HR0000044

NUCLEAR POWER FOR DEVELOPING COUNTRIES

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Abstract

Nuclear power is a proven technology which currently makes a large contribution to the electricity supply in a number of countries and, to a much lesser extent, to heat supply in some countries. Nuclear power is economically competitive with fossil fuels for base load electricity generation in many countries, and is one of the commercially proven energy supply options that could be expanded in the future to reduce environmental burdens, especially greenhouse gas emissions, from the electricity sector.

Over the past five decades, nearly ten thousand reactor-years of operating experience have been accumulated with current nuclear power plants. Building upon this background of success and applying lessons learned from the experience of operating plants, new generations of nuclear power plants have been, or are being developed. Improvements incorporated into these advance designs include features that will allow operators more time to perform equipment protection and safety actions in response to equipment failures and other off normal operating conditions, and that will reduce and simplify the actions required. Great attention is also paid to making new plants simpler to operate, inspect, maintain and repair, thus increasing their overall cost efficiency and their compatibility with the infrastructure of developing countries.

The paper provides a discussion of future world energy supply and demand projections, current status and prospects for nuclear power, a short summary of advanced reactor concepts and non-electrical applications of nuclear energy for developing countries, and a review of the role of the IAEA.

FUTURE WORLD ENERGY SUPPLY AND DEMAND

Highly populated developing countries at present consume much less energy per capita than do developed countries, and it is quite obvious that the per capita consumption of energy in developing countries will increase substantially, in particular if increased economic growth and improved standard-of-living are to be achieved. The world-wide phenomena of urbanisation, allowing easier access to electrical distribution systems, together with the electrification of rural areas, will also contribute to a steadily increasing share of energy demand from developing countries in the future. The results of these trends on the distribution of world energy demand over the last decade and projections for the next two decades, as projected by the International Energy Agency are shown in Figure 1[/1/]. The figure shows the total energy demand and the fractions in the developing countries, Eastern Europe and the Former Soviet Union, and the industrialised countries for the period 1990 to 2020. The increasing energy demand that was observed in developing countries over the past decade is projected to intensify in the next two decades, while energy demand in the rest of the world experiences only modest increases. The demand for new energy production facilities is driven by two primary factors: replacement of old or obsolete facilities among existing generation, and the rate of increase in energy demand. Thus developing countries can be expected to represent a major portion of the market for new generating capacity in the next several decades.

Global energy supply has been dominated by fossil fuels throughout the twentieth century, with recent data and near term projections indicating that this will continue for the foreseeable future. Concerns about global environmental effects of fossil fuel consumption have increased in recent years, most

