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The rise of interest in the CANDLE reactor

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Upon opening my email client on the morning of March 23, I found a message from a friend who asked, "Have you seen the article in this morning's *Nikkei* about Toshiba and Bill Gates? Isn't that about your reactor?" Our office secretary's first task that morning was to go out and get a copy of the morning edition. I thought I knew what had prompted the article. When a *Nikkei* reporter visited my office a few days before about another matter, I had told him about an article on the Internet concerning a visit to China by Bill Gates. The Internet article mentioned near the end that he had also visited Toshiba. I assumed the reporter had then decided to visit Toshiba for some follow-up information, but when my secretary gave me the *Nikkei* morning edition, I found the story on the front page as the lead article. Though it did not mention my name, the article immediately brought a rush of media requests for interviews and information, as it was obvious to many experts interested in innovative fast reactors that the one described in the *Nikkei* was similar to the CANDLE reactor that is a focus of my research.

Among the requests was one from the "Nuclear Viewpoints" journal. In previous media requests, I have often responded to questions about what the CANDLE reactor is, and I will not repeat that description here. My website also contains some technical information on the CANDLE reactor, and I am planning to post an updated version of this on the website (http://www.crines.titech.ac.jp) of the CRINES center, where I serve as director, for readers interested in the technical and academic aspects of the reactor.

Those whose interest is more general than specialized, however, invariably ask "When did you first think of the CANDLE concept" and "Does this concept exist anywhere else". I have found, moreover, that my answers are subjected to various forms of bias or distortion in many of the resulting articles, perhaps because it is relatively easy for others to expand on such questions. In this article, therefore, I would like to describe the germination and growth of the CANDLE concept, and the recent burgeoning interest in its background and potential.

Initial conception

The fact is I do not recall exactly when the CANDLE burning concept first occurred to me. When I was studying fast reactors as an undergraduate student, I began wondering rather vaguely what would happen if a blanket fuel continued to burn, which involved questions about fuel burning methods. In relation to fast reactors, the first specialized book I had read was "Fast Reactors" by Palmer & Platt, and this also brought to mind questions and musings on various types of fast reactors.

When that phase of my studies was just about complete, I was able to attend the Summer Internship Program of the Japan Atomic Energy Research Institute (JAERI, now the Japan Atomic Energy Agency). There I was asked to perform neutronics analyses for reactor cores, and found with some surprise that the computational code used in those analyses was apparently also used in actual design work, and that I could immediately make it myself. The diffusion equation was solved by Gaussian elimination, and at the university I had already written a program for analyzing exponential experiment. Also, the ABBN set was being used for group constants, and it reminded me that my thesis advisor had a book on ABBN on his office bookshelf. When I returned to the university campus, I told him about my thoughts, but he said there was something more important to do at the moment. For my master's thesis I was to go to the Kyoto University Research Reactor Institute and measure the energy spectra of neutrons leaking from a large iron assembly, and compare the obtained spectra with the computational ones obtained with the neutron transport code that I had written.

My master's thesis was good experience but was apparently going to have little to do with fast reactor design. I thought that when it was completed I might join JAERI. Around that time, however, I was informed that the Power Reactor and Nuclear Fuel Development Corporation (PNC, now also merged into Japan Atomic Energy Agency) had just been formed to oversee the Japanese fast reactor program and that JAERI would no longer be working on fast reactors. When I inquired about opportunities at PNC, I learned that the type of nuclear reactor to be developed there had already been determined, and the envisioned program did not include research on the innovative nuclear reactors that I had in mind. Working in industry would apparently provide even less freedom. Ultimately, in accordance with my supervisor's advice, I decided to pursue my studies in the U.S.

At the outset of my study for a doctorate in the U.S., my dissertation advisor and I talked about my crude idea of CANDLE burning, as part of our discussion on which area of research to pursue. About 30 years later when I met him again and talked about

CANDLE burning, he spoke with fondness of the original discussion and I was surprised and quite moved to find that he had remembered it so clearly. He recalled our original discussion better than I did myself. Ultimately, I decided to do research on in-core fuel management of light water reactors for my dissertation. At the time, interest in fast reactors was waning, and the possibility also existed that CANDLE burning might simply be impossible.

Subsequent twists and turns

After receiving my doctorate, I joined General Atomic Co. (GA), which was then deeply engaged in HTGR (high-temperature gas reactor) development. I felt that I would at last be able to focus on innovative reactors. I became engaged in work on spatial distribution stability of power density in large-scale reactors. GA generously permitted me freedom in my research, but I felt that my proposal for innovative reactor research was a bit out of place. Before long, however, the HTGR project was drastically shrunk. I began to feel a desire to pursue research on innovative reactors in a university setting, and had the good fortune of being invited to work at Tokyo Institute of Technology (Tokyo Tech).

Initially I was a research associate at Tokyo Tech and my research was focused on fusion neutronics in accordance with the needs of the laboratory. But when I was appointed associate professor, I soon made up my mind to focus on innovative reactors. I believed that it might be difficult to join fast reactor communities as an experienced researcher if I immediately began a study on such reactors, so I started out with research on HTGRs. My research experience at GA seemed to be evaluated highly by Japanese HTGR communities. While I was at GA, I had proposed that an optimum power distribution could be obtained using fuel with just one kind of enrichment by having the fuel migrate in the axial direction. I learned that this concept had already been developed in Germany as the pebble-bed reactor. Although my idea is not a new one, I realized that the computational method I had used in my doctoral dissertation could be effectively applied to the pebble bed reactor, and this work marked my first study in Japan directed toward launching my research on innovative types of nuclear reactors.

