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NUCLEAR POWER OPTIONS VIABILITY STUDY

VOLUME I, EXECUTIVE SUMMARY

D. B. Trauger, Editor
J. D. White
R. S. Booth
H. I. Bowers
R. B. Braid
R. A. Cantor
J. C. Cleveland
J. G. Delene
Uri Gat
T. C. Hood[1]
T. Jenkins[2]
D. L. Moses
D. L Phung[3]
S. Rayner
I. Spiewak[4]
K. D. Van Liere[5]

[1]The University of Tennessee
[2]Tennessee Valley Authority
[3]Professional Analysis, Inc.
[4]Consultant
[5]The University of Tennessee (now with Heberlein Baumgartner Research Service, Madison, Wisconsin)

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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
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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 selected on the basis of three ground rules: (1) the potential for commercialization between 2000-2010, (2) economic competitiveness with coal, 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. Although the information available is not adequate for a definitive evaluation of economic competitiveness, all of the concepts appear to be potentially viable in the time frame selected. Public and institutional acceptance of nuclear power was found to be affected primarily by four issues: (1) operational safety, (2) waste handling and disposal, (3) construction and operating costs, and (4) the adequacy of management and regulatory controls.

1. INTRODUCTION

The Nuclear Power Options Viability Study (NPOVS) was initiated at the beginning of calendar year 1984 by Oak Ridge National Laboratory (ORNL). The objective of NPOVS was to explore the viabilities of several nuclear electric power generation options for this country in the 2000-2010 time frame. The identification and development of methods and criteria for evaluating new reactor concepts were important efforts. Innovative concepts were identified that may be marketable at the time when studies show that the demand for new electrical energy capacity is expected to have increased significantly. These concepts were considered and evaluated with respect to the criteria and with emphasis on cost, safety features, operability, constructibility, regulation, research needs, and market acceptance. Nuclear reactors are recognized as a valuable resource to meet future energy demands.

ORNL, recognizing the need for a broad base of knowledge and experience, engaged the Tennessee Valley Authority (TVA) and The University of Tennessee to participate as partners in the study. TVA concentrated its efforts on evaluation of the concepts and licensing. The University of Tennessee assisted in the evaluation of construction costs and public opinion issues. Both institutions contributed extensively to the evaluation of issues and in review of the reports. In conducting the study, the authors extensively contacted segments of the nuclear industry for current information concerning the concepts studied and for other valued assistance.

Many of the problems encountered by the nuclear industry are institutional in nature and relate to the way in which the utility companies, designers, constructors, and regulators are organized and function. This study attempted to identify these institutional factors but has not addressed them in all aspects. It was observed in the study that the institutional problems derive in some measure from technical features, which, in turn, originate at least in part from the large size, complexity, and exacting requirements for existing nuclear plants. Emphasis in the study was placed on the technical aspects that have potential merit and on improved design concepts that can help to alleviate institutional problems. Other institutional factors are addressed, first, where they are judged to have a substantial impact on technical features of design and construction and, second, with respect to market acceptance. Consideration of additional institutional aspects is thought to be desirable, perhaps necessary, but is beyond the scope of this study.

The study emphasized criteria by which nuclear power reactors can be judged and which are considered appropriate for judging future commercial viability. Other design or operational needs that are important but are more difficult to quantify were also considered. These are presented as either essential or desirable characteristics. Several innovative reactor concepts are described and evaluated with respect to these measures.

This study differs in several respects from other studies concerning the future of nuclear power in the United States. The first is the time frame of interest. The NPOVS effort was focused on a little later period (2000-2010) than most studies. For the near term, existing Light Water Reactor (LWR) designs, or their evolutionary modifications, are available nuclear choices if there is a sufficient demand for increased electrical generating capacity. Projections by the electric industry indicate that new base load capacity will be needed before the year 2000. Therefore, it is highly probable that decisions to order baseload capacity will be made by 2000-2010 (Ref. 1) and, furthermore, that the reactor concepts discussed in this report have the potential for competing with existing LWR designs or coal-fired plants at that time. For the more distant future, nuclear plant concepts incorporating more innovative, if not revolutionary, features could be the best choices.