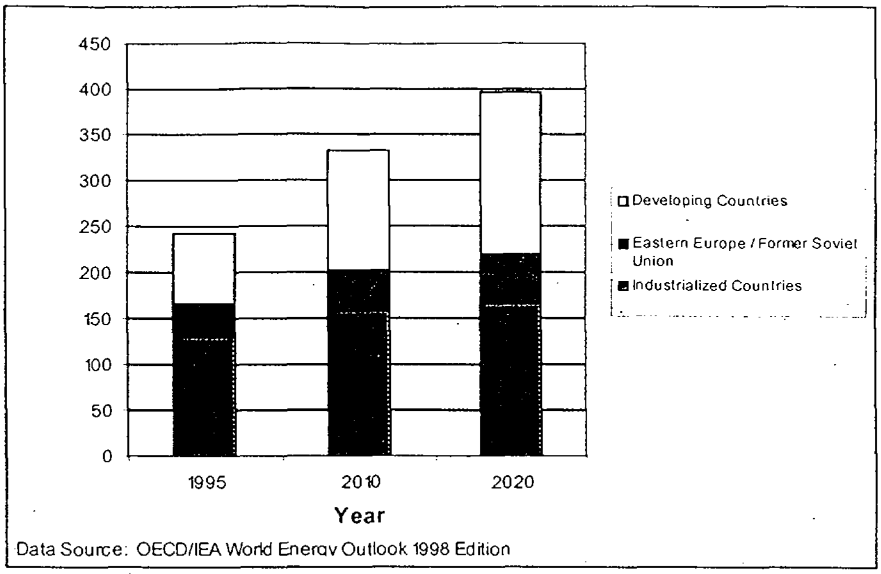

Figure 1 Energy Demand -Global Energy Consumption Data and Projections

particularly with regard to greenhouse gas emissions, but they are not expected to substantially curtail the consumption of fossil fuels. This is illustrated in a projection of world energy supply for the period 1995 to 2020 produced by the International Energy Agency and shown in Figure II[2]. In this case, energy supplied by all three forms of fossil fuels is projected to continue to increase, with the greatest increase expected in natural gas consumption resulting from continuing deployment of combined cycle gas turbine electrical generation plants. While fossil plant technology development will include means to reduce emissions of greenhouse gases, the level of emissions envisioned by global environmental conferences (e.g. a reduction from current levels) is unlikely to be achieved under this scenario. Nuclear power is making a significant contribution to the reduction of greenhouse gases, as it causes no significant release and is currently generating about 17% of the world's electricity. However, many projections of future energy supply show limited contributions from nuclear power, with the reference case shown below indicating a reduction in nuclear energy production by 2020.

