and property and the owner's investment. ["Passive safety" refers to the reliance on natural physical laws and properties of materials to effect shutdown and radioactive decay heat removal without relying exclusively on mechanically or electrically activated and driven devices as employed in most engineered (active) safeguards.]

The concepts selected and described in Volume II of this report[2] are considered advanced and have various degrees of innovation as compared to current concepts. For convenience, the selected concepts were classified in the traditional way by their coolants and respective generic names. The concepts selected are:

1. Light-Water Reactors (LWRs)

   - PIUS (Process Inherent Ultimate Safety) - promoted by ASEA-ATOM of Sweden

   - Small BWR (Boiling Water Reactor) - promoted by General Electric (GE)

2. Liquid Metal Reactors (LMRs)

   - PRISM (Power Reactor Intrinsically Safe Module) - The GE advanced concept supported by the U.S. Department of Energy (DOE)

   - SAFR (Sodium Advanced Fast Reactor) - The Rockwell International (RI) advanced concept supported by DOE

   - LSPB (Large-Scale Prototype Breeder) - The Electric Power Research Institute-Consolidated Management Office (EPRI-CoMO) concept supported by DOE

3. High-Temperature Reactor (HTR)

   - Side-by-Side Modular - The core and steam generator in separate steel vessels in a side-by-side configuration. The concept is supported by DOE and promoted by Gas-Cooled Reactor Associates (GCRA) and industrial firms.

These concepts are judged to be potentially available in the chosen time period, are estimated by their promoters to be economically competitive with coal-fired power plants, and have varying degrees of passive safety attributes. Although the designs are too preliminary for a complete and definitive assessment, each is believed to have potential for a significant future role. The Advanced Pressurized-Water Reactor (APWR), the Advanced Boiling-Water Reactor (ABWR), and the large HTR are recognized as viable systems that could meet electric power generating needs prior to or following the year 2000. These reactors were not included in this study except for reference because they do not fully meet the third ground rule and because they have already been the subject of extensive study and development by industry.

Although the comprehensive evaluation of the concepts selected is given in Volume II, frequent reference is made to the concepts and to further points for evaluation in several of the chapters of this volume. However, the principal thrust of Volume III is to consider in a generic way the subjects of the five chapters which follow.

1.5 REFERENCES FOR CHAPTER 1

1. D. B. Trauger (ed.) et al., Nuclear Power Options Viability Study, Volume I, Executive Summary, ORNL/TM-9780/1, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1986.

2. D. B. Trauger (ed.) et al., Nuclear Power Options Viability Study, Volume II, Reactor Concepts, Descriptions, and Assessments, ORNL/TM-9780/2, to be published by Oak Ridge National Laboratory.

3. D. B. Trauger (ed.) et al., Nuclear Power Options Viability Study, Volume IV, Bibliography, ORNL/TM-9780/4, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1986.

2. CONSTRUCTION

D. L. Phung H. I. Bowers R. M. Davis

2.1 INTRODUCTION

Problems with construction of light water reactors (LWRs) in the late 1970s and early 1980s are seen as central to the runaway cost escalation reported for many of these reactors. The most commonly cited problems include regulatory ratcheting, quality noncompliance, nonstandard design, incomplete design before start of construction, high inflation, high interest rates, and poor management. Less known problems, which are nevertheless the cause of many of the above, include the high core power density of large LWRs, the horizontal fragmentation of the utility/vendors/engineers/constructors, the rapid market penetration of nuclear energy, the evolution of a regulatory system which must devise regulations as it learned new operational experience, and, last but not least, the largely unpredicted slowdown of electricity demand following the 1973 oil crisis. From the historical perspective, the problems that nuclear energy faces today come as a matter of course.[1-3]

With the reduced demand for energy, high capital costs, and longer construction times, the new trend in the United States has been toward designing small modular reactors with passive safety features. It is hoped that this will achieve several benefits. A passively safe reactor could alleviate investors' fear of financial loss and public fear of core melt accidents. A small modular reactor could be designed to be passively safe, could be standardized and prelicensed, could be built faster (preferably most of it in a factory), and could be readily integrated into the grid.

The six reactor concepts[4-9] selected by NPOVS for assessment all claim passive safety features and superior constructibility. This chapter is devoted to assessing the constructibility features of these designs in view of what has occurred in LWR construction. In essence, the following questions are explored:

- What are the constructibility claims of the six designs selected by NPOVS?
- Is there enough design information to evaluate these constructibility claims?
- What are the advantages and disadvantages of modularization and shop fabrication?
- Can the new concepts be licensed and constructed in a shorter time than current LWRs?
- What are the new construction management methods, techniques, and tools that can help these concepts to achieve the claims?
- What are the R&D needs in support of constructibility for these new concepts?

2.2 CLAIMS OF CONSTRUCTIBILITY

Table 2.1 shows the constructibility claims of the six reactor concepts selected for study, classified in 12 logical categories.

1. Simple design for easy construction

   The LSPB concept is designed with the structures in box shapes and is arranged in such a way that crane access is feasible from all sides. Cell walls are built to serve as seismic stiffeners; rigid rod hangers are used for mounting the main in-containment piping; rooftop hatches are designed into the flat-roof containment to allow crane access to the equipment from above.

   The SAFR design[7] is also based on box-shaped structures and a flat-roof containment with several roof-top hatches.

   The PRISM design[7] proposes to build simple silos at the site in which prefabricated reactor and containment modules are placed.

   Other concepts studied also claim simplicity of design, but these claims are not as explicit and can be classified in other categories as shown below.

2. Reducing the number of safety systems

   LSPB eliminates large vessels around primary pumps and intermediate heat exchangers.[8]

   PIUS eliminates the control rod drive mechanism (CRDM), emergency core cooling systems (high pressure, low pressure, and recirculation), and the containment. It also relaxes the requirements on the diesel generators and control room systems.

   The GE Small BWR eliminates the external recirculation loops, conventional emergency core cooling system, shutdown cooling loops, and the air supply system to the safety relief valves.

   The MHTR eliminates the containment; only a filtered confinement (similar to the secondary building of current boiling water reactors) is used.

   The PRISM claims a reduction in the number of redundant active safety systems because of its inherent radiant vessel auxiliary cooling system (RVACS).

   The SAFR has the reactor air cooling system (RACS) and the direct reactor auxiliary cooling system (DRACS) both of which operate by natural circulation. It thus can claim reduction in the number of active safety systems, although the documents available to NPOVS do not explicitly make such a claim.

Table 2.1 Constructibility claims of NPOVS-selected design concepts[a]

	Category of claims	PIUS	GE small BWR	MHTR	LSPB	SAFR	PRISM
1.	Simple design for easy construction				Box-shaped bldg. Flat roof containment	Box-shaped bldg. Flat roof containment	Containment shop fabricated
2.	Elimination of many safety systems	DG, HPSI, LPSI RHR, shut down control, containment	External recirc, ECCS, spray, pumps, DG, air supply to SRV	DG, CACS, Containment	Guard vessel around primary pumps and IHX	X	X
3.	Low commodity quantities	Slightly higher than conventional LWRs on per KW(e) basis			Comparable with best LWR	Comparable with best LWR on per MW(e) basis	
4.	Small design	X (except PCPV)	X	X		X	X
5.	Modular design	X		X		X	X
6.	Shop fabrication	X (except PCPV)	X	X	Many components	X	X
7.	Ease of shipping	X (except PCPV)		X		Barge only	X
8.	BOP nonsafety grade	X	X	X	X	X	X
9.	Parallel construction	X		X	X	X	X
10.	Ease of licensing	X	X	X	X	X	X
11.	Dedicated crews		X				X
12.	Short construction time[c]	60 mos.	48 mos.	38 mos.	61 mos.	28 mos.	36 first segment;[b] 24 mos. ea. additional segment

[a]Claims are either expressed or implied in the information available to the project. No entry only means that we did not find the information in the documents available to NPOVS.

[b]Each PRISM segment consists of three reactor modules each rated at 134 MW(e).

[c]Construction time is the duration from first concrete pouring to reactor criticality.

Abbreviations: CACS = containment auxiliary coling system;
DG = diesel generator;
ECCS = emergency core cooling system;
HPSI = high pressure safety injection (system);
IMX = intermediate heat exchangers;
LPSI = low pressure safety injection (system);
PCPV = prestressed concrete pressure vessel;
SRV = safety relief valve.

3. Low commodity quantities

With an all-out determination to reduce space and commodities, the LSPB proponents claim a reduction in the containment volume and a simultaneous increase in power capacity over an earlier design, the Large Developmental Plant. Overall, the LSPB claims commodity requirements comparable with the best LWR experience.

The SAFR proponents claim low construction commodity quantities.

The PIUS shows total commodity quantities for the 600 MW(e) plant's prestressed concrete pressure vessel (PCPV) to be in the same ballpark as the concrete and steel required of the 1050 Mw(e) Oskarshamn BWR plant including the BOP. Taking into account the fact that PIUS does not need a reactor steel vessel and a containment building, we estimate that concrete requirements per kW(e) are, in principle, about the same as those of an LWR, but the steel requirements, particularly tendons, would be more.

Most concepts are not explicit in commodity requirements. In general, one can logically conclude that licensing requirements and the economy of scale dictate that the commodity requirements of a smaller reactor plant are greater per kW(e) than those of a larger sized LWR plant.

4. Small design, low power density

All concepts are to have lower core power density compared to their respective predecessors (to facilitate inherent safety features). Except for the LSPB, all concepts also have small power ratings for each reactor module. The PRISM incorporates three reactor modules of 134 MW(e) each to build a segment of 400 MW(e). The SAFR proponents made a technical and economic study and decided on a "power pak" of 350 MW(e), four of which share some common facilities such as the control room. The PIUS designers opted for a 200 MW(e) reactor-steam generator set, three of which share a PCPV. The GE Small BWR has a 600 MW(e) power rating.

The MHTR is based on reactor-steam generator segments of approximately 100 MW(e) each. Four such segments share common facilities such as the control room and the turbine-generator-condenser set.

5. Modular design

The PIUS, MHTR, SAFR, and PRISM incorporate modularized equipment and components. The modularized systems include reactor cores, reactor vessels (except the PCPV of the PIUS), heat exchangers, steam generators, and associated pumps and valves.

6. Shop fabrication

The PIUS, Small BWR, MHTR, SAFR, and PRISM are claimed to have shop fabricable modular equipment and components. In particular, the entire containment vessel, reactor vessel, and internals of the PRISM are to be shop fabricated and shipped to the site as a unit.

7. Ease of shipping and transport

All reactor concepts require civil construction work at the site. In particular, the containment and/or confinement building or shield building (of the PRISM) must be erected at the site prior to the arrival of factory fabricated equipment.

The LSPB reactor vessel and guard vessel dimensions are too large for truck or rail shipment. They must be shipped to the site by barge or in separate pieces. The reactor and guard vessel of the SAFR are similarly shipped.

The proponents for the PIUS, Small BWR, MHTR, SAFR, and PRISM claim that their respective components can be shop-fabricated, shipped to the site, and installed in place easily by heavy-duty trucks, rail, Schnabel cars, or air casters. The PCRV of the PIUS must be built at the site. So must the confinement/containment for the reactor vessels of the other five concepts.

8. Non-safety grade balance of plant (BOP)

All concepts are claimed to have passive safety features in the design that allow safety-grade equipment to be confined to the nuclear island. The balance of plant (BOP) can thus be separated from the nuclear island (by a fence if necessary) and built to conventional standards.

9. Parallel construction

The PIUS, Small BWR, MHTR, LSPB, PRISM, and SAFR are claimed to allow parallel construction, which can be achieved because the BOP and the nuclear island are separable.

For the GE Small BWR, it appears probable that factory fabrication, nuclear island construction, and BOP construction can be conducted at the same time. Parts and components of large structures such as the containment building or the PCPV can also be built in parallel at temporary facilities at the site, then moved into place by heavy-duty cranes or air casters. Parallel construction is limited only by the interface of the three activities: equipment delivery, site readiness to erect the equipment, and the connection between the nuclear island and BOP.

10. Ease of licensing

All six concepts are claimed to possess ease of licensing. While all the concepts feature new designs with no prior licensing or operating precedent, the proponents implicitly assume that licensing will be straightforward without the "ratcheting problems" of LWRs.

11. Dedicated crews

The modular reactors should achieve high construction productivity by the use of dedicated crews. This is presumably because the crews of a segment will move on to build more segments if the utility should need more capacity.

12. Short lead time/construction time

Lead time is the duration from decision to commercial operation. Construction time is the duration from construction permit to first power.

All concept proponents claim short construction time for the "mature" plant. The claim for PIUS is 5 years (3 for the PCPV); the GE Small BWR 4 years; the LSPB 61 months, the MHTR 38 months; the PRISM 36 months; and the SAFR 28 months. The claim for PRISM is also only 24 months for any subsequent segment each consisting of three reactor-steam generator modules and their on-site silos and BOP facilities.

2.3 INFORMATION SUPPORTING CONSTRUCTIBILITY CLAIMS

The information available to NPOVS for support of the constructibility claims about the various reactor concepts has been changing and uneven. This is of no surprise because most concepts are in early evolutionary stages of development with their proponents still looking for longer term development funds.

The documentation for the MHTR, the LSPB, and the PIUS provide more construction information than others. While the side-by-side MHTR concept was only recently selected by the Department of Energy in early 1985, it and its sister (vertical-in-line) design have been studied for some time both in the United States and in Germany. As more information and design details are developed or made available, one is faced with several realities that tend to cloud the constructibility claims. Some of these include:

- The MHTR vessels and their horizontal cross-ducts must be joined together at the site. Because of their configuration within imbedded silos, welding, postweld heat treatment, and in-service inspection may be difficult. Perhaps bolted flanges could be used here.

- The MHTR relies on some components that have never been licensed in the United States in spite of the Fort St. Vrain precedent. These include a new helium circulator design and a silo that is intended to conduct away the heat to the earth in the extreme case of loss of all primary and auxiliary cooling.

- The assembly of the core reflector blocks and associated control rods must be done at the site.

- There are unanswered questions about the amount and availability of shop space required for manufacturing reactor vessels for small modular reactor plants as compared with shop space requirements for large LWR plants. For example, the MHTR and PRISM shop requires approximately eight reactor vessels to produce 1000 MW(e), each vessel essentially as large as those for 1100-1300 MW(e) LWRs.

The GE Small BWR has new design features for the containment, the isolation condenser, and the suppression pool/emergency core cooling pool. Several highly reliable devices are also required, such as the steam injector for the feedwater line, the internal recirculation pump (which is proven technology in Sweden and Germany but the GE BWRs do not have a working precedent), valves controlling the piping between the reactor vessel and the isolation condenser, valves that allow depressurization into the elevated suppression pool, and valves that allow water from the suppression pool to flow into the pressure vessel. Detailed design features that could support constructibility claims of these features are not available.

The LSPB makes available adequate information concerning the efforts to provide crane access to every spot of the construction site and to minimize building volume and complexity. However, an all-out effort to reduce building volume and commodity quantities and to build only flat-wall, box-shaped structures gives rise to questions of capability to maintain leak integrity of the structures as well as the availability of sufficient space for future repair and maintenance.

The SAFR and PRISM won support from the Department of Energy in 1984 on the basis of their small modular and inherently safe characteristics. There is not enough information at present to judge the claims made by their proponents. One can speculate, however, that the claim of 24 to 38 months of construction time is very optimistic. In many cases, such as for PRISM, the claim pertains only to the civil structures at the site and does not include many more months of lead time for the reactor vessels, which must be factory fabricated. The same limitations on factory capability to manufacture the large reactor and containment vessels are found for the PRISM and for the reactor and steam generator vessels of the the MHTR.

While information on the PIUS is also incomplete, it represents a rather comprehensive picture for deployment from the demonstration stage to the commercial stage. Two features that give rise to most questions are the massive PCPV and the bayonet once-through steam generator. ASEA-ATOM engaged the civil engineering firm, VBB, and the construction firm, Skanska, to study the design and construction of the PCPV. Their conclusion is that it can be built in just over three years on the basis of existing technology.[10] Regarding the steam generator, the claim is made that it can be manufactured completely in the shop and would not present a critical path for construction.[11] We judge that installing and servicing these "tube within a tube" steam generators can be a problem, but there is insufficient information to fully evaluate this topic.

2.4 STANDARDIZATION, MODULARIZATION, AND SHOP FABRICATION

The French nuclear program is widely believed to be successful because of the collaboration of (a) the government; (b) the French national utility, Electricite de France (EdF); (c) the only reactor vendor, the Framatome; (d) the only heavy equipment manufacturer, the Alsthom Atlantique; and (e) the EdF-led construction consortium that includes nationwide specialty suppliers and local construction workers. Due to a clear decision on the capacity additions and to the cooperation of parties involved, the French have been able to standardize their designs and construction. There are basically three standard design classes: the 900 MW(e), the 1300 MW(e), and the 1500 MW(e) classes. The first class progressed in three series: Series 1 with 6 units, Series 2 with 18 units, and Series 3 with 10 units. The second class is now well in progress. A third class, the 1500 MW(e) design, is only started. Because of this national plan, each 4-unit project involves only about 500 different contracts (as compared to over 10,000 for the Washington Public Power Supply System). Cost estimates for each project are said to be relatively good up to 75% of the scope. Learning from standardization and replication is achieved for the second, third, and fourth unit at each plant, and for the successive plant within a series. For example, construction time for each 900 MW(e) unit is now reduced to 60 months.[12-16]

The aforementioned French experience has not been realized in other Western countries except possibly Sweden and Canada. Nonstandardization is particularly prevalent in the United States because of the horizontal fragmentation of the U.S. nuclear industry. This fragmentation exists because of the existence of many reactor vendors, equipment vendors, architect-engineers, constructors, and utilities which built nuclear plants for the first time. Fragmentation is further encouraged by anti-trust laws enforced upon U.S. industries. This wide variety of choice at the early stage of nuclear power has compounded problems in the licensing, construction, and operation of nuclear power plants.

The lesson has been learned, however, that if nuclear plant capital costs are to be reduced, a degree of standardization must be adopted for a series of units or for a certain period. The Germans adopted the Convoy System[17,18], which is similar to the series system of the French. The Russians devised the Flow Line Building Method.[19,20] The Japanese have been building several units of exactly the same design.[21,22] In the United States, some reactors at the same site or of the same utility have been built almost exactly alike (the "cookie cutter approach"). These include Palo Verde, Byron/Braidwood, and McGuire/Catawba. As early as 1974 the Offshore Power System was formed to build 1300 MW(e) PWRs completely on a barge at a factory located in Jacksonville, Florida. In 1983 the standardized concept won licensing approval from the NRC; unfortunately, by that time, past orders had been cancelled, and no new orders were in sight.

A natural advantage of standardization is the ability to build many components as modules and, if possible, build them in a controlled location such as a factory. The modules can thus share in the cost of engineering, tooling, and personnel training, and can achieve faster fabrication by replication. If they are also done in a shop, then the cost saving is further achieved as a result of the controlled environment which is conducive to better fit, better quality, and better craftsmanship at comparably lower wages.[23] Construction of a series of similar reactors also benefits from learning and from a practically dedicated crew.

Learning the LWR lessons in the United States, the designers of the six concepts selected by NPOVS aim at maximum standardization, modularization, and shop fabrication. In particular, the following components and/or systems can be claimed to be modularized and shop fabricated:

PIUS: Reactor core frame, steam generator and riser module, recirculation pumps, hydraulic locks, spent fuel storage racks, bellows and seals, piping, valves, control room, and all BOP components.

GE Small BWR: Many equipment items are standardized and/or modularized. These include the reactor vessel, reactor internals, valve piping assemblies, RPV pedestal, pool liners, large sections of the containment liner, control room, diaphragm floor, plus major BOP components.

MHTR: Reactor vessel (reflector graphite blocks must be assembled at the site), steam generator vessel and coils, helium circulators, vessel cross-ducts (must be welded at the field), refueling machine (must be fitted to the reactor vessel at the site), control room, and all BOP components.

LSPB: The LSPB proponents do not make any particular claim regarding shop fabrication because the majority of major components have an outside diameter in excess of 20 feet. Truck, Schnabel car, air caster, and rail shipment are often limited to components having a diameter below that dimension. However, the LSPB is claimed to employ several modular construction techniques at the site. BOP components are shop fabricated.

SAFR: Reactor assembly including all internals and deck (must be shipped by barge), direct reactor auxiliary cooling system (DRACS), intermediate heat exchangers, and much of the BOP, both components and structures.

PRISM: Reactor vessel, containment vessel, electromagnetic cartridge-type pumps, electrical vaults, intermediate heat exchangers, reactor core frame, control rod drive mechanism, "all safety-related items," piping, valves, control room, and all BOP components.

While the above list is impressive, one should ask whether it is any different from what has been common practice in the LWR technology. Practically all major components of current LWRs are shop fabricated; and in the case of the French reactors, some Swedish reactors, some Japanese reactors, German Convoy reactors, and some U.S. reactors, many components are even modularized and standardized. These include the reactor vessels, the recirculation pumps, the hot legs and cold legs, the steam generators, all emergency core cooling tanks and pumps, valves, the control rod drive mechanisms, the containment sprays, the containment air circulators, panels of the control room, and all major components of the BOPs.

An important difference between the NPOVS selected concepts (except the GE Small BWR and the LSPB) and the current generation LWRs is that the new designs are planned to be small (100 MW(e) to 200 MW(e) modules). This smallness was decided upon less on the basis of modularization, standardization, and shop fabrication and more on the basis of inherent safety, financing, and the small projected capacity addition needs on most utility grids. The small size and large number of units required for a given electric energy production tend to favor factory fabrication.

Two other observations are also made.

First, many recent LWR construction projects have achieved impressive on-site modularization and prefabrication for faster and cheaper construction.[21,22] For example, the Takahama 3 & 4 890 MW(e) units in Japan have been constructed in just over 39 months. Constructed at the site and hauled into place were large modules of rebars, steel liners, concrete walls, and containment roof sections. This was achievable because of meticulous schedule planning, construction of temporary facilities at the site, installation of automatic welding machines at temporary facilities, and availability of high capacity cranes (2400 tons at Takahama, 800 tons at Fukushima).

Second, not all shop fabrication will be advantageous. After abandoning the prestressed concrete reactor vessel (PCRV) for the steel vessel, the 100 MW(e) MHTR must use a reactor vessel as large as that of a 1300 MW(e) BWR. We have indicated earlier the requirement for shop facilities. In this case, the factory capital charge and operating cost must be more costly per kW(e) for the MHTR than for the conventional PWR.

The same consideration appears to apply to the PRISM, which is based on shop-fabricated 134 MW(e) reactor vessel and containment modules comparable in size to that of the MHTR vessel.

With the above observations, we conclude that there are clear benefits to the concepts of standardization, modularization, and shop fabrication but that there is little basis at this time to judge whether any of the NPOVS-selected concepts will achieve an advantage over the others or over current LWRs. One key to the benefits is a clear backlog of orders. If a vendor receives, say 10,000 MW(e) of capacity order without individualized design demanded, then the natural laws of economics will dictate standardization, modularization, and shop fabrication of any chosen concept. Assured construction of a large number of small units is a prerequisite for investment in a new or refurbished factory dedicated to efficient manufacturing of the standardized and modular components.

2.5 DESIGN COMPLEXITY: IMPACT ON LICENSING, MODIFICATION, RETROFITTING, AND OPERATION

The current LWR plant is a very complex system to design, construct, operate, and maintain. Examples of complexity include several systems of emergency core cooling and several systems that must be kept extremely reliable (e.g., diesel generators, residual heat removal systems, containment isolation system, emergency feedwater system). Another indication of the complexity of LWRs is the need for over 100,000 cable connections, 40,000 valves, 30,000 pipe hangers, 4000 pipe supports and snubbers, several hundred thousand welds, several hundred valves that must operate within a few seconds following an actuation signal, and 14,000 annual checks and settings.[24,25]

The PIUS, the GE Small BWR, and the MHTR appear to be simpler in design than LWRs. This claim appears to be reasonably feasible to achieve due to two features: (a) the proposed concepts have lower core power densities than have been designed heretofore for the same reactor types and (b) the proposed concepts rely on passive safety features to shut down and cool the reactor core in the ultimate worst case when all active systems fail. This reliance on passive safety reduces the requirement for redundancy, diversity, and reliability on engineered systems. Fewer active components are therefore required.

In response to the request of many concept sponsors for early interactions, the Nuclear Regulatory Commission (NRC) has published the Proposed Policy for Regulation of Advanced Nuclear Power Plants.[26] (An advanced concept is defined as a concept that is significantly different from the present generation LWRs.) The characteristics of advanced reactors which the NRC believes may facilitate early licensing or standard design approval are listed in Chapter 4, Regulation.

