SCIENCE AND TECHNOLOGY IN SOCIETY FORUM
10TH ANNUAL MEETING
KYOTO, JAPAN

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October 6, 2014

My topic is nuclear innovation, and its role in solving the world's energy problem. This is a challenging subject, especially here in Japan, but it is also a very important one.

Of course, the world doesn't have only one energy problem, it has four separate though interrelated problems. The first is to meet the rapidly growing global demand for affordable, reliable energy supplies. The second is to manage the security challenges arising from the growing dependence of many nations on energy imports, especially of oil and gas. The third is to mitigate the local and regional environmental impacts of fossil fuels, particularly coal burning for electricity and industry and oil burning in vehicles. And the fourth is climate; how can we meet the rapidly growing need for affordable, reliable, secure energy supplies without wrecking the global climate? Each of these four problems is enormously challenging, but in my judgment the fourth problem will be the most difficult to solve, as well as perhaps the most important.

To solve the climate problem we'll need to do many difficult things. We'll need to deploy very large amounts of new solar, wind, and geothermal resources, as well as carbon capture and storage capacity for both coal and natural gas-fired power systems. And, especially important, we'll need to accelerate efforts to increase the efficiency of energy use. But even if we succeed in all of these things, it seems certain that we will also need a major expansion of nuclear energy worldwide.

Today, however, the prospects for nuclear energy are mixed. There are ambitious programs in some countries, most notably China, India, Russia, and Korea, and a growing number of 'newcomer' countries are entering the nuclear energy field for the first time. But other countries are retreating from nuclear, including Germany, Italy, Spain, and, perhaps, Japan too.

The reasons are familiar: public concern over nuclear safety and waste disposal, and the high costs and risks of new nuclear plant construction.

When you add up all of the current plans for nuclear expansion, while also taking account of the expected retirement of much of the existing nuclear fleet as those plants reach end of life, the nuclear contribution to global carbon mitigation seems as likely to shrink as to grow.

So here is the puzzle: on the one hand, the world has little or no chance of maintaining even a modest rate of economic growth while avoiding the worst risks of climate change without a large scale expansion of nuclear energy. On the other hand, if you look at what the world is actually planning to do about nuclear energy today, it doesn't really add up. And so the question – and this may be the most important question for the nuclear energy community today – is how to close the gap between the world's nuclear needs and its nuclear plans.

The most likely answer is through innovation, of three kinds: innovations in nuclear governance; innovations in nuclear technology; and innovations in people – specifically, in education and training. I want to say a few words about each of these.

On the question of nuclear governance, the most important lesson of Fukushima, as well as of Chernobyl and TMI previously, is that what might otherwise have been serious but manageable accidents were transformed into disasters by multiple failures of governance. We know very well what will help to fix these, including transparent decision-making, independent regulatory bodies, and the overwhelming importance of building and sustaining a safety culture in nuclear operating organizations. But we also know that achieving these things will require much more capable institutions – especially international institutions – than we now have, and that this will take a high level of organizational and political innovation.

The second requirement is for innovations in technology. For many decades, the primary goal of nuclear innovators was to extend the uranium resource base through more fuel-efficient reactor technologies. That is still important, but other goals have now become more important: reducing capital cost; reducing the risks of accidents; reducing the burdens of nuclear waste disposal; controlling the threat of nuclear terrorism; facilitating the siting of nuclear facilities; anticipating and responding to changes in how electricity services will be delivered to customers; and reducing nuclear cycle times, which in some countries are becoming almost pathologically long and are adding cost, reducing flexibility, and exposing investors to greater risks.

Nobody today can say for sure what the nuclear technologies at the end of the 21st century will look like. But we might reasonably expect that future nuclear plant designs will be much more reliant on passive safety mechanisms. The new generation of light water reactors has moved in this direction. But other designs go much further toward the goal of 'walkaway safety'. It doesn't seem far-fetched to suggest that such a goal will become a requirement for all nuclear power reactors 30 or 50 years from now, and perhaps even sooner.