The second aspect making this study different is the level of technical detail considered in evaluating the specific designs. A significant amount of design information was generated in the last three years by all of the nuclear designers involved with innovative concepts, and much of this information was made available to the NPOVS. Recognition has been given to the special features of each concept and thus to the role that each may achieve in a mature nuclear economy.

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 the various nontechnical factors that influence commercial use, for example, regulatory requirements, industry perspectives on future technologies, market acceptance, electric power growth needs, and economic conditions.

The report of the NPOVS is organized into four volumes, as follows:

- Volume I, Executive Summary
- Volume II, Reactor Concepts, Descriptions, and Assessments[2]
- Volume III, Nuclear Discipline Topics[3]
- Volume IV, Bibliography.[4]

2. CRITERIA FOR EVALUATION OF CONCEPTS

An early effort of the study was to develop criteria that reactor designs would have to meet to become viable in the future. In the reactor assessments, these criteria were used as a guide to assess nuclear concepts. In most cases, lack of data necessitated the use of engineering judgment to determine the status of, or potential for, conformance with the criteria. Often such judgments must be supplemented by the formulation of further R&D needed to facilitate more reliable conclusions. These needs are identified for each of the concepts.

The evaluative criteria established in this study 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 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 items 1 and 2 deal with the probabilities for successful operation or failure, items 3 to 6 are primarily economic, and item 7 relates to demonstrated operational experience. However, we deem each criterion to have sufficient stand-alone merits to justify separate consideration.

The criteria are augmented by a list of characteristics that provide further guidance for properties judged to be of importance to nuclear power viability. The characteristics chosen are not as quantifiable or demonstrable as are the criteria and have been chosen to include features that complement and amplify the criteria. 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.

Related desirable characteristics are as follows:

1. practical research, development, and demonstration 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. 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.

3. CONCEPT SELECTION AND CLASSIFICATION

In selecting the concepts to be studied, three ground rules were used:

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 heavily on mechanically or electrically activated and driven devices as employed in active (engineered) systems.]

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[5]

    - Small BWR (Boiling Water Reactor) - promoted by General Electric (GE)[6]

2. Liquid Metal Reactors (LMRs)

    - PRISM (Power Reactor Intrinsically Safe Module) - The GE advanced concept supported by DOE[7]

    - SAFR (Sodium Advanced Fast Reactor) - The Rockwell International (RI) advanced concept supported by DOE[7]

    - LSPB (Large-Scale Prototype Breeder) - The Electric Power Research Institute-Consolidated Management Office (EPRI-CoMO) concept supported by EPRI and DOE[8]

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.[9]

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.

4. SUMMARY OF FINDINGS FOR CONCEPTS

Most advanced reactor concepts are smaller than present LWRs; therefore, they suffer the economic disadvantage, whether real or perceived, associated with economy of scale. This disadvantage is claimed to be offset or compensated for in varying degrees through an improved match with load growth, reduction in capital risk, increased shop fabrication, shorter construction time, increased standardization, design simplification, and less demanding construction management requirements. Licensing may also be simplified if credit can be taken for passive safety features such that other traditional safety systems, required by the defense-in-depth philosophy, can be eliminated. A substantial problem in achieving these compensations derives from the need for a large front-end investment for certain of these features. Automated shop fabrication, in particular, will require a substantial backlog of orders to be economically feasible. Nuclear plant standardization is widely viewed as an important goal for viability.

To be concise in this summary, we have assumed that the reader is familiar with the concepts. The claims, advantages, disadvantages, and important development needs will be summarized in the order in which the concepts are described in Volume II of this report.[2] It must be noted that each of these concepts is currently in design development. The descriptions and assessments of this study reflect the status for each as of September 1985 except that some updating has been done where information was readily available. The reader should recognize that further development is expected to change design features and thus affect the conclusions from future evaluations.

All the concepts chosen for the study appear to be potentially viable, but the available information has been insufficient to fully assess their economic competitiveness. Specific findings for each concept follow.