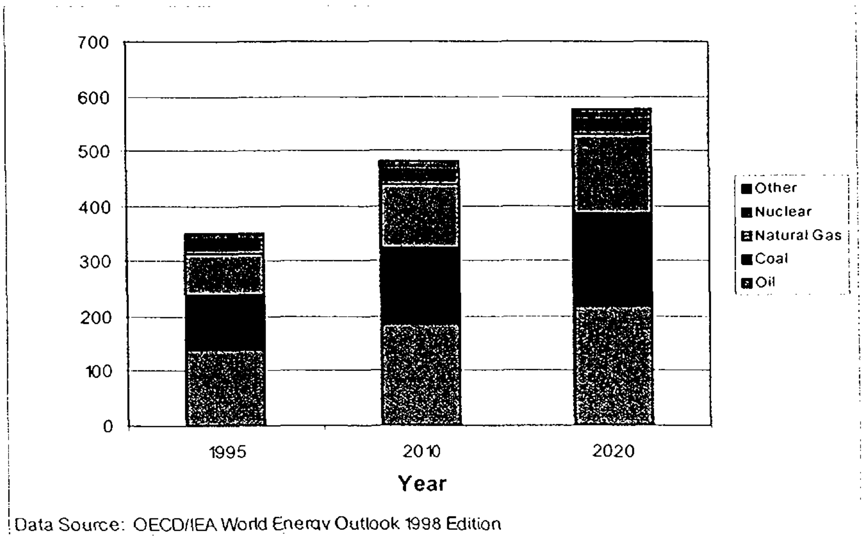

Figure II Energy Supply – Global Energy Use Data and Projections

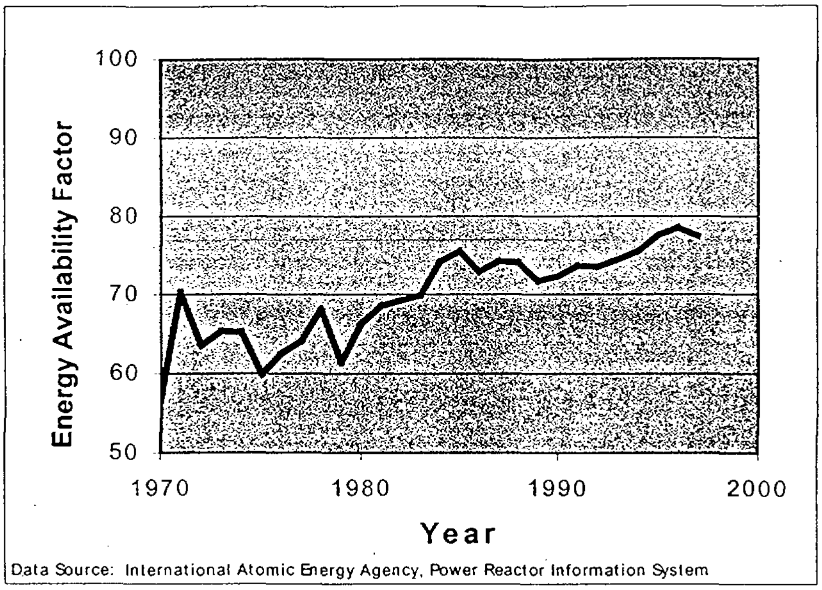

Figure III Global Nuclear Power Plant Performance

CURRENT STATUS AND PROSPECTS FOR NUCLEAR POWER

Nuclear power technology has been under development for five decades. Substantial orders for commercial power plants began in the 1960's, and widespread commercial operation began in the 1970's. Currently, nuclear power supplies about 17% of world-wide electricity demand. The majority of currently operating plants have performed well and continue to improve, as illustrated by an increasing global average Energy Availability Factor, as shown in Figure III[3]. However, substantial problems have been encountered on several fronts, most notably the Three Mile Island and Chernobyl accidents, as well as at plants that were prematurely shut down or completed but never operated. The global nuclear power plant market experience, in terms of construction starts and connections to the electrical grid, is illustrated in Figure IV[3]. Construction starts peaked in the 1970's and connections to the grid in the 1980's, with current levels of both on the order of five units per year, far below the values achieved earlier. Many factors have contributed to this decline in new nuclear plants, with four of the more significant being an oversupply of baseload generating capacity, low growth in energy

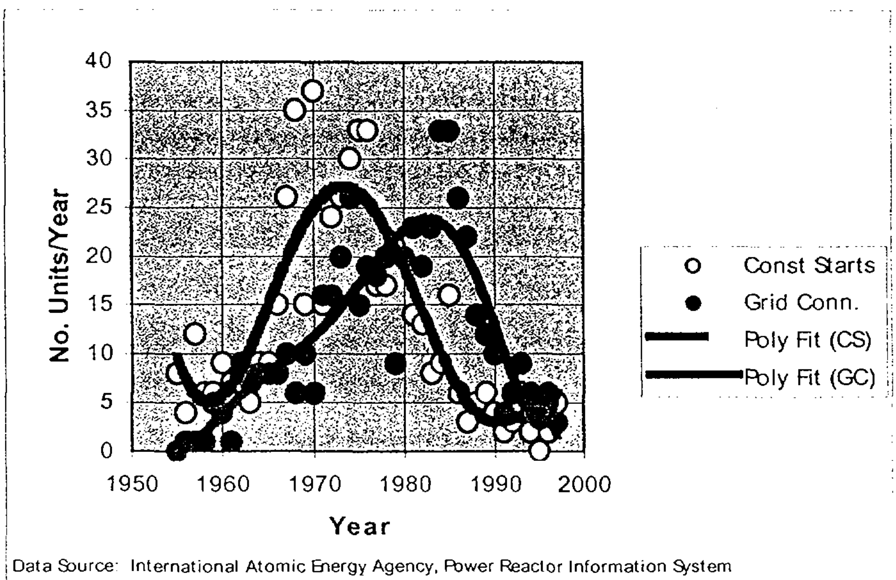

Figure IV Global Nuclear Power Plant Deployment History

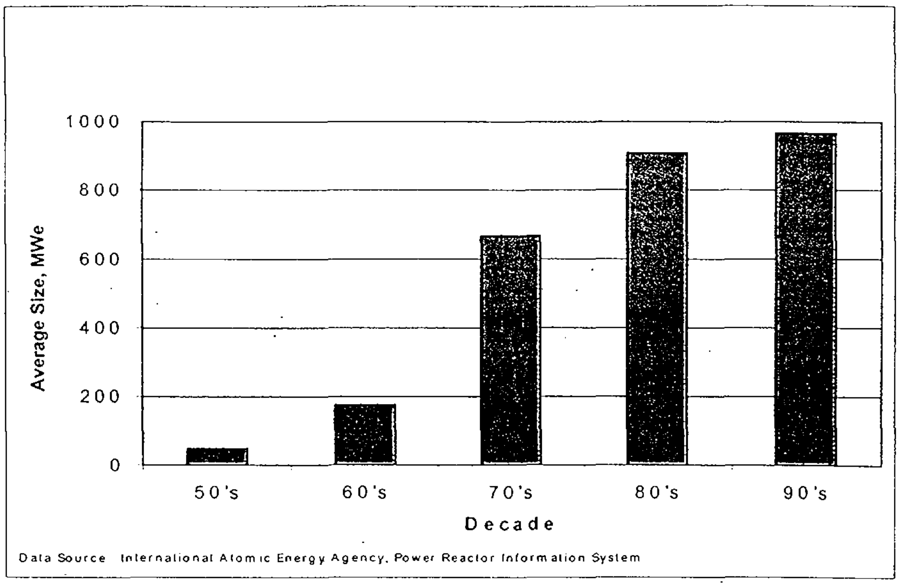

Figure V Evolution of Nuclear Power Plant Size

demand in the industrialised countries, low fossil fuel prices coupled with a dramatic improvements in fossil generation technologies (e.g., CCGT), and public acceptance issues. The decline is projected to continue as shown in Figure II.

