The Role of Nuclear Energy in a Sustainable World

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1. Introduction

Compelling factors are making nuclear energy more attractive today than the case was even a few years ago. First, there is a wide agreement about the importance of limiting emissions of carbon into the atmosphere. While some countries are already moving to reduce their emissions by providing incentives for non-emitting sources, others are adopting firm goals for future reductions in these emissions. Nuclear energy is a major option for meeting this desire. The second important factor is the sharp rise in the price of gas and oil over the last few years. While the prices have come down from their peaks, they remain at multiple times their values at the beginning of the century, and the trend in the rest of the century will be upwards as the demand outstrips the supply of finite resources. The third and equally important factor is geopolitical distribution of energy sources, which makes much of the world vulnerable to interruptions in the supplies due to political developments in Russia or the Middle East, regions which supply most of the World's exported oil and gas. Uranium on the other hand is principally available from a wider group of countries, ranging from Australia and Canada to Kazakhstan and Namibia. Fourth, performance of nuclear power plants has been impressive in the last decade all around the world, and such proven reliability gives confidence that management of the plants can be done safely. These factors have combined to create a shift in the official and public attitudes in many parts of the World towards re-examination of ways to deploy nuclear plants in the coming years, and to undertake further development efforts to enhance the performance of nuclear energy in economic and environmental terms.

2. Key Ingredients of Improved Nuclear Energy

There are 440 nuclear plants around the world, including 104 in the United States. The owners of nuclear power plants have realized the economic advantages of operating the old plants at higher capacity factors and also at increasing power levels. Thus 76 reactors in the US have applied for, and 48 have already received, extensions of 20 years to their original license time of 40 years. While 2 plants with about 2% of the US nuclear capacity have started operation in the last decade, nearly 5 % of additional capacity has been licensed for the existing US plants and 3% are expected to be added over the next 10 years. This trend is likely to continue, and innovative technology has to be explored for that purpose, not just improvement of methods for calculation of plant conditions, as has been the case in most of the uprates to date.

In addition, there are signs that many new plants will be coming. US electricity supply companies have plans to add 30 reactors by the year 2025, but each of China, India and Russia have plans to add more than that. Many countries are considering nuclear power for the first time, including UAE, Jordan, Turkey and Indonesia. Some concern has been voiced about the infrastructure needed to support the planned expansion, from skilled labor to manufacturing capacity of large forging parts. The more certain the nuclear energy expansion, the more willing would the infrastructure institutions be to invest in expanding their capacities.

The demand for nuclear energy is likely to grow at a rate that depends on steady improvements in the economy, safety and waste management. A key element in this regard is the ability to increase the safety margins while improving the cost of the plant per unit capacity. At MIT we are working on several ideas that might enable very large increases in the power density of the predominant type of reactors today, the light water cooled reactors. One is utilization of new fuel designs, such as annular fuel with internal and external cooling, in place of the externally cooled solid rods. This will increase the surface to volume ratio of the fuel thus lowering the fuel temperature and the heat flux to the coolant considerably, which will add to the margins for safety. Some of the expanded thermal margin can be utilized for increased power density in the fuel assemblies. A second idea being explored is the addition of nanoparticles to the coolant to enhance the limiting heat flux to the coolant, which would allow the operating heat flux to reach higher levels. A third idea is the use of a ceramic cladding instead of a metallic one, thus nullifying the worry about cladding corrosion due to a temporary rise in the fuel cladding temperature during transients, as well as eliminating a source of hydrogen in severe accidents. Each of these ideas appears to promise an increase of 20 to 30% in the permissible power densities of LWRs. If combined, it may be possible to increase the power density in future cores by 60-90%, significantly reducing the cost of future plants as the increased power is extracted from the same vessel and containment building volumes. This could decrease the total plant cost by at least 20%

Moreover, nuclear power plants with improved thermal to electrical energy conversion efficiency are also needed in the next 25 years. If the thermodynamic conversion efficiency is raised from 33% to 45%, production of spent fuel is reduced by 33%. For light water reactor technology, there is a need to reach higher temperatures through operation of either superheated plants or supercritical steam/water turbines. Such concepts have yet to be developed, but are being examined in many parts of the world. Alternatively, it is possible to raise the energy conversion efficiency by adoption of gas turbines connected to high temperature gas cooled reactors, and those are being developed in South Africa, but also are part of the efforts in other countries.

