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Objectives for the development of advanced nuclear plants

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FOREWORD

The drafting of this report was initiated in late 1989 subsequent to the 1989 General Conference of the IAEA held in Vienna in September. In parallel with the General Conference, a Special Scientific Programme was held on the subject "The Next Generation of Nuclear Power Plants". Speakers representing the vendor/supplier industry, the utility/energy user industry and governmental agencies responsible for the development or the regulation of nuclear power plants were asked to express their views regarding requirements for the next generation of nuclear power plants. One of the recommendations from the Conference was for the IAEA to consider preparing a set of universally acceptable requirements for advanced reactors.

Initial considerations regarding the possible content of a document and its intended use were discussed during a Consultants Meeting held in October 1989. Endorsement for the preparation of the document was received from a Senior Advisory Group Meeting held in November 1989 in Vienna on the subject of future roles for the IAEA in advanced nuclear power plant development. The first draft of the document was prepared in early 1990 and was reviewed by consultants in May 1990. As a result of this meeting and a preliminary review by the International Working Group on Advanced Technologies for Water Cooled Reactors in June 1990, it was decided to rework the document so that it was less specific regarding design requirements.

The second draft of the document was prepared during the summer of 1990 and was reviewed by workshops held in conjunction with three separate Technical Committee Meetings organized under the framework of the three International Working Groups on advanced reactors as follows:

- Technical Committee Meeting and Workshop on Requirements for the Next Generation of Water Cooled Reactors held in Chengdu, China, 22-27 October 1990 attended by 18 participants from China and 27 participants from 17 other countries;
- Technical Committee Meeting and Workshop on Requirements for the Next Generation of Gas Cooled Reactors held in Vienna, 24-28 June 1991, attended by 23 participants from 12 countries; and
- Technical Committee Meeting and Workshop on Development Goals for Fast Reactors held in Vienna, 15-17 October 1991, attended by 13 participants from 10 countries.

Mainly as a result of these meetings and workshops, the document was again redrafted. Changes included a reorganization of the material under broad subtitles which have been typically used by the industry to categorize ongoing development work. An attempt was also made to include the multitude of comments received. Since some of the comments were inconsistent with the intent of the document or, in some cases, in conflict with each other, it was not possible to incorporate all of the suggestions.

The final version of the report was prepared during and subsequent to a Technical Committee Meeting and Workshop held in Vienna, 18-22 May 1992, attended by 20 participants from 13 countries. A. Goodjohn and J. Kupitz of the IAEA's Division of Nuclear Power acted as Scientific Secretaries for all of the Technical Committee Meetings. The final drafting was done by A. Goodjohn.

EDITORIAL NOTE

CONTENTS

1. THE STATUS OF NUCLEAR POWER

In the approximate one-third of a century since the beginning of its development for civilian applications, nuclear power has progressed to providing greater than one-sixth of the worldwide generation of electricity. About 6000 reactor-years of operating experience have been accumulated on several different types of reactor systems. Additions to fossil fueled electrical generating capacity have been correspondingly reduced.

The otherwise excellent safety record has been marred by two significant accidents at Three Mile Island (TMI) and Chernobyl. The accident at the Three Mile Island plant strongly influenced public opinion regarding nuclear power plant safety even though there were no public consequences. However, the feedback from the TMI accident has led to large improvements in the design and in the man-machine interface, particularly through better training of operators. From this point of view, the consequences of the TMI accident can be considered beneficial for nuclear safety. The accident at Chernobyl did have significant off-site consequences and exacerbated the public opinion problem on a more worldwide scale. These two accidents have had a profound impact, more so than any other factor, on the continued deployment of nuclear power. Although the use of nuclear power has indeed expanded worldwide, the expansion has been much less rapid than had been earlier forecasted. While some countries have been able to continue their nuclear power programmes, the nuclear programmes in several other countries have completely stalled and new generation capacity, where needed, has been primarily fossil fired. Moreover, nuclear power is not being deployed in many developing and industrializing countries whose increasing electricity demands are presently being met almost entirely by fossil fired generation. This gives rise to the threat of several potential major risks, mainly with respect to:

- Ecology: Increased rates of consumption of the world's finite resources of oil, gas and coal, leading to higher prices and a decreasing capability for developing countries to develop economies that relieve the concerns regarding the over-exploitation of nature (deforestation, soil erosion, etc.).
- Climate and environment: Increased levels of CO_2 and other gases from fossil fuel burning, threatening deterioration of the climate and other environmental impacts which would worsen the living conditions for an increasingly larger proportion of mankind.
- Political conflict and possible war due to increased dependence on oil imports from politically unstable countries.