Nuclear power plant designs evolved to meet the needs of the electricity generation market in the industrialised and industrialising countries during the second half of the twentieth century, built almost exclusively around water-cooled reactor technology. As early prototypes in the 50's and 60's were followed by deployment of commercial plants, average plant size increased rapidly to gain the benefits of economies of scale, as shown in Figure V[/3/]. Advanced evolutionary plant designs are typically in the range of 1,500 MWe and larger. Operation of plants approaching this size range has occurred primarily within the institutional and electricity transmission infrastructure of large industrialised countries. Generating capacity additions in the developing countries typically range from a few hundred MWe to well below 100 MWe.

The current situation and near term future conditions for nuclear power remain uncertain. Despite continuing improvements in the operation of existing facilities, as illustrated in Figure III, challenges continue to be experienced in areas such as:

- **Economics** – The global trend toward deregulation and enhanced competition in electricity generation, along with continuing low prices for fossil fuels and a widespread excess of baseload generating capacity in industrialised countries present challenging power cost targets. Existing plants with substantially amortised capital costs are well positioned to compete, but new plants will find it difficult without substantial reductions in capital costs.
- **Public and Political Acceptance** – Emergency evacuation plans, equipment and exercises in conjunction with recurring media programs on nuclear accidents and risks degrade local support. Continuing institutional issues, such as long term disposition of spent fuel and nuclear weapons proliferation concerns, introduce uncertainties regarding future operation.

Evolutionary plant designs have addressed these areas to the extent achievable within the constraint of moderate changes from existing operating plant designs. Detailed designs have been completed and reviewed by licensing agencies over the past two decades in preparation for future deployment. A major near term change in the economic environment for nuclear power, such as credit for reductions in CO_2 emissions, could result in a resurgence of demand for new plant construction. This demand could be effectively addressed with the evolutionary nuclear power plant designs that continue to be developed and refined. However, political resistance to further deployment of nuclear plants similar to existing plants remains strong in many areas of the world, and near term needs for alternatives to fossil fired generating capacity may not be sufficient to overcome this resistance.

In the longer term, the global power market conditions remain uncertain, but most uncertainties are strongly supportive of the need to retain the nuclear option. Continuing growth in population and energy demand, particularly in the developing countries, in combination with further experience with and understanding of global climate change phenomena could produce a global imperative for rapid and extensive deployment of non fossil-fired generating capacity. Non-nuclear alternatives may be severely limited in their cumulative ability to satisfy the baseload capacity addition needs. Establishing and maintaining a nuclear energy option for the longer term that can effectively address such a global imperative will require a sustained near term effort. General acceptance of nuclear energy as a long-term option will depend on the successful application of innovative solutions to the problems encountered during the deployment of nuclear energy in the twentieth century.

OBJECTIVES OF FUTURE NUCLEAR POWER PLANT RESEARCH & DEVELOPMENT

The overall objective of advanced nuclear plant development is to use the experience, skills and technology gained from the first half century of nuclear power plant research, development, design, construction and operation, along with advancements in other relevant technologies, to address the issues anticipated in the twenty-first century, as summarised below.