Table 2.2 compares the design characteristics of the six concepts under study against the above cited NRC desirable characteristics. Noting that we are not attempting in this chapter to assess the licensability of the concepts, the following observations are discernible:

1. The balance-of plant layout for the 1200 MW(e) 2-PCPV PIUS appears to be based on the "mirror-image, symmetrical" approach. The "cookie cutter" approach has proven to be more efficient for construction and quality assurance.

2. The containment configuration of the GE Small BWR appears to be effective but somewhat complicated. One is reminded of the Mark I and Mark II BWR containments and the PWR ice condenser which looked equally unusual and which had problems with construction and maintenance. For example, how does one get access to the bottom of the GE Small BWR reactor vessel for maintaining the control rod drive (CRD) system? The method of replacing the CRDs remotely as recently improvised by the Japanese during their BWR Improvement Program, Second Phase,[21] appears not to have been used.

Table 2.2 Characteristics of NPOVS-selected reactor design concepts in view of NRC proposed policy for regulation of advanced reactors

NRC proposed policy for regulation of advanced nuclear plants (desirable characteristics)	PIUS	GE Small BWR	MHTR	LSPB	SAFR	PRISM
1. Designs that require few supplementary safety features and/or provide longer time for response	No supplementary features needed within 7 days	No supplementary features needed within 3 days	Core never melts; graphite burn unlikely	Not clear	25-30 hrs.	Not clear
2. Simplified designs such that few systems, components, or operator actions must be called upon	Negative temp. coefficient; automatic shut-down by borated water; relief valves for PCPV	Negative temp coefficient; safety valves; highly reliable equipment to refill the pool	Negative temp. coefficient; aux. heat removal; radiant heat removal	Negative temp. coefficient; passive shutdown rod release (Curie point) two diverse cooling systems (one natural circulation)	Negative temp. coefficient passive shutdown rod release (Curie point); DRACS, RACS	Negative temp. feedback; RVACS
3. Designs that minimize safety system challenges, minimize potential for core damage, are easy to maintain, and reduce occupational doses	Yes on all; maintenance uncertain	Not clear	Yes on all; maintenance uncertain	Not clear (claims low doses)	Not clear (claims low doses)	Not clear (claims low doees)
4. Designs that increase standardization and shop fabrication without creating new problems	Claimed but not clear	Not clear	Yes, but may be factory limited	No	Yes, but requires barge shipment	Yes, but may be factory limited
5. Designs that use existing technology or suitably developed technology	LWR technology	BWR technology	Fort St. Vrain; AVR; and THTR-derived technology	CRBR derived technology	CRBR and EBR-2 derived technology	CRBR and EBR-2 derived technology

3. The MHTR does not show an easy way to assemble and later to maintain the cross ducts between the two vessels and the auxiliary core cooling circulator at the bottom of the reactor vessel.

4. The use of a rectangular-structure, in-line layout of the LSPB and "power paks" of the SAFR and PRISM is basically conducive to simplicity. However, we noted earlier that there is so much emphasis on space and commodity saving in these concepts that they may eventually run into licensing, construction, retrofit, or maintenance problems. There is not enough information at this time to assess whether any of these problems exist.

   The emphasis on savings in volumes and commodities may have been influenced by the assumption that these measures go hand in hand with construction time and capital cost. This is justified in general, but one must note that the relationship is seldom linear and that there are trade-offs. For example, the Takahama Units 3 and 4 were constructed in just over 39 months (per unit), not because Kansai Electric Power saved on space and commodities. They actually increased the size of the containments over those of Mihama 3 in order to improve work efficiency and earthquake resistance.[21]

5. The transportation and placement may be difficult for the PRISM reactor vessel-containment modules, which weigh 850 tons and measure about 6 m x 20 m with very little side clearance. It is not clear how connection with the BOP systems is made and where the large electrical vaults will be housed if the silos are mostly below grade. There is also the question of access and of equipment maintenance (GE claims that the whole module can be removed and replaced.)

In summary, we have not identified any severe design deficiency but have identified several engineering and/or economic concerns that can create problems for construction and cost control of the NPOVS-reviewed concepts.

2.6 CONSTRUCTION SCHEDULE

The proponents for the six concepts under study all project the building of a prototype by the early 1990s, the prelicensing of a standard design, and the availability of such design to the marketplace by the mid 1990s. While there are many barriers to be overcome in the development and licensing, all proponents assume a streamlined licensing process. Infrastructures such as factories and transportation are assumed to be available and not to be on the critical path of construction. With these assumptions, construction time has been estimated to be about 5 years for the PIUS and LSPB, 4 years for the GE Small BWR, and about 3 years for the MHTR, SAFR, and PRISM.

We have indicated earlier that all concepts under study seem to possess many of the characteristics deemed desirable by the NRC for a speedy licensing process. This does not imply, however, that licensing of these concepts for commercial operation will be a matter of course and that construction and operation of the power plants will unfold as planned. A prototype or demonstration plant must first be built to verify and/or modify major design parameters. When LWRs were first introduced in the 1950s, little or no indication was evidenced that they would be beset by problems such as stress corrosion cracking, steam generator tube degradation, recirculation line damage, auxiliary feedwater unreliability, pressurized thermal shock, fire protection complexities, high occupational doses, and, last but not least, the Three Mile Island 2 accident. Many of these problems have caused extensive changes in design during construction of later LWRs.

The experience at Fort St. Vrain has also indicated that a new HTGR plant based on the prismatic core, PCRV concept would incorporate many changes derived from experience with the Fort St. Vrain design.

We conclude that the short construction schedules claimed by the concepts are feasible in idealized conditions - just as they are feasible for current LWRs - but there are many uncertainties that can upset these claims. More study is needed to quantify such uncertainties.

2.7 CONSTRUCTION MANAGEMENT

Several recent studies, such as the Construction Research Council of the American Society of Civil Engineers,[27] the Business Roundtable's Construction Industry Cost Effectiveness Project (CICEP),[28] and ORNL's preliminary NPOVS studies, have indicated that success or failure in construction and start-up of nuclear power plants depends on factors such as project organization, design completion, need for capacity, interfaces between technical engineering and safety-related problems, and design and construction.

Most of the generic problems commonly cited on LWR projects have been studied effectively by CICEP. This study was conducted between 1978 and 1983 with the involvement of over 250 experienced individuals from some 125 companies (30 of which were actively involved in nuclear plant construction). Results of the study were published in 23 reports and an executive summary. The CICEP detailed specific findings and recommended actions in six areas: information, management, training and education, technology, labor, and regulation. The findings on management include the following:

1. Many projects are lacking in safety practices.

2. Prolonged overtime reduces productivity.

3. High absenteeism is the result of carelessness in hiring and negotiation and lack of good working conditions, communication, and motivation.

4. Many supervisors lack ordinary management skills.

5. Management is slow in adopting new ideas, new techniques, and modern tools.

6. Successful managers are those who have skill, dedication, versatility, and authority.

Studies conducted for EPRI by Applied Decision Analysis (ADA) have targeted the benefits from improved management and modularity on nuclear construction, lead times, and cost.[29] ADA categorized the organizational structures frequently used in the nuclear power industry as follows: design-build, project management, general contractor, prime specialty contractor, and in-house construction. Project management was cited as the best organizational structure for carrying out complex construction projects, although exceptions to this generalization can be found. Project management organizations require a dedicated team with a clear objective and responsibility.

Past nuclear project success was also correlated by ADA with nuclear experience, project control, adaptability and initiative, project commitment, and communication and coordination as shown in Table 2.3. It was indicated that this type of experience can be developed in-house or acquired outside the organization. While each of these is a key factor in the successful construction of power plants, it was concluded by EPRI and ADA that formal management structures are less important than management attitudes and philosophies. While there is no guarantee that if these factors are followed, project construction will be successful, these management factors were considered important to project success.

Management issues also include larger concerns such as the organization of the overall industry. As alluded to above and also pointed out by Weinberg,[1] Kemeny,[30] the Office of Technology Assessment,[31] and Lester,[32] the nuclear industry is extremely fragmented and lacks vertical integration. This situation has hampered development of light water reactors in several important ways: (1) by inhibiting standardization, (2) by retarding the rate of learning in the industry, and (3) by weakening management control in general.

With this background, how can one assess the construction management prospects of the six NPOVS concepts? First, we observe that managing a complex project is extremely difficult without a proven product (in this case a good reactor design which has been licensed and which can be built with existing technologies). Even a super-manager cannot assure a successful construction job if the central component of the job is not yet available or proven. Thus the developing nature of the concepts under study renders an assessment of construction project management premature. Second, in the market system, a successful construction project must have the active participation of the private sector. As of this date, it seems doubtful that any vendor or utility will embrace any of the proposed concepts solely with their investors' capital, and it is well known that managing a project that depends on year-to-year funding from the government is extremely difficult. We, therefore, have little basis at present to assess project management of the various concepts except by trying to point out pitfalls of the past.

Does any concept lend itself more readily to successful construction management than others? It is noted that all concepts claim non-safety grade BOP design. This helps in constructing the BOP with conventional codes, material, and crews. It is also noted that the PIUS and the LSPB units require more commodities than the others, the former because of its massive PCPV and the latter because of its higher power rating. These two observations, however, do not matter much from the construction management viewpoint. With proper planning and direction, they are only parts of the logistics and economics. The success or failure of project management will be less dependent on technical features (provided that they are proven and licensed) than on the key ingredients outlined above.

We conclude that there is no firm basis to believe that construction management is made easier for early models of any of the design concepts studied. Although these concepts potentially require less manpower and commodities and less time to construct than large LWRs and thus could be at an advantage from a construction viewpoint, they are exposed to more uncertainties than large LWRs because of their developmental nature.

Table 2.3. Common characteristics of project management

Nuclear project experience	• Recent experience of utility and contractor personnel • Utility/contractor experience working together • Experience of different contractors working together
Project control	• Authoritative decision making • Direct lines of responsibility • Regular cost and schedule estimates • Supervision and control by proper party • On-site engineers • Proper documentation • Attention to quality assurance detail • Critical and comprehensive design review • Smooth system handoff
Adaptability and Initiative	• Prompt recognition and problem resolution • Dismissal of unimportant issues • Assertiveness in dealing with contractors • Assertiveness in dealing with scope changes • Schedule aggressiveness
Project commitment	• High priority by corporate decision makers • High availability of financial resources • Dedicated personnel and contractors
Communication/coordination	• Cooperative working attitudes • Effective information flow • Coordination of project responsibility • Sensitivity to other project concerns

Source: Applied Decision Analysis, Inc.

2.8 CONSTRUCTIBILITY CONSIDERATIONS FOR PIPING AND ELECTRICAL AND INSTRUMENTATION SYSTEMS

Piping and cabling represent two major cost areas which have escalated more severely than other cost areas of U.S. nuclear power plants. Typically a large LWR plant involves 500 miles of cables, 40 miles of piping, several hundred thousand cable connections, 30,000 pipe hangers, 4000 snubbers, and several hundred thousand field welds. Most piping must be designed to withstand the safe shutdown earthquake and the blowdown forces that could result from the sudden guillotine break in the largest primary pipe. The cables must be designed to minimize damage by fires of the type that occurred at Browns Ferry in 1975.

Piping and cables in nuclear power plants overseas are designed and installed in a manner similar to those in the U.S. However, a comparative cost study of U.S. and French nuclear plants by the Electric Power Research Institute (EPRI)[33] revealed a factor of 2 difference in labor productivity between the French and U.S. plants where mechanical and electrical work is concerned. Productivity in the civil work was, however, about equal. This indicates that there is much to be gained in finding out what the problems are in the areas of cables and piping. The EPRI has conducted two workshops on the constructibility of piping, electrical cable routing, and instrumentation and have revealed several areas of potential improvement. These include standardi-zation of design, freezing of regulatory requirements, more embedments, more multiplexing, and inherently safe design so that requirements can be relaxed.[34-36]

After a decade of ratcheting regulation, the NRC has started to relax on certain requirements as a result of new safety information that has become available since the Three Mile Island accident. For example, new safety information on seismic margins and on leak-before-break behavior of piping has allowed the removal of several pipe restraints and supports from newer U.S. plants such as Palo Verde, Comanche Peak, and Vogtle.[37,38] Future nuclear plants, including the new concepts that NPOVS has studied, are expected to be able to take advantage of this relaxation.

While the six concepts under study have not been developed to the point where piping and cable costs can be estimated, there are at least three indications that the ratio of these costs to the overall plant cost will be less than that of current LWRs. These indications are:

1. Most designs are of the pool type or are similarly compact, thus requiring shorter pipe runs.

2. Most designs limit safety-grade systems to the nuclear island, allowing conventional grades of material for the BOP.

3. The concepts incorporate maximum use of computer-aided design (CAD), computer-aided engineering (CAE), computer-aided construction (CAC), multiplexing, modular design, and models.

2.9 NEW MANAGEMENT TECHNIQUES AND CONSTRUCTION TOOLS

The pooling of positive experience from several nuclear plant construction projects worldwide has revealed that several successful management techniques and new construction tools are available. We summarize below a few prominent items.

1. Standardization of design, equipment, components, training, documentation, warehousing, quality assurance, and quality control. These have been cited most often in the success of the French nuclear program, of Oskarshamn and Forsmark (Sweden), and of St. Lucie, Byron, and Braidwood (United States).

2. Extensive use of models by the German, Japanese, Swedish, and Swiss projects to avoid holdups in the critical paths and to maximize productivity. Simulation is an American trademark, but somehow it was not successfully carried out in the design and construction of many nuclear projects in the past.

3. Extensive use of computer systems for 3-D designs, engineering, tabulating as-built data, storing as-built drawings, job filing and checking, and inventory control. It is hoped by piping installers that one day the computer will be able to admit voice filing of job completion and QA/QC reports.

4. Extensive use of new concrete building techniques such as slipforming, concrete placement by pumps, staircase decking, and prefabrication of modules for rebar, air locks, liner segments, and liner floor and dome segments.

5. Rolling 4-10 shifts for large projects to increase labor productivity, and night shifts for lesser construction or housekeeping tasks.

6. Separation of construction for the safety-grade nuclear island.

7. Establishment of engineering expediting office at the field with direct contact by phone, computer terminals, and video transmission with the home office to achieve resolution of changes without delay (e.g., satellite communications between home and field offices as used today by U.S. constructors for overseas job sites).

8. Use of temporary facilities at the site to prefabricate modules in parallel with other construction.

9. Use of heavy duty cranes to set large modules and equipment directly into their places.

10. Use of heavy duty Schnabel cars and air casters to haul heavy equipment.

11. Use of automatic welding machines where possible and potential use of robots for cable pulling and splicing.

12. Involvement of the start-up staff early at the site to receive, test, and preoperationally-test systems as installation is completed.

13. Coordination of inspection teams and establishment of fair and complete investigations of allegations by whistle blowers.

It is obvious that the above management techniques and construction tools are not the exclusive claims of any reactor concept. Perhaps some are more suitable than others to a specific concept, but that determination can be made only by the management in charge after a project has been committed. The degree of success of the project will still depend largely on the experience, dedication, authority, and skill of that management.

2.10 EVALUATING THE CONSTRUCTIBILITY OF THE CONCEPTS WITH RESPECT TO NPOVS CRITERIA

Of the seven criteria NPOVS uses to evaluate the chosen concepts, the fourth, fifth, sixth, and seventh have some bearing on their constructibility. These are:

Fourth criterion: The design of each plant is complete enough for analysis to show that the probability of significant cost/schedule overruns is acceptably low.

This criterion also addresses the economic risk to the capital investment as affected by unanticipated requirements and schedule delays during the construction period up to the start of revenue-producing operation. Sufficiently complete and detailed designs, schedules, and specifications must exist to permit orderly planning and to prevent or minimize unanticipated events that lead to cost or schedule overruns. An appropriate review would include the complexity of design, requirements for accuracy and tight tolerances, compactness of arrangements, room for expansion, and strictness of sequencing requirements. Review by NPOVS is limited since designs of the concepts considered are not complete enough for thorough analysis.

Fifth criterion: Official approval of the plant design must be given by the NRC to assure the investor and the public of a high probability that the plant will be licensed on a timely basis, if constructed in accordance with the approved design.

This criterion addresses concern for delays and associated risk for fully designed or replica plants and is closely related to Criterion 4. Criterion 6 also addresses the concerns of the adequacy and sufficiency of the first plant. Although current regulations provide a mechanism for the preapproval of standardized plant designs (10 CFR 50, Appendices M, N, and O; and 10 CFR 170.21) and early site-suitability reviews (10 CFR 50, Appendix Q), there is little experience in applying this mechanism. Also past experience shows that the existence of a completed and licensed plant does not guarantee that a replica will encounter no obstacles in obtaining a license. This criterion's prime concern is with the licensing process, including potential further changes in requirements and regulations. Experience with licensing is extensive and should be sufficient to permit the induction of one-step licensing at the completion of design. Verification of quality control during construction, of course, would be required. This criterion is also addressed in the chapter on regulation in Volume III.

Sixth criterion: For a new concept to become attractive in the marketplace, demonstration of its readiness to be designed, built, licensed and to begin operation on time and at projected cost is necessary.

For a concept to be seriously considered as a viable option in the power industry, convincing evidence must be provided relative to major economic and performance claims. A demonstration plant offers an effective way to acquire this competence. Presumably the demonstration plant would be used for extensive validation of computer codes related to safety and operability. It might directly demonstrate selected safety features to the regulators, the industry, and the public. The construction and start-up of the demonstration plant would provide a base of experience from which future standardized plants could be designed. It is possible that following the test phase, the demonstration plant would be operated for an extended life as a first-of-a-kind unit. Where extensive related prior experience is available, the probability for demonstration in a first-of-a-kind plant may be high.

Seventh criterion: The design should include only those nuclear technologies for which the prospective owner/operator has demonstrated competence or can acquire competent managers and operators.

For the operation of a new or substantially different concept to be satisfactory, utility plant managers and operators must have acquired an adequate background and experience with the technology and equipment. This criterion relates closely to Criterion 6 since the demonstration plant can provide an exceptionally good training facility. Simulator training has proven effective for current power plants, and simulators would be necessary tools for new concepts. Where the concept derives from a prior system such as the small BWR, this criterion should be relatively easy to meet.

While all six concepts studied by NPOVS are ingenious designs, have passive or near passive ultimate safety features, and have promise to be reliable and economical, none appears to satisfy all of the above criteria. These designs are in their infancy, need public funds to develop further, have not been reviewed or approved by the NRC, nor have they drawn substantial interest from the utilities. The MHTR has a group of utilities supporting it, but this support does not yet include a commitment to purchase and operate. Except for the GE Small BWR and for the PIUS, whose technologies are closest to the current LWRs, no prospective owner/operator has demonstrated competence or can acquire competence to commercially build and operate one of these designs in the next 10 years. The situation may be different in the following 10 years if the government supports or aids in the construction of prototypes.

In view of the above observations, we conclude that none of the concepts has met the NPOVS criteria yet from the constructibility standpoint but may do so by 2000-2010.

At its present stage of design the MHTR may not be able to increase its power output without having to make the reactor vessel even larger or without compromising its claim on passive safety. There is also indication that the present design may incur high costs in factory capacity, transportation, and site construction on a per kilowatt basis. This latter observation also applies to the PRISM concept.

The prospect for the three liquid metal concepts (LSPB, SAFR, and PRISM) must be viewed in the framework of national liquid metal reactor deployment strategy in addition to the NPOVS criteria.

2.11 RESEARCH AND DEVELOPMENT NEEDS IN SUPPORT OF CONSTRUCTION

Research and development (R&D) needs in support of construction can be divided into two categories: those that support nuclear plant construction in general, and those that support construction of the six concepts studied.

R&D needs in support of general nuclear plant construction include:

1. Better piping design and installation: monoplanar piping layout, three-dimensional computer-assisted design, better material for resistance against process corrosion as well as against seismic load, better welding tools, better alignment tools, more embedments.

2. Development of an improved tugger for cable pulling, use of multiplexing and fiber optics, and use of robotics in cable pulling and splicing.

3. More computer-aided design, engineering, modeling, management, and record keeping. What software is the most useful? How can artificial intelligence be used more extensively? Are improved communications technologies available to facilitate onsite and offsite design, review, approval, and quality assurance assignments?

4. Effects of the use of more modularization and prefabrication. What are the quantifiable advantages and benefits of modularity and shop fabrication? What is required to enable shop fabrication of the reactor assembly to reduce significantly plant construction time and cost?

5. More and better temporary facilities at the site including better lighting and worker accommodations.

6. Better methods for training and motivating workers.

7. More exhaustive preplanning, prelicensing, preengineering, use of models, and simulation.

8. Advantages and disadvantages of separating the work force into two parts, one for the safety grade nuclear island, one for the conventional BOP.

9. The relationship between commodity requirements, safety requirements, schedule, and cost. In terms of labor productivity, cost and scheduling, how significant is the spillover to the BOP of nuclear safety procedures, requirements, and quality assurance.

10. The effect of the labor-management approach. How important for increased productivity are labor-management relations and dedicated labor forces versus contracted or unionized labor forces?

11. Effects of organization and management style on the construction process.

12. Effects of limiting the number of workers on site at a given time on construction efficiency and productivity. What trade-offs are there at construction sites by spreading out activities, thus easing congestion and dispersing project functions?

13. Impact of the learning or experience curve on the efficiency of construction programs.

We also identify the following construction R&D needs for the six concepts under study:

1. Extensive studies of equipment location and piping layout to insure adequate space allocation for construction and maintenance needs including some remote surveillance and maintenance operations.

2. Methods for building, concrete pouring and curing, and quality assurance for the massive PCPV of the PIUS. Foundations structure and seismic effects on the PCPV should also be better known.

3. Development of installation and maintenance methods for MHTR vessel, refueling machine, and fuel element loading and recirculation conduits and couplings.

4. Mechanics and logistics of moving the SAFR, LSPB, PRISM, and MHTR vessels from the factory to their final location.

5. Impact of seismic design requirements and valve actuators of the GE Small BWR on its construction. If the reactor is placed below grade, requirements for servicing the control rod system should be defined.

2.12 SUMMARY

We have assessed the six NPOVS-selected reactor concepts from the viewpoint of constructibility. The various constructibility claims, both expressed or implied, of the concepts were first reviewed and tabulated in a logical order. Factors that were considered include availability of information supporting the claims; design complexity; standardization, modularization, and shop fabrication; construction schedule; construction management; and new management techniques and construction tools. Research and development needs in support of construction of these concepts have also been explored.

A positive factor contributing to the potential success of the concepts is that the designers include constructibility considerations from the outset. The construction goals and criteria of most concepts include (a) simplicity of structural design; (b) optimal standardization, modularization, and shop fabrication; (c) use of heavy-duty transport means to ship shop-fabricated components to the site and heavy duty cranes and/or air casters to erect heavy modules at the site; (d) use of limited size and dedicated crew to increase field productivity; (e) limiting of safety-grade construction to the nuclear island and separation of BOP construction; (f) short construction schedule; and (g) effective project management.

There are several design features that would facilitate achieving the above goals. Most concepts have built-in passive safety systems to cool the reactor core for several hours before additional remedial measures must be called upon. Because of these passive safety features, many concepts are able to reduce the number of systems and structures from that necessary in current LWRs. The ability to reduce the number of safety systems and components and to confine them to the nuclear island would permit savings in construction material, construction requirements, construction schedule, and quality assurance requirements.

On the other hand, additional data are needed to substantiate the claim that the concepts studied could be constructed more easily, faster, and cheaper than current LWRs because of the higher projected degree of standardization, modularization, and shop fabrication. These meritorious cost-cutting, productivity- and quality-increasing techniques are more dependent on the assurance of a large order than on specific reactor concepts. Such a large order for reactors without customized demands would allow any concept, including LWRs, to be standardized, modularized, extensively shop fabricated, and built in a period of less than five years. The number of units to be manufactured for a given addition of power is inversely proportional to the size of the units; hence, it is more likely that the initial cost for factory automation can be justified for many small units than for a few large reactors. However, there may be some drawbacks in the constructibility of the concepts studied vis-à-vis large reactors: the commodity requirements per kilowatt (electrical) of most of the concepts are higher; the steel vessels of the MHTR, SAFR, and PRISM are as large as those of LWRs, which have up to 10 times the power rating; and the concepts may have to undergo several improvements before standardization and modularization will bring any real benefits.

From the management viewpoint, we conclude that there is little in the designs except for size that makes a difference in comparison to managing an LWR project. The sequential construction of smaller units will make the job more flowing and productive, but this approach is not the exclusive characteristic of the concepts studied. However, the passive safety features of the concepts and the proposed separation of the nuclear island and BOP construction are expected to help.

We recommend that more attention be given to substantiating the constructibility claims, particularly in comparison to current LWR technology in the U.S. and overseas.