There are three reasons for pursuing high plant efficiencies: (1) reducing the rate of consumption of uranium, thus delaying the need for the more expensive breeder reactors (2) reducing the volume of spent fuel per unit electricity production, which reduces the burden of storing and handling the spent fuel while a more permanent solution for its management is being developed and (3) reducing the cost of electricity, which is also helpful for introduction of nuclear energy driven production of future transportation fuels.

The role of nuclear energy in mitigating CO_2 emissions extends beyond serving as an alternative supplier of electricity for household and industrial purposes. It includes in the long term the use of electrolysis or thermochemical means for hydrogen production for use in vehicle fuel cells, and also in the nearer term production of hydrogen needed as an additive to heavy oils extracted from rocks and tar sands so that they may be used in gasoline engines. If we use hydrocarbons for the production of such hydrogen, as done today, we will be further aggravating the CO_2 problem. Furthermore, it might be attractive to use stationary hydrogen fuel cells in power plants as a means to increase their capacity to handle peaking loads.

Long term use of nuclear power requires careful management of the uranium resources, and storage of spent fuel from reactors. Uranium resources of 25 million tons of mined uranium or extracted from phosphates can last for about 80 years if the worldwide nuclear share of electricity generation remains at its level today, and if no breeding of fuel is introduced. In fact, introduction of fuel recycling in breeder reactors by 2050 will assure that the rise in the cost of uranium will be limited. Nuclear spent fuel need only to be stored in repositories that would allow its retrieval to produce additional fuel at that point. Breeder reactors will multiply the energy derived from uranium by a factor of 60-70, thus enabling nuclear power to be an important contributor to CO_2-free energy for some 5000 years. Subsequently, either the uranium in sea water or thorium would have to be used. Each of these sources can supply 15,000 years of today's world energy needs.

Spent fuel recycling (for one time) in existing LWRs has been adopted in France, Japan and Russia among others, but is not practiced in the US and several other countries. Eventually recycling of the fuel in breeder fast reactors will be needed for fuel multiplication. However, there are some who argue for an earlier start for recycling in the US to help reduce the level of radioactivity that will be long lived in the geologic repository. Indeed such a goal can be achieved, but the process has costs as well as benefits. It might be that interim storage should be adopted as a policy until the need for breeding fuel arises, at which time the spent fuel for LWRs can be processed to get the benefits of both extending the resources as well as reducing the waste burden.

There is a need to develop an internationally agreed upon system of trade in nuclear fuel that enables some user countries to rely on the others for fuel supplies, for spent fuel storage and treatment and for eventual waste disposal. In the next few decades, discussion should be pursued to allow a stable system of fuel supply and retrieval to be developed, to enable some countries to avoid full development of fuel handling facilities. Regional centers for enrichment of fresh fuel and storage of spent fuel might be a good way to assure the World of peaceful expansion of the use of nuclear energy.

3. Conclusions

The use of nuclear energy in the world energy mix is expected to rise due to favorable environmental, economic and energy security factors. The technology of nuclear power has proven to be manageable with high reliability and safety for many years. Storage needs for discharged fuel and/or processed waste require a geopolitical system that promotes regional cooperation. Promising ideas for improving both light water and gas cooled reactors exist, and the supply of energy (heat and electricity) from those types of reactors would enable wider use of nuclear power in the traditional market of electricity, and also in the market for process heat and hydrogen, which would reduce the CO_2 footprint of the transportation sector.

Speaker's Biography

Mujid S. Kazimi is Professor of Nuclear and Mechanical Engineering at Massachusetts Institute of Technology. He is the current and founding director of the *Center for Advanced Nuclear Energy Systems (CANES)* at MIT. He has authored more than two hundred papers in journals and conferences and the two-volume textbook *Nuclear Systems* on the thermal hydraulic analysis of nuclear reactors.

Professor Kazimi holds the Tokyo Electric Power Company Professorship in Nuclear Engineering at MIT. He has participated in advisory panels for the US Department of Energy, the Electric Power Institute and the US Nuclear Regulatory Commission and at several national laboratories and universities in the US as well as in Kuwait, Japan, Jordan, Spain, and Switzerland. He was a member in 2003-04 of the National Academy of Engineering (NAE) Committee on *The Hydrogen Economy,* and in 2006-07 of the committee on the US R&D programs for development of nuclear energy. He is a member of the Board of Managers of Battelle Energy Alliance, which manages the Idaho National Laboratory. He is a Fellow of the American Nuclear Society and The American Association for the Advancement of Science.

Dr. Kazimi was born in Jerusalem, Palestine. He obtained the B.Eng. from University of Alexandria, Egypt in 1969, and the M.S. and Ph.D. degrees from MIT in 1971 and 1973 respectively, all in Nuclear Engineering.