4.1 PIUS

The basic design premise of this concept is to achieve a very high degree of passive safety with respect to equipment failure, operator error, and external threats. The large pool of borated water, which can enter the core without mechanical, electrical, or operator action, is to provide both shutdown and seven days of passive cooling for decay heat removal. These claims appear to be justified, although questions remain concerning the safety of fuel and equipment handling operations within the pool. The availability of water for introduction to the pool after seven days is site dependent but potentially viable. Overall, the concept appears to be licensable without major redesign, assuming that the NRC will accept a reactor with no control rods. The features that promote safety also appear applicable to protection of the investment. ASEA-ATOM claims that the plant can be economically competitive with coal-fired plants. This may depend on further evaluation of the identified problems that follow.

The steam generator located inside the Prestressed Concrete Pressure Vessel (PCPV) is of a difficult design with respect to maintenance. This and the problems of handling fuel and equipment deep (30 m) in the pool require careful design and detailed assessment and are considered a disadvantage with respect to the potential availability of the plant. Management of refueling appears difficult for the three-core design if the sequence becomes out of phase.

Development and testing needs include further demonstration of fluid interface stability, extensive study and testing of steam generator modules, thorough testing of underwater fuel and equipment handling systems, steam flow and pressurizer stability for the multimodular design, thermal insulation development and testing, and demonstration of the PCPV design, particularly for the top closure. A demonstration reactor may be required to adequately test the novel features of the concept; however, this plant may be determined commercially viable following a successful test period.

4.2 SMALL ADVANCED BWR

This reactor obviously derives advantage from its many operating similarities to existing BWRs. The gravity-fed Emergency Core Cooling System (ECCS) appears well conceived and adequate to provide shutdown cooling for up to three days, although its reliability is dependent on a relatively untried fail-open valve. A reliable site-dependent supply of additional cooling water would be required beyond the three days. Operator training should be straightforward since the basic operation is similar to that of existing BWR plants. A first-of-a-kind demonstration whereby the plant would later be used for power production may be practical and adequate for this concept. In this case, the first plant essentially would be a commercial unit that is subjected to an extensive test program prior to acceptance by the utility.

Cost competitiveness is difficult to assess at this early stage of design development. Licensing requirements, although not thought to be particularly difficult, have not been adequately addressed. Model testing for the gravity-drain ECCS, steam injector testing, and thermal hydraulic and seismic analyses must be thorough. The depressurization valve also requires design, development, and testing.

4.3 LMR CONCEPTS

The LSPB is an evolution of previous Liquid Metal Fast Breeder Reactor (LMFBR) designs. It includes several innovations to reduce capital costs and to enhance safety. The latter include diverse and independent reactor shutdown and dedicated decay heat removal systems. Although this design offers lower costs than previous breeder concepts studied, these features are yet to be evaluated fully with respect to construction methods and licensability. The LSPB appears attractive in offering economy of scale and increased passive safety.

Since PRISM and SAFR are both under development in a DOE program and are at a preliminary stage, they were assessed primarily in common. LMRs benefit from the inherent features of low system pressure and high thermal conductivity of the coolant, which are common to all concepts. These features permit the design of primary containment pool concepts with reliable passive natural convection decay heat removal to atmospheric air. These smaller modular concepts provide potential for testing of the core stability for conditions that might result from reactivity increases or from loss of flow of primary sodium. In this respect, smaller reactors, in general, have an advantage over the larger LMRs. Although the hypothetical core disruptive accident (HCDA) is claimed to be incredible by the proponents, the case for disregarding this accident is yet to be approved by the NRC. If the Clinch River Breeder Reactor (CRBR) can be taken as a precedent, then it would be reasonable to expect that a HCDA would be a beyond design basis event (BDBE). Acknowledging passive accommodation of HCDAs could significantly reduce design complexity, facilitate licensing, and improve public acceptance. Reliable control rod shutdown systems, feedback response from temperature increases, and the resulting thermal expansion are important safety features. Although containments or confinements are provided, careful design and perhaps testing will be required to ensure that air oxidation of the sodium is unlikely. Such containments must be protected from external threats.