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3. ECONOMICS

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3.1 INTRODUCTION

The goal of the economics effort is to gain an insight into the factors which are important to the economic competitiveness of the various NPOVS concepts. It is not intended to rank one concept relative to the others. The objective is instead to provide a perspective on the economics of the various concepts using traditional methods and to form the basis for future efforts when more is known about the costs of each concept. The economic evaluation is essentially divided into three parts. First, each of the concepts for which information is available is compared as to capital investment costs, bus-bar power generation costs, and commodity requirements. Second, factors are discussed which affect the comparative economics and may temper the results of the bus-bar analysis. Finally, information and research and development (R&D) needs are discussed which can improve understanding of the economics of the concepts.

The analyses are discussed in Section 3.2. These include capital investment costs, bus-bar power generation costs, and commodities necessary to build the plants. These analyses use basic cost and commodity information provided by the concept proponents. The available information on the study concepts is at various stages of development, and for some concepts the needed information was not available. No effort was made to judge any of the proponents' cost data as to accuracy or to develop cost data not provided. However, various independent evaluations are under way by others, and these may result in changes to the proponents' cost estimates.

The power generation cost comparisons in Section 3.2 use traditional bus-bar cost calculations. However, the use of bus-bar cost economic evaluations, though simple, can be misleading. Financial and economic power system evaluations should ultimately be performed. These evaluations should account for the effects and uncertainty of load growth, unit availability, system reserve requirements, financial parameters, construction time, capital investment costs, operating costs, and the interdependence of these parameters.

Generic issues germane to the economic attractiveness of small modular plants relative to large plants are discussed in Sections 3.3-3.8. Availability and reliability of small vs large plants and the economic benefit of increasing plant availability are discussed in Section 3.3.

Sections 3.4 (Shop Fabrication), 3.6 (Modular Construction and Size Scaling), and 3.7 (Plant Standardization) are interrelated issues. The advantages and disadvantages of constructing plant modules in a shop environment and then shipping them to the site for final assembly are discussed in Section 3.4. Modularity as it pertains to adding power generation capacity in small increments (modules) and the effects of size scaling are discussed in Section 3.6. The potential benefits of standardization and learning are discussed in Section 3.7.

The economic issues involved in the separation of the nuclear island from the balance of plant (BOP) and an estimate of potential savings are discussed in Section 3.5.

Fuel cycle considerations as they impact the various concepts are discussed in Section 3.8.

Finally, information and R&D needs are discussed in Section 3.9. This section discusses the further studies and analyses that will be needed to properly evaluate the economic competitiveness of the concepts relative to current Light Water Reactor (LWR) technology and to coal-fired power plants.

3.2 ECONOMIC EVALUATION

An economic evaluation was made for the various concepts as to total capitalized costs, power generation costs, and commodities used in construction. Cost information of sufficient detail was not available for the PIUS and small BWR reactors, so these were not included. The capital investment cost estimates shown in Figure 3.1 are total capitalized costs in 1985 dollars and include owners' cost, contingency allowance, and interest during construction. The reference coal-fired plant, median and best experience LWR plants, and LSPB plant overnight investment costs are based on reference cost models developed by United Engineers and Constructors for the Energy Economic Data Base (EEDB),[1] Phase VII. The LSPB plant costs in the EEDB are for a replicate (second of a kind) plant and were reduced by 11% to approximate n^{th} of a kind plant costs. The "median" experience LWR plant costs are typical of the average cost of building a nuclear plant today while the "best" experience LWR plant costs are based on the best of current experience and reflect the potential effects of proposed improved construction practices and nuclear regulatory and licensing reforms. The coal-fired plant costs are typical of current experience for plants burning pulverized coal and equipped with flue gas scrubbers for sulfur removal conforming to current standards for new plants. A 0.5 scaling factor (total cost) was used for the LWRs, and a 0.6 scaling factor was used for coal-fired plants to extrapolate to plant sizes other than the reference size.

The capital investment costs for the modular plants (PRISM, SAFR, and MHTR) are based on information supplied by the proponents. The modular plant cost estimates generally fall in a range between coal-fired plants and the best current experience LWRs. There are uncertainties in the scale factor, especially extrapolating over such a large size range so that the exact cost relationship between small LWRs and the modular concepts is not well-defined. A discussion of cost-size scaling is included in Section 3.6.

A comparison of the estimated total power generation costs for the concepts is shown in Figure 3.2. Consistent methodology and financial and economic parameters were used in the analyses. The methodology used to obtain capitalized costs and to estimate the power generation costs is given in the Nuclear Energy Cost Data Base (NECDB).[2] The method uses year-by-year revenue requirements calculations and levelization techniques to establish a single equivalent cost of power over the life of the plant. Financial and economic parameters used are given in Table 3.1. The nonfuel operation and maintenance (O&M) cost estimates for LWRs, LSPB, and coal-fired plants were based on the consistent procedures given in the OMCOST[3] computer program. The O&M costs for the modular concepts (PRISM, SAFR, and MHTGR) were obtained from estimates by the proponents. Levelized nuclear fuel cycle costs were calculated using procedures recommended in the REFCO-83 fuel cycle cost computer program.[4] Although

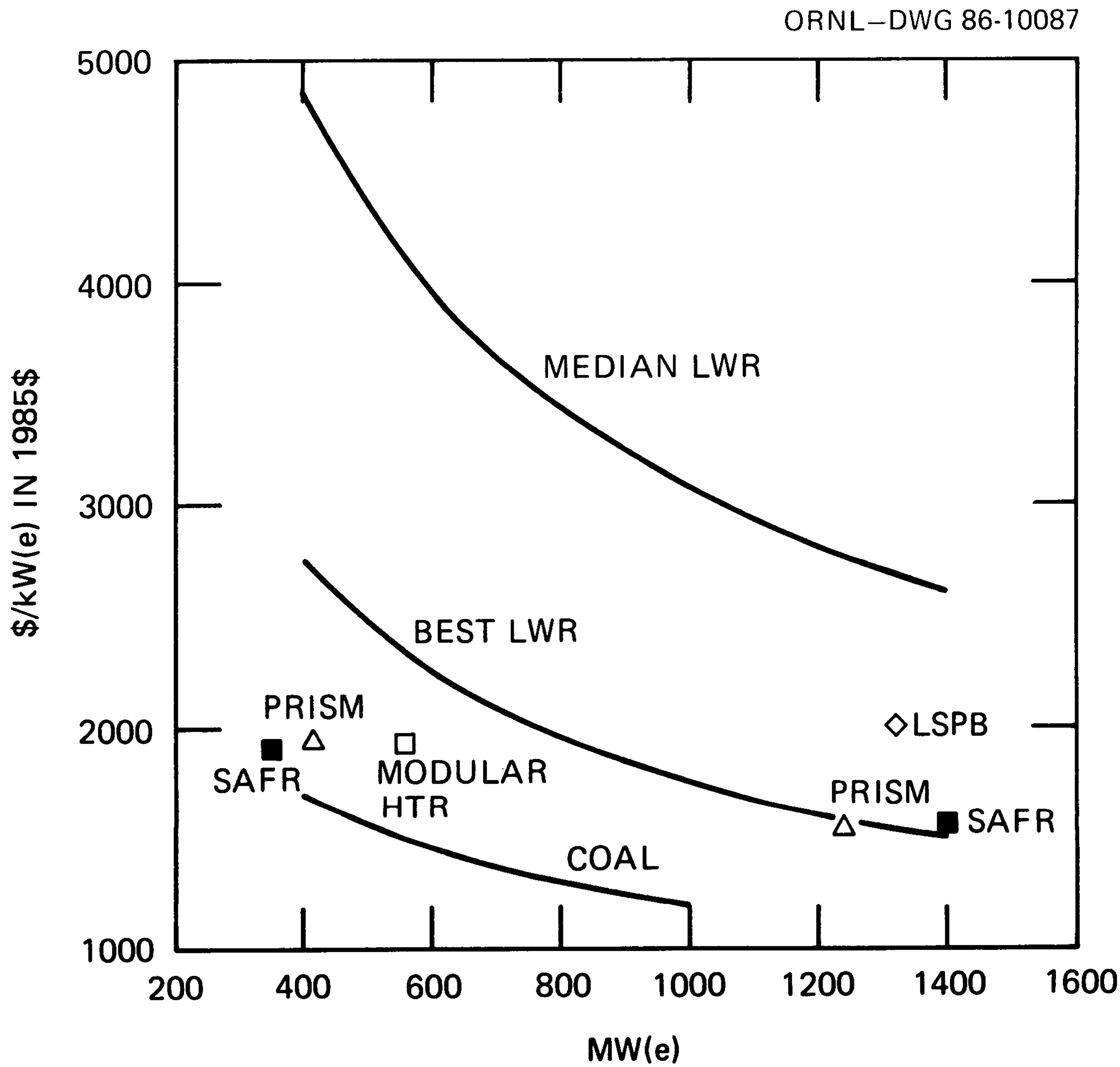

Fig. 3.1. Capital investment costs. (SAFR, PRISM, and the MHTR increase capacity by incremental additions of blocks.)

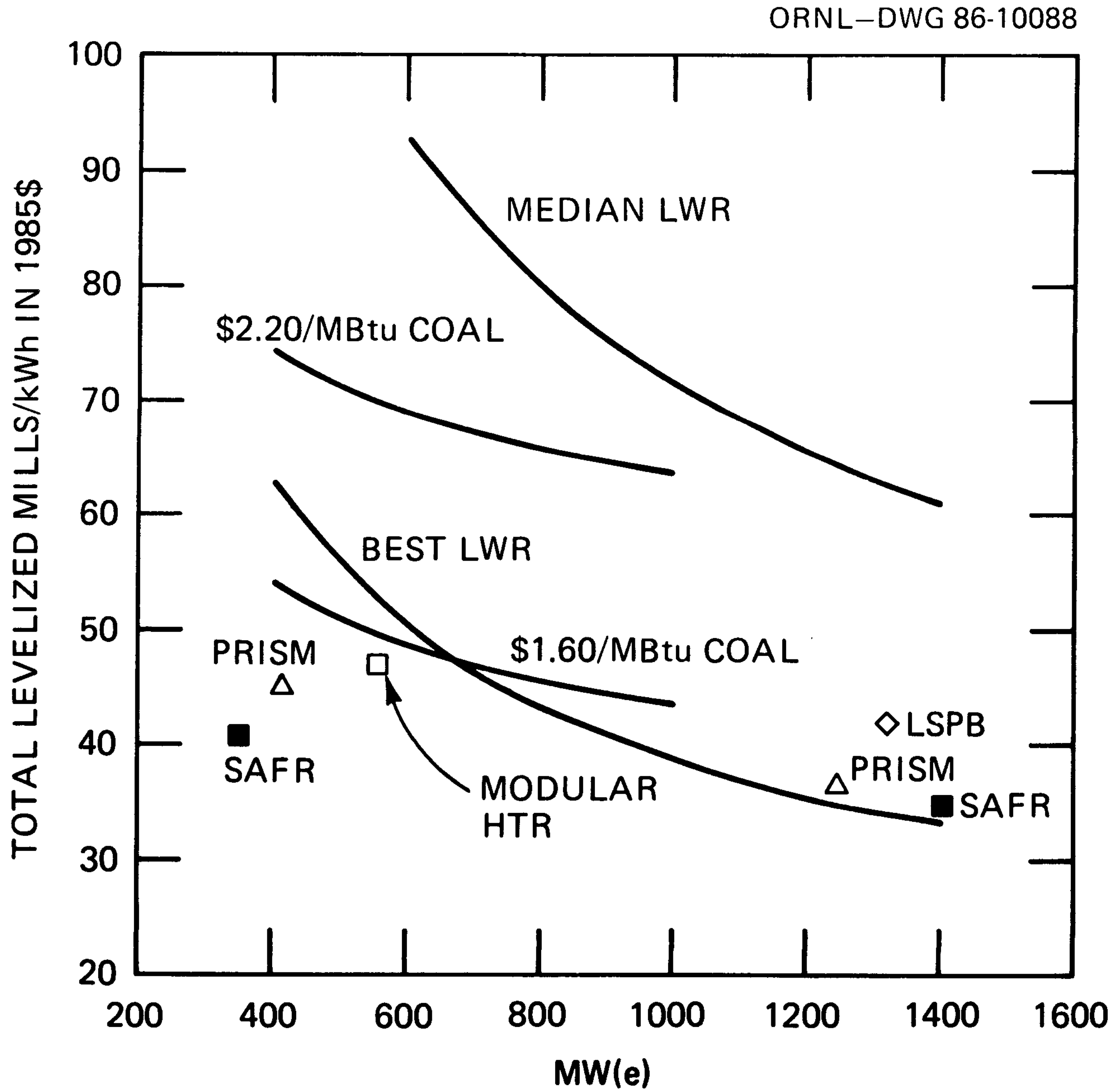

Fig. 3.2. Power generation costs. (SAFR, PRISM, and the MHTR increase capacity by incremental additions of blocks.)

Table 3.1. Economic and financial parameters

Plant economic life, years	30
Reference year	1985
Plant startup year	2005
Capacity factor, %	80[a]
Inflation rate, %/year	5
Real escalation rate for construction, %/year	0
Nominal cost of money, %/year	11.4
Real cost of money, %/year	6.0
Nominal after tax cost of money, %/year	9.0
Real after tax cost of money, %/year	3.8
Levelized fixed charge rate, %/year	
Nominal cost of money	17
Real cost of money	10

[a]65% for median experience LWR.

the cycle-by-cycle mass charge and discharge data are based on vendor supplied information, the nuclear fuel component cost parameters were estimated using the NECDB costs and methodology. This information is shown in Table 3.2.

The LWR and MHTR costs are based on once-through fuel cycles, whereas the LSPB, SAFR, and PRISM costs are based on recycle. To maintain consistency among concepts, the results shown in Figure 3.2 assume that all fuel fabrication and reprocessing are performed in large centrally located plants. The proponents of the SAFR and PRISM concepts, however, included an integral fuel recycle (IFR) facility in their studies. If SAFR and PRISM fuel costs were based on an IFR, the results for oxide fuels would be 2-3 mills/kWh higher for the full-size plants and 10-15 mills/kWh higher for the single-block plants, assuming that the IFR is supported by a single block.

As stated previously, it is not the intent of the NPOVS economic evaluation to rank one concept relative to the other. We must emphasize that the cost information now available on the concepts is not adequate to effect such a ranking. The bus-bar cost analysis, however, can give perspective on whether these concepts have the potential to be economic compared to alternatives. The costs are based on an 80% plant capacity factor for all systems except the business as usual median LWR for which a 65% capacity factor is assumed. Plant availability may be higher for small-sized plants than for large plants and is discussed in Section 3.3.

The power generation costs for the full-sized plant advanced concepts fall in a range enclosed by the best of current LWR construction cost experience and coal-fired plants burning coal at \$1.60/MBtu (\$1.52/GJ) and 1% per year real escalation rate. The estimated power generation costs for single-block nuclear plant concepts fall below both the coal-fired costs and the extrapolated best experience costs for LWRs. There are, however, large uncertainties in the basic cost information for all of the concepts, along with uncertainties in the costs for LWRs and coal-fired plants. The basic cost data for the advanced concepts in the analysis was preliminary vendor-supplied information. The relative economics of the concepts will most likely change as more detailed design and cost studies are made. No attempt has been made to critique the level of optimism in vendor-supplied information. In addition, it must be recognized that considerable research and development is in progress to reduce the costs of future coal-fired plants. Studies sponsored by EPRI indicate that advanced coal-fired plants may have bus-bar generation costs 1-5 mills/kWh lower than conventional pulverized coal-fired plants.[5]

A comparison of the labor and materials used in construction of the various systems is shown in Table 3.3. Here, as was the case for the capital cost and power generation cost, information is preliminary and was not available for all of the plants studied.

3.3 AVAILABILITY AND RELIABILITY

The proponents of the modular reactor concepts claim that small units will have higher availability than today's large size plants. This is both because there is a smaller probability of all units in a multiple small unit plant being down as opposed to one large unit of the same total capacity being off-line and because, historically, smaller units have had a lower forced outage rate than large units. In addition, the small modular passively-safe reactors should be less complex than large units, leading to fewer equipment outages.

Table 3.2. Fuel cost parameters

	Reference (1985 $)	Real escalation (%/year)
U_3O_8, $/lb	34	1.2
Thorium, $/kg	35	0
Plutonium, $/g	25	0
Enrichment, $/SWU	60[a]	0
Conversion, $/kg U	8	0
Fabrication		
MHTR, $/block ($/kg)	9400 (1680)[b]	0
Current LWR, $/kg	220	0
Extended burnup LWR, $/kg	240	0
LMR core assemblies, $/kg	2300	0
LMR blanket assemblies, $/kg	300	0
Reprocessing, $/kg		
LMR fuel	650	0
Nuclear waste disposal, mills/kWh	1	0
Coal price, $/MBtu		
Low	1.60	1
High	2.20	2

[a]Average cost after 2005.

[b]Based on equilibrium reload.

Table 3.3. Commodity and labor requirements for selected nuclear and coal-fired generating stations

Concept	MW(e)	Structural concrete		Reinforcing steel		Structural steel	
		yd^3	yd^3/kW(e)	Short ton	Short ton/kW(e)	Short ton	Short ton/kW(e)
Median LWR	1 x 1399	172,000	0.151	27,000	0.024	11,000	0.010
Best LWR	1 x 1139	141,000	0.125	21,000	0.018	7,000	0.006
PRISM	3 x 415[a]	131,000	0.105	12,900	0.010	6,100	0.005
SAFR	4 x 350	160,000	0.114	[b]	[b]	9,300	0.007
LSPB	1 x 1319	125,000	0.095	22,000	0.017	16,200	0.012
Pulverized coal	1 x 486	63,000	0.130	4,200	0.009	14,400	0.030
Pulverized coal	1 x 791	88,000	0.111	5,900	0.007	18,100	0.023

Concept	MW(e)	Piping		Wire and cable		Craft labor	
		lb	lb/kW(e)	lin ft	lin ft/kW(e)	h	h/kW(e)
Median LWR	1 x 1399	18,070,000	15.9	6,275,000	5.5	29,802,000	26.2
Best LMR	1 x 1139	14,530,000	12.8	5,394,000	4.7	16,838,000	14.8
PRISM	3 x 415[a]	9,612,000	7.7	2,554,000	2.1	11,700,000	9.4
SAFR	4 x 350	[b]	[b]	5,800,000	4.1	14,000,000	10.0
LSPB	1 x 1319	[b]	[b]	5,671,000	4.3	20,545,000	15.6
Pulverized coal	1 x 486	4,011,000	8.3	2,660,000	5.5	6,717,000	13.8
Pulverized coal	1 x 791	5,262,000	6.7	3,105,000	3.9	8,530,000	10.8

[a]Three reactors and one turbine-generator unit for each unit.

[b]Not available.

The North American Electric Reliability Council (NERC) Equipment Availability Report[6] for the 10-year period, 1974-1983, supports the claim that smaller turbine generators contribute to higher overall plant availability. As shown in Table 3.4, fossil-fired plant turbine-generator sets in 400 MW(e) and below sizes have distinctly lower forced and scheduled outage rates and higher availabilities than turbine-generator sets in the larger sizes. The advantage is even more significant for nuclear plant turbine-generator sets below 800 MW(e) size, when compared with those above 800 MW(e). It also is observed that nuclear plant turbine-generator sets have a distinct performance advantage over fossil-fired plant sets in most size ranges. We speculate that this may be due to the lower steam temperatures and pressures and slower rotational speeds of nuclear turbine-generator sets, which result in a less severe operating environment.

As shown in Table 3.5, the area having the greatest potential for improving LWR plant availability is with the reactor and associated systems. It is obvious that R&D for plant availability improvement must concentrate on the reactor and its related systems. A postulated 50% reduction in reactor scheduled outage factor plus a 50% reduction in reactor forced outage rate would result in 80% overall plant equivalent availability. Since the data in Table 3.4 show that equivalent availability of turbine-generator sets decreases as plant size increases, it provides support to a premise that small modular reactors will have a higher availability than large size plants.

There is an economic benefit for baseload plants with higher availability and a concomitant higher capacity factor. Whereas availability measures the fraction of time that a plant is able to produce power (see Table 3.4 for definition), the capacity factor is the ratio of energy actually produced to that which could be produced if the plant were operating 100% of the time at full power. The magnitude of the benefit depends on the situation of the utility. Factors affecting the benefits include the existing generation mix and size of the system.

If the choice is between two alternative plants with the same capacity (size) but different availabilities, one can most likely afford to pay more for the one with the higher availability. Higher availability increases the electric system reliability, and the time at which the next increment of capacity is needed will be delayed. The higher availability plant will have a higher capacity factor, therefore producing more energy which can be used to displace production from plants with higher variable operating costs. Based on the LWR displacing oil at $4.20/MBTU ($3.98/GJ), one could afford to pay about $30/kW(e) more in 1985 dollar overnight costs for each percentage point superiority in capacity factor.

Another and perhaps more likely scenario is that the utility will choose the size of alternative plants to maintain the system reliability at a prescribed level. The analysis of such a choice involves detailed utility system studies which were not a part of NPOVS. However, some economic observations can be made. Multiple smaller sized plants have a higher load carrying ability than single larger sized plants (same total capacity) when both plant types have the same equivalent availability. This is because of the smaller probability of losing all generation from the multiple plants compared to the one large plant. Less reserve capacity is required on-peak to compensate for the unexpected loss of a small unit compared with a large unit. Therefore, less total capacity is needed with multiple small plants than with one large plant. For instance, if the on-peak availability of the large plant were 65% and that for the small plant were 80%, the total capacity needed for the small plants would be 65/80 = 0.81 that of the large plant, and the utility could afford to pay 23% more [$/kW(e)] for the small plants than for the large plant.

Table 3.4. Turbine-generator set performance data for 1974-1983[a]

	Equivalent forced outage rate[b] %	Scheduled outage factor[c] %	Equivalent availability[d] %
Fossil			
100-199 MW(e)	1.90	5.71	92.98
200-299 MW(e)	2.61	5.91	92.18
300-399 MW(e)	3.31	7.21	90.30
400-509 MW(e)	3.41	8.26	89.23
600-799 MW(e)	4.01	7.52	89.47
800 MW(e) and above	4.81	8.38	88.54
Nuclear			
1-399 MW(e)	1.11	3.66	95.59
400-799 MW(e)	2.23	4.61	94.30
800 MW(e) and above	3.91	6.39	90.52

[a]Source: Ref. 6.

[b]Equivalent forced outage rate =

$$\frac{\text{(forced outage hours) - (equivalent unplanned derated hours)}}{\text{(forced outage hours) + (service hours)}} \times 100\%$$

$$\text{forced outage rate} = \frac{\text{(forced outage hours)}}{\text{(forced outage hours) + (service hours)}} \times 100\%$$

[c]Scheduled outage factor $= \frac{\text{(scheduled outage hours)}}{\text{(period hours)}} \times 100\%$

[d]Equivalent availability =

$$\frac{\text{(available hours)} \quad \text{(equivalent unplanned derated hours)} \quad \text{(equivalent planned derated hours)}}{\text{(period hours)}} \times 100\%$$

Availability $= \frac{\text{(available hours)}}{\text{(period hours)}} \times 100\%$

Equivalent derated hours =

$$\text{(derated hours)} \times \frac{\text{size of reduction}}{\text{maximum dependable capacity}}$$

Table 3.5. Nuclear plant performance data for 1974-1983[a]

	Equivalent forced outage rate %	Scheduled outage factor %	Equivalent availability %
Reactor	10.00	18.17	73.92
Turbine-generator	3.11	5.60	92.14
Condenser	1.06	1.70	97.47
Balance of plant	3.12	2.31	95.22
Regulatory	2.09	1.41	97.05
Total plant	17.68	21.05	65.25

[a]Source: Ref. 6.

3.4 SHOP FABRICATION

Plant modularization, standardization, and shop fabrication are all interrelated. The economics of constructing plant modules (subassemblies) in a factory environment and shipping these modules to the plant site for final plant assembly is discussed in this section. The economics of plant standardization are discussed in Section 3.7.

The economic benefits of shop fabrication can be traced principally to the use of factory labor as opposed to field construction labor.[7] Factory labor hourly earnings rates are usually less than field labor rates. Since the factory is a more controlled environment, management problems are reduced and productivity is greater than that for site fabrication. Better quality control can also be maintained as caused in part by the smaller turnover of skilled labor in a factory environment as compared with the field where labor must move between sites. Standardization is a necessity for the economics of factory fabrication to be achieved. Repetitive operations lead to reduced cost.

Factory construction of plant modules has been used to a limited extent for nuclear plants for many years. Increased modularization can reduce costs in all size nuclear units. A DOE task force study[7] estimates a 12% savings in an n^{th} of a kind modular LWR plant compared to conventional construction. Small plants may offer more savings than large plants. Smaller unit sizes [in MW(e)] are physically smaller than larger unit sizes. Therefore, larger percentages of the plants may be factory-built in individual modules. The limit, of course, is to build the entire power plant at a factory and ship it to the site as a single module for final installation. There is also a greater automation potential for construction of smaller units since a greater number of the smaller units will be needed than large units for a given total capacity. Although initial manufacturing costs may be higher, automation will produce cost savings through reduced labor requirements.