Conservation of oil, gas and coal for future generations and preserving land masses from being flooded for hydrogeneration are also of paramount importance.

Some retraction from the optimistic early forecasts for nuclear power deployment is recognizably due to significant decreases in the electrical energy growth patterns in many countries. But the more significant factors have been the increased relative concern on the risks associated with nuclear technology compared to the concern on the risks associated with energy production by other technologies and the increased intensity of safety regulation and public scrutiny following the two aforementioned accidents.

Public scrutiny, in fact, has expanded into areas other than just safety. The concerns related to economic competitiveness, to plant reliability, to waste handling and to the capability of understanding and managing the complex nuclear enterprise are notable examples. Unless significant changes are made in the level of public acceptance through improvements in the technology, in its management and in the manner in which government policies are structured and handled, nuclear power may not expand much beyond its present level. In fact, the use of nuclear power may slowly decline as nuclear plants presently under construction or operating reach the end of their useful lifetimes, no new commitments are made and various moratoria continue in most countries. Even today, this trend is being displayed in forecasts which show nuclear power's contribution to future worldwide electricity generation essentially levelling off over the next 15 to 20 years and, in some countries, actually peaking and declining thereafter.

The development of advanced nuclear plants is considered to be one of the key steps in resolving some of the issues. The use of the word "advanced" in this context means any nuclear plant which is not yet operating and is therefore being developed, designed or possibly in construction. All advanced nuclear plants take into account the experiences gained from presently operating nuclear plants and the issues already described. Likewise all of these advanced nuclear plants have the goal of offering some degree of improvement in areas such as safety, reliability, economics, etc. All are evolutionary in the sense of basing the indicated improvements on the use of proven technology and accumulated experience.

All advanced nuclear plant designs can be divided into two groups. One group can be termed "evolutionary" since the designs emphasize improvement based on proven technology and experience. The other group can be termed "innovative" since the designs emphasize the use of new features, particularly with regard to enhancing safety. While there is clearly some innovation in the "evolutionary" designs and evolution is clearly being considered in the "innovative" designs, it has been convenient and well accepted to distinguish the two types by whether a prototype reactor plant is needed. Thus, "evolutionary" designs are those designs which do not require a prototype prior to commercial introduction. "Innovative" designs, on the other hand, are those designs having so many new features that a prototype may be needed. Hence "evolutionary" designs are expected to be ready for commercial introduction before the "innovative" designs. The objectives of this document apply to both evolutionary and innovative designs.

2. OBJECTIVES FOR THE DEVELOPMENT OF ADVANCED NUCLEAR PLANTS

Worldwide, at least 20 different advanced nuclear plant designs are being developed. All of these advanced nuclear plant designs reference the key words enhanced safety, improved reliability and better economics in stating the overall objectives for their development. Some of the advanced designs have also indicated the goals that are intended to be met as result of the development work. More detailed design objectives (or subobjectives within the broad framework) and goals are typically established on the basis of prior knowledge of the expectations resulting from a design change, a design improvement or the incorporation of a particular feature in a particular reactor type, e.g. as shown in Refs [1-6]. In most cases, the national interest in the development of a particular advanced nuclear plant(s) took precedence in the setting of these detailed objectives and goals so as to establish a pattern for the national advanced nuclear plant design effort. Moreover, the policies, rules and regulations of that country are implicitly included, as are also the experiences gained from the already operating reactors in that country. All such efforts are obviously commendable since they are within the framework of the basic motivation for advanced nuclear plant development and design.

Yet, several more global trends should also be considered. First, and probably foremost, is the trend towards minimizing the environmental impact of the energy cycle, including mining, transportation, plant operation and waste disposal. Although this relates to some obvious factors such as noise levels, land use and thermal releases, the major concern with nuclear plants relates to releases of radioactive material both on-site and off-site during normal operation and particularly as a result of potential upset conditions. Emergency plans involving the possible need for rapid sheltering or evacuation of the proximate public after an accident and the possible subsequent limitations on land use have become a significant burden in some countries. The absolute aversion to sudden catastrophic events, such as Chernobyl, which have both national and international consequences, is apparent.