An advantage of the LMR is the extensive operating experience available from the Fast Flux Test Facility (FFTF), the Experimental Breeder Reactor-II (EBR-II), and from European and Japanese plants. However, much of this experience base is not at the utility level, and the loss of the Clinch River Breeder Reactor (CRBR) slowed the pace of development of LMRs in the United States. Even though it appears possible to design, construct, and operate a demonstration plant and to reach commercialization within the 2000-2010 time frame, it would require an early dedication to the task.

The availability of related experience, the simplicity of the proposed designs, and the passive features mentioned above strongly suggest that the licensing of these LMRs should be achievable. Standardization of reactor designs should enable a generic license to be issued by NRC thus limiting licensing consideration, after the initial plant, to site-specific issues. An obvious long-term advantage of the LMR is its potential for breeding and thereby creating an essentially unlimited extension of uranium fuel resources. This is not an immediate objective of the current program, but it should not be overlooked.

Historically, LMR concepts have had higher capital costs than LWRs. This cost experience is manifested in European as well as U.S. designs. Although the current concepts address this issue, it is not yet adequately resolved. The high burnup core designs represent one approach to overall cost reduction. Another disadvantage is the requirement for enriched uranium or plutonium as the starting fuel. The former is available from U.S. enrichment systems. The latter is at an early stage of both institutional and technical development for acceptable fuel reprocessing plants in this country, although considerable experience exists abroad and in military facilities. Other countries offer the prospect for purchase of plutonium fuel, but this is unlikely to be an acceptable continuing source. Once-through cycles are not adequate for long-term nuclear energy viability; therefore, reprocessing remains an important objective for future LMR concepts. Integral Fast Reactors, which would be collocated with the supporting fuel reprocessing and refabrication facility, face significant institutional problems for the combined operation.

LMR development needs include advanced core design and proven neutron counting systems, improved shielding, and self-actuated shutdown systems. Testing of heat removal systems is an obvious requirement. Depending upon the choice of initial fuel, the fuel cycle development requirements may be extensive. The metal fuel cycle, which is claimed to offer safety and operational advantages, requires an extensive fuel development and testing program. Concepts under consideration could benefit from proposed safety demonstration tests for licensing purposes; the experience would be valuable and analytical methods could be tested. However, we caution against overly optimistic expectations from this approach because many disturbances (such as the effects of severe seismic events, interference with air cooling, and sabotage) cannot be fully tested and would require extensive analysis for evaluation. A more desirable and convincing approach with respect to utility acceptance may be to construct and operate a demonstration or prototype plant based on an adequate program of analysis, component development and testing, and design. This plant probably could achieve commercial operation, but some iteration would no doubt be beneficial before selecting a specific design for standardization.

4.4 MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR (MHTR) SIDE-BY-SIDE CONCEPT

A high degree of public protection is achieved through a capability for extended afterheat removal through the vessel wall by convection, conduction, and thermal radiation without operator, mechanical, or electrical intervention. This advantage is made possible by the very high temperature capability of the fuel, including retention of fission products and the slow thermal response of the core, which eliminates the need for a fast-acting shutdown system. The same protection applies to the probability of events leading to a loss of investment and offers the possibility for advantageous siting of plants. The "low-enriched" fuel is beneficial for proliferation resistance but requires enrichment substantially higher than that of a conventional LWR (20% vs ~4%). The potential for producing high-temperature process heat is a long-term advantage.

A disincentive for the application of an MHTR in the United States is the poor performance to date of the Fort St. Vrain reactor (FSVR). However, the difficulties with this reactor are unique to its equipment and are not common with the new concept. (In many ways, the MHTR design can benefit from the lessons learned at the FSVR.) Also, the performance of the Peach Bottom Unit 1 reactor in the United States and of the AVR in Germany has been satisfactory. Since the THTR-300 reactor in Germany is the latest HTR to operate, its performance is important to watch.