There are, of course, some additional costs connected with factory fabrication which are not present with field construction. The costs of acquiring the factory site and buildings and of tooling-up the factory need to be included. This is front-end money not required for site construction. The costs will be written off with interest over the number of units expected to be built.

One of the advantages often quoted for small plants is a shorter construction lead time (see Section 3.6). However, the preconstruction lead time may have to be extended to accommodate ordering of long lead time materials and factory fabrication of the reactor module. Since factory fabricated components represent a larger fraction of the total plant costs for modular plants than for conventional construction, there may be a heavier weighting of costs in the early preconstruction period than in current practice. Even if the owner does not pay for the module until it is received, the financing costs of the fabrication of the module will be included as an additional charge.

The cost of transporting large reactor modules to the construction site and installing them at the plant also needs to be considered. Barge transportation is usually most economical for large modules if it is available.

For the factory construction of the module and site interconnection to other modules to be achieved, the plant design and engineering must be virtually complete before manufacturing is started. A careful analysis of the cash flow requirements of the total operation is needed. This should include front-end costs of building the factory, finalizing a reproducible design, and putting together the modules at site for production runs from the first to n^{th} of a kind unit.

3.5 SAFETY SEPARATION OF NUCLEAR ISLAND AND BOP

It has been postulated that systems outside of the nuclear island can be procured and installed to non-nuclear standards resulting in an overall savings in capital investment costs. The principal factor cited is that labor productivity for the non-nuclear portions of LWR plants is much less than for coal-fired plants. The reasons given are as follows:

- Nuclear quality standards affect the attitudes of all persons working on the entire project (management, engineering, and crafts).
- Bulk materials for the entire project, such as rebar, anchor bolts, embedments, small bore piping, and concrete, are procured and handled as required by a nuclear quality assurance program to eliminate the danger of degrading the quality of safety-related structures and systems by inadvertent substitution.
- Non-safety structures adjoining safety-related structures are designed to prevent collapse in the event of a design basis earthquake or tornado.
- Management and supervision are preoccupied with problems associated with safety-related facilities and often neglect planning for non-safety facilities.

Bechtel addressed these problems in a 1982 report[8] by proposing to provide physical separation both between the nuclear and non-nuclear facilities and between the construction forces so that the low productivity experienced in nuclear construction is not transferred to the non-nuclear areas.

The EEDB cost estimates developed by United Engineers and Constructors indicate that large nuclear plants currently require about 25-30 man hours/kW(e) of construction labor compared with about 12 manhours/kW(e) for large coal-fired plants. It is argued that one of the reasons for the higher labor content of nuclear plants is that the materials' placement rates and the quality control practices required of nuclear safety-grade systems tend to carry over into the non-nuclear BOP.[8,9] For example, concrete placement labor (expressed in manhours/yd^3 of concrete) for turbine pedestals are two to three times higher for nuclear power plants compared with coal-fired plants.

A cursory analysis of the EEDB cost estimate for the 1139 MW(e) PWR plant indicates total construction labor amounts to approximately \$600 x 10^6 in January 1985 overnight costs. Of this amount, \$200 x 10^6 is for the construction of nuclear safety-grade systems and structures, and the remaining \$400 x 10^6 is for the construction of the non-nuclear BOP systems and structures that are similar and in many cases identical to those in coal-fired plants.

If coal-fired plant placement rates are applied to the non-nuclear balance of plant, it is conservatively estimated that construction labor costs could be reduced by approximately

$200 x 10^6, which translates to a reduction of almost 10% in total plant capital investment cost. There will be additional savings of indirect costs due to reduced labor content and shorter construction time.

There are also reasons why these savings may not be fully realizable:

- Dispersion of plant facilities with longer runs for piping and wiring and cables.
- Redundant construction management and construction facilities.

The question of separation of facilities to achieve increased labor productivity is discussed further in Chapter 2, Construction.

3.6 MODULAR CONSTRUCTION AND COST-SIZE SCALING

Small modular plants have several economic advantages when compared to large plants. Modular here is defined as units which can be added to generating systems in small increments. This definition of modular relates to system effects and is different than the definition of modular given in Section 3.4. The advantages of small modular plants have been widely discussed in the literature.[10-16] The benefits of modularity are utility system dependent and can vary depending upon utility size, existing generation mix, financial status, electric demand growth, etc. Some advantages of small plants include: a better match to electric load growth, thereby decreasing overcapacity; shorter lead times for small plants than for large; better system reliability for given capacity (see Section 3.3); and better accommodation of demand uncertainties. There is also less financial risk leading to a decrease in the overall cost of money since there is less construction work in progress. The magnitude of the investment entering rate base at any given time is less; thus, the magnitude of rate increases is reduced, improving the chance of recovering the full cost of construction. The smoothing out of costs over time reduces the sharp swings in the need to raise new capital for construction with a concomitant reduction in the cost of capital.

The principal advantage for the large plant is the economy of scale. In terms of unit overnight construction costs [$/KW(e)], it is theoretically cheaper to build a large plant than a small plant. The total cost of building a plant of a different size may be approximated by the traditional scaling relation.

$$\text{Cost}_{\text{new}} = \text{Cost}_{\text{base}} \left(\frac{\text{MW(e)}_{\text{new}}}{\text{MW(e)}_{\text{base}}} \right)^{a}$$

There are uncertainties, however, as to the correct value of the scaling exponent, a. The overall scaling exponent on overnight costs for nuclear power plants has been found to range generally from 0.4 to 0.6 (Ref. 17), based on design studies. The exponent has been found to generally increase with plant size. Statistical studies, based on nuclear plants already built or nearing completion suggest higher scaling exponents (less economy of scale).[18]. However, this may be due in part to differences in plant lead times.[19]

Studies of introducing small modular plants as opposed to large plants into a utility system indicate that one can afford to pay more [in terms of $/kW(e)] for the small size plant than for the large plant. The reasons for this were given earlier in this section. An analysis done for EPRI[11] by Applied Decision Analysis, Inc. (ADA) compared one

500 MW(e) coal-fired plant with a 4-year lead time versus four 125 MW(e) plants with 2-year lead times. The study indicated that the utility could pay 24% more in overnight costs for the 125 MW(e) units than for the 500 MW(e) unit with no increase in average rates to the consumer. This estimated cost differential rose to 50% when viewed only from the stockholders' interests.

Another study by Los Alamos National Laboratory[12] (LANL) analyzed only the financial effect on the utility and estimated how much more a utility might be willing to pay for shorter lead time plants based on various criteria of utility financial health. The criteria included a pre-tax interest coverage ratio greater than 3.0, a fraction of earnings due to the Allowance for Funds Used During Construction (AFUDC) under 20%, an internal generation of funds greater than 40%, and a common stock market price in excess of book value. LANL made the study for a specific western utility and repeated the analysis for a generic utility with coal-fired capacity. The results are similar to those of the ADA study. LANL concluded that shorter lead time units are more attractive to utilities and that utilities could pay up to 4 times as much for a 5-year lead time than for a 15-year lead time unit. The ratio was 1.5 for a 10-year lead time unit.

Utility system and financial studies are needed to properly assess the economics of large vs small plant addition strategies. A simplified calculation to demonstrate the effect of lead time and cost of money differences is shown in Table 3.6. This table demonstrates that the utility can afford to pay about 12% more in overnight costs for a 4-year lead time plant as compared to an 8-year lead time plant if the AFUDC rate for each plant is 9% (6% inflation rate). The AFUDC fraction of the total cost is less for the 4-year span resulting in a slightly lower fixed charge rate. In all cases, the levelized revenue is held constant so the average cost to the consumer is constant.

Longer lead time plants have a higher investment risk; therefore, the cost of money for these plants may be higher. The final column in Table 3.6 shows the costs for an 8-year lead time plant with a 10% cost of money (one percentage point increase over 4-year lead time). For a constant levelized revenue, the utility could afford to pay 26% more for the 4-year lead time than for the 8-year lead time. The higher money costs are embedded into utility capital so that the fixed charge rate is higher with higher money costs.

Small units can be built in less time than large units. In addition to the advantages shown in the previous example, these smaller plants should increase system reliability, may indeed have higher availability, and should reduce average system reserve margins; each of these effects can provide further savings for the small plant relative to the large.

3.7 PLANT STANDARDIZATION

Standardization is an important factor in determining the competitiveness of nuclear plants, particularly for small units. Standardization means that each subsequent unit will be essentially the same as previous units. There are definite economic benefits to standardization. The principal advantage is that the design and engineering costs, although they may be higher initially, are spread over a large number of units. A second advantage is that learning takes place from one unit to another, the craft labor requirements can be reduced and the overall lead time decreased. Since each design is assumed to be prelicensed, the licensing time for each individual follow-on unit should decrease. Since the units are not one of a kind as they essentially are now, there should be a greater potential for shop fabrication and lower unit equipment costs through larger production

Table 3.6. Allowable capital investment costs for equal revenue requirements[a]

Lead time, years	4	8	8
AFUDC[b] rate,%	9	9	10
Cost breakdown, $/kW(e)			
Overnight, 1985 $	1,670	1,500	1,322
Escalation:			
To order date	2,573	1,518	1,338
After order date	517	819	721
AFUDC[b]	922	1,522	1,548
Total (2005 startup)	5,682	5,388	4,929
Fixed charge rate, per year	0.160	0.168	0.184
Levelized revenue, $/kW(e)-year	907	907	907

[a]For variations in lead times and AFUDC[b] rates.

[b]Allowance for funds used during construction.

runs. It should be noted, however, that some of these benefits also apply to standardized, large conventional nuclear plants (for example, the French series and German convoy approaches).

There are costs and potential problems associated with plant standardization. There are potentially large up-front infra-structure costs associated with new reactor concepts and expenses in developing the reference design and obtaining its generic license. There is also the potential economic disaster of a design defect being found after many plants are operating, causing the shutdown of a large part of a utility's (or the national) electric production capacity. Another disadvantage is that standardization may act to deter innovation, particularly that needing a large step change in technology to obtain a longer term economic benefit. It should not deter small evolutionary changes in design as long as these changes have a benefit-cost ratio greater than unity.

A learning factor is sometimes defined as the cost reduction each time the total number of units doubles. For instance, if the learning factor is 0.1 and first unit cost \$1000 million, then the second would cost \$900 million and the fourth \$810 million, etc. The equation for this is given by

$$\text{Cost}_N = \text{Cost}_1(N^A)$$

where

A	=	ln (1-LF)/ln 2
LF	=	learning factor
N	=	unit number in series
ln	=	natural logarithm

As shown in Figure 3.3, standardization may offer economic benefits through reduced costs for subsequent units but does not necessarily favor small plants over large. Here a large plant is compared with a small plant, one-quarter of its size, so that four small units have the same capacity as the single large unit. For the purposes of this example, the small plant is assumed to have a 0.1 learning factor. Learning factors of 0.0, 0.05, and 0.1 are assumed for the large size plant. An LF of 0.0 means no learning between subsequent units. The learning factor for small units should be greater than that for large units if automated factory production of the small units is achieved. The relative cost of the last unit put in place is plotted as a function of total capacity in place. If both the large and small units have the same learning factor (0.1), then the cost plot lines are parallel, and no relative economic benefit from learning is achieved past the introduction of the fourth small unit. (At this point total, the capacity of four small units equals one large unit.)

If there is no learning for the large size unit and the first small unit costs twice as much to build [\$/kW(e)] as the large unit as would be indicated by a 0.5 cost-size scaling factor (see Section 3.6), then approximately 90 small units would have to be built before the cost of the subsequent units would be equal to or less than that of the large unit. However, as explained earlier, the overnight costs of the small units can be greater than those of the large and still be of net benefit to the rate payer and utility stockholder. If, for instance, a utility system and financial analysis were to show that the utility could afford to pay 1.5 times as much in overnight cost for the small plant as for the large, then only six small units would have to be built in the above example (where the first-of-a-kind small plant costs are twice LWR plant costs) before subsequent small units would be directly competitive.

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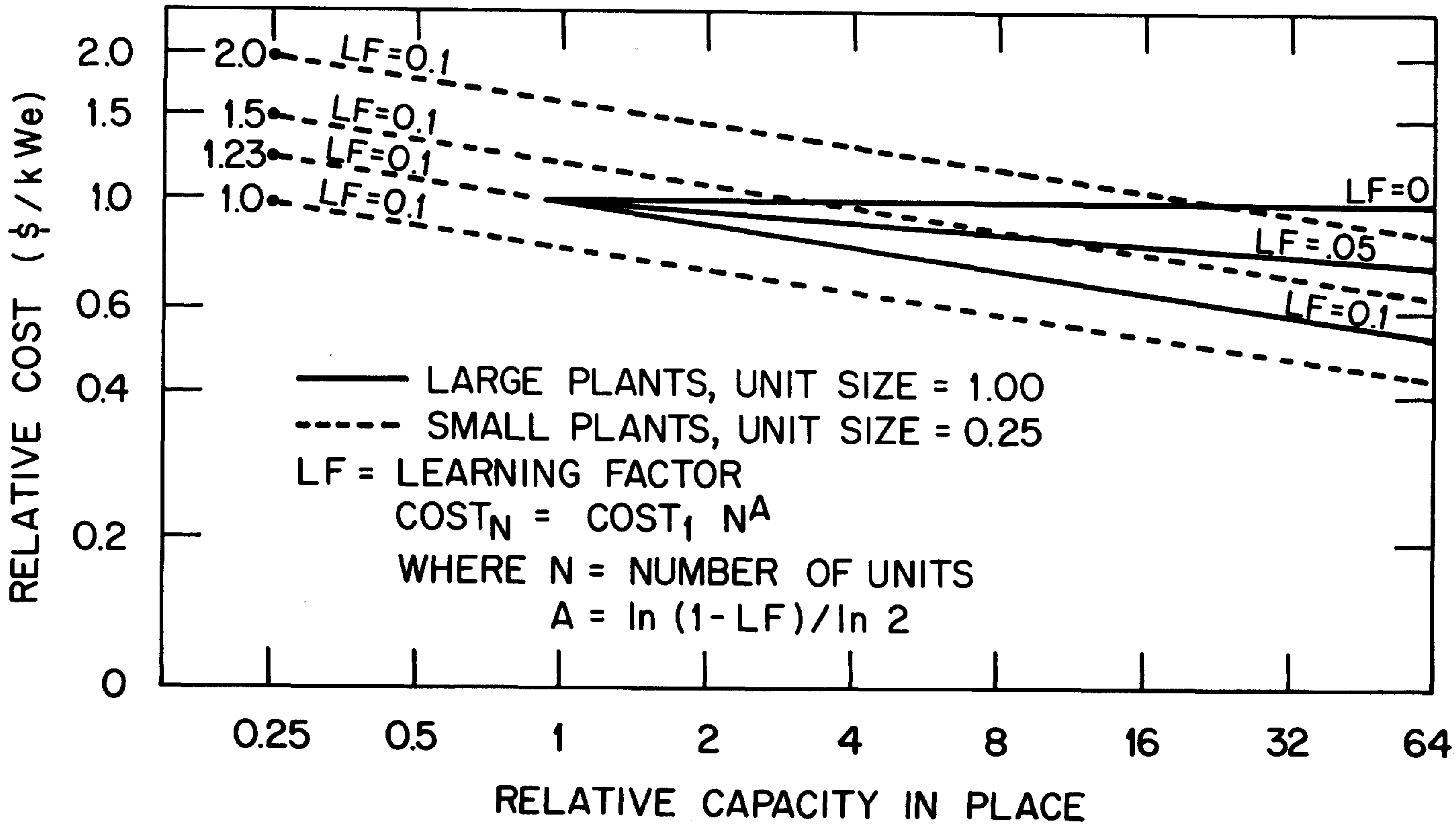

Figure 3.3. Effect of learning on plant cost.

3.8 FUEL CYCLE

The nuclear plant fuel cycle includes all fuel related activities from the procurement of the fissile material (mining of uranium) to the disposal of the spent fuel. With the exception of spent fuel disposal, the once through fuel cycle for LWRs is in place and commercial. Spent fuel disposal is the goal of a vigorous government program and should be available by the time the study concepts are assumed to be commercialized.

The fuel cycles for the PIUS and small BWR are the same as for current LWRs and use similar fuel. Other fuel cycles will involve development and considerable capital investment to implement.

LMRs will need reprocessing facilities and mixed oxide fuel fabrication. The technology for aqueous reprocessing of mixed oxide fuels is well known and is being implemented in Europe and Japan. Costs for these plants are not well defined for U.S. experience. Also, the costs of large, centrally located plants as opposed to small, reactor-integrated plants are not well-defined. The small, integrated plants may have advantages in the recycle of partially reprocessed fuel and in the use of metallic fuels. However, their small size may cause their cost of product to be high. Small integral plants are discussed further in Appendix E of Volume II. The use of enriched uranium for LMRs is a possibility that can at least temporarily bypass the need for reprocessing and plutonium fuel fabrication. Plutonium pricing for LMR fuel is also a problem. This involves institutional as well as economic issues. Variations on tax depreciation treatment for plutonium are possible and will need resolution.

The MHTR uses a once-through fuel cycle with spent fuel from the reactor stored for long times. The technology has been demonstrated in the United States for Fort St. Vrain fuel. These are not large-scale commercial operations, however, and additional capital investment will be necessary if the MHTR is to become commercial.

There are also economic issues surrounding the cost of spent fuel and fission product waste disposal from the concepts. The waste disposal act specifies a 1 mill/kWh fee for disposal of spent fuel and high-level waste from reprocessing. Extended burnup LWR fuel or different fuels (LMR, HTR) may pose problems since the real cost of disposing of each fuel or its waste is different. In the future, based on comprehensive analyses, surcharge or credits may be implemented for the various fuels.

3.9 INFORMATION, DATA AND R&D NEEDS

There is a great deal of information needed to better assess the relative economics of the various concepts studied. A list of such information is shown in Table 3.7, not necessarily in order of importance.

Of primary importance is the development of basic cost information for the concepts. These costs need to be developed under a consistent set of ground rules for all concepts. The cost information available to NPOVS is at various stages of development based mainly on preconceptual designs. More detailed conceptual designs and capital investment cost studies need to be made. Operation and maintenance (O&M) cost estimates will require detailed manning studies, especially for some of the small modular plants; these are under way for the MHTR. A primary issue for small modular plants is whether a full operating

Table 3.7. Economic information and analysis needs for advanced concepts

- Detailed conceptual design and capital investment cost studies
- Detailed O&M cost estimates
- Refinement of fuel cycle calculations
- Maintainability, reliability, and availability studies
- Design studies for greater maintainability
- System and financial impact studies
- Economic analyses of introducing modular reactor concepts into the market
- Benefit/cost analyses of shop fabrication
- Study on value of plant standardization and impact vs plant size
- Economics of LMR startup on U-235
- Detailed conceptual design and cost estimates for integral recycle plan
- Economic analysis of starting up and phasing in reprocessing and fabrication for LMR industry
- Uncertainty analyses (probabilistic analyses)

crew will be needed for each unit or whether the multiple modular units can be operated by one integrated crew. Reactor core designs will need to be firmed up and core physics and fuel cycle mass flow information developed for each concept.

Maintainability and reliability studies, O&M costs, and plant availability are all interrelated. Since unit down time, either for routine maintenance or forced outage, is important to the plant operating costs and plant availability, detailed assessments of the maintainability and reliability of each concept are needed. Also, studies of designing plants for maintainability are needed. If one type plant is more easily maintained than another, the maintenance costs and maintenance down times become important considerations in estimating relative cost reductions. A more reliable plant will also have a smaller forced outage rate, thereby increasing availability and potential capacity factor and reducing unit energy costs.

To properly assess the economic potential of small reactors, integrated system studies and financial impact analyses are needed. System analysis provides an additional dimension to the study of the economic competitiveness of a reactor by analyzing the impact on the utility system and the utility economic viability of adding capacity of a given type and size to the utility system.

Economic analyses are needed on the introduction of modular reactor concepts into the market. The progression from first of a kind through n^{th} of a kind plant should be analyzed. The study should include infrastructure costs as well as the costs of building and operating the plants. Market analyses should also be made.

Analyses of the benefits and costs of increasing the scope of shop fabrication are needed. Experience in other industries, notably ship building and chemical process plants, indicate potential benefits, but there are also costs which should be included in a complete, overall analysis.

Plant standardization will reduce unit costs for n^{th} of kind plants although the costs for the first of the series may be higher. Standardization should be of economic value for any size of plant. The degree of learning may be different for different plant types, depending in part on factors such as amount of factory fabrication. A uniform analysis for each of the reactor design concepts is needed to assess the economic potential of plant standardization.

There are several analyses which are needed in the area of LMR fuel cycle economics. Historically, the LMR program has concentrated on fuel cycles involving reprocessing with recycle of bred plutonium. Since commercial recycle facilities are presently not available in the U.S. and the deployment of small plants needed for an early industry would be costly, the fueling of LMRs with enriched uranium needs to be considered. Economic trade-off studies are needed to compare LMRs fueled with enriched uranium and those fueled with plutonium.

Another approach to the problem of early plant fuel cycle is the use of integral reprocessing and refabrication as discussed in Appendix E of Volume II. Conceptual design cost estimates based on detailed small plant designs are needed in order to evaluate the competitiveness of integral fuel recycle facilities. Such studies are under way at Argonne National Laboratory and elsewhere.

In a more comprehensive vein, an analysis is needed of the total cost of implementing an LMR fuel cycle industry, starting from the initial prototype fuel facilities to the ultimate large-scale process plants.

In all of the economic and cost analyses, uncertainty needs to be considered explicitly. Probabilistic analyses are needed to augment the deterministic cost projections. Probabilistic analysis will help to quantify the effects of uncertainties in the basic technical and cost data on the resulting competitiveness of the reactor systems. It will help in determining the degree of economic risk of a given concept and in identifying where increased R&D effort should be placed to obtain data to reduce the economic risk.

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4. REGULATION

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4.1 SIGNIFICANCE OF LICENSING AND REGULATION TO VIABILITY

A utility's confidence in its ability to obtain a license to operate a nuclear power plant is paramount in any decision to undertake a nuclear project. A nuclear plant design option loses all or part of its economic viability as a function of the perceived or real difficulty in obtaining a license in a timely manner. The NPOVS criteria 5 and 6 recognize timely licensing as a need. This chapter addresses the issues of licensing and regulation of innovative reactor plants.

Experience has shown that the licensing process for construction and operation of a nuclear plant can be cumbersome and unpredictable. Unless the Nuclear Regulatory Commission (NRC) or the industry can significantly improve the licensing process, either jointly or independently, there probably will be no viable long-term nuclear power options. New simplified reactor designs that reduce the potential for severe accidents may minimize the regulatory burden and lead to improved perceptions of safety by the NRC, the utilities, and the general public.[1]

Sufficient improvement in licensability could be solely the result of NRC improvements in administration of licensing review since the public safety record of existing nuclear plants has been excellent. Legislative proposals have been advanced toward this goal covering one-step licensing, standard plants, preapproved sites, freedom from backfit, and simplified technical specifications. If all of these regulatory proposals were adopted and implemented by NRC, even conventional light water reactors (LWRs) might be perceived by prospective owners as having low financial risk.

Sufficient improvement in licensability also could result solely from industry improvements in design and administration of the licensing interface as demonstrated in the construction of St. Lucie 2. The industry and DOE could demonstrate a design which has simpler safety systems, slower transients, and more predictable response. The industry could standardize and could file for a one-step license, submitting applications for early site approval (ESA) and for final design approval (FDA) of the standard design and the lead plant.

Some combination of initiatives by NRC and industry to enhance licensability are more likely to occur than the independent improvements outlined in the previous paragraphs. Interaction among vendors, utilities, DOE, and NRC is necessary. However, certain licensing interactions such as preapproval of revised general design criteria (GDC) for an advanced reactor do not appear practical since the NRC cannot redefine the GDC without complete review by all applicable NRC organizations followed by rulemakings. It is incumbent upon the industry to define a combination of initiatives and to pursue methodically these initiatives in parallel or in sequence as the situation dictates. Licensing requires good planning more than it ever has in the history of nuclear power.

4.2 LICENSING ISSUES - WHAT REALLY COUNTS

4.2.1 Impact of Evolving Regulations and Backfitting: The Need for Stability

The lack of stability in the regulatory process and the extensiveness of regulatory, as well as nonregulatory, backfits to construction and to operating plants have been cited by utilities as major reasons for the decline of the nuclear option in the United States.[1] This decline may have other causes but the perceived cause may become self-fulfilling if enough of those involved believe it to be so. Therefore, until the regulatory process is reformed to provide the assurance that new plants incorporating a high degree of safety will be licensed in a stable environment, they are not likely to be ordered. The NRC must either demonstrate stability or the industry must offer a suitable product to be prelicensed and require stability as a precondition for construction.