- **Cost** – In the deregulated electricity market emerging in the last decade of the twentieth century, competitive total power costs are an essential condition of market penetration.
    - As a capital intensive option, the cost of design, licensing, construction and start-up of a nuclear power plant must be known with reasonable confidence, and it must be stable at a level required to meet a competitive overall cost target.
    - Projected operating costs, including fuel, operations, maintenance, engineering and licensing support, spent fuel disposition, fees and decommissioning allowances, must also meet the same conditions in concert with capital costs.
    - The magnitude of the investment required to construct the plant must be within the combined capabilities of the local financial institutions and external financing.
    - The overall result of addressing the above issues must be an expected rate of return on investment that is competitive with other options, considering the level of investment risk.
- **Investment Risk** – In order to attract the required capital there must be a high level of confidence in the cost and revenue production projections.
    - The construction schedule must be well established with a high degree of confidence that the projected construction time can be met within relatively small contingency allowances.
    - Confidence in reliable plant operation and a high energy availability factor, essential elements of total power costs, must be established.
    - Regulatory review procedures for plant construction and operation must be well established with minimal potential for identification of new or unresolved issues.
    - The regulatory regime for the full range of activities covering the plant and supporting fuel must be stable and independent of normal changes in national or regional government.
- **Safety** – With the notable exception of the Chernobyl accident, nuclear power plants operated with an exceptionally high level of public safety over the past half century. The specific characteristics of Chernobyl that were the primary factors in the accident are unique to that class of nuclear power plants. Thus nearly ten thousand plant-years of operating experience of a wide range of designs support the view that substantial improvements in safety over most of the existing plants should not be considered a primary objective. However, the cost, both capital and

operating, and the complexity of achieving this high level of safety have been substantial. Innovations will address making more effective use of intrinsic characteristics to simplify safety related system design, analysis, construction, operation and maintenance.

  - Simplification of design, operation and safety analysis will enhance understanding of and confidence in plant safety.
  - A primary goal is a level of confidence in plant safety sufficient to eliminate the need for detailed evacuation plans, emergency equipment, and periodic emergency evacuation drills.

- **Infrastructure Compatibility** – Much of the future increase in electricity demand is projected to take place in developing countries. Innovative designs must consider the infrastructure in these countries and minimise requirements for substantial modifications or upgrades to accommodate the plant.
  - A new generating facility should be a small fraction of the existing capacity on the electricity transmission grid. This allows a better match to demand growth, accommodation of a sudden loss of the plant capacity without destabilising the grid, and minimises the impact on existing generating units (e.g., increased load follow and voltage/frequency regulation operation).
  - The plant must be capable of stable operation within the environment of the local grid (i.e., variations in voltage and frequency).
  - Manpower requirements, in terms of education level, training and skills to accomplish the required operation, maintenance, and engineering support tasks must be locally achievable within a reasonable investment of time and resources.
  - Local safety review and licensing capabilities required for plant construction and operation must be achievable in a reasonable time at a reasonable cost.
  - Disposition of spent fuel must not place substantial burdens on the host country.
- **Safeguards Compatibility** – An increasing number of developing countries with nuclear fuel cycle and power plant facilities, along with distributed siting of smaller units, could provide new and increased demands on safeguards against diversion of nuclear materials. The effort required to achieve a satisfactory level of confidence in the security of nuclear material may be simplified and reduced, and confidence in the effectiveness of the safeguards regime may be enhanced by innovative fuel cycle and plant design.

These objectives cannot be achieved in isolation, as they are often conflicting. For example, increasing unit size has been a traditional approach to reducing projected power cost, while reducing unit size would improve compatibility with smaller grids in developing countries. Development must be performed in an integrated fashion, taking into account the full range of activities involved, including engineering, testing, manufacturing, licensing, construction, operation and decommissioning on a long-term global scale.

ADVANCED REACTOR CONCEPTS AND NON-ELECTRICAL APPLICATIONS OF NUCLEAR ENERGY FOR DEVELOPING COUNTRIES

Advancement of technology and improvement of plant design and performance has been an integral element of nuclear plant deployment throughout the history of the industry. However, as was noted earlier, the development effort was primarily focused on the electricity generation market in the industrialised countries, where most of the new capacity additions were occurring into the early 1990's. The large plant designs that resulted from this process are not well suited for many developing countries because of the demands placed on supporting infrastructure.