The small base of operating experience in the United States suggests an important need for a successful MHTR demonstration plant. Because of the ruggedness and resiliency of the fuel and the inherently slow time response for temperature excursions, it seems possible that a demonstration plant could be used extensively for experimentation in safety and operability and could later serve as a first-of-a-kind power plant. However, since the design experience is also limited, it is quite possible that a standardized plant design might benefit from the experience of the demonstration.

Development needs include improved determination of fission product retention by the fuel coatings, graphite, and metal surfaces under hypothetical extreme accident conditions. Graphite development should include additional irradiation creep data, a statistically determined physical property data base, and evaluated failure criteria. Fuel fabrication development is far advanced in Germany and the FSVR fuel has been successful; however, the reference fuel for the MHTR has higher performance specifications than FSVR fuel. Process development and fuel testing are needed for production methods to meet the higher specifications. Structural materials development needs relate to obtaining physical property data to satisfy code requirements, including the effects of neutron irradiation on physical properties. Another important area of development is the testing of key components under actual conditions. This is especially important in the case of the circulator to assure high availability. Materials and corrosion testing for various projected impurity levels in the helium would also be desirable but probably is not a requirement.

5. SUMMARY OF TOPICAL FINDINGS

Several subjects that were judged to be important in the evaluation of concepts have been considered in detail, both for the evaluations and generically. These topics (Construction, Economics, Regulation, Safety and Economic Risk, Nuclear Waste Transportation and Disposal, and Market Acceptance of New Reactor Technologies) are discussed in order in the following sections.

5.1 CONSTRUCTION

The various constructibility claims, both expressed or implied, of the six NPOVS-selected reactor concepts were first reviewed and tabulated in a logical order (Table 2.1 in Volume III).[3] Factors that were considered include availability of information to support 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 studied is that the designers included 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 a limited-size, dedicated crew to increase field productivity; (e) limitation of safety-grade construction to the nuclear island with separation from the balance-of-plant (BOP) construction; (f) short construction schedules; and (g) effective project management.

Several design features would facilitate achieving these goals. Most concepts have built-in passive safety systems to cool the reactor core for several hours before additional remedial measures must be taken. These passive safety features enable many concepts to function with a smaller number of systems and structures than the number necessary for current LWRs. Reducing the number of safety systems and confining them to the nuclear island would permit savings in construction material, construction requirements, construction schedule, and quality assurance documentation 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 units 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, the sequential construction of smaller units can make the job more manageable and productive, but this approach is not the exclusive characteristic of the concepts studied. The passive safety features of the concepts and the proposed separation of the nuclear island and BOP construction should definitely help to reduce construction costs. However, care must be taken to insure that the total plant operates smoothly as a unit even if the BOP is not required to serve a safety function.

We recommend that more attention be paid to substantiation of the constructibility claims, particularly in comparison with current LWR technology in the United States and overseas. Recent studies concerning the capability of the Combustion Engineering heavy component facility in Chattanooga, Tennessee, to manufacture vessels for the MHTR and other concepts provide a step in this direction.

5.2 ECONOMICS

The goal of the economics effort was to gain an insight into the many factors that are important to the economic competitiveness of the various NPOVS concepts. It was not intended to rank one concept relative to the others but to form a basis for future efforts when more is known about the design and costs of each concept. The economic evaluation included analyses of capital investment costs, busbar power generation costs, and commodities necessary to build the plants. The objective of the analyses was to provide a perspective on the relative economics of the various concepts using traditional methods and not to offer a judgment on their absolute competitiveness. The analyses indicated that estimated capital investment costs for the modular plants generally fall below or at the the best of current-experience LWRs when the LWRs are scaled to the size range of the modular plants. The results of the analyses also showed that the power generation costs of all the concepts fall in the same competitive range. There are, however, large uncertainties in the cost information for all of the concepts.

The power generation cost comparisons are traditional busbar cost calculations and may not take into consideration factors that are important to the economics of small plants. Generic issues germane to the economic attractiveness of small modular plants relative to large plants include plant availability and reliability, shop fabrication, safety separation of the nuclear island and the BOP, modular construction and cost-size scaling, plant standardization, and fuel cycle.