4.2.2 Standardization

The following is quoted from the NRC's Proposed Policy for Regulation of Advanced Nuclear Power Plants:[2]

> "On standardization of the current generation of nuclear power reactors, the Commission's 1985 Policy and Planning Guidance states: The NRC recognizes that there are advantages in the development and use of standardized nuclear power plant and balance of plant designs. Such designs can benefit public health and safety by concentrating the resources of designers, engineers and vendors on particular approaches, by stimulating standardized programs of construction practice and quality assurance, by improving the training of personnel and by fostering more effective maintenance and improved operation. The use of such designs can also permit more effective and efficient licensing and inspection processes. Therefore, the Commission strongly encourages industry to pursue standardization in future reactor designs."
>
> "The Commission is preparing a policy statement on standardization which will be applicable to future reactors. ...The Commission's ultimate goal is the approval of essentially complete standard plant designs."

NRC's commitment to standard plants as a means of conserving resources and reducing risk must be matched by a commitment from the industry to depart from the historical pattern of customized utility plants. Fortunately, there are strong economic incentives to purchase prelicensed standard designs as opposed to original designs. It is, nevertheless, a challenge to the nuclear supply industry to join forces for their common good, while maintaining a receptiveness to improve technology and preserving a sufficient degree of competition to satisfy antitrust laws.

4.2.3 Preapproved Siting Policy for Nuclear Plants

A companion to the reactor standardization policy is the preapproved siting policy. The time gained in construction schedule from referencing an approved standard design could well be lost in dispute over the adequacy of a proposed site. It should be possible to gain site approval in advance of applying for a construction permit.

4.2.4 Prescriptive vs Performance-Based Regulation

The current licensing and regulatory regime is based on a safety philosophy of "defense in depth" implemented through prescriptive General Design Criteria (10 CFR Part 50, Appendix A) and NRC Regulatory Guides. In addition, an applicant for a nuclear plant license must address a number of unresolved generic safety issues. The plant design and supporting documentation are scrutinized by a large number of specialists, each certifying that a part of the plant is satisfactory or else requiring changes. Defense in depth as currently applied implies the existence of engineered systems to prevent accidents and, if all else fails, systems and multiple barriers to mitigate the release of radioactivity from an accident. LWR plants have become increasingly complex as the body of prescriptive regulations has grown.

One of the issues raised in the NRC's proposed policy for advanced reactors[2] is the desirability of reduced dependence on prescriptive regulation in favor of performance standards. We believe that performance standards should be carefully considered inasmuch as their application should be facilitated as reactors are made safer. Performance standards can contribute to plant simplification (and reduced cost) while retaining a high degree of protection against public risk. They should be applied to essentially all aspects of the nuclear steam system design and should extend to all safety-related systems which determine the safety of the public. It is most likely that such a goal could be achieved through a strong initiative by the Commissioners or through legislation. Several of the following actions could be included in such an initiative:

a. Adoption of passive safety systems to replace or supplement active safety systems. The use of passive systems makes verification simpler in that safety becomes more deterministic and less probabilistic.

b. Performance standards can be applied to the plant's response to certain accident initiators such as an earthquake of a specified intensity or a pipe break of a particular timing and size. A combination of test and analysis can then be used to determine that a severe accident will not result.

c. As experience is gained with the application of performance standards of limited scope and in the use of probabilistic risk assessment (PRA), greater weight can be placed on the use of PRA to verify the achievement of safety goals on an overall basis.

d. The response of plants to actual challenges to safety systems (Licensee Event Reports) can be analyzed to verify that the PRA is soundly based.

4.2.5 Severe Accident Policy: The Source Term

The accident of March 1979 at Three Mile Island focused attention on severe accidents as (a) events that could really happen and, therefore, had to be planned for, and (b) events whose consequences insofar as radionuclide release was concerned were likely to be far less than current regulations anticipated. The six years of research that have occurred since 1979 have confirmed that additional major changes to the design of operating nuclear power plants to protect the public were not needed. The research has confirmed that many of the postulated accident sequences would result in releases that would be orders of magnitude below earlier planning assumptions.

The research has not, on the other hand, totally ruled out certain unlikely accident sequences that may generate a substantial source term but has verified that the frequency of such occurrences is small. So far the NRC has not issued a new policy for dealing with this exceptionally difficult issue, but it is our understanding that such a policy will soon be announced. The severe accident policy is one of great relevance to advanced reactor designs. The concepts evaluated by NPOVS rely to a great extent on passive features to prevent accidents but postulated sequences (involving knowledgeable saboteurs, for example) may exist that would produce a substantial source term. To what extent must the plant deal with these presumably extremely rare events (perhaps at considerable expense)?

One might argue that event sequences below some minimal probability need not be considered if the cost of mitigating the consequences is greater than the expected damage (say at $1000/person-rem) based on the accident probability. Accepting such an argument requires some consideration be given to PRA and cost-benefit analysis to support qualitative judgments about minimal acceptable risks. Defining a de minimis frequency below which severe accident sequences need not be mitigated would be highly desirable. In any event, the cutoff on rare events that must be mitigated or prevented by design could have a very strong impact on the economic feasibility of the concepts.

This issue may be critical with respect to the LMRs under consideration. Historically, the hypothetical core disruptive accident (HCDA) has been considered in U.S. licensing. Some of the LMR proponents claim that their designs prevent HCDAs. If these claims can be substantiated, the risk associated with these LMRs would be less than that previously associated with fast reactors.

4.2.6 The Alternative Regulatory Philosophies

T. Jenkins[3] has described the current licensing process as follows. The utility contracts with a vendor for a nuclear steam supply system and usually with an architect-engineer to complete the design and construction of the plant. The design stage is generally 20-25% complete at the time the utility submits its Preliminary Safety Analysis Report and its Environmental Report to NRC in support of an application for a construction permit. The NRC staff raises numerous questions about the design, but eventually a point is reached allowing construction to begin. The NRC and its examining boards assume they will catch anything missed at the operating license stage. The utility, vendor, and architect-engineer continue to design the plant as it is being built. Roughly two years before construction is completed, a "final" design document is assembled. Unfortunately, the final design does not really exist because field changes, improvements, and regulatory backfits are continually being made. After additional rounds of questions and hearings, a point is reached where an operating license can be granted. There are still open technical issues, however. Plants that were begun and licensed to operate under this system are still making major modifications.

Jenkins envisions an improved process where the reactor vendor assumes responsibility for developing and prelicensing a standard plant. A complete plant design (except for certain site-related facilities) would be provided to the utility purchaser based on an operational lead plant. Once a standard product is established in this fashion, the design would change very little as a result of siting, utility desires, or presumably regulatory backfits. The utility purchasers would participate in the original concept development through "requirements" documents and review groups.

During construction, and especially at the end of construction, readiness reviews in conjunction with the NRC should be conducted to ensure that the plant, as built, conforms to the approved and tested design. The NRC must also certify that the proposed operator is qualified to run the plant.

Regulatory procedures which apply after the operating license is granted need radical change. If the new process works (i.e., if there are few modifications to the approved design during construction and if there is no list of open items carried over to the operation) then it is entirely conceivable that only periodic reviews by the NRC would be needed. The Final Safety Analysis Report could be updated annually if changes are made, but a comprehensive review should be needed no more than every 10 years. The standard tested design would be nearly immune to the problems which result in extensive outages, and outages would consist only of fuel loading, necessary periodic inspections, routine equipment overhauls, and only occasional unplanned maintenance.

Roger J. Mattson[4] has analyzed five alternative regulatory philosophies for advanced nuclear plants:

a. Case-by-case design reviews, such as have been used in the past for projects such as the Clinch River Breeder Reactor and the Fort St. Vrain HTGR.

b. Incremental changes in LWR regulatory requirements, where the present general design criteria and regulatory guides would be used insofar as applicable, and new criteria would be negotiated with NRC where needed.

c. De novo regulatory requirements, where new regulations would be developed for a new reactor type.

d. The configuration management approach (resembling DOE's Integrated Approach) where there is step-wise agreement on top-level regulatory criteria followed by agreement on detailed criteria and finally NRC's stepwise approval of predefined construction phases of a plant project.

e. The Federal Aviation Administration's (FAA) approach, which includes reliability assurance techniques, accident investigation methods, and design certification; this is usually considered a pure performance-based set of regulations.

Mattson favors the configuration management approach as having the best chance to lead to effective regulation of an advanced design. The NRC's proposed policy on advanced nuclear reactors appears to support this approach in the following paragraph:

"The Commission's proposed policy is to encourage the earliest possible interaction of applicants, vendors, other government agencies and the NRC to provide the most effective regulation for advanced reactors, and to provide all interested parties, including the public, with a timely, independent assessment of the safety characteristics of advanced reactor designs. The NRC would undertake, within its statutory responsibilities, to minimize complexity and add stability and predicability in the licensing and regulation of advanced reactors."

The potential pitfalls of "earliest possible interaction" are the premature rejection of an innovation at an early stage of development and/or early acceptance of an innovation by an advanced reactors branch and later rejection of the same innovation through a more formal staff review (i.e., double jeopardy). To circumvent the pitfalls, the proponent must have his innovations well prepared for early interaction at high levels of the NRC (i.e., the Staff Director, the ACRS, the Commission itself).

4.2.7 Public Participation in the Licensing Process

The current licensing process includes adjudicatory hearings (a trial-like procedure) with public participation, if requested, before a construction permit is granted and before the operating license is granted. Opponents of nuclear power contend that, at present, the first hearing is at such an early stage of design that they cannot effectively comment on the plant's safety, while the second hearing, after huge sums have been invested in the plant, is so late in the process that only superficial backfits are possible.[5]

From the utilities' point of view, adjudicatory hearings contribute little to plant safety but require overwhelming amounts of paperwork and management attention. Public participation is considered a contributor to the risk of the licensing process.

Should the licensing procedure be amended, some thought will have to be given to procedures for public participation. Public participation during generic approval of a standard design would permit effective public review of a plant's safety systems at a time when design changes would be practical. Similarly, public participation during early site approval would permit effective consideration of alternative sites. The timing of this public participation would be favorable to the utilities since little investment would be at risk. The NRC would still be required to get public comment on environmental impact statements. There appears to be some opportunity for making public participation more satisfactory both to public interest groups and the industry.

Intervenors appear to be challenging NRC's decisions in the Federal courts, with some recent success in delaying Diablo Canyon-1 and Shoreham. Legislative or judicial action to provide a clear definition of issues that are subject to judicial appeal after plant construction is completed would be helpful to plant investors.

4.3 LICENSING INNOVATIVE PLANTS

4.3.1 NRC's Proposed Criteria for Advanced Nuclear Plants

The following criteria are proposed in the NRC's advanced nuclear plant policy:[2]

"The Commission believes that reactor designs with some or all of the following general characteristics would be desirable. Combinations of some or all of them may help obtain early licensing or standardized design approval with minimum regulatory burden and should be more readily understood by the NRC, the utilities and the general public.

1. Designs that require few supplemental safety features to ensure safety, and/or designs that provide longer time constants to allow for more diagnosis and management prior to reaching safety systems challenge.

2. Simplified safety systems which require the fewest operator actions, the least equipment (especially equipment subjected to severe environmental conditions), and the minimum number of components needed for maintaining safe shutdown conditions, thereby facilitating operator comprehension and reliable system function. Such simplification can also reduce the uncertainties associated with deterministic engineering judgment and probabilistic risk analyses.

3 Designs that (a) minimize the potential for severe accidents and their consequences by providing sufficient inherent safety, reliability, redundancy, diversity and independence in safety systems; (b) provide reliable equipment in the rest of the plant, thereby reducing the number of challenges to the safety systems; (c) provide easily maintainable equipment and components; and (d) reduce potential radiation exposures to plant personnel.

4. Increased standardization and shop fabrication to minimize the potential for field construction errors without creating new difficulties in factory-to-field transport, installation and maintenance.

5. Design features that can be proven by citation of existing technology or which can be satisfactorily established by commitment to a suitable technology development program."

The broad use of passive safety features is not specifically called for in these criteria. Perhaps a strong endorsement of passive safety features would be an appropriate addition to an advanced reactors policy. On the other hand, many in the industry might interpret such an endorsement as a rejection of current LWR technology. In any event, we believe the concepts studied by the NPOVS satisfy the NRC criteria.

4.3.2 Definition of Safety Envelope and its Significance

The NPOVS reactor concept proponents, relying as they do on passive safety features to prevent or mitigate accidents, in most cases claim that nuclear safety-grade equipment can be limited to certain parts of the nuclear island. Other elements of the nuclear island and the balance of plant can be considered nonsafety and built to normal power plant construction standards. There may be instances in which components or systems contribute substantially to minimizing routine releases of activity and thereby require special attention in licensing but do not have strict safety grade requirements. The definition of the safety envelope could have a critical impact on the economics of the NPOVS concepts.

4.3.3 The Need for Containment

The containment of a conventional reactor serves a number of functions: (a) mitigating or preventing the release of fission products to the environment following a severe accident; (b) reducing or preventing low-level releases of radioactivity from normal operation and maintenance; and (c) acting as a barrier against external events (tornados, airplanes, saboteurs) that could potentially damage the nuclear plant or initiate an accident. Proponents of some of the concepts studied believe that minimal or no containment can be justified because of a lack of credible accident sequences. We agree that a reactor proponent should not be required to mitigate very unlikely accidents unless cost effectiveness (<$1000/person-rem averted) can be demonstrated. The present reliance on a strong containment for defense in depth to mitigate accidents constitutes a formidable precedent. We believe that the licensing authorities may well require a controlled-ventilation filtered structure around the reactor to satisfy the three functions cited in the previous paragraph.

4.3.4 Licensing by Demonstration

Some proponents of concepts studied by NPOVS have proposed licensing by safety test demonstration. Also criteria 5 and 6 on the assurance of licensing and need for market demonstration may be met in part by demonstration testing. If not a casualty of the safety test, the plant used for the safety test may then be used for the lead demonstration of overall operability. Where this approach is compatible with an overall concept design and fits within an R&D program budget and schedule, it may have some attractive features. Chief among these is the validation of key portions of safety analysis and perhaps a substantial reduction in "what-if" type of analysis. Proponents of this approach claim that an important advantage is the psychological reinforcement of safety claims among the public, government officials, and potential investors.

There are, nonetheless, some limitations and disadvantages. Not all safety claims or hypothetical accident sequences can be demonstrated; substantial amounts of analysis will still be required. Also a license may be required for the test prototype. The licensing tests would not be simple and undoubtedly would be expensive. The test module may have to be sited remotely, perhaps at a DOE site because of the potential risk of failed tests. Savings in analysis may be minimal or even negative when the design needs for a successful set of tests are defined.

4.3.5 Licensing Modular Plants and Shop-Fabricated Systems and Components

Presuming that modular plant designs (nuclear steam supply system only, or with balance of plant as well) will be licensed as standard plants, then the further licensing and regulation of the deployment of these plants could resemble FAA regulation of large commercial aircraft. The NRC may already have all the needed authority for such licensing in 10 CFR 50, Appendix M. Presumably backfits for safety reasons would be rather unlikely, but in deploying any new design (even one that has had a prototype) some deficiencies requiring correction are likely to surface in the first few years of operation. Much of the quality assurance/quality control function can be executed at the factory. This is likely to increase the efficiency and reduce the cost of those functions as compared to field operations. However, final field testing of the installed equipment will still be required.

Greater use of shop-fabricated systems and components may be advantageous for more conventional LWRs, the large HTGR, or for the LSPB. In that case, some of the advantages of factory quality assurance can be captured. Greater stress should be placed on the "configuration management" concept of NRC stepwise approval of installed systems at the reactor site, as opposed to the present practice of postponing all approval to the very end of the construction project.

4.3.6 R&D Needs and Clarification of NRC Positions for Licensing Advanced Concepts

The R&D needs of the various concepts have been defined in Volume II of this report. While generic technology research on the licensing of advanced nuclear plants is not considered necessary, there are some areas of policy research that should be addressed.

It is apparent that the design safety of reactors in the future can substantially exceed the NRC's proposed safety goals. This is true not only of the concepts which depend largely on passive safety features but also on more conventional LWRs such as Sizewell-B. The core melt frequency of these systems is likely to be in the range of 10^{-6}/reactor year- or less.

Coupling this extremely low risk of core damage with more realistic appraisal (and mitigation, if desired) of the source term, the apparent risk of operating reactors would be much less than predicted in earlier studies such as WASH-1400 or the present NRC-industry severe accident research. The applicant for licensing such a plant should benefit through the elimination of much of the present prescriptive regulatory structure. There is a need to re-think design basis accidents, requirements for containment, the site suitability source term, emergency electrical power, fire protection, and other requirements that have been made a part of nuclear plant licensing. On the other hand, there is a continuing need to look carefully at potential accident initiators (especially external events) that might circumvent an otherwise near foolproof design.

4.3.7 Licensing Fuel Cycle Facilities

The NPOVS light-water and gas-cooled reactor concepts utilize once-through fuel cycles similar to the present commercial practice. Licensing of fuel cycle facilities would not appear to introduce any delay or risk assuming that the nuclear waste program is completed approximately as scheduled.

The LMR concepts, on the other hand, are based on the recycle of plutonium fuels with either on-site or off-site fuel reprocessing and fabrication facilities. The licensing of these facilities must be addressed early in the process of developing a lead plant. The experience with the aborted generic licensing of mixed-oxide fuels indicates there are nonsafety issues that must be faced; these include nonproliferation, adequacy of the uranium resource base, relative economics of once-through and recycle fuel cycles, and the scheduling of facilities to match the deployment of reactors.

4.4 LICENSING - SUMMARY AND CONCLUSIONS

The uncertainty of the licensing process is a key impediment of the long-term viability of nuclear power in the U.S. Utilities require assurance of stability and freedom from non-essential backfits as a condition for additional commitments to nuclear plants. Prelicensed standard plants represent an important option for contributing to regulatory stability. With a complete design available at the front end of a nuclear project, there are prospects for concentrating the key approvals and public participation at the beginning of the project, prior to the major expenditures.

Advanced reactors possessing a high degree of safety based on passive features could contribute to licensing stability and the adoption of performance-based, as opposed to prescriptive, regulation. However, there are some general issues applying to many of the concepts studied by NPOVS where clarification of the NRC's position is important; need for prevention and/or mitigation of very unlikely accident sequences (at considerable expense), requirements for containment, the definition of the safety envelope, and the definition of the site suitability source term.

4.5 REFERENCES FOR CHAPTER 4

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5. SAFETY AND ECONOMIC RISK

Uri Gat and I. Spiewak

Adequate safety and acceptable economic risk are vital to nuclear power viability. Safety refers to freedom from harm to people; economic risk refers to potential harm to investors. They are coupled here because loss of plant integrity is a potential threat both to people and to property. The risk criterion of 10^{-4}/reactor year pertains to accidents leading to a loss of capital investment. As PRAs are carried out, such potential accidents should be evaluated independently of those accidents with public health consequence. NPOVS criteria address safety and economic risk by providing limits for the probability of occurrence of events related to safety and risk.

The assessment of safety of the individual reactor concepts is covered in Volume II of the NPOVS report and will not be repeated here. This discussion focuses on some safety and economic risk issues generally applicable to all the concepts evaluated. First, we review the NPOVS criteria applicable to safety and economic risk. Then, we address the implications of the requirement in the NPOVS ground rules that each concept possess a high degree of passive safety. Probabilistic risk analysis is discussed as the tool for making quantitative estimates of safety and economic risk. Finally, several key risk issues are discussed.

5.1 APPROACH TO SAFETY AND ECONOMIC RISK ASSESSMENT

Our study has identified seven criteria and several characteristics which are considered essential to successful nuclear power projects of the future. These are listed in Volume III, Section 1.3, and are discussed in Volume II, Section 2.2. Two of the criteria by which a reactor concept might be judged relate to safety and economic risk are:

Criterion 1: The calculated risk to the public due to accidents is less than or equal to the calculated risk associated with the best modern LWRs.

Criterion 2: The probability of events leading to loss of the plant capital investment is less than or equal to 10^{-4} per year.

Also, a set of ground rules were chosen by which the several concepts included in the study were selected. These are listed in Section 1.4 of this volume and are discussed in Section 2.1 of Volume II. The third ground rule relates to safety and states:

Ground rule 3: The design option should possess a high degree of passive safety to protect the public and the owner's investment

The criteria require probabilistic risk assessment (PRA) to ascertain compliance. Since PRAs are not available for all advanced concepts, judgment has to be substituted for preliminary assessments. The broad use of passive safety features circumvents the need for a PRA in many accident sequences since the design may eliminate the adverse consequences.

5.2 PASSIVE SAFETY

Passive safety may be considered to be a condition where the fuel and structure of a reactor are protected from damage by virtue of the physical characteristics of the design and require no response or action by human operator or mechanical or electrical control. The protection applies both to the public and to the plant capital investment. In conventional LWRs, there is a negative temperature coefficient that shuts off the chain reaction, in the event of a large temperature increase. In many designs, shutdown heat can be removed from the core through natural circulation without pump operation. These passive features provide time for engineered safety systems to function and/or for operators to intervene in response to a potential accident initiator.

The concepts studied by NPOVS incorporate a higher degree of passive safety than do conventional LWRs. The result is that much more time is available for engineered systems or emergency response, i.e. days for most anticipated accident initiators rather than minutes. During the period of time that the passive protection is functional, the safety of the reactor is assured.

The designers of the passively safe concepts have responded to this characteristic in the following ways:

- There has been an emphasis on accident prevention as opposed to mitigation.
- Few or no operator actions are required, and even then perhaps many hours or days after the initiating event.
- Simplified engineered safety systems, with few critical components, are used.
- In some cases, it is proposed to demonstrate the safety by subjecting a prototype to specified accident initiators.

Passive safety (and the resulting longer response times brought into play) has important ramifications with respect to emergency response. There is a reduction in source term due to radioactive decay from the time of reactor shutdown to the time of potential release. Should there be an emergency, much more time would be available to alleviate the problem or to provide for sheltering or evacuation. Such decisions could be made over a period of days rather than hours or minutes.

The operational sensitivity of passive safety features is likely to require investigation. Some activation mechanisms, such as the PIUS density lock, may be sufficiently sensitive as to cause undesired shutdowns. On the other hand, if the control range is too broad, some damage to the reactor may result before the passive mechanism has functioned. One of the important objectives of a prototype reactor or a safety demonstration would be the adjustment of passive features to enhance plant operability.

5.3 PROBABILISTIC RISK ASSESSMENT

The quantitative measure of safety and risk requires a probabilistic risk assessment (PRA). There are many difficulties in the use of PRA. The data and information required for the probabilities of occurrence of events are often difficult to obtain and could contain large uncertainties and errors. This may be particularly true for predicting the frequency of events that would bypass or disable passive protection, since such actual experiences are unlikely. The data and models used to quantify consequences are uncertain, often disputed;

furthermore, the two measures most commonly used (fatalities and cost) cannot be reconciled to the satisfaction of all concerned. As the result of such difficulties, there is no commonly accepted quality standard for PRAs.

NPOVS in recognizing the above difficulties chose the criteria for safety of nuclear power in a way that facilitates a practical approach. The public safety risk is done on a comparative basis, comparing with the best modern LWRs. Since the modern LWRs are considered acceptable in terms of risk to the public, we concluded that reactors which derive comparable safety through more passive means also are acceptable and viable from the public safety aspect.

The Westinghouse PRA for the Sizewell-B reactor predicts a core melt frequency of 1.16×10^{-6}/reactor year; and the probability of a large release of radioactivity is stated to be 3×10^{-8}/reactor year.[1] These estimates have since been reassessed by the United Kingdom Nuclear Installations Inspectorate showing a core melt frequency of about 7×10^{-6}/reactor year and the risk of a large release of about 1×10^{-6}/reactor year.[2] Recent source term evaluations[3-5] show that large releases for a PWR with a large, dry containment are unlikely; the frequency of a large release below 10^{-7}/reactor year would therefore be expected for a core melt frequency of 7×10^{-6}/reactor year. The Westinghouse Advanced PWR and the General Electric Advanced BWR are also expected to have PRA results satisfying the NPOVS criteria.[6]

Although the concepts studied do not generally have PRAs available, it is our judgment that they can be designed to be consistent with the NPOVS criteria discussed above. Some concept proponents conclude that there is no need to address at all the very rare events, of a frequency less than 10^{-7}/reactor year; these are traditionally lumped into "beyond design basis" events. NPOVS criteria require a careful look at rare events that have very severe consequences; the risk must still be less than or equal to that for the best modern LWRs. Hypothetical severe consequences, regardless of probability of occurrence, may have a significant impact on public acceptance. There are regulations, derived from LWR licensing experience, that require mitigation of certain severe accidents without respect to probability of occurrence. These items are addressed for each concept and discussed in the chapter on Regulation.