Beyond the direct impact of large plant size on transmission systems and capital requirements, most of the demands on infrastructure stem from a unique aspect of a nuclear power plant - a significant

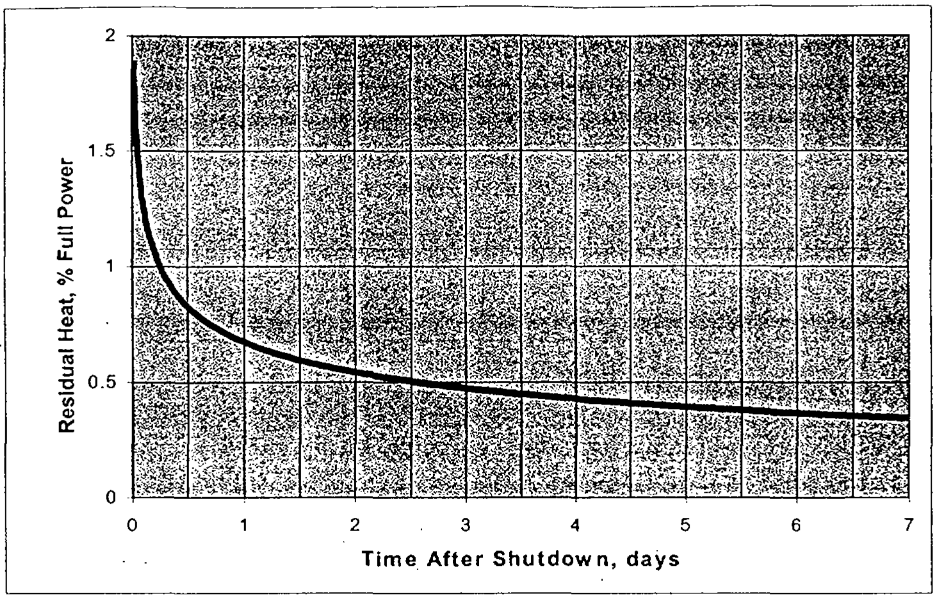

Figure VI Nuclear Power Plant Typical Post Shutdown Residual Heat Generation

percentage of the energy produced during operation is released by the decay of fission products. This energy release continues after the fission reaction is shut down, declining rapidly at first as the short half life fission products decay, but continuing at a low level over the days and weeks following shutdown, as shown in Figure VI. While the percentage is small, the amount of energy release is significant and proportional to initial power level. For example, a plant operating at 4,000 MWt would still be producing about 20 MWt three days after shutdown. If the heat were not removed, temperatures would continue to increase, ultimately leading to component failures and radiation release. The large plant designs utilise highly reliable systems to assure that residual heat is removed, as demonstrated by operating experience over the past five decades. However, these systems must be maintained at a constant state of readiness, and must operate reliably and effectively in the face of individual component failures (in normally operating components as well as failures in components that are not normally operating but would be needed under off-normal conditions), loss of external power, earthquakes, etc. Establishing and maintaining the operational and oversight capability required to assure the required level of readiness places demands on manpower, organisations and institutions that are difficult to meet in general, and particularly in many developing countries, and that are not required by other forms of energy production.

In the past two decades, considerable effort has been directed toward defining the needs of developing countries, assessing existing technologies relative to these needs, and exploring nuclear plant concepts that have the potential to address these needs. With the strong support of Member States, the IAEA has actively fostered international communication and co-operation in this area, as indicated by a partial listing of relevant documents produced in the 1980's and 1990's[4,5,6,7,8,9,10,11,12,13]. Much of the information and understanding developed through these interactions is reflected in the discussion of objectives of future development in the previous section. In addition, developing country needs in areas other than electricity production have been identified by numerous Member States. These have included use of nuclear plants for district heating, desalination of seawater, heavy oil recovery, and high temperature process heat applications. These applications can be addressed by use of an electricity generation plant operating in a cogeneration mode or by designs supplying thermal energy directly with no electricity generation or generation in a lower temperature bottoming cycle.

Many future reactor design concepts have been developed in recent years to varying degrees of completeness ranging from concept descriptions, to basic design, to detailed design. A survey of the development status of small and medium reactor systems conducted by the IAEA in 1995[10] identified 44 designs and provided design data and status of 29 of those identified. The concepts included heat only, cogeneration, and electricity generation applications, and spanned water, liquid metal and gas cooled reactor technologies. Several design efforts have been directed toward minimising or eliminating the need for active systems to remove post shutdown residual heat. By limiting power level and designing for enhanced heat loss to the environment by natural means, the concepts strive to limit temperatures below component failure limits. If successfully demonstrated to a high degree of confidence, this feature could eliminate many of the difficult challenges to developing country infrastructure and lead to substantial reductions in capital and operating costs. However, achieving this result will require that the design features and supporting data be accepted by licensing agencies as providing a sufficient basis for elimination of requirements for safety systems that are universally required of more conventional nuclear plants.