About the time I was preparing to begin research on fast reactors, the Central Research Institute of Electric Power Industry (CRIEPI) launched with much fanfare its research program for the 4S reactor, a small fast reactor with metallic fuel. With my experience in research on the HTGR at GA, I initially felt it would be most difficult to

achieve a practical small fast reactor, because of the obvious demerits of scale involved in the concept. But their explanation of the concept showed that it actually did hold strong promise for ultimate practical realization, and I naturally became quite interested. By a fortunate turn of events, moreover, a student from Indonesia joined us at Tokyo Tech, and this proved an excellent opportunity for research on long-life small reactors in a scenario where a reactor would be constructed in Japan, transported to Indonesia where it would be operated, replaced at the end of its life span by a new reactor built in Japan, and the used reactor returned to Japan.

The 4S Reactor was being designed to utilize reflectors for burn-up control, with the fuel burning region migrating from the bottom of the reactor core to the top. I felt the same thing should be possible without any burn-up control methods such as the use of reflectors, if lead or lead bismuth (LBE: lead bismuth eutectic) were used as a coolant rather than sodium for a metallic fuel fast reactor. With this in mind, we studied the question of whether CANDLE burning could be accomplished in an LBE-cooled small fast reactor. The study predicted complete failure. Everything would go wrong. I thought it might work if the nuclear reactor was made larger, but in that case the overall scenario would fall apart. But I realized that if natural uranium was positioned in the central part of the core and burned from the circumference, the reactor could easily be operated continuously for more than ten years. I therefore quickly gave up on the original CANDLE burning configuration and decided to proceed with research on "out-in" burning in a small long-life fast reactor.

At this point, the development of the proposed LBE-cooled small long-life fast reactor took an unexpected twist. It was not long after the collapse of the Soviet Union, and I was invited to speak at a conference on small reactors being held near Moscow. When I presented the concept there, many in the audience had been involved in designing lead-bismuth cooled beryllium-moderated small reactors for submarines, and they became so interested by my concept that I was virtually mobbed by their questions and excitement. At that conference, there was no other report on a lead-bismuth small fast reactor, and up to that time the concept apparently did not exist. But it wasn't long before they completed an excellent design, and through steady progress in research and development they are now about to begin construction.

Successful CANDLE burning computation

About the time when the design work at Tokyo Tech for the LBE-cooled metallic fuel small long-life fast reactor had been completed, a new student named Kouichi Ryu

began studying there for his doctorate. As the timing seemed perfect, I decided to have him work on designing the CANDLE reactor as a hard-spectrum fast reactor. At the same time, however, major doubts still existed concerning the ultimate feasibility of the CANDLE reactor. For that reason, I first had the fast reactor designed as a pebble-bed reactor. The computational method had already been established with good results for the HTGR pebble-bed reactor, and I felt certain it would also be effective in this application. It did indeed give the expected results, and I had him complete a monograph on this research. When its acceptance for publication was assured, I next had him proceed to work on the CANDLE reactor. Only a slight portion of the computational code had to be modified for this purpose, and several new innovations were necessary, but it resulted in effective realization of CANDLE burning.

As Ryu had by then completed his dissertation and left the university, I compiled a paper on the validity of CANDLE burning, with the help of master's degree candidates who had subsequently joined our laboratory. As I believed it would be epoch-making in its import, I submitted it to Nuclear Science and Engineering (NSE), the journal of the American Nuclear Society, which was at that time regarded by many of those engaged in nuclear energy research as the most authoritative. Though the paper was submitted in 1999, the referees apparently found it difficult to believe the findings and requested various types of additional data, which were then added, and it was not until 2001 that the paper was finally published.[1] Following its submission, several applications have been filed for presentations at international conferences, and these presentations were thus actually made before the publication in NSE. When I spoke with an American friend concerning the content, he informed me of the publication of a similar concept by Edward Teller,[2] which was ultimately added to the references in the NSE publication. The paper by Dr. Teller was to become the basis for the Travelling Wave Reactor.

Some time later, I was asked to give a presentation on the CANDLE reactor to a study group of senior members in the field of nuclear energy in Japan. Around that time, I had happened on the following interesting passage in a review column of Nuclear News: "The process demonstrated well the three stages of scientific discovery. In the first stage, people call your idea crazy and say you'd be a fool to propose it. In the second stage, with the evidence mounting, people say it just might be correct. By the time you have enough evidence to offer proof, you are at the third stage, when people say the idea is so obvious that of course it's true, any idiot could have seen that." At the group study meeting, I asked the listeners what stage they thought the CANDLE reactor was in. Everyone naturally replied that it was in the first stage. Some time later, I happened to meet one of the participants and asked him again. Without hesitation, he replied that it

was still in the first stage. Though this was not unexpected, I must admit that I found his response discouraging. Since that time, however, events have taken a new turn. Bill Gates has become part of the picture, and perhaps I should ask once again. The reply just might be that the CANDLE reactor is now in the second stage, though not on the strength of the technical findings but rather due to the financial prowess of Bill Gates. The path to the third stage, in any case, still appears quite long.

In 2003, Tokyo Tech has initiated its 21st Century COE program entitled "Innovative Nuclear Energy Systems for Sustainable Development of the World (COE-INES)" and selected the CANDLE reactor as one of its leading projects. The research will continue thereafter at the Center for Research into Innovative Nuclear Energy System (CRINES), as the COE successor.

The entry of Bill Gates

INES-2, the second COE-INES international symposium, was held in 2006. Edward Teller had passed away, but his co-researcher Lowell Wood was invited and we were honored by his acceptance and presentation.[3)] Though it had been some time since the publication of Dr. Teller's paper, Dr. Wood's presentation was essentially the same in content, which led me to wonder whether their work might have been a one-shot wonder. Some time later, I received an invitation by email to visit Dr. Wood and his colleagues, not at