NPOVS assumes for studies of reactor safety that each reactor is independent. This, of course, may not hold and, particularly for standard plants, a deficiency or accident occurring in one plant may adversely affect the marketability or licensability of others of the series. Actually, any core melt accident taking place in the next 20 years may further delay a revitalization of the nuclear industry.

5.4 GENERIC SAFETY AND RISK ISSUES

5.4.1 Capital Investment Risk

There are other circumstances that may put the capital investment at risk and may be considered by investors to be more compelling than the accident risk. These include political actions (such as at the Austrian Zwentendorf reactor), quality assurance deficiencies (such as at Zimmer), or financial problems (such as at Marble Hill). There is also the precedent at Three Mile Island Unit 1 where reactor operation was delayed extendedly partially as the result of the Three Mile Island Unit 2 accident. Some of these situations may have been complicated by changes in the applicable regulations after the start of construction. The need for stability in licensing is treated in the chapter on Regulation.

5.4.2 Operation Risk

Operation risk is related to unexpected events and occurrences that affect the revenue producing operation and result in increased power production cost. NPOVS has only an indirect criterion for acceptability of operation risk, that of economical competitiveness with coal-fired plants. Assume, for orientation purpose only, that an unplanned forced outage of 8% can be tolerated. This amounts to about 15 million dollars per year in lost revenue for a 500 MW(e) plant. Though this may be considered more an expected cost, likely to occur every year, rather than a risk, it is nonetheless greater than the cost of severe accident insurance for the plant. A utility is therefore more likely to be concerned about the risk of poor operation than the risk of a severe accident when deciding to commit to a nuclear plant.

New and untested concepts are particularly vulnerable to operation risk. NPOVS requires demonstration of a concept as a prerequisite to its viability. This will reduce the uncertainty in the operation risk, including ordinary risks such as the difficulty experienced at Fort St. Vrain with the leakage of lubricating water from the gas circulator bearings. Other considerations about operation risk involve judgment of the complexity, sophistication, and maintainability of the designed plant. A complex plant is likely to have more problems leading to forced outages, especially for a new concept. A plant that is difficult to maintain and overly compact can take more time to restore to operation. Some of these aspects are discussed in the chapter on Construction.

Of particular interest are multi-module plants and their control. The degree of independence of each module and module grouping will impact the capacity factor of the plant. The efficacy of the control system determines the speed of recovery from minor disturbances. In a multi-module plant, it may be possible, when demand requires it, to restore to, or retain in, service a module scheduled for planned maintenance in lieu of a unit that suffers a forced outage. Thus, the capacity factor will not be reduced by some of the unavailabilities. On the other hand, several modules may be idled by a single failure in one of them because of control problems or for regulatory reasons. Occurrences of this nature may multiply the unavailability by the number of modules in a plant. These aspects of control and mutual relations between modules and their control systems need to be explored thoroughly. At present, none of the modular concepts have sufficiently developed systems to enable an assessment of these potential problems or of the cost savings that can be obtained from the use of common elements.

5.4.3 Source Term and Containment

The proponents of the NPOVS selected concepts have not in general calculated source terms for their systems. The source term, radioactivity released to the environment in a severe accident, determines the consequence factor of risk. The conventional reactor containment serves as a very effective engineered system for containing materials generated during a fuel melt accident.

NRC regulations require that there be a containment system to mitigate the release of an arbitrary fraction of the reactor's fission products, independent of reactor design.[7] The NRC's radionuclide release, as defined by 10 CFR 100, is probably much greater than the actual release that would be experienced in most accidents. Most concept proponents have not, at this point, either performed the research required to define the source terms or proposed strong containments.

As discussed in the Regulation chapter, the NRC has reached no decisions about how to deal with these issues. We believe that it is likely that each of these advanced concepts will be required to have containments, or at least some form of a confinement building, though not necessarily the large, expensive structures in use with current LWRs. It would be desirable that these containments be designed to mitigate realistic source terms determined for the specific reactor design.

5.4.4 Impact of Standardization on Safety

The proponents assume that their concepts will be translated into standard designs. Standard plants appear to have safety advantages over the same number of customized plants in that more effort can be justified for the safety analysis and research of the standard design. Complete preapproved designs should be available before the start of construction. These should have been reviewed thoroughly by the NRC, by the constructor, and by the utility. We believe that the risk of loss of the capital investment would be much less than with custom-designed plants developed by the design-as-you-build process that has been common in the U.S. The operating experience with many reactors of a standard design would provide a good data base and good understanding of the operations, thereby improving public safety and reducing the economic risk, and improving operational and economic performance.

The degree of standardization is an important factor. If the envelope of parameters is to include a wide range of sites and conditions, some plants may become excessively expensive for their location. The other extreme leads to the existing situation where each plant is individually tailored and trimmed. Optimization of standardization is primarily a construction and economic question, but the licensability of the design must address safety related issues of standardization. Research is needed to determine the optimum degree of standardization as it affects safety.

5.5 ISSUES RELATED TO SAFETY AND ECONOMIC RISK REQUIRING FURTHER INVESTIGATION AND RESEARCH

The following issues related to safety and economic risk have been identified in the preceding discussions to require further investigation:

4.5.1 Risk Criteria

NPOVS has developed criteria for evaluating risk from advanced reactor concepts. These criteria are somewhat more restrictive than those the NRC has proposed for its safety goal, and it is possible that the various criteria do not form a consistent set. Further review and refinement of risk criteria are recommended, including both safety and economic risk criteria.

NPOVS applied a probability criterion for capital investment risk. This criterion was related to the frequency of severe accidents. It would be desirable to expand this criterion to include other risks, such as the risk of project non-completion because of political or financial circumstances. The potential role of insurance in reducing these risks should be investigated.

5.5.2 Passive Safety: Is It Different?

If passive safety features can be relied upon fully, then the risks from reactor designs based on passive safety might be considered to merit a different regulatory approach from that imposed on reactors relying primarily on active safety systems. This could have a profound impact on licensing. The extent to which "unanticipated" accidents, such as those that might be initiated by terrorists or knowledgeable saboteurs, needs to be determined.

5.5.3 Rare Events

How should rare events be handled? There is a need to determine if there is a lower limit to the frequency of rare events below which they need not be prevented, mitigated, or even analyzed. As designs improve in the overall level of safety, the designer requires guidance on and preferably relief from the continuing need to focus more attention on the least likely accident precursors.

5.5.4 Containment-Confinement

Is a containment, or merely confinement, required and under what circumstances? If containment is required, research is needed for establishing the minimum requirement for safeguarding the public. If not, then the criteria and conditions under which a nuclear reactor concept becomes acceptable without containment, or even confinement, needs to be determined.

5.5.5 Operational Risk

Operational risk has a component of such high probability that it is included as an operational cost. Design choices such as degree of complexity, redundancy, space for access, and special maintenance provisions can reduce operational risk. Trade-off studies should be made to define an optimal degree to which operational risk should be reduced. This is an area frequently overlooked in developing new designs.

5.5.6 Standardization

It is claimed that standardization improves safety. Yet it is not clear that safety improvement is automatic. Those factors such as more intensive licensing review, enhanced learning of construction and operating skills, and a broader experience base should be delineated clearly. Having defined the critical aspects would improve the prospects for actually improving safety.

5.6 REFERENCES FOR CHAPTER 5

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6. NUCLEAR WASTE TRANSPORTATION AND DISPOSAL

I. Spiewak

6.1 THE ANTICIPATED STATUS OF WASTE BY THE YEAR 2000

Legislation is in place which, if effectively implemented, should provide the technology and facilities required for light water reactor (LWR) waste handling and disposal prior to the year 2000. The Nuclear Waste Policy Act of 1982 calls for development of repositories for the disposal of high-level radioactive waste and spent nuclear fuel.[1] Under the requirements of this act, the U.S. Department of Energy is directed to request a construction authorization for the first full-scale facility by 1987, and the U.S. Nuclear Regulatory Commission (NRC) is directed to take steps necessary to authorize construction by 1989. Similarly, the Low-Level Radioactive Waste Policy Act[2] of 1980 assigns responsibility for low level waste disposal to the States, with provision for regional compacts among the States.

The technology for handling, shipping and ground disposal of low level wastes (including transuranium wastes) is also in active use. Additional disposal sites should become available pursuant to the legislation, reducing the amount of transportation. By the time the concepts being studied by NPOVS could be commercialized, a complete nuclear waste handling and disposal system should be available.

Shipping casks have been developed, have been qualified for license, and are in wide-spread use transporting high level waste from reactor sites to storage sites. Technology also exists for shipping vitrified waste forms from reprocessing. These activities are regulated by the NRC and the U.S. Department of Transportation.

Appropriate waste forms and containers are under development to satisfy the proposed criteria for 1000 years of complete containment, followed by radionuclide release rates of no more than one thousandth of one percent (10^{-5}) of the radioactive inventory per year after 1000 years. Geologic conditions are to give a minimum groundwater transport time to the biosphere of 1000 years.

6.2 SPECIAL WASTE CONSIDERATIONS OF THE CONCEPTS STUDIED BY NPOVS

The two light water reactor (LWR) concepts being evaluated by NPOVS utilize fuel quite similar to that of present light water reactors. For some extended time the high level waste will be in the form of spent fuel. All the technology and facilities for waste handling and disposal should be operational by the time a utility would make a decision to build one of these concepts. Should there be a later desire to reprocess the spent fuel, then technology would be in place to deal with vitrified waste.[3]

The LMR concepts use reprocessing in their reference fuel cycle. The reference high level waste form is a vitrified material similar to that from LWR reprocessing, and should be suitable for emplacement together with LWR wastes. Should a once-through

LMR fuel cycle be developed, then some research would be needed into the encapsulation and burial of that fuel, because it would be a more concentrated source of decay heat than spent LWR fuel. Metal fuel wastes also would require development for fixation and encapsulation.

The modular HTR fuel cycle is once-through with extended storage of the hexagonal graphite fuel blocks. Each fuel block will remain integral containing the fuel, which is in the form of small cylindrical graphitized sticks embedded with silicon carbide coated fuel particles. Fuel elements are first stored at the reactor site, then shipped to a permanent repository. The bulk of this material is greater than spent LWR fuel elements because it consists mostly of graphite moderator. An alternative process would be to remove the fuel sticks from the blocks for separate placement in both temporary and permanent storage facilities.

Casks fabricated of stainless steel with depleted uranium as gamma shielding have been developed and licensed for transportation of spent fuel from the Fort St. Vrain HTR. These casks are designed to survive and maintain their containment during the hypothetical accident conditions specified in the appropriate NRC regulation (10 CFR 71). Analyses have shown that the mass of the cask walls acts as a thermal barrier to maintain the temperature of the contained graphite below its ignition temperature during the portion of the NRC hypothetical accident where the cask is fully enveloped in fire.

For the German pebble bed HTR, the silicon carbide coated fuel particles are embedded in 6 cm diameter fuel spheres. The reference plan for spent fuel handling in Germany (which has been licensed there for development and testing purposes) is encapsulation of the spent fuel in a cannister and then burial in a mined repository.

Each of the reactor types would generate low level wastes, and those fuel cycles using reprocessing would have some transuranium wastes. The technology for handling and disposal of these materials is already available, as indicated in the previous section of the report.

6.3 RISKS OF WASTE TRANSPORTATION AND DISPOSAL

Risk analyses are reported[4-5] for a projected 26-year experience in transportation of wastes to a high-level repository. The nonradiological fatalities are reported in the range of 16 to 80 deaths depending on the repository site and the waste form. These predictions, being based on highway and rail experience, can be considered relatively accurate.

Radiological fatalities predicted in Refs. 6 and 7 over the 26-year period are 7 to 36. Of these radiological fatalities, the portion attributed to accidents is only 0.015 to 0.06 fatalities. The remainder of the radiological fatalities are attributed to excess cancers from low-level exposure to radiation. The maximum such dose calculated to any individual over the 26-year period is 74 mrem; this compares to background exposures unrelated to nuclear power in the range 100-150 mrem/year. There is no physical or epidemiological evidence that such low doses of radiation above background cause cancer; therefore the range of radiological fatalities should really be stated as <1 to 36.

The Electric Power Research Institute (EPRI) has made an accident risk assessment of the nuclear fuel cycle,[6] including waste transportation and disposal. The pertinent radiological risks (consequences times probability) in person-rems of exposure to the public per GW(e)-yr are expressed as follows based on the EPRI assessment:

Nuclear power plant	257 [based on WASH-1400 (Ref. 7)]
Transportation	3×10^{-2}
Waste repository-preclosure	4×10^{-5}
long-term (10^6 yr)	5×10^{-11}

From these risk analyses, it must be concluded that the radiological risks of nuclear waste transportation and disposal are extremely small barring totally unforeseen events such as a future generation mining the waste without knowledge of its radiation hazard.

6.4 DISCUSSION OF WASTE DISPOSAL ISSUES

Chapter 7 on market acceptance highlights nuclear waste as one of the major areas of public concern in connection with nuclear power. The concerns of many people might be summarized as follows:

1. Waste transportation is dangerous,

2. It will not be possible to select and develop a geologic waste repository site,

3. There is no proven technology to satisfy the long-term need to isolate the wastes, and

4. It is impossible to guard against future events that would release radionuclides to the biosphere.

Of these concerns, only the first two may be reasonably alleviated by extensive experience taking place before the year 2000. Utilities selecting conventional or advanced nuclear plants of any type would have to consider residual public acceptance issues.

6.5 WASTE DISPOSAL: SUMMARY AND CONCLUSION

Legislation has been enacted which, when implemented, will provide the technology and facilities for waste disposal prior to the year 2000. Utilities choosing to build one of the concepts studied by NPOVS would have firm guidelines on waste management and disposal. The only reactor types considered here that may require special waste development are the modular HTR, for which it may be desired to reduce the high level waste volume, and the metal fuel system of the Integral Fast Reactor, for which waste processing has not yet been fully developed.

The public risks due to potential accidents in the transportation and disposal of nuclear wastes are exceedingly small, according to conventional risk analysis. Many members of the public, nevertheless, consider the wastes a major hazard. Some of these concerns are likely to persist into the time when concepts studied by NPOVS are deployed.

6.6 REFERENCES FOR CHAPTER 6

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7. MARKET ACCEPTANCE OF NEW REACTOR TECHNOLOGIES

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7.1 INTRODUCTION

The viability of the nuclear power options examined in this study does not depend solely upon their technical plausibility and projected economic feasibility. The future development of commercial nuclear power technologies will depend largely upon the needs of the potential purchasers, rather than on federal policy to transfer a technology for commercial application. To be attractive in a regulated electricity market, new nuclear technologies, like other technologies, must be seen by utilities, their regulators, and their customers, as effectively filling a need for power in addition to being economically competitive, and meeting applicable safety and environmental requirements.

Characterization of the potential marketplace for new reactor technologies around the year 2010 is, therefore, central to any assessment of the viability of new nuclear technologies. Large public and private expenditures on research, demonstration and manufacture of new reactors cannot be justified on technical criteria alone. An assessment is needed of the extent and nature of the demand for new nuclear generation by the year 2010 based upon identification of the most promising reactor candidates that are currently evolving and the presently perceived needs of the future market. It is quite possible that a market will exist for a variety of nuclear technologies and that the ability of the nuclear industry to respond to this demand would be severely constricted if only one of the possible concepts were developed.

The NPOVS approach to assessment of the future marketplace necessarily involves a high degree of informed speculation on the part of the researchers, and the work reported here is exploratory rather than definitive. However, it is based on a core of empirical research that was performed especially for this study. The reader should note that the views contained in this chapter with respect to the future market for nuclear power rely on the opinions of the subjects of the research as interpreted by the authors; no attempt has been made here to debate the opinions of the subjects since the purpose of the study was to identify their perceptions and preferences. The market acceptance research consists of three major components:

- Definition and characterization of issues relating to current nuclear technology;
- Characterization of likely preferred market strategies based on utility decision making procedures;
- Characterization of likely constraints on utility market preferences arising from public utility commissions (PUCs) and public interest groups.

Nuclear power has been engulfed in a long list of public and technical issues. The results from this research are intended to clarify two sources of conflict that surround nuclear technology in order to assess the market acceptability of new reactor concepts. The first part of the research addresses how these issues are characterized by the proponents and critics of nuclear power and their perceived importance to each group. Thus, it deals direc ,y with the conflicts that stem from the persistent debates over the technology. The secor d part of the research seeks to understand the conflict over capacity choice. This focuses on the utilities' preferences and the constraints imposed on these preferences by regulators and public interest groups. The two parts of the research are drawn together to define a set of major issues central to the acceptability question for new reactor technologies and to match characteristics of reactor concepts to the various types of utility institutions and regulatory environments.

7.1.1 Issue Definition

The issue definition component of this research consisted of conducting semi-structured interviews with 20 technically informed supporters of nuclear energy and an equal number of similarly informed critics. The object of the interviews was to establish whether similar problems are defined as primarily technical or institutional by both groups, the reasons for such judgements, and the preferred solutions to such problems. Clearly, some commonality of definition of a problem is a prerequisite for any technical, institutional, or mixed solution to be acceptable to both sides. Similar issues were identified in the research on utility, regulatory, and interest group decision making, which was conducted independently of the issue definition research.

7.1.2 Structure of the Market

The market for electric generating technology is determined by the electric utilities that purchase the technology (the primary consumer), the government agencies that regulate it, and the utility customers who pay for and experience the effects of that technology (the secondary consumers). This broad definition of the marketplace is appropriate because both the electric utility industry and nuclear technology are regulated and have high public visibility. Omitted from this analysis were the Nuclear Regulatory Commission (NRC) and the firms that manufacture nuclear components, both of which have significant roles in structuring the marketplace. The NRC is discussed in the section on licensing, and vendors are discussed in the context of reactor concepts. The utilities, PUCs, and the public interest groups each play a critical role requiring a positive decision for nuclear technology if any of the new reactor concepts is to be commercialized.

In order to analyze this marketplace, five case studies of decision making organizations, including utilities, PUCs, and public interest groups, were undertaken. Extensive interviews of key participants in the decision process were conducted using a semi-structured interview format. Each case study analyzed the decision process used by a utility to build additional capacity in conjunction with that used by its PUC to permit construction of new plants. This information was combined with a decision theoretic model that categorizes four types of utilities and identifies the likely strategy that each would prefer in respect to a future decision on new nuclear reactor technologies.

The role of interest groups in relation to the construction and operation of nuclear plants was analyzed through a series of focus group discussions. Opinions were sought from members of a variety of environmentalist and anti-nuclear organizations on matters relating to confidence in institutions associated with nuclear power, the manner in which liabilities from potentially hazardous technologies, such as nuclear power, are distributed within society, and the problems associated with obtaining legitimate societal consent for such technologies. The purpose of this inquiry was to indicate how the constraints that intervenors can impose on the utilities' capacity choice decisions arise from these preferences. Understanding these constraints is necessary to appreciate how the utility's preferred strategy regarding new nuclear technologies might be altered by the influence of the public interest groups.

7.2 SUMMARY OF RESULTS

7.2.1 General Conditions for a Future Nuclear Market

The findings of this pilot study must be treated as provisional, especially as they are not entirely consistent with some of the prevailing views of the nuclear power industry. Analysis of the interviews conducted for the study indicate that a commercial market for some sort of nuclear generation technology is feasible after the turn of the century, subject to three necessary, but not sufficient, conditions. These are:

- A projected need for new baseload capacity;
- Narrowing of the gap in construction costs between environmentally acceptable fossil and nuclear plants; and
- Absence of a third option for baseload power to compete with nuclear.

The first condition requires that new capacity must be needed by a number of the utilities. Gradual incremental increases in load are more likely to be dealt with through non-baseload options, such as conservation, load management, plant refurbishment, and cogeneration. The number of utilities that need additional power is important because the amount of new capacity ordered must be sufficient to sustain a nuclear supply industry.

The second necessary condition is that the problems associated with coal fired plants must be given increased recognition by the public, regulators, and the utility industry to the extent that demands for environmental controls on emissions and increased safety standards for workers in the fossil fuel cycle render the fossil options uneconomic relative to the available nuclear options.

The third necessary condition is that a future nuclear market depends on the unavailability of alternative baseload options that are economically competitive with nuclear, even if coal is excluded from the choice set. Such alternatives may include cogeneration, some hydroelectric generation, biomass, geothermal, and presently unforeseen improvements in photovoltaic technology. This condition will be met if the available nuclear technologies are clearly more cost-effective than competing options. An exception to this condition could be turnkey units offered by the vendors that insure the utilities' cost and operating expectations.

The research indicates that the above conditions must be satisfied for a viable market for new nuclear technologies without significant financial subsidies accompanied by technical and administrative support from the federal government. If all three necessary conditions are satisfied, there is a further set of facilitating conditions that would improve the position of nuclear technologies within the market. These include improvements in the following areas:

- Stability of the regulatory environment;
- Accuracy and reliability of load forecasting techniques;

- Improved cost controls in nuclear construction and operation, including standardized or turnkey plants; and
- Demonstrated feasibility of new nuclear reactors.

Interviews with utility decision makers revealed the skepticism of the industry that these conditions will be met within the NPOVS time frame. Consequently, utilities indicated no active interest in constructing future nuclear units at this time (Jackson[1] arrived at similar findings from a much larger data base). Although nuclear options are retained in modeling alternatives for future baseload system planning, none of the utility respondents in our sample was actively entertaining the notion of ordering a nuclear reactor between 1985 and 2010.

7.2.2 Public Acceptance Criteria

The issue definition research identified four dominant issues that may preoccupy the prospective secondary consumers of future nuclear technology: the utility customers. These issues identified by the respondents are as follows:

- Operational safety of power plants;
- Transportation and disposal of nuclear waste;
- Effect of construction and operational costs of plants on rates;
- Adequacy of management and regulatory controls.

In order to obtain widespread public support, it would be advantageous to any nuclear technology competing in the marketplace to show substantial improvements over existing nuclear technologies in all these areas. Although the descriptions of the advanced concepts considered by NPOVS indicate that each concept may have some advantages over the others, and over current LWR technology, none of the technologies show an overall superiority in all four. Similarly, at this stage of development, respondents in the second part of the research did not feel that any one of the new nuclear concepts represents an improvement over current LWR technology that is so substantial as to overcome the problems currently associated with nuclear power generation.

7.3 DEFINING ISSUES AS TECHNICAL OR INSTITUTIONAL

The future of nuclear power depends in part on the industry's ability to identify and address issues raised about the technology. The types of solutions that are offered, however, must be sensitive to more than the design and procedural adjustments that experience and new engineering concepts suggest. They must take account of the institutional and social interrelationships that impinge on the development of nuclear power. Research was, therefore, initiated to explore the range of technical and institutional issues encompassed by the nuclear debate, and to examine how these issues come to be viewed as technical or institutional in nature. The reader should note that the intention here was to identify a range of issues and not the distribution of all opinion-holders across a set of issues.

To accomplish this goal, an exploratory study of the issue definition process was designed and conducted. Briefly, the research involved semi-structured interviews with a sample of technically knowledgeable proponents and critics of nuclear power (Appendix A). Potential interviewees were identified by contacting major organizations and individuals involved with nuclear power and asking them to identify knowledgeable individuals. A sample was then chosen to reflect the range, but not the proportion, of perspectives represented by various constituencies participating in the nuclear power debate. The sample included university faculty, government employees, Congressional staff, members of lobbying groups, and other related groups.

The researchers classified the respondents into two groups (proponents and critics) for much of the analysis. Interviews were conducted with 19 proponents and 22 critics. Proponents came from groups and businesses favoring the continued development of nuclear power. Opponents came primarily from intervenor and lobbying groups opposing nuclear power. A variety of occupational positions and geographical locations are represented in the sample (see Appendix B). All participants indicated that they were generally knowledgeable about current Light Water Reactor (LWR) technology. Their areas of training and expertise varied considerably including engineering, chemistry, physics, social science, business, communications, law, mathematics, and other fields.

7.3.1 Technical and Institutional Definitions of Nuclear Issues

Nuclear power is a complex technology. Because it is part of a broader social system, any piece of the information about this complex technology can potentially become a point of debate. For our purposes, the information associated with nuclear power can be characterized as either routine or problematic. Routine information is understood and widely accepted with a general consensus among users of the information on its meaning. For example, the nature and properties of concrete and steel used in constructing reactor containment buildings is understood by most of those interviewed as being routine information. Problematic information refers to information that is controversial (that is, information which is actively being debated regarding its interpretation). An example is the impact of low-level radiation on human health.

The issue definition process in the nuclear power debate involves specifying what issues are in need of resolution and what types of solutions are appropriate. Many pieces of information about nuclear power have become recognized as controversial, and a wide range of solutions have been considered. But it is also important to understand that these solutions are not simply placed on an agenda, evaluated objectively, and ruled as appropriate or inappropriate. Rather, they evolve out of individual or group interpretations of what the problem is, who is to blame, what effects the solution will have, and how effective it will be. This broader set of interpretations provides a context for understanding and assessing alternative solutions.