Second, it has also become apparent that efforts should be made to simplify nuclear power plants, to gain higher reliability, to standardize equipment, to harmonize procedures, rules and regulations, to clarify policies, to establish the means to handle wastes and to generally require a less complex infrastructure to manage the enterprise. Gaining such improvements would certainly tend to improve the economic competitiveness of nuclear power. These matters become especially important when considering the greater use of nuclear power worldwide, particularly in developing countries [7].

A third consideration relates to the fact that the nuclear enterprise is indeed becoming a global enterprise. The formation of consortia, national and international, to undertake development, design and supply and to also spread the risks has become a trend. The intent to be suppliers to an international market is apparent. The need for standardization, objectives, goals and for a broader basis for the accumulation of operating experience and learning therefrom become obvious for such undertakings.

Advanced nuclear plant designs do appear to be taking into account some of these aspects. Nevertheless, the extent to which this is true is difficult to ascertain. Hence, objectives which are expressions of a more globally harmonized interest would be useful; and, even more so, the goals or the intended end result of the development effort.

Most of the objectives as used in this report are qualitative expressions of what an advanced nuclear plant designer <u>should be</u> aiming for. The remaining objectives have a direct impact on the economics and marketability of nuclear power. The top-level or broad objectives of enhancing safety, improving reliability, etc., are not new. They have been used universally to justify and motivate the development of new products, improve existing products, perform continuing research, etc. The goals, i.e., the quantitative, the semi-quantitative or even qualitative statements of the intended end result of the development, have been changing as time and the technology have progressed. It is, in part, the various aspects discussed herein that are motivating further changes in the goals beyond those contemplated from normal product evolution.

In this context, the subobjectives as used in this report are, similarly, qualitative statements regarding the intent of various development programmes which are related to the broader objective. Many of the subobjectives and the goals may be interrelated within the same broad objective or be cross-related to some other objective. Hence, trade-off studies may be required to determine the appropriate goal. In such cases, the report only identifies matters that should be considered.

Certainly, neither the objectives nor subobjectives are intended to be expressions of how the advanced reactor shall be designed. Indeed, in the following text, the prescriptive verb "shall" will not be used unless it refers to some accepted standard to which it is believed all designs must comply.

The evolution of advanced nuclear plants to meet future goals also demands, correspondingly, an evolution of the regulations, standards, etc. which form the bases for designing, licensing, constructing, operating, maintaining and decommissioning the plant. Interaction between all parties involved for such evolution is necessary. Explicit treatment of this topic is beyond the scope of this report.

3. SCOPE OF THE REPORT

The scope of this report is to reiterate the broad objectives for the development of advanced nuclear plants, to set forth some related subobjectives and to propose some universal goals for the development programmes. The majority of these can, as already noted, be categorized under the headings of enhancing safety, improving reliability and gaining better economics. These categories are used in the report followed by additional categories considered to be important within the global framework intended. Additional broad objectives appear unlikely but more subobjectives may become evident as time progresses and the need arises to express them in the intended more global framework. The goals also may change.

The scope is therefore a set of objectives for development of advanced nuclear plants. The objectives are believed to be universally acceptable; they have been reviewed on that basis.

4. OBJECTIVES RELATED TO ENHANCING SAFETY

General Objective: Advanced nuclear plants are expected to equal or enhance the safety characteristics of the best presently operating plants. In this regard, the general objective is to move the technology in the direction of having less radiological impact on the public during normal operation or as a result of an accident. Therefore, the goal of development programmes should be to attain improvements in the technology so as to provide a negligible radiological impact on the public in the immediate vicinity of the plant and on the public well beyond the immediate environs of the plant who might be impacted by the broader dispersion of any released radioactive matter.

4.1. Assuring stability of the reactor core

Objective: Providing assurance that the reactor core will always tend toward stability if upset from any normal operational mode should lead to greater assurance that fission products will be retained close to where they are generated. A robust reactor core is desired together with the incorporation of materials of adequate quantity, strength and other physical properties, in configurations which facilitate this objective. Such a reactor core should have sufficient margins to allow small deviations in operating conditions. Large deviations, which would require the intervention of safety systems, should be prevented by an optimum set of feedbacks so as to provide for short term self-stability at all times. In addition, shutdown systems with sufficient negative reactivity insertion capability to assure long term shutdown should be provided.