The challenge for the future is to establish focused efforts centred on one or more of the most practical and promising concepts, with sufficient motivation and resources to complete a successful field demonstration. In the current energy industry environment of increased privatisation and reliance on commercial forces, it can be expected that this process most likely can only be carried to completion as a commercial project. Before this can happen there must be sufficient confidence in the market for a concept, in its economic performance, and in its political acceptability, to justify the investment risk.

THE ROLE OF THE INTERNATIONAL ATOMIC ENERGY AGENCY

International co-operation has been an essential factor and a principal driving force in the global development and deployment of nuclear power. In the current situation, where the resources assigned to innovative R&D are limited, and where the efforts invested are dispersed among many countries and projects, international co-operation could once again serve a central role. For more than forty years the IAEA has fostered international communication and co-operation in the three principle areas of technology development, safety, and safeguarding against proliferation of nuclear weapons. It is well positioned and prepared to serve as a catalyst in the continuing development of nuclear power technologies for developing countries.

Current Agency activities of particular relevance to the subject include the following:

- **Contribution of Advanced Reactors for Sustainable Development** - An Advisory Group Meeting was held in June 2000 to identify and characterise potential strategies, roles and prospects for advanced nuclear power technologies to achieve long term sustainable energy production.
- **Natural Circulation Data and Methods for Innovative Nuclear Power Plant Design** – A Technical Committee meeting will be held in July 2000 to assess the current base of experimental data and the applicability of current methodologies for computing natural convection phenomena in innovative reactor designs. The meeting addresses one of the recommended topics from an Advisory Group Meeting held in October 1999 on development of a strategic plan for an international R&D project on innovative nuclear fuel cycles and power plants.

In addition to the above mentioned specific efforts, most of the work performed within the Nuclear Power Technology Development Section (NPTDS) of the Division of Nuclear Power is directly relevant to innovative R&D. Similarly, much of the work of the Department of Nuclear Energy as well as of the Department of Nuclear Safety and the Department of Safeguards is relevant.

Existing Agency mechanisms for supporting technology development, as summarised below, will continue to be used to establish and refine developing country needs and support relevant technology development.

- **Information exchange** - The Agency is well positioned and has ample experience in this kind of activity. Consultancies, Technical Committee Meetings and Advisory Group Meetings are established mechanisms for fostering direct communications of varying degrees of formality among representatives of the IAEA Member States. Where appropriate, the results of these exchanges are documented, published and distributed by the Agency.

- **National, Regional or Interregional Technical Co-operation Projects** – These projects are of particular relevance to developing countries as a means to provide support and assistance to the Member States on request. The services are provided by the Agency on a non-commercial basis and usually consist of expert assignments, equipment grants and training (courses, seminars, workshops, individual fellowships and scientific visits). Technical Co-operation projects could make significant contributions in the following areas:
  - Further defining the issues associated with infrastructure requirements and economic development, and assuring that the results are factored into the innovative reactor and fuel cycle designs
  - Identifying and addressing the issues associated with the possibility of implementing an innovative power plant prototype unit in a developing country
  - Identifying and establishing developing country research activities that could contribute to the implementation of innovative systems
- **Co-ordinated Research Projects** - In these projects, the main role of the Agency is to catalyse the organisation and launching of joint activities and, once they are underway, to serve as a co-ordinator. Financial assistance is also provided by the Agency when needed, but at a low level. The participating countries and organisations provide most if not all of the input to these CRPs. Such projects are usually of a limited scope, with precise objectives defined according to the common interest of the participants. Identification of areas of common interest can be done through Advisory Group Meetings. Implementation of corresponding CRPs would then proceed, subject to finding suitable partners.

As indicated by the partial list of documentation provided as references 4 through 13, the agency has been actively applying these mechanisms to the support of nuclear technology development over the past two decades. Recent expressions of interest and support among Member States for nuclear energy applications for developing countries are increasing the priority and focus of these activities. Ongoing activities in the areas of nuclear desalination and small and medium reactors will be continued and enhanced as an element of an increasing focus on innovative concepts for addressing the needs of developing countries.

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