Although there is room for improvement in availability for plants of all sizes, historically, small-size power plants appear to have had better experience than large-size plants.[10] Also, there is a smaller probability of losing generation from multiple small plants compared to one large plant of the same capacity, and, therefore, less total capacity is needed with multiple small plants than with one big plant.

Factory fabrication of plant modules is applicable for all sizes of plants, but the economic benefits may be realized only if there is a large order for such plants. However, factory fabrication is especially applicable to smaller plants since a larger percentage of the plant may be factory built in individual modules. A greater automation potential exists for construction of smaller units since a greater number of smaller units would be needed than large units for a given total capacity. However, the additional costs connected with factory fabrication, including costs for acquiring the factory facility and tooling up, transportation of modules, and carrying charges must be accommodated.

The physical separation of the BOP from the nuclear island offers potential for economic savings. A conservative analysis indicates that, if coal-fired plant placement rates are applied to the nonnuclear BOP, the overnight costs of nuclear plants can be reduced by nearly 10%, based on construction labor cost reductions alone. Additional savings in indirect costs will result from reduced labor content and shorter construction time, but additional costs may also be caused by dispersion of facilities and redundant construction management and facilities.

Small plants may have additional economic advantages relative to large plants when the utility system is included in the analysis. Some of these advantages include a better match to electric growth, thereby lessening overcapacity; shorter lead times for small plants than for large ones; better system reliability for a given capacity; and better accommodation of demand changes. There is also less financial risk, which leads to a potential decrease in the overall cost of money. Estimates indicate that utilities could afford to pay an additional 25% or more for a short-lead-time, modular plant than for a long-lead-time, large-size plant with no increase in average rates to the consumer.[11,12]

Plant standardization offers large potential economic advantages. A principal advantage is that the design and engineering costs are spread over a large number of units. Also, learning takes place as additional units are designed, thus reducing design cost, labor requirements, and lead time. The benefits of standardization apply to large-size plants as well as to small ones, albeit probably to a lesser degree, since fewer units would be built.

The fuel cycles for the PIUS and small BWR are the same as for current LWRs and will use similar fuel. The LMR and HTR fuel cycles will involve development and perhaps considerable capital investment to implement. However, HTR requirements are primarily for fuel testing and fabrication facilities since a once-through cycle is planned. Economic issues involve the cost for reprocessing and fuel fabrication, the economics of integral recycle facilities, use of enriched uranium for LMRs, plutonium value and tax treatment, and waste disposal issues. Preliminary studies (Appendix E, Volume II)[2] indicate that there is a cost disadvantage in small, integrated fuel recycle facilities relative to large, common, central fuel recycle facilities.

Further information, studies, and analyses are needed to properly evaluate the economic competitiveness of the concepts relative to current LWR technology and to coal-fired power plants. Of primary importance is the development of basic cost information for the concepts, applying consistent ground rules for all concepts. Also, each of the generic issues needs to be explored quantitatively in depth to determine if small plants in fact have an economic advantage relative to large plants.

5.3 REGULATION

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. Experience has shown that the licensing process can be cumbersome and unpredictable. A number of steps have been proposed which, taken either independently or in combination, would improve the regulatory climate both for existing reactor types and for new designs. A better integration of the design process, with a complete design available when a license is applied for, would facilitate the regulatory review and would reduce the number of changes called for during construction. The same design could be used for a series of plants, preapproved by the NRC as a standard design. When combined with a preapproved siting policy, preapproved standard designs would substantially reduce the front-end risk and would accelerate project schedules. There are also strong economic incentives to adopt standard plant designs. Several standardized plant programs were initiated in the 1970s but were terminated by plant cancellations.

The extensiveness of regulatory, as well as nonregulatory, backfits to operating plants and those under construction have been cited by utilities as major reasons for the decline of the nuclear option in the United States. Stability and consistency in the NRC regulatory process must somehow be achieved to make new nuclear plants viable.