4.2. Assuring the removal of residual heat

Objective: Assuring the removal of residual heat from the reactor under shutdown conditions or under conditions in which the reactor is manually or automatically in a shutdown mode is a unique requirement coupled to the fission energy process. Such assurance would be facilitated by having sufficient residual heat removal capability available at all times, without reliance on short term operator action and without reliance on any equipment and systems whose operational status for the function is not continuously verifiable. Such sufficiency may be measured in terms of the ability to limit maximum temperatures in the reactor core below prescribed limits for a grace period [8] long enough to permit well considered, operator controlled corrective action for the residual heat removal function. Considerable benefit can be seen in having long grace periods and extensions in the grace period should be a development goal.

4.3. Taking advantage of inherent safety characteristics, utilizing passive safety systems

(Please see Ref. [8] for an explanation of the terminology of inherent and passive safety)

Objective: An inherent safety characteristic provides assurance of the elimination of a potential internal hazard to the safety of the nuclear plant. Hence, the plant design should seek to take maximum, feasible advantage of inherent safety characteristics through selection of materials, their quantity, their physical properties and their configuration in the plant design, to the extent that these characteristics have been proven to provide enhanced safety.

Objective: A passive safety system provides a safety related function without reliance on operator action or on external mechanical and/or electrical power, signals or forces. A passive safety system, when initiated, relies instead on natural forces such as natural convection, heat conduction and heat radiation, on inherent safety characteristics and on internally stored energy. To the extent that passive systems can be shown to be as reliable and as cost effective as active safety systems for the same function, efforts should be made to utilize such passive safety systems in the plant. Providing adequate negative reactivity insertion to assure shutdown and providing adequate residual heat removal to limit temperatures of the fuel, components, systems and structures appear to be functions amenable to the use of passive systems.

4.4. Improving man-machine interfaces

Objective: The plant should be designed with increased consideration given to human factors so as to enable easy operation of the plant from the control room(s). The goal should be to minimize both the opportunity and the potential for human error by providing a high degree of automation adapted for each situation and by providing well organized displays, controls and operator manuals. The instrumentation and control system and the reactor protection system should be designed so as to minimize the need for operator intervention. Advantage should be taken of advances in electronic and information processing technology such as microprocessors, video displays, multiplexing, fibre optics, etc. and in the use of artificial intelligence techniques. Improved diagnostic systems incorporating self-testing and automatic failure indication are available technology and should be given proper consideration. The man-machine interfaces throughout the plant should serve to minimize operation and maintenance errors that could influence safety.

4.5. Reducing on-site impacts

Objective: In considerations related to lowering the impact of radiation on operating personnel, the plant design should, if feasible, utilize materials which minimize the accumulation of radioactive materials at undesirable locations.

For normal and routine operational, maintenance, testing and inspection duties, the plant design and layout should permit personnel accessibility while limiting the individual exposure levels to less than the occupational dose limits specified by national authorities. These authorities may wish to give appropriate consideration to the recommendations of the International Commission on Radiological Protection (ICRP) [9].

For duties involving repair or replacement of components, including fuel handling, the individual exposure levels per event shall be limited to less than the occupational dose limits specified by national authorities. Again, these authorities may wish to give appropriate consideration to the limits recommended by the ICRP.

For the whole of the plant personnel, the objective is to significantly lower the total exposure to radiation. The goal with respect to radiation exposure of plant staff should be to reduce such exposures to as low as reasonably achievable (ALARA).

4.6. Reducing off-site impacts of normal operations

Objective: The plant should be designed to have minimal off-site impact as a result of all duties associated with normal operations. Consideration should be given to fuel quality, coolant leakage, coolant treatment, materials selection and waste treatment so as to minimize the accumulation and release of radioactive and chemical wastes. The transportation of materials such as waste, fuel and equipment to and from the site should be carefully planned. Consideration should also be given to increasing the utilization of the heat produced by the plant, so as to reduce its thermal effluents.

The exposure levels due to releases from the plant of gases and liquids containing radioactivity as a consequence of normal operational activities and including repair and replacement activities shall be less than the public dose limits specified by national authorities, who may wish to consider the relevant ICRP recommendations.

If necessary to meet the specified limits, the plant should be provided with a system (installed or mobile) for transforming liquid waste into solid waste that can be immobilised and water that can be released to the environment or recycled.

The plant should have provisions for a system (installed or mobile) for the volume reduction and immobilization of low and medium level solid waste, unless such capability is assured by the existence of a central facility. The goal should be to minimize the total gross volume of immobilized low/medium level solid waste, packaged in containers with long term stability and having a low surface dose rate to facilitate handling and storage.