We might also expect that advances in the simulation of neutronic, thermal hydraulic, and fuel behavior enabled by new generations of supercomputers will shorten design lead-times and reduce development costs; that new modular construction methods will shorten construction leadtimes; and that smaller, modular reactor designs will reduce capital at risk and accelerate learning cycles.

Perhaps we'll see other developments too, such as lifetime fueling of reactor cores (the so-called nuclear battery concept). Or integrated power plant/waste disposal systems, with spent fuel never leaving the power plant site and disposed of directly in modular deep boreholes several miles below the earth's surface in the stable, dry bedrock that is abundant in most countries. (Deep borehole disposal technology may be especially suitable for nations with small nuclear programs, as well as densely-populated nations in seismically active regions like Japan and Taiwan.)

Another possibility involves developing reactors optimized for burning nuclear waste.

Still another possibility is that advances in computational power and new tools for materials synthesis may one day make it possible to design and build radiation-resistant materials from the ground up, atom by atom, and to create ultra-secure nuclear waste materials with lifetimes of tens of thousands of years.

All of these developments can be imagined today. (Indeed, each of them is being pursued in my own department of nuclear science and engineering at MIT.) And, surely, much greater advances lie over the horizon.

And this brings me to the third element of the nuclear innovation agenda: people.

The need for the intellectual vitality, flexibility, and creativity of new generations of young nuclear scientists and engineers to lead the development of these innovations has never been greater. And I'm glad to report that at MIT, and at other universities in the U.S., growing numbers of students seem to be realizing this. They see great engineering challenges in designing new nuclear power systems that are safer and also less expensive. They see an opportunity to help reduce the grave threat of climate change. Some of them call themselves 'nuclear greens'.

At MIT we are developing new educational approaches based on the principle that, if our students are to be successful nuclear engineering leaders in the future, they must be equally at home in three different 'worlds': the world of science, i.e., the fundamental scientific principles, models, and methods on which nuclear energy is based; the world of systems – the methods for engineering and building the complex aggregations of technology that are needed to deliver energy safely and economically; and the world of society – including the analytical tools and historical insights into how the nuclear systems they design and build interact with society and the natural environment, including economic, social, ecological, political and international aspects. Our students therefore must combine scientific rigor, engineering excellence, and knowledge of society. Science-Systems-Society: that is how we think of the future of nuclear engineering education.

So those are a few comments about the nuclear innovation agenda. And now, let me conclude with some thoughts about Japan. Nuclear energy is a difficult subject to discuss here today. Since 1945, Japan has been a

symbol to the world of nuclear catastrophe. And, unfortunately, that symbol has been reinforced since Fukushima. Japanese engineers and businesses have made important contributions to the development of nuclear energy. But when politicians and pundits elsewhere predict the end of nuclear power and argue that it isn't worth the trouble (as the editors of the *Economist* did recently, among others), they are thinking of Japan.

But I believe there is a different and more credible view of the future of nuclear power, and that is that the nuclear era is only just beginning. Let's not forget that it's still only 75 years since the nuclear fission reaction was first demonstrated. Chronologically, that puts the field of nuclear engineering today roughly where the field of electrical engineering was in the year 1900, a few decades after the great discoveries in electrochemistry and electromagnetism by Michael Faraday, Maxwell, and others. Think about what the electrical engineers accomplished in the decades that followed: the creation of the electric power grid; radio and television; the revolutions in microelectronics, computation, telecommunications, and the internet; and much more – an astonishing series of advances, not one of which was anticipated by the electrical engineers of the year 1900, or by anyone else.

Likewise, no one today can foresee the range of practical applications of nuclear science and technology at the end of the 21st century, in either energy or non-energy fields. But it seems very likely that we are still at the beginning of the era of nuclear energy. And I hope very much that our colleagues here in Japan, as well as a new generation of young Japanese scientists and engineers, will join in the effort to make nuclear safe for the world through innovation – and so enable nuclear to realize its great potential to help overcome the menace of climate change.