The adoption of performance-based regulation, as contrasted with the present prescriptive mode, has been proposed as a means of stabilizing the regulatory process. The adoption of passive safety systems, such as are used in the concepts studied by NPOVS, may increase the applicability of performance standards.

The NRC has proposed an advanced reactors policy calling for simpler, more reliable reactor designs.[13] We believe that the concepts studied by NPOVS are consistent with that policy.

A number of licensing issues appear to be associated with the advanced concepts:

- The NPOVS reactor concept proponents, relying as they do on passive safety features to prevent adverse effects of accidents, in most cases claim that nuclear safety-grade equipment can be limited to the nuclear island.
- Proponents of some of the concepts believe that minimal or no containment can be justified because of a lack of credible severe accident sequences.
- Some proponents believe that a safety demonstration plant would greatly facilitate licensing.
- There is considerable support for the concept that very rare accident precursors, with frequency below some particular value such as 10^{-7} per reactor year, need not be considered as design basis events. However, current experience and probabilistic risk assessment (PRA) methods may not be adequate to establish such values.

Potentially large costs are associated with the resolution of these issues; therefore, early NRC consideration of these matters would be desirable.

5.4 SAFETY AND ECONOMIC RISK

The NPOVS criteria address safety and economic risk by providing limits for the probability of events related to safety and risk. The criteria require PRA to ascertain compliance. Since PRAs are not available for all of the advanced concepts, judgment has to be substituted. The broad use of passive safety features may eliminate the adverse consequences of many accident sequences, but the PRA would still be useful to identify deficiencies and to assure safe designs.

As the result of passive safety features, much more time would be available to reactor operators for the use of engineered systems or other emergency response (i.e., days for most anticipated accident initiators). The designers of passively safe concepts have responded to this characteristic in the following ways:

- Accident prevention as opposed to mitigation has been emphasized.
- Few or no operator actions are required.
- Simplified engineered safety systems, with few critical components, are used.
- In some cases, it is proposed to demonstrate safety by subjecting a prototype to specified accident initiators.

Circumstances other than accident risk may put the capital investment at risk and might be considered vital by investors. These include political actions (such as the Austrian Zwentendorf Reactor), quality assurance deficiencies (such as at Zimmer), or financial problems (such as at Marble Hill). Operation risk, related to unexpected events that affect revenue, can have very high costs. New and untested concepts are particularly vulnerable to operation risk. Preapproved standard plant designs with a good operational data base would tend to minimize the above risks.

Proponents of the advanced concepts have not in general calculated source terms for their systems. 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. This fraction is probably much greater than the actual release that would be experienced in most accidents. It is desirable that containments be designed to mitigate realistic source terms determined for the specific design.

Further investigation and research are required to reduce the uncertainties associated with safety and economic risk. These include attention to issues such as:

- Development of quantitative risk criteria for advanced reactors.
- Consideration of the significance of passive safety features to risk reduction.
- Determination of the frequency of rare events that would constitute a lower limit for design basis.
- Appropriate treatment of source term and containment for very safe designs.
- Appropriate focus on safety and risk reduction in the development and application of standard designs.

5.5 NUCLEAR WASTE TRANSPORTATION AND DISPOSAL

Legislation has been enacted that (if implemented as scheduled) would provide the technology and facilities for waste disposal prior to the year 2000. Utilities choosing to build one of the concepts studied by NPOVS should have firm guidelines on waste management and disposal by that time frame. The only reactor types considered here that may require special waste system development are the modular HTR and the metal-fueled LMR. For the former it may be desirable to reduce the high-level waste volume, and for the latter a new waste technology is required.