The plant should be designed to provide for the on-site storage of solid radioactive waste (low/medium level) and all chemically toxic waste for a period of time consistent with the expected schedule of shipments from the plant to disposal sites. If off-site storage of such wastes is not assured, provisions should be made for a later enlargement of on-site storage, if necessary, to provide sufficient capacity to store these wastes for the life of the plant.

4.7. Reducing off-site impacts of accidents

Objective: The plant should be designed to have a minimal off-site impact as a result of accidents. The intent of development programmes related to this objective should be to re-examine each element of the defence in depth concept so as to enhance the capability to prevent, manage and mitigate accidents and reduce the off-site impact to an insignificant level, irrespective of the seriousness of the event. As such, considerations beyond those required up to now to obtain a license to construct and operate the plant may be necessary.

For accidents considered within the licensing basis for the plant, the exposure level for any individual outside the plant boundary due to the release of radioactivity shall be less than specified by national authorities, who may wish to consider ICRP recommendations.

For all accidents, efforts should be made to design the plant so as to establish a technical basis for reducing the off-site impact of radioactivity releases to levels less than the levels which require the implementation of those aspects of emergency plans involving evacuation of the public and long term land contamination.

4.8. Reducing impacts of external events and internal intervention

All safety related equipment and buildings in the plant should be designed, within reasonable limits, to withstand external events such as earthquakes, tornadoes, floods, fire, explosions and airplane crashes, with due consideration to the actual site. Likewise, protection should be provided against intervention with the intent of sabotage or initiating a fire or explosion. To realize the potential cost benefits of standardization, design approaches, where appropriate, which provide protection irrespective of local variations of the magnitude of impact should be considered. Appropriate separation of equipment should be provided. The location and number of access points to the plant grounds and to various plant buildings and equipment rooms should also be minimized.

5. OBJECTIVES RELATED TO IMPROVING RELIABILITY

General Objective: Advanced nuclear plants should be designed to have improved reliability even though present plants are becoming very reliable as operational experience is gained. For advanced nuclear plants both scheduled and unscheduled downtimes should be decreased. Operating margins should be increased, equipment capabilities should be better understood, improved maintenance procedures should be implemented and repair and replacement methods, when required, should be facilitated by the design. Also, advanced nuclear plants should be designed to minimize the potential for, and be tolerant of, human error to the extent practicable.

5.1. Improving inspectability and maintainability

Objective: The plant should be designed to facilitate inspection and maintenance. The plant design should utilize equipment that, by design and operational evidence, requires minimal maintenance and reduces the possibility of maintenance errors. The capability for in-service inspection and the use of automated equipment should be optimized for cost effectiveness in terms of meeting availability goals. The use of automated equipment should also be examined taking into account the goal to minimize the radiological exposure to onsite personnel. The use of condition monitoring equipment and its capability to reduce the need for routine maintenance should be expanded.

5.2. Improving provisions for repair and replacement

Objective: The plant should be designed to facilitate repair and replacement. The layout should provide for rapid and adequate access for the removal and replacement of components and equipment from the plant and include sufficient laydown space. The need for special tools should be foreseen and the potential for the use of robotics should be examined.

5.3. Gaining greater simplicity

Objective: Simplicity should be pursued in all aspects of the plant design. An important aspect of simplicity relates to reducing the demands on the operating staff during normal operation and under upset conditions, and in providing simple logic and unambiguous indications of the plant condition at all times. Minimizing the amount of equipment to perform particular functions, and utilizing equipment to perform multifunctions only when equivalent or improved overall reliability is achieved, should be considered. Minimizing system interactions particularly between systems performing essential safety functions and segregating, to the maximum extent, both in function and in layout, the plant systems performing safety and non-safety functions, should also be considered.

5.4. Attaining standardization

Objective: Standardization is a factor whose impact is widespread. Important impacts include improving reliability, constructability and gaining better economics. Standardization should be sought within the framework of specifying, at least, identical functional specifications if not detailed manufacturing specifications (within proprietary limitations) for components, systems and equipment including instrumentation and of using identical components such as pipe sizes, valves, materials, etc. even in various systems. Such standardization should provide for broadening and hence assuring sources of supply, for shortening of construction schedules and for simplifying spare parts inventories. Standardization is also desirable for design methods and design tools. Such standardization should also facilitate the preparation of operation, maintenance and repair procedures, licensing and the reporting of experiences.

In addition, within a broader framework for standardization, it should be the intent of the plant designer to establish a standardized design by way of sufficient design detail and qualification testing to enable the certification, or the equivalent thereof, of the design of the plant or at least the nuclear related portion thereof as the reference for replicated application on a worldwide basis. However, it is recognized that, for cost reasons, details of the design of components and their qualification may not be completed before the decision to construct early plants in an intended replicated series.