It is within this broader system of ideas that issues are classified under different labels. As individuals or organizations react to the array of issues encompassed by the debate, there is a tendency to reduce the complexity of the arguments and pinpoint appropriate solutions that fit with their own views. Dimensions discussed in the nuclear debate including scientific versus ethical issues, rational versus irrational issues, and perhaps most commonly, technical versus institutional issues. The last method of categorization was used in this study. "Technical" means a problem that can be solved by engineers or scientists through further investigation or more thorough preparation, if it can be solved at all. "Institutional" refers more broadly to problems of politics, the legal system, and the coordination, or social organization, of the nuclear generating industry. Solutions to these problems often involve consensus building and change of laws, regulations, or other patterns of human organization. In general, the labeling of issues by various groups serves to simplify the debate and structure the communication between groups.

The goal of this part of the research was to examine how this issue definition process has functioned with regard to LWR technology, and to speculate on how the process might influence future reactor designs.

7.3.2 Issues Facing the Development of LWR Technology

In investigating the issue-definition process, four basic questions were examined. They include the following:

- What are the four or five major issues facing the continued use of LWR technology?
- What are the solutions to these issues?
- How are the issues defined (e.g., as technical, institutional, etc.)?
- What reasons are given for these definitions?

The questions focused on current LWR technologies because the issues are more familiar to people who are not specialists in advanced nuclear technologies. The project was based on the assumption that studying issue definition for current nuclear technology would provide an avenue to explore the process for future nuclear power alternatives. The following sections describe the responses given to each of the questions noted above.

7.3.3 Identifying the Issues

There have been several important efforts to enumerate issues facing nuclear power over the past decade. In this study, a wide range of issues was cited by proponents and critics. The most frequently discussed issues had to do with the costs of nuclear power and why the costs had skyrocketed over the past decade. Thirty-three (or 80%) of the 41 interviewees pointed to importance of cost related problems to the future development of LWR technology. Also among the most frequently discussed issues were waste-related issues (listed by 61% of the sample) and safety-related issues (listed by 54%), and issues related to the regulatory process (listed by 44%). Other issue areas that were mentioned less frequently included public acceptance and/or participation, the link to nuclear weapons, technical complexity, the design process, management, and load projections.

There are important differences between proponents and critics in the issues they perceive as most important. The first three issue categories (cost, waste, and safety) are emphasized to a much greater extent by critics than by proponents (although cost is mentioned by a substantial group of proponents). In all three categories, the critics mention these issues nearly twice as often as proponents. In contrast, proponents identify public acceptance/participation, the design process and management issues significantly more often than do critics. Based on our categorization, the two groups raise only three areas of concern in about equal numbers (the regulatory process, the link between nuclear power and nuclear weapons, and technical complexity issues). Thus, in terms of defining the problem, there are obvious differences between the diagnosis proposed by critics and the one suggested by proponents.

7.3.4 Solutions Given for the Issues

Study participants offered a variety of solutions to the issues that were raised in the interviews. Solutions are usually provided in the context of a specific issue, but similar solutions occurred for many different issues.

Four types of solutions are discussed by at least one-half of the study participants. Standardization of reactor designs is the most frequently mentioned solution. Many respondents feel that standardized designs will resolve a wide range of cost, safety, regulatory, and design problems. Changes in the regulatory process are also a favored solution. Twenty respondents suggested ways of restructuring the regulatory agencies, while ten argue that the regulatory process should be broadened to include a wider range of issues in regulatory decisions. Finding effective solutions to the nuclear waste problem is discussed by 29 respondents. Two specific solutions (underground burial and reprocessing) account for the largest proportion of responses in this category. Finally, utilizing alternative energy sources, least-cost energy, or conservation, is proposed by 22 participants, 21 of whom are in the sample of critics.

One important question in this research is whether different solutions are offered for technical issues versus institutional issues. The results suggest that standardizing reactor design, while viewed as a solution to both technical and institutional issues, is most frequently discussed as a solution to technical problems. In contrast, regulatory reform and solving the waste problem are viewed primarily as ways to resolve institutional issues. Energy conservation is seen as a solution to both technical and institutional problems by those who mention it.

A second important question is whether proponents and critics differ markedly in the solutions they endorse. Not surprisingly, the results point to some obvious differences. Proponents tend to favor standardized reactor designs and solving the nuclear waste issue through reprocessing, while critics most frequently mention conservation, increasing public awareness, and requiring better training. Many interviewees also believe that solutions do not exist for some issues facing nuclear power. For example, about one-fourth of the respondents view the problem of nuclear waste disposal as having no realistic solution. The two groups mention regulatory reform in nearly equal numbers, but even here important differences exist. Proponents focus on streamlining the process through options such as one-stop licensing. Critics primarily cite a need to break a historically close relationship that they perceive to exist between the NRC and the nuclear industry. Thus, the two groups come to widely differing conclusions about solving the major issues facing LWR technologies.

7.3.5 Defining the Issues

A major purpose of the issue definition task was to discover whether participants in the debate about nuclear power tended to view the issues as primarily technical or institutional in nature. Respondents were allowed to use the terms "technical" and "institutional" in an undefined way as they talked about the issues, but were pushed to tell us why they classified an issue as "technical" or "institutional." Table 7.1 provides the most direct evidence regarding these definitions. This table shows how each group of issues (e.g., cost-related issues, waste-related issues, etc.) was classified by proponents and critics. The table was constructed by counting each issue listed in each category as defined by the individual who mentioned the issue and summing these for that category. For example, 33 individuals identified cost related issues as important. Of these, 7 said the issue they mentioned was technical in nature, 9 said the issue was institutional, 15 believed

Table 7.1. Frequency of Classifications[a] for 11 categories of issues

Issue areas	Respondents' classification of issue[b]: Technical Pro	Technical Critic	Institutional Pro	Institutional Critic	Both Pro	Both Critic	Total[c]
Cost-related issues	4	3	5	4	2	13	33
Waste-related issues	1	3	3	3	1	10	25
Safety-related issues	1	2	4	3	1	11	22
Regulatory issues	1	1	7	2	0	5	18
Public acceptance/ participation	1	0	5	2	3	1	15
Management issues	1	0	3	1	7	2	14
Nuclear weapons issues	0	0	1	5	3	3	13
Technical complexity	2	2	1	2	1	2	10
Design process issues	2	2	4	0	2	0	10
Demand projections	0	0	6	1	0	1	9
Total	13	13	39	26	22	48	174
Total for each type of issue	26		65		70		

[a]Respondents were asked: "How do you classify this issue?"

[b]Thirteen respondents classified issues as "other."

[c]Totals represent inclusion of "other."

the issue was both technical and institutional, and 2 gave some other label to the issue (the last group is not shown). These responses are also broken down by proponents vs critics.

Several important points can be made about these results. First, the bottom row of the table shows the total number of times each definition was used. The most frequently used response (70 responses) is "both," suggesting that participants are aware of both the technical and institutional complexities of the nuclear debate. The second most frequently used response (65 responses) is "institutional," which appears to support strongly the view that nuclear power's problems are more a function of the social context of the technology than the technology itself. Study participants used "technical" 26 times in defining major issues, suggesting that few major issues are perceived as purely technical in nature. Finally, most people felt reasonably comfortable with the technical/institutional terminology since very few offered other labels when given the option. Out of 174 issues being classified, respondents gave "other" as a response only 13 times.

The second important result in Table 7.1 is the apparent differences between proponents and critics in the labels assigned to the issues. The second to the last row of the table reports the number of times proponents and critics used each label. The difference is quite striking. Proponents are more likely to define issues as institutional (39 responses), whereas the critics most frequently define issues as both technical and institutional (48 responses).

These differences are most evident in the first three categories of issues. The majority of critics describe the cost, safety, and waste issues as both technical and institutional. For critics, these are the major issue areas, and they do not believe that the technical problems have been fully resolved; nor do they believe a technical fix will solve the problems. In part, classifying the issues as both technical and institutional may very well reflect a strategy by critics to keep their options open in critiquing nuclear power. Broadly based criticism of nuclear power, encompassing both technical and institutional dimensions, is likely to gain wider support than a narrowly focused critique. However, it would be a mistake to assume that critics are simply manipulating the issues to gain support. The response we received suggested that knowledgeable critics do have real concerns about both nuclear technology per se and about the institutional infrastructure in which it is embedded.

In contrast, proponents tend to define the issues they view as important as institutional issues. Proponents frequently mention cost, management, the regulatory process, and public acceptance/participation as issues. In most cases, the major issue involves a problem with organizations or institutions with which the industry must interact, not the technology. For example, regulatory issues are classified as institutional because nuclear power is faced with inefficient and costly licensing procedures and instability in the licensing process. Similarly, public acceptance is institutional because it is being affected by institutions that control the communication of information about nuclear power.

The one issue area that proponents predominantly define as "both" is the area of management issues. They view management issues as institutional because the problem involves personnel, training, and organizational characteristics, but they also view these management issues as technical because they partially involve technical problems in quality control.

Since the proponents and critics tended to select different issues in their initial identification of the issues, there are frequently too few responses in any one category to discern clearly a pattern in the definitions. But, taken as a whole, the results suggest strongly that proponents and critics define the issues in different terms. Critics seem more willing to point to technical as well as institutional concerns, but proponents, apparently more confident of the technical reliability of nuclear power, tend to define issues as institutional.

7.3.6 Reasons Given for Definitions

The terms "technical" and "institutional" served as catalysts to aid respondents in gathering thoughts about an issue. Analyzing their use of these two terms provides an understanding of the interpretive set a respondent is bringing to the debate. By pushing respondents to use these terms, a clearer understanding can be gained of positions taken on various issues. The respondent has the option of rejecting the two dimensions entirely. Most did not. Nor did they see issues as clearly neither technical nor institutional. Instead, when asked why they considered an issue as technical or institutional, they analyzed the characterizations given for each issue and gave us reasons for their interpretation. These characterizations and reasons provide valuable clues to differences in the way proponents and opponents see what appears to be the same issue if you simply look at a brief statement.

When examining these reasons, the meaning of "technical" seemed a bit clearer to most respondents. The term "institutional" was sometimes broadened to social issues, and sometimes narrowed to refer specifically to political or legal questions.

Reasons given for the classification of the cost of nuclear power generation illustrate the complex answers given by the respondents. Persons labelling the cost issue as a technical problem most frequently see design and construction errors as creating a need for expensive corrective measures. They state that some of these problems could have been avoided by more thorough pilot plant work and testing. Persons labelling the cost issue as institutional argue that safety requirements cost money. Others see interest rates and the factors that lead to construction delays as interactive factors that increase interest paid by the utility. Regulation in an industry, which has no standard approved designs, increases costs as the regulators try to determine what is safe for each specific situation. The taxpayer or the rate payer pays for increased costs due to inadequate design and coordination of effort in plant construction.

Persons who see the waste disposal problem as a technical issue believe that no satisfactory solution has been discovered. A few believe that it was primarily a problem of finding a suitable site for long-term storage. Half of the persons who classify the issue as institutional see a technical solution as either available or close to available. However, political debate over siting, the role of government in providing waste disposal sites, and the general unwillingness of business, the utilities and the government to provide final answers suggest that the issue should be called institutional.

Safety-related issues are labeled as institutional by two-thirds of those mentioning them. An important theme running through the answers of those who see this as an institutional problem is the perception that the nuclear industry is not to be trusted. These respondents contend that nuclear power generation requires risks; the risks are taken without consulting the public; financial concerns and the threat of bad press on the public health problems keep the industry silent about their controversial actions.

An examination of reasons given for classification of the regulatory issue revealed most answers emphasized institutional themes. The NRC is an important focal point in these responses. Problems with the agency are noted. Some proponents see these problems as classic bureaucratic ones where access and response are difficult to obtain and slow to come. Discussion of management issues echo the problems mentioned in the regulatory area above. Proponents emphasized this issue and noted that no one appears to have final responsibility for establishing design standards. The diffusion of responsibility leads to licensing by proper documentation and causes problems in the quality control process by requiring multiple reviews of the completed work.

The reasons given by proponents for the lack of public acceptance emphasize that the industry has failed to communicate with and educate the public. Most of the reasons offered by both proponents and critics for the public acceptance problem emphasize the institutional aspects of the problem. Reasons given for the nuclear weapons issue include both technical and institutional dimensions. While neither proponents nor critics view the issue as strictly technical, reasons given by both critics and proponents indicate proliferation is seen as an institutional issue. Critics emphasize institutional themes in their reasoning (for example, they mention problems of organizing the protection of nuclear plants from sabotage and the problem of political stability with respect to the governments to whom we sell the technology.

Interestingly, the technical complexity issue is interpreted as an institutional problem in that the industry has not developed the ability to construct plants economically. This issue repeats themes of regulation, design problems, and available knowledge.

The design process is described more often as an institutional issue, where the focus among both proponents and critics is on design standardization. Demand projections were viewed as being both technical and institutional. Some see these projections as a result of poor technical judgments, others see this as an institutional problem of failure to question the projections.

7.3.7 Implications for the new nuclear reactor technologies

This task is largely an exploratory effort. Any specific implications for future reactor concepts must be speculative. With this in mind, the following points summarize some of the major implications of the issue-definition process and this research:

1. The major issues facing nuclear power are defined as having important institutional dimensions that make a technical fix approach incomplete. (We find very few issues defined as purely technical).

2. Survey participants view nuclear technology as embedded in a broader social context that will have major influence on the future of nuclear power. (Many of the issues identified by study participants involve forces not controlled by nuclear engineers and the nuclear industry).

3. Both critics and proponents expect no new nuclear plants in the immediate future. (There are too many unresolved issues facing the industry).

4. Where proponents and critics identify similar issues, the issues often have different meanings and different potential solutions.

5. Proponents and critics identify different issues as critical. (Many proponents focus on management issues whereas critics tend to concentrate on waste disposal issues).

6. Proponents tend to believe that nuclear technology is a safe, efficient technology, but institutional problems have prevented the industry from achieving what they considered to be successful operation (proponents classify issues as institutional). Opponents do not trust technical claims of the industry and they feel that current institutional arrangements are unfairly supportive of the nuclear industry. (Critics tend to view issues as both institutional and technical).

7.4 INDUSTRY DECISION MAKING AND FUTURE NUCLEAR MARKETS

The issue definition research provides some insight into the conflicts surrounding the use of nuclear power. To explore these conflicts further, an analysis was conducted on the decision making process of the electric utilities with respect to new capacity additions. This analysis emphasized the preferences of the utilities and the constraints imposed on these preferences by two external groups, the state public utility commissions and public interest organizations.

7.4.1 Reasons for Looking at the Decision Making Process

To understand the preferences of the utilities for specific reactor characteristics, case studies were conducted to examine the process by which new capacity decisions are made at different utilities. Direct analysis is likely to be unreliable because utility executives, asked about nuclear power, repudiate the idea of purchasing nuclear generation based on current experience, and are reluctant to project themselves into future circumstances when the nuclear option may prove more attractive than at present.

It was therefore decided that the best way to project what the systems planners might do in the year 2010 is to look at the process rather than to conduct an attitude survey of the present incumbants of systems planning departments. A method was designed to investigate the criteria used to select new capacity, the types of employees participating in capacity decisions, the data sources and modeling techniques applied, and the alternatives considered in a particular utility's process of capacity choice. Concentrating on these factors allowed a long term view of how preferences for specific technical characteristics would be formed. The underlying premise of the research is that the process of decision making ultimately influences how alternative technologies are valued by the utility. If the process differs among utilities, presumably their preferred choices will also differ.

Extensive interviews were conducted with a cross section of system planning personnel and executives of five utilities. The utilities chosen for these case studies were selected on four criteria. The first was based on a determination[2] of which regions of the country are likely to need new generating capacity within the time frame of the NPOVS study. The second was based on our prior experience of which utilities were likely to offer a good level of cooperation. The third was that the utilities studied should all currently own a nuclear power plant. The final criterion was to select as wide a range of organizational variation as possible so that a generalization that the entire industry makes decisions in only one way did not result from having selected only one kind of corporate culture. This was not a random sample and has no statistical significance, but it is justified as a pilot study that attempts to map out the terrain of the various decision making modes that exist within the utility industry.

In order to characterize these decision making modes, we developed a model of these processes from the social science literature. The model is used as a tool to explain decision making behavior and yields testable hypotheses that were used to structure the actual interviews.

The five utilities selected control generating systems that range from medium to large. Regions of the country included the southeast, mid-Atlantic, southwest, and west. One utility was not investor owned. In addition, limited interviews were conducted at two large municipal utilities.

7.4.2 A Decision Theoretic Model of Electric Utilities.

The modeling perspective on the process of choice that was used in this research is based upon cultural, or institutional, theories of decision making. Concisely, these theories argue that different institutional settings generate their own views of the world, in other words, a cultural bias[3]. In addition, important attributes can be identified for a cultural bias that lead members of that type of institution to favor a particular process for making decisions. Thus, the decision process is constrained by the corporate culture of the decision making institution.

The cultural model of the decision process differs most significantly from other theoretical approaches by using an institutional perspective rather than that of the individual decision maker. This is why it is more suited to the type of decision we are examining here, where new capacity choices are made within rather large and complex electrical utility corporations. Proponents of the cultural theory argue that the social institution is a more appropriate basis for analysis than the individual because the institutional culture already represents a degree of social consensus and is not as susceptible to such wide variations in values and viewpoints as individual thought.

Recognizing that there are features of the other major theoretical models that are important within a cultural framework, we developed a cultural model that reflects these features in the context of decision making. In the model developed for this task, the calculated, rational behavior associated with the expected utility model of economics[4] (here, expected utility refers to the expected satisfaction or gain that is derived from a particular decision and does not refer to an electric utility) and the bounded rationality behavior or "satisficing" of psychology and sociology[5] are not seen as two extremes of a single spectrum. Rather, they are treated as two attributes which, in combination, can be associated with the decision-making process of a particular type of institution.

Figure 7.1 summarizes the four ideal institutional types that are described by the model. The two variables or attributes that are combined to define the institutional characteristics, which are then associated with a particular decision-making process, are called "utility maximization" and "boundedness," respectively. Utility maximization refers to the degree to which the institution pursues a calculated process to maximize the net gain (usually, but not necessarily, defined financially) so as to select the optimal choice. A low degree of this attribute is consistent with satisficing behavior. In such cases, the institution is seen as simply trying to muddle through or "not rock the boat" when making major decisions.

Boundedness refers to the degree to which information is filtered or weighed by the routines of the institution. Important to this notion is the range or the scope of processes that are used by the institution to gather and manipulate information. For example, the number and quality of forecasting models would be of interest in determining the degree of

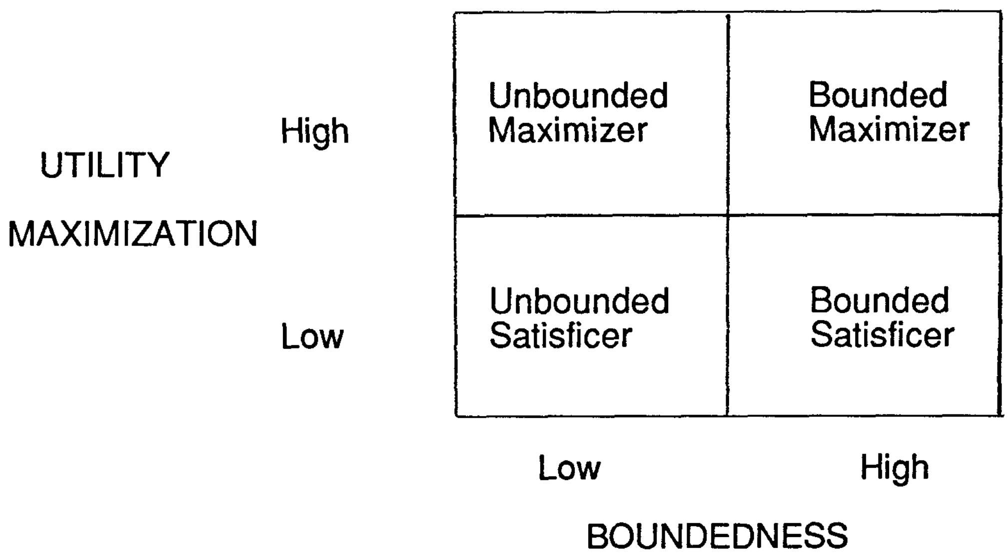

Figure 7.1. The institutional types of the Cultural Decision Model.

boundedness, as well as whether or not results from analyses prepared by the institution were validated by independent analyses. A high degree of boundedness would be indicative of a very limited collection and use of information, with little or no external influences. A low degree of boundedness would suggest multiple data sources, multiple computerized models for analyses, and a lot of input from outside analysts for both validation and additional information.

Looking at the diagram, the upper left-hand corner represents a combination of high utility maximization and low boundedness, "unbounded maximizers." This combination is associated with an institution where the objective of decision making is to maximize the gain to the institution, and information is actively sought, when it is profitable to do so, as a means to this end. Information from both internal and external sources is used and weighed equally in the decision-making process.

The upper right-hand portion of the diagram is associated with "bounded maximizers." Given the constraints on the way they collect and use information, institutions of this type will attempt to do the absolute best they can. These constraints may include the use of one or a small number of in-house models to analyze data that is also collected internally. The analysis and importance of the information is also likely to be constrained by strict channels of authority so that the filtering of information is routine within the institution. Thus, as long as alternatives and the decisions to be made are consistent with the internal routines, the institution will select an optimal choice. Otherwise, an optimal choice may not even enter into the decision process if relevant information about it has not already been introduced and promoted through internal channels.

"Bounded satisficers" are indicated by the lower right-hand portion of diagram. Here, an institution does not attempt to maximize its net gain from a choice, but merely picks a satisfactory alternative that meets its need to create as little discord over the decision as possible. As with the bounded maximizer, its range of alternatives is limited by the routines that govern information processing within the institution as well as its bias towards in-house analysis and experience.

The last type of institution is the "unbounded satisficer." This type has the advantage of the wide range and variation in information that is associated with a low degree of boundedness, but does not pursue the objective of making optimal choices with that information. The collection of information and its analysis is done for justificatory purposes only; real decisions are made on the basis of minimizing the amount of conflict that would arise from each of the alternatives under consideration. This type of institution will not use most of the information to improve the decision-making process, but rather, to protect the institution from criticism or attacks by others for "not knowing."

As outlined above, the Cultural Decision Model can be a useful tool to study actual decision-making processes of electrical utilities. Because it does not treat all utilities the same or lead to an endless list of heuristics and biases which yields ambiguous results, the Cultural Decision Model provides a practical means to describe this process without becoming too simplistic or too general. For example, if the model provides a good representation of reality, then clearly all electrical utilities do not use the same means to examine new capacity alternatives and do not have the same objectives in selecting among the alternatives they examine. Thus, any marketing program that targets a single reactor concept to be promoted to all utilities is likely to be inconsistent with the decision process of most, if not all, of its intended purchasers.

7.4.3 Generalizations About the Primary Market

Despite the fact that this study has emphasized the variations in utilities, there are some generalizations arising from the interviews that seem to apply across the board, based on explicit preferences expressed by interviewees. First, all utilities are likely to opt for a mixed generation strategy rather than concentrate on a single source such as nuclear, fossil or hydro. The question facing NPOVS is what are the utilities' preferences likely to be for one or another of the future nuclear options to fill any appropriate niche that might arise in such strategies? Therefore, we are faced with the dual question of what capacity needs are likely to arise in utility generation strategies and what is the preference of a particular type of utility likely to be to fill that gap?

The second generalization is that among those utilities that have a successful experience with LWR technologies, there is likely to be a preference for staying with the LWR technology rather than switching to a different nuclear technology.

Third, municipal utilities that we interviewed seem to have a favorable attitude to modular technologies, nuclear or non-nuclear, (they are aware of the modular HTR) because of the potential benefits of adding capacity in small increments when approaching municipal electorates for approvals for capacity additions.

7.4.4 Market Preferences Suggested by the Model

Having identified some generalizations that apply across the industry, there are some variations that are specific to the four categories of our cultural model. This model forces us to pay attention to three important factors for assessing future markets for nuclear technologies. First, the choices made by different organizations will vary, not just because of variations in market conditions, but because the organizations will have different preferences based on what kind of decisions they are trying to make. Second satisficing does not necessarily mean, as we shall see, that the decision maker is trying to avoid an experimental technology while utility maximization does not necessarily mean that decision makers will be adventurous. Third, the cultural model implies that there will not be a single set of criteria that all utilities will use for technology selection. However, characterization of the various utility decision making preferences will enable us to identify important packages of preferential criteria for technology selection. The results of the five case studies suggest that the Cultural Decision Model is potentially useful to predict the receptiveness of different types of utilities to new nuclear reactors. However, predictions at the present stage must be tentative and subject to validation through further research.