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

5.6 PILOT STUDY OF MARKET ACCEPTANCE OF NEW NUCLEAR TECHNOLOGIES

This part of the NPOVS represents exploratory research designed to provide a basis for assessing the market acceptability of new reactor concepts. The first part of the research addressed whether issues are characterized as technical or institutional by proponents and critics of nuclear power. Thus the market acceptance research dealt directly with the conflicts that arise from the persistent debates over the technology. The other part of the research sought to understand the conflict that emerges over nuclear power in the process of choosing the capacity needed. This research was carried out through a series of case studies of public utilities, public utility commissions (PUCs), and interest groups critical of nuclear power. This second study was focused on the utilities' preferences and the constraints imposed on these preferences by regulators and public interest groups. The two parts of the research were drawn together to define a set of major issues that are likely to be at the core of the acceptability question for new reactor technologies.

5.6.1 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
- a narrowing of the gap in construction costs between environmentally acceptable fossil and nuclear plants; and
- the absence of a third option for baseload power to compete with nuclear.

Even if all three necessary conditions are satisfied, there is no guarantee that nuclear options will be chosen. There is a further set of facilitating conditions that would substantially improve the position of nuclear technologies within the market. These include improvements in the following areas:

- stability of the regulatory environment
- improved accuracy and reliability of load forecasting techniques
- improved cost controls in nuclear construction and operation, including standardized or turnkey plants; and
- demonstrated technical feasibility of new nuclear reactors.

The first of these facilitating conditions has been highlighted by many utilities, only one of which appeared in the study, as the primary condition for their ordering new nuclear capacity. However, data from the utility respondents and economic behavior in other fields suggest that if the economic incentives are strong enough, regulatory difficulties will be overcome. This factor in market acceptability of new nuclear technologies, therefore, requires further investigation.

Interviews with decision makers of five utilities revealed the skepticism of the industry that these conditions will be met within the 2000-2010 time frame. Consequently, utilities indicated no active interest at present in constructing new nuclear units. However, nuclear options are retained in modeling possible alternatives for future baseload system planning.

5.6.2 Public Acceptance Criteria

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

- operational safety of power plants;
- transportation and disposal of nuclear waste;
- effect of construction and operational costs of plants on rates; and
- adequacy of management and regulatory controls.

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 four of these areas.

5.6.3 Generalizations About the Electric Utility Industry

Despite the fact that the research identified a variety of preferences in utilities, some generalizations arising from the case study interviews seem to apply across the board. First, all utilities will probably choose a mixed generation strategy rather than concentrate on a single source of supply. The important question is, "What nuclear options are likely to be chosen by the utilities to fit in with these plans for mixed generation?"

Second, 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 toward modular technologies, nuclear or nonnuclear, because of the potential benefits of adding capacity in small increments when approaching municipal electorates for approvals for capacity additions.

Several important factors were also identified that result from the institutional differences found in the case studies. The choices made by different organizations will vary, not just because of variations in market conditions, but also because the organizations will have different preferences based on the kind of decisions they are trying to make. This implies that there may not be a single set of criteria that all utilities will use for technology selection.

5.6.4 Constraining Preferences of Secondary Markets

The research identified that two of the major constraining forces on the utilities' preferred capacity choices, the state PUCs and public interest groups, will have different ways of conceptualizing problems in three critical regulatory concerns: (a) Is there a need for the plant? (b) How are costs distributed? (c) How will the technology be managed? The PUCs and intervenor groups tend to have different perspectives on these concerns, which, in turn, multiply the constraints on utility preferences.

In the absence of political changes, the state-level regulatory process in 2000-2010 is expected to be similar to that used today, and the delays it encourages are not likely to diminish. Similarly, there is no legislative interest in restricting judicial intervention in the process, and this open-endedness implies a continuation of delays in building nuclear plants and in commercializing new reactor technologies.

5.6.5 Future Research Directions

The results of the market acceptance pilot research indicate that much can be learned about the future of new reactor technologies from a more detailed application of the case study approach that focuses on industry decision makers. We recommend that the model be validated with a larger sample of utilities, PUCs and interest groups and that the model then be used as the basis for surveying the electric utility industry as a whole. The results of this survey should provide the necessary data to construct a map of the potential market for new nuclear reactors that 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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7. LIST OF PUBLICATIONS RELATED TO NPOVS

The reports listed below were derived either fully or in part from the NPOVS.

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