5.5. Using new technologies only after adequate testing

Objective: The plant should be designed using materials, components and systems whose required capability for the service intended is based, as much as possible, on proven performance under closely similar conditions in presently operating plants. If other than such conditions are intended in the advanced nuclear plant, the capability should be shown to be satisfactory, if possible, by being within a range of conditions that can be interpolated from the proven technology. If materials, components or systems are intended for service under conditions which are beyond the range of proven capability or are new in terms of intended application, then such materials, components and systems should be subjected to thorough testing under conditions that permit interpolation or minor extrapolation to those of the intended service prior to their use in the plant.

5.6. Improving availability/capacity factors

Objective: The plant should be robust and designed for ease of operation, maintenance and inspection activities so as to provide the capability of attaining a high availability factor (percentage of time that any power can be produced). The goal for the capacity factor should be consistent with the economic optimization of the plant, with such optimization including consideration of the maneouverability requirements desired to meet the needs of the intended application.

Consistent with these goals, the plant should be designed to minimize the number of spurious scrams, unplanned outages and unplanned power reductions. Likewise, depending on an economic evaluation of the relative costs and benefits, it may be desirable to design the plant to be capable of sustained and controlled operation following partial or full load rejection from full power without reactor scram or turbine trip. Similarly, it may be cost-effective to design the plant to be capable of sustained and controlled operation following turbine trip (except on loss of condenser capability) from any power level without scramming the reactor.

6. OBJECTIVES RELATED TO GAINING BETTER ECONOMICS

General Objective: Evaluations involving the projection of economic competitiveness were key factors motivating development programmes in nuclear power and the resulting present deployment of nuclear power plants in the world. Such evaluations did not take into account in an adequate manner, and in some cases not at all, several factors which, as time progressed, led to significantly increased costs. Longer than initially projected licensing and construction times and added equipment, sometimes backfitted, to meet new safety requirements are noteworthy examples. These added costs resulted and will continue to result, unless relieved, in the inability for nuclear power plants to display economic competitiveness with fossil fired power plants in some countries. The goal of development programmes related to economics is simply to have nuclear power plants increase, maintain, or regain the economic advantage over fossil fired power plants with better recognition of the societal costs (including environmental) associated with both types.

With such a goal, it is necessary to recognize and properly account for several factors in evaluations in which cost comparisons play a major role. A valid evaluation is clearly difficult between some nuclear plants which can claim firmness in costs based on experience and other nuclear plants which cannot claim such firmness due to incorporating some innovation requiring demonstration or proof. Such nuclear plants are typically burdened with some first-of-a-kind costs and possibly additional contingencies. Including such costs in an evaluation could override the benefits claimed for the innovation. The cost impact of proposed innovation must be carefully examined in terms of all facets of the cost evaluation. Hence, the time frame of the intended application must be recognized in any evaluation and evaluations should attempt to clearly project both costs and contingencies within this time frame. The justification for proceeding with several developments related to advanced nuclear plants, including even normal product improvement, might otherwise be lost.

Within the context of the time frame for comparative evaluations, two other factors must also be considered. The first factor is that the total time frame for complete evaluations for energy production plants is long and must be accounted for even though long term benefits may be discounted in present value. Moreover, the time frame may be significantly different in industrialized countries compared to developing countries. The second factor is to properly account for potential long term risks with other technologies for the same application. The long term cost impact of possible regulations regarding the burning of fossil fuels is one example. Another example would be the risks associated with oil procurement for the life of the plant.

Hence the goal could be restated as follows: the advanced nuclear plant should have an economic advantage, all factors considered, relative to the most economic, environmentally acceptable alternative plant, of any type, of the same rated capacity for the intended application.

6.1. Attaining long plant lifetime

Objective: In recognition of the large capital investment, the plant should be designed for as long a life as technically and economically feasible. Attention should be given in the design to the choice of materials and operating conditions for the intended service. Where necessary, provisions should be made for component inspection, component replacement and possible upgrading in order to assure the long life capability. Operation of the plant should include a well documented plant history so that fatigue and neutron embrittlement effects can be assessed.

6.2. Assuring design stability

Objective: The status of the design for the specific application should be such as to give a high assurance that the licensing and construction schedules can be met and delays will not occur. Consideration should be given to achieving the highest feasible state of completion of detailed plant engineering including site specific documents, vendor documents and any ongoing proof testing of equipment or systems. Preferably, such documents and proof-testing should be essentially complete prior to the placement of the first structural concrete.