Unbounded maximizers may be generally described as using an innovative decision making structure. Indeed, the utility we looked at that has this kind of organization is currently conducting a variety of experiments with cogeneration, load management, and renewable energy resources. These decision makers express a singular lack of interest in any nuclear options. They regard themselves as having entered a post-nuclear era, and this self image clearly figures in their expressed preferences. Moreover, they are calculated risk spreaders. By looking at small-scale generation options that can incrementally increase their capacity, they do not risk a major investment loss from failure of any single option. To be attractive to these decision makers, any nuclear option would have to provide a very high probability of success, or provide a large incremental increase in income. A problem for such a utility is that any large increase in income might be disallowed by the PUC in determining rates.

The bounded satisficer is the opposite of the unbounded maximizer. At face value we would not expect these decision makers to experiment with innovative technologies. However, willingness to act as industry guinea pig may depend on the source of this utility's satisficing behavior. For example, a publicly owned utility which depends on legislators for funds, will tend toward satisficing behavior in order to avoid alienating political constituencies. Attempts at utility maximization in such organizations would likely place them at the center of political controversy and provide an unstable operating environment for the company. For this reason, bounded satisficers that are tied to local or federal government may accept the burden of risk from constructing and operating demonstration plants for new technologies if the legislators determine that a public good is being provided that would not be provided by private industry. Publicly owned utilities also have the advantage that they are not likely to be allowed to go bankrupt by the legislators that forced the burden of experimentation upon them. Therefore, counter-intuitive to our definition of bounded satisficers, they may prove to be the most fertile gound for promotion of new nuclear technologies.

Bounded maximizers would be considered a contradiction in terms according to classical organization theory, which tends to associate boundedness with the narrow vision characteristic of stereotypical, inefficient, self-perpetuating bureaucracies (the fuddy-duddy corporate culture). However, bounded organizations may be very successful if they have selected a decision making mode that is appropriate for their operating environment. Indeed, this was the case with the bounded maximizing utility that we looked at. Although they use a narrow range of models to assist decision making, collect and manipulate information internally, and operate according to well-established procedures, these decision makers are investor oriented, concerned with efficient use of resources, and are recognized as industry leaders.

The preference of this sort of utility will be for a technology with which it already has operational experience, in this case, a largely happy record with construction and operation of LWRs. Qualitative improvements to, or new technologies arising from, existing technologies will be received well here, but altogether new technologies would be more problematic and would have to emanate from within the organization in order to be accepted by it. Boundedness in this case precludes serious experiments with innovations proposed by outside sources. Because they are maximizers, these decision makers have none of the incentives to provide public goods that may prevail on bounded satisficers. However, extrapolating from the model, they may be persuaded to construct a demonstration plant if the industry as a whole (or the federal government) were to satisfy three conditions: First, the utility would have to be idemnified against financial loss. Second, the industry as a whole would have to guarantee availability of replacement purchased power at a cost no higher than the utility would have had to pay if it had constructed a plant of its own first choice. Third, the utility would have to perceive some advantage accruing to itself as compensation for its time and trouble. If these conditions are not met, bounded maximizing utilities are unlikely to venture far from the path of past experience in their selection of a generating technology.

Our final category is the unbounded satisficer. This type of utility would be one that collects a great deal of information, but is insulated from pressures to act upon it. The case of this type that we examined is a company that has a capacity glut, sells power outside, has a healthy bond rating and recently increased shareholder dividends without much apparent effort. The dominant ideology here is to hold the course steady, don't rock the boat, don't take any risks. This kind of decision maker can afford to sit back and observe industry trends, and follow those that appear to exhibit the most satisfactory balance of financial security and return on investment. There are no pressures to innovate here. These decision makers will be industry followers, not leaders in the adoption of new technologies.

7.4.5 Application of the Model to Three Key Issues

The preferences of each type of utility with respect to a wide range of relevant issues can be identified using the Cultural Decision Model model. For example, three issues are considered here; joint ownership, standardization and size. The predictions that we make are based on the formal properties of the model and exemplified by our case studies. Further, preferably quantitative, research is required for confirmation.

Joint ownership of larger nuclear units by several utilities is a fairly common arrangement for the current generation of LWRs either under construction or recently completed. Approximately 40% of these reactors involve joint ownership[6]. Joint ownership is an important issue for future reactor technologies since it affects financing, construction and operation management, and ultimately, reactor costs. Because of these issues and their relevance for the future construction of large units, preferences among utilities were examined for joint ownership of generating facilities.

The unbounded maximizer is likely to prefer joint ownership arrangements if the risks are balanced and the returns are consistent with other investments. The bounded satisficer is likely to respond to such arrangements based on the preferences of the constituencies to which the utility must supply public goods.

In contrast, neither the bounded maximizer nor the unbounded satisficer is likely to favor full joint ownership arrangements where financial and managerial responsibilities are shared with other utilities. However, the reasons for these preferences differ. The bounded maximizer, although willing to share the financial burdens with other investors, will prefer not to relinquish managerial control over one of its major generating sources. This derives from its confidence in its in-house capabilities. The unbounded satisficer simply dislikes the additional managerial complexity involved with maintaining joint ownership agreements. This type of institution seeks to minimize complications, and thus, it will avoid the contractual and political demands of these arrangemnts.

Preferences for standardization of plant designs are likely to vary consistently according to utility type. The unbounded maximizer has no inherent reason for supporting or rejecting plant standardization at either corporate or industry-wide levels. If it perceives design standardization within the corporation to be advantageous to its aim of delivering the best possible combination of profit and service, then the utility is likely to adopt its own standard, based on its own research and experience. If the utility perceives that industry-wide standardization will improve its own profit and service, then it will participate in the industry's standard-setting activities with the aim of setting the optimum achievable standard.

The pragmatic approach contrasts with the unbounded satisficer which will favor an industry-wide standard design as a way of spreading responsibility, demonstrating an industry consensus about the technology, and contributing towards a more secure and comfortable climate for its decision makers. However, this type will probably remain indifferent to corporate standardization unless there seems to be industry-wide recognition that benefits would accrue from such an effort.

The opposite preference is demonstrated by the bounded maximizing utility, which has little time for arguments in favor of industry standardization unless the industry is proposing to adopt the utility's own standard. There will, however, be a strong urge to standardize the utility's own plants according to its best operating experience.

The bounded satisficer will share this preference for internal corporate standardization and would also be happiest if its own standard were to be adopted by the rest of the industry. However, in contrast with the bounded maximizer, this sort of utility would probably prefer that the industry adopt any reasonable standard for the same reason as the unbounded satisficer; it views industry standardization as facilitating a stable environment for its operations.

These generalizations should apply to any attempts at standardization within the utility industry, irrespective of fuel sources. It has already been noted that the unbounded maximizing utility is the least likely of our four types to favor the new nuclear alternatives.

Consistent variations in utility preferences for unit size may also be predicted with reference to the Cultural Decision Model. Of course, each utility will prefer to follow the predicted pattern of load growth as closely as possible. However, different technological choices can force a decision maker to make different kinds of trade-offs. For example, we have already noted that the unbounded maximizer recognizes an advantage in being able to make incremental additions to capacity that enable it to follow the load very closely. It is likely, therefore, that these utilities will prefer smaller units, perhaps modular, regardless of fuel sources.

On the other hand, bounded maximizers are likely to opt for large plants, maximizing traditional benefits of scale for construction and operation. This will result in periodic leaps of capacity in excess of load growth. This kind of utility will aim to sell any initial excess capacity to other utilities until its own load curve catches up with its enlarged capacity. Small units are likely to be seen as wasteful of material and administrative resources.

Satisficers, both bounded and unbounded, seem likely to opt for the safest course of action in responding to load forecasts, which may be interpreted as a need to construct medium-sized units in order to ensure their ability to cover the load with the least risk of undercapacity (as faced by the unbounded maximizer) or overcapacity (as faced by the bounded maximizer).

7.4.6 Constraining Preferences of Secondary Markets

The preceeding section set forth criteria that utilities would generally prefer to use in decisions to build power plants. The following section discusses constraints exercised by public utilities commissions and interest groups on utility decision making.

The Public Utility Commission's (PUC) role in the marketplace is generally to approve the need, site, technological option, and apportionment of financial responsibilities for building a plant. Depending upon state legislation, PUCs may have a number of subsidiary responsibilities that affect plant certification and that give them considerable flexibility in fulfilling their primary responsibilities; however, a major exception is public safety issues, which are supposed to be within the sole control of the NRC. Because few plants can generate electricity without PUC approval, these state regulatory agencies hold a potential veto over commercialization of any nuclear technology. Thus, PUCs must be thoroughly understood regarding their legislative mandate, regulatory philosophy and procedures, analytical skills, and the degree of access of all parties to the state regulatory process.

Public interest groups have significantly affected the commercialization of LWR technology in recent years, and this role is likely to continue in the future because of the great interest in nuclear technology and provision of affordable electricity to the public. Opposition groups that were of particular interest to NPOVS were those that have enjoyed institutional longevity and continuing interest in nuclear issues and represent philosophical positions that are likely to remain current through the early 21st century.

Groups critical of nuclear technology were selected for study because of their ability to place major hurdles in nuclear licensing activities. These groups generally place critical importance on achieving their objective, which is stopping construction or operation of nuclear power plants. Their successes in slowing plant construction, if not stopping construction permanently, has made them a major factor to be reckoned with by the industry. As a result of this importance, it is essential to understand the perspectives of these groups on the technology and the issues it poses, as well as the regulatory process, their skill in obtaining access to and using the process, and their dedication to achieving a particular outcome.

7.4.7 Key Issues Shaping Criteria from PUC and Interest Group Perspectives

The responsibility of PUCs is essentially to ensure that the public is provided with reliable electric service at reasonable prices and that, in return, utilities are permitted to make an acceptable profit. Historically, there has been concern that PUCs, like many regulatory bodies, have been captured by either the regulated industry or the industry's principal antagonists. The anti-nuclear groups covered by this research appear to adhere to the general view that the PUCs are too closely aligned with the regulated.

No evidence obtained during the utility case study research indicated general bias for or against nuclear energy on the part of PUC commissioners or staff. Interest groups' perceptions of pro-utility bias by PUCs on the nuclear issues may be influenced by the PUCs' need to act within constraints established by their legislative mandates, the framing of issues within a practical, hands-on format closely associated with the manner in which utilities conduct business, and the legalistic, status-quo orientation of the regulatory process. Anti-nuclear groups generally view themselves as being on the fringes of the governmental process with little confidence in that process, whereas PUCs see themselves as legitimate, objective arbiters of the public good. These differing views are important to understanding the ways in which both types of organizations conceptualize basic nuclear issues. Such incompatabilities make the search for solutions considerably more difficult.

The different ways of conceptualizing problems are indicated in three critical regulatory concerns: (a) is there a need for the plant?; (b) who pays for the plant; (c) how will the technology be managed? The PUCs and intervenor groups tend to have different perspectives on these important concerns, as shown in Table 7.2.

In regard to the basic question of the need for the plant, the PUCs frame the issue primarily as a forecasting problem that simply requires the utility to present adequate data and justification that the power will be needed when the plant becomes operational. Many PUCs have also become involved in judging whether the utility has selected the correct

Table 7.2. Different emphases of PUCs and Interest Groups on parallel problems of utility capacity additions

Problem	PUC emphasis	Interest group emphasis
need for the plant	need for power	consent of affected parties
who pays for plant	allocation of costs	distribution of liabilities
management of the technology	management prudency	institutional trust

technological option to meet the demand forecast. While intervenor groups must contest the issues on these terms, since they are generally basic responsibilities of the PUCs' legislative mandate, the more important philosophical question in intervenors' minds is the need to secure consent of the parties affected by construction and operation of a nuclear plant. Rather than delegating responsibility to regulatory bodies to decide if the plant is needed, intervenors would prefer to decide, perhaps by popular referendum, if people want the plant. Thus, the perspectives on the basic concern of establishing the plant's need emphasize quite different, but parallel dimensions of the problem. The PUCs view the problem as essentially a technical one requiring use of accurate data and competent analytical procedures. Intervenors view the problem as an ethical one that requires the clear consent of people who will be affected by the plant.

The second important concern is that of who pays the costs of the plant. PUCs view this concern as primarily a financing one with some overtones of equity frequently entering the decision. If the utility can demonstrate that its construction costs were reasonably incurred and not the result of poor management, then costs of the plant will be allowed in the rate base and consumers will pay for the plant. If some construction costs are found by the PUC to be unwarranted, then the normal procedure is to pass those costs along to stockholders rather than ratepayers. The decisions about whether or not costs are warranted require detailed analyses and are highly technical.

Intervenors, again, tend to view concerns associated with costs of the plant in broader ethical terms. While intervenors will address the issue of paying for the plant on the PUC's terms because the regulatory process requires it, intervenors would prefer to focus on the more basic issue of who bears the various safety, economic, and managerial costs in society resulting from the plant and who enjoys the benefits and how can the costs and benefits be shared equitably. Thus, we again see differing views on a basic concern. PUCs view the matter in narrower economic terms requiring technical analyses of complex data, whereas intervenors concerns are directed at a number of broader social concerns that are difficult for PUCs to address even with an appropriate legislative mandate.

The last important concern is that of management of the nuclear enterprise. PUCs focus on issues associated with management prudency. Management prudency admittedly lends itself to vagueness and regulatory expansiveness and has evolved in recent years into a catch-all category of issues that facilitates greater regulatory intervention into utility management. This has occurred to the extent that virtually any utility decision appears subject to challenge by the PUC ex post facto.

PUCs frequently appear to approach management prudency issues from technical bases in the sense that technical problems may have been created or exacerbated by mismanagement. Also implied is the belief that use of the correct data and analytical techniques will produce the appropriate response if management is carrying out its responsibilities and that inappropriate responses may well indicate management imprudence.

Intervenors conceive the management concern to be not merely a judgement of the utility's qualifications but, also, a questioning of the regulators' qualifications as well. Ultimately, there is the question of whether nuclear technology can, indeed, be managed. Intervenors demonstrate a strong consensus among themselves that the technology is simply too complex to oversee and that nothing can be done to alter this inherent flaw. Their view of the regulators is that such agencies are too sympathetic to the industry and are not to be trusted. Thus, in respect to the concern of managing the nuclear enterprise, PUCs tend to view the issues in narrower terms that allow regulators to address specific management problems frequently in technical contexts. Intervenors expand the scope of management beyond the utilities to include any institutions that are responsible for nuclear technology. Their trust in these institutions is practically nonexistent (managers, regulators and the technology itself are parts of the nuclear problem).

Process is the domain of the regulators, and their objective is primarily the adherence to that process, as long as the outcome is politically acceptable. On the other hand, intervenors are concerned with achieving an outcome that is consistent with their anti-nuclear goals. Adherence to process is irrelevant. Their concerns are broad and directed at policy level questions for which regulatory environments are not well-suited. Indeed, intervenors in a very real sense are fighting legislative battles in regulatory proceedings.

There is no evidence to indicate that the situation described above will change fundamentally by 2010. PUCs throughout the country are important state regulatory bodies that oversee critical industries. Their regulatory responsibilities have been strengthened in many states substantially during the last decade in respect to plant certification, and they will remain viable agencies with considerable influence over implementation of any new nuclear technologies. It is also unlikely that liberal access to the regulatory process, the timing of such admittance, and the range of issues that are permitted will be restricted. Thus, in the absence of any major political changes, such as those that may arise from severe energy shortages, the regulatory process is expected to be reasonably similar to that used today, and the delays it encourages also are not likely to diminish. Similarly, there is no legislative interest in restricting judicial intervention in the process, and this open-endness implies a continuation of delays in building nuclear plants and in commercializing new reactor technologies.

7.4.8 Summary

This analysis of the potential market for new nuclear reactor technologies has resulted in a cultural model of decision making that describes four types of utilities and the response of each to these technologies. A number of tentative conclusions about the market were developed and summarized.

Although the case studies suggest that the model is a useful device to describe decision making behavior and predict the reactor characteristics that will appeal to different types of institutions, it is recommended that the model be validated with a larger sample. Subsequently, the validated model could be used as the basis for surveying the electric utility industry as a whole in order to provide a more accurate forecast of the potential market for new nuclear reactor technologies. The results of this survey should provide the necessary data to construct a map of the potential market for new nuclear reactors which would be based on the institutional, geographical, and economic characteristics of the users. Such a map would be valuable in shaping the development of these technologies.

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Wisconsin Electric Power Company

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* Now with JBF Associates, Knoxville, Tennessee,

APPENDIX A

INTERVIEW FORMAT FOR THE ISSUE DEFINITION RESEARCH
AND OUTLINE OF ISSUES USED FOR THE CASE STUDY INTERVIEWS

A.1 INTERVIEW FORMAT FOR THE ISSUE DEFINITION RESEARCH

The purpose of this project is to assess the issues relevant to the nuclear power debate. Specifically, to understand whether the issues are identified as technical and/or institutional (social) and the process by which they are defined as such. To accomplish this, we would like to first ask about issues associated with current Light Water Reactor (LWR) technologies (PWR's and BWR's) as you understand them and then ask about characteristics of future technologies.

Let me begin by asking a few questions on your background in nuclear energy:

I.

1a. Compared to the variety of proponents and opponents involved in the nuclear power debate, how knowledgeable would you rate yourself regarding Light Water Reactor technologies?

(Probe: on a scale of 0-100 where would you put yourself)

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1b. Compared to the variety of proponents and opponents involved in the nuclear power debate, how knowledgeable would you rate yourself regarding future nuclear power alternatives such as: Advanced Pressurized Water Reactor (ABWR); High Temperature Gas-Cooled Reactors (HTGR); Process Inherent Ultimate Safety System Reactors (PIUS); Liquid Metal (LM) and others such as Breeder Reactors?

(Probe: on a scale of 0-100 where would you put yourself)

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II.

2a. What do you feel are the four or five most important issues facing the development of LWR technologies?

(If response is general probe: what specific issues in this area will be important)

1.______________________________

2.______________________________

3.______________________________

4.______________________________

5.______________________________

ISSUE 1 ______________________

a. (Beginning with respondent's 1st issue), what solutions do you envision for this problem and why?

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b. How would you classify this issue? Do you view it as largely:
__Technical; __Institutional; __Both; __Other

c. Why do you classify it as such?

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ISSUE 2 ______________________

a. (Continuing with respondent's 2nd issue) What solutions do you envision for this problem and why?

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b. How would you classify this issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

c. Why do you classify it as such?

____

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ISSUE 3 ______________________

a. (Continuing with respondent's 3rd issue) What solutions do you envision for this problem and why?

b. How would you classify this issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

c. Why do you classify it as such?

ISSUE 4 ______________________

a. (Continuing with respondent's 4th issue) What solutions do you envision for this problem and why?

b. How would you classify this issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

c. Why do you classify it as such?

ISSUE 5 ______________________________

a. (Continuing with respondent's 5th issue) What solutions do you envision for this problem and why?

____

____

____

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b. How would you classify this issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

c. Why do you classify it as such?

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III.

Now let me ask you about a few issues that others have mentioned. Please tell me if you think this is an issue, why or why not.

1. NUCLEAR POWER PLANT DECOMMISSIONING ______________________________

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a. Given what you have said, how would you classify the issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

b. Why do you give it this classification?

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2. ADEQUACY OF ENGINEERED SAFETY FEATURES ____________________

a. Given what you have said, how would you classify the issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

b. Why do you give it this classification?

3. ADEQUACY OF MATERIALS USED IN THE MANUFACTURE OF CONTAINMENT BUILDING FOR THE LIFE OF THE PLANT ____________________

a. Given what you have said, how would you classify the issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

b. Why do you give it this classification?

4. ALLOCATION OF FINANCIAL LIABILITY FOR AN ACCIDENT ____________________

a. Given what you have said, how would you classify this issue? Do you view it as largely:

__Technical; __Institutional; __Both; __Other

b. Why do you give it this classification?

IV.

I would like to change the focus of the interview to the future of nuclear energy.

a. Do you think that in the year 2010 nuclear power will be more or less important or about the same as it is today?

__More important; __Less Important; __About the same

b. Given your estimate of the future of nuclear power, what issues would have to be resolved, or; what events would have to occur for it to become even more important than you expect it to be?

c. Given your estimate of the future of nuclear power, what issues would have to emerge, or; what events would have to occur for it to become even <u>less</u> important than you expect it to be?

d. What do you believe will be the three or four main sources of additional electric generating capacity in the year 2010 and beyond? Why?

1.

2.

3.

4.

V. Finally:

1. What training or background do you have in nuclear power production processes?

7

2. What is the highest degree you've earned and your major field of study?

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VI.

1. What would you say are your main sources of information regarding nuclear power issues?

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A.2 ISSUES FOR INTERVIEW WITH UTILITIES AND PUBLIC UTILITY COMMISSION

The following outline of issues was used as a guide in the interviews conducted for the case studies at the utilities and state public utility commission. These issues were used to lead the discussions with interviewees; however, topics that were discussed were not necessarily limited to the list below.

- Personal history, responsibilities of group, job description, prior experience with supply/and or cancellation decision

- The nature of the respondent's role

  - Perception of the role of other parts of the organization in the decision

  - Perception of external events on the process

  - Perception of external groups on the process

- Perception of the criteria and the decision process

  - Chronological sequence of events that would lead to a decision about capacity additions

  - What kind of events might interrupt the sequence?

  - Criteria to add supply/new capacity. Ranking.

  - Criteria to select among supply alternatives. Ranking. Discontinue construction, big vs small, cogeneration, joint ownership, fossil, nuclear, conservation, load management

  - Criteria to evaluate decision afterwards. Ranking.

- Provision of information

  - Informational input of the respondent to the decision process

  - When and how is the information of all parties synthesized for the decision. By whom?

  - Are there gaps or shortcomings in the process just described?

APPENDIX B

TABLES ON THE SAMPLE USED FOR THE ISSUE IDENTIFICATION RESEARCH

Table B.1. Number of interviews completed by selected background characteristics and orientation toward nuclear power

Background characteristics	Orientation toward nuclear power		
	Proponents	Critics	Total
Sex			
Male	17	19	36
Female	2	3	5
Location			
Washington, D.C.	10	8	18
Raleigh-Durham, N.C.	4	0	4
Atlanta, Ga.	4	1	5
Birmingham/Huntsville/Tuscaloosa, Ala.	1	2	3
San Francisco, Calif.	0	3	3
Chattanooga, Tenn.	0	5	5
Knoxville, Oak Ridge, Tenn.	0	3	3
Current position			
University faculty	3	1	4
Congressional staff	4	2	6
Government agency	4	1	5
Nuclear industry	6	2	8
Utilities	2	0	2
Lobbying groups (activist's groups)	0	10	10
Self-employed/consultants	0	6	6

Table B.2. Summary of self-ratings of knowledgeability regarding current LWR technology[a] and future nuclear energy alternatives[b]

Knowledge rating (0-100 scale)	Current LWR technology			Future Nuclear Alternatives		
	Proponents	Critics	Total	Proponents	Critics	Total
95-100	4	3	7	4	2	6
85-95	6	9	15	3	1	4
75-85	8	2	10	5	4	9
65-75	0	1	1	0	4	4
50-65	1	4	5	2	4	6
Below 50	0	2	2	3	4	7
No rating given	0	1	1	2	3	5

[a]Respondents were asked: "Compared to the variety of proponents and opponents involved in the nuclear power debate, how knowledgeable would you rate yourself regarding Light Water technologies?" (Probe: "On a scale of 0-100, where would you put yourself?")

[b]Respondents were asked: "Compared to the variety of proponents and opponents involved in the nuclear power debate, how knowledgeable would you rate yourself regarding future nuclear power alternatives such as: Advanced Pressurized Water Reactor (APWR); High Temperature Gas-Cooled Reactors (HTGR); Process Inherent Ultimate Safety System Reactors (PIUS); Liquid Metal (LM); and others such as Breeder Reactors? (Probe: "On a scale of 0-100, where would you put yourself?")

Table B.3. Frequency of training backgrounds by orientation toward nuclear power

Educational background[a]	Orientation toward nuclear power: Proponents	Critics	Total
Applied Science	8	2	10
Nuclear engineering	5	0	5
Mechanical engineering	3	1(2)	4(2)
Cybernetics	0	1	1
Basic Science	8	8	16
Physics	3	3	6
Chemistry	3	2	5
Biology	2	0(1)	2(1)
Mathematics	0(4)	2	2(4)
Geology	0(2)	1	1(2)
Business/legal/other	1	7	8
Business administration	0(1)	3	3(1)
Law	0	2	2
Planning	0	1	1
Education	0(2)	1	1(2)
Social science	2	5	7
(Social work, psychology, sociology, economics)	1(2)	3	4(2)
Political science	1	2(1)	3(1)

[a]The numbers is parentheses represent respondents who listed the given area as an additional or secondary area of training.

Table B.4. Frequency of highest degrees awarded by orientation toward nuclear power

Degree	Orientation toward nuclear power		
	Proponents	Critics	Total
PhD	6	8	14
MA/MS	6	8	14
BA/BS	6	5	11
Some college	1	0	1
No college	0	1	1

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