6.3. Assuring regulatory licensing stability

Objective: The status of the regulatory licensing processes in the country where the reactor is to be deployed should be such as to give confidence that construction, fuel loading and operation will not be impeded by regulatory processes. A significant step in this direction would be the ability, through established national regulatory policy, to obtain a one-step license to construct the plant. Furthermore, a one-step license covering both construction and operation of the plant should be a goal.

6.4. Assuring construction schedules

Objective: In recognition of the significance of the interest charges on the debt being accumulated during construction of the plant, efforts should be made to develop techniques and procedures which can not only shorten the construction schedule but also prevent delays once construction has started. Short construction schedules also reduce uncertainties that may impact costs ranging from regulatory changes to labour disputes.

The status of the design and the ability to preorder long lead items should be considered. Reducing on-site construction labour by using factory-fabrication or on-site prefabrication of components and the pretesting, prior to installation, of large components should be considered. Likewise, modularization and factory-fabrication and pretesting of complete systems or subsystems, piping, control and instrumentation systems etc. should be considered. Cost-benefit analyses should be used, wherever possible, in the above considerations. Maximizing the on-site separation of nuclear and non-nuclear activities during construction should also be considered.

6.5. Minimizing operation and maintenance costs

Objective: In recognition that operation and maintenance costs have a significant impact on the competitiveness of a nuclear plant and that such operation and maintenance costs for presently operating plants have been tending to increase, efforts should be made to critically examine the contributors to such costs for advanced nuclear plants. An optimum staff level should be sought with the goal of reducing the associated costs below those of presently operating plants. Replication and standardization could be key factors in permitting the sharing of some activities which would help to reduce costs.

6.6. Minimizing decommissioning costs

Objective: Decommissioning of nuclear plants is a significant cost factor for which the planning for decommissioning and the accumulation of an adequate reserve during plant operation to cover the costs requires greater consideration. Consideration of such preliminary decommissioning plans should be part of the design effort so as to optimize, where possible, the capability to decommission the plant and minimize the associated costs.

6.7. Providing enhanced investment protection

Objective: In order to provide a high degree of investment protection, the plant should include specifically identified measures and margins which extend beyond those provided just to minimize the safety related environmental impact of the plant. Consideration should be given to reducing and localizing both the physical damage and the spreading of radioactive contamination due to accidents. The objective is to minimize the time and costs associated with the decontamination, and the replacement or repair of components and equipment in the plant after any accident. In particular, the economic loss of the plant following an accident should be avoided. The measures provided to enhance the safety of the plant provide some measure of enhanced investment protection, particularly so if those measures enhance the capability of retaining the fission products close to where they are generated.

With regard to costs, a goal of providing enhanced investment protection should be to enable the plant owner to have an adequate basis to be able to secure commercial property damage insurance coverage comparable in cost to that for similar industrial enterprises.

7. OBJECTIVES RELATED TO ASSURING THE FUEL CYCLE

General Objective: Although most of the development objectives related to the fuel cycle could be classified under the category of gaining better economics, some of the objectives are clearly broader, extending for example to improving reliability, lessening environmental impact and reducing proliferation risks. Moreover, fuel cycle costs, including back end, are a long term factor in cost evaluations and are typically separately identified. Considering those objectives related to gaining better economics leads to the goal of achieving an assured fuel cycle and competitive fuel cycle costs for the life of the plant.

7.1. Assuring fuel qualification

Objective: The fuel should be qualified for the intended service. Qualification of the fuel should be based on proven performance under closely similar conditions as for the intended service in presently operating plants. If other than such conditions are intended, the fuel should be subjected to thorough testing under the conditions intended prior to insertion into the core.

7.2. Providing fuel cycle flexibility

Objective: Irrespective of the fuel cycle chosen for initial operation, it may be desirable and in the national interest to consider and include provisions in the plant design for other fuel cycles which might, when proven, provide better assurance of long term fuel availability and lower fuel cycle costs. Fuel cycles being developed to conserve and/or to better utilize the world's fissile and fertile material resources, or to reduce the uncertainties and costs associated with present fuel cycles, should be considered.

In considerations related to fuel cycle flexibility for plants using off-power refueling, the refueling scheme, the refueling interval and the length of time for refueling should be optimal on both a technical and economical basis. To enhance the capability of achieving a high availability factor, consideration should also be given, when optimizing the refueling interval, to inspection and maintenance intervals for major equipment which could coincide with the refueling interval.

For both off-power and on-power refueling, and particularly for the latter, thoroughly tested and reliable refueling equipment should be assured.

7.3. Providing adequate spent fuel storage

Objective: The plant design should provide for adequate spent fuel storage. The plant design, site arrangement and licensing activities should take into account the possibility of providing expansion to the on-site facilities sufficient to store the spent fuel resulting from the lifetime operation of the plant, unless assurance of the availability of an off-site spent fuel storage facility exists.

8. OBJECTIVES RELATED TO EXPANDING THE MARKET FOR NUCLEAR POWER

General Objective: The objectives and goals of most advanced nuclear plant development programmes are concentrated, as noted in Section 2, on resolving the issues inhibiting the expansion of the use of nuclear energy as a resource for electricity production. Moreover, most of the programmes are addressing the issues within the framework of a national interest. Even if international in intent, most programmes appear to have goals which are concentrated on meeting the needs of developed countries rather than developing countries.

Nuclear energy is capable of providing just heat alone or, with cogeneration, both heat and electricity. Potential applications for nuclear generated heat beyond electricity generation are diverse, including district heating, desalination, enhanced oil recovery, coal gasification, steam-methane reforming for chemical plants and metals processing. Nuclear generated steam and hot water are already being supplied at about a dozen sites and studies have been made for several other process heat applications [10-12]. Development objectives covering this potential utilization in many areas of the heat supply market require an examination which is beyond the scope of this report.

For the electricity generation market alone, there are several developments which are foreseen as helping to expand this market on a more worldwide basis and in which designers could play a more active role. The subobjectives discussed in this section cover the obvious areas. Full consideration of aspects relevant to the introduction of nuclear power in any country is a broader subject covered in greater detail in other reports [13].

8.1. Expanding the range of plant output

Objective: The development programmes on advanced nuclear plants for the electricity generation market cover advanced nuclear plant designs with single-unit outputs ranging from a minimum of about 200 MW(e) to a maximum of 1400 MW(e) or higher. However, most of the development programmes have been concentrated on the larger advanced nuclear plant sizes which best meet the needs of developed countries with reasonably sized electricity distribution grids and sufficient reserve capability to withstand the shutdown of the nuclear plant. The expansion of the market to developing countries may be facilitated by nuclear plants with smaller output, particularly if licenseable in the country of origin. Possible modularity in the framework of small, independent, power producing modules being built on a site on a time-scale better meshing with deployment capability requires a critical examination of all cost benefits related to such deployment. The expansion of the market for nuclear plants to heat supply would appear to also benefit from such examinations.

8.2. Investigating indigenous supply

Objective: The extent of indigenous supply of materials, equipment and labour could influence the economic viability of the plant. Efforts should be made to:

- investigate the indigenous capability for such supply;
- determine the need for licensing, technology transfer and training to enhance this capability; and
- incorporate indigeneous supply whenever project objectives are served.

8.3. Assuring infrastructure readiness

Objective: Infrastructure readiness refers to many factors related to the goals of successfully deploying a nuclear plant and to having the required capability to properly construct, manage, operate and maintain the plant and manage the waste. The factors involve owner readiness, government readiness and supplier readiness.

The ability and readiness of the owners to recruit and train adequate staff to manage, operate and maintain the nuclear plant should be reviewed.

Government readiness should be interpreted primarily as having the policies, rules, regulations and procedures to determine the licenseability of the plant and assuring public health and safety.

Nuclear plant and fuel supplier readiness should be reviewed in terms of:

- experience with the technology;
- capability of providing material, equipment and fuel, and the related services as agreed;
- capability of complying with the specified warranty provisions.

The adequacy and capability of off-site services should be reviewed in terms of:

- provisions for the supply of materials, equipment and labour, as needed;
- the training required to assure this capability;
- the need for and availability of reserve capacity for meeting demand during planned and unplanned outages of the nuclear plant; and
- the capability and reliability of the grid.

8.4. Expanding technology transfer

Objective: The transfer of the technology applicable to and supporting the particular advanced nuclear plant chosen for application in a country not previously involved in the particular technology development is necessary to assure adequate infrastructure development and to gain a decreasing dependence, since such is typically a national interest, on foreign supply. Methods and procedures whereby such technology transfer, as is required to adequately support the nuclear plant, can be effectively implemented should be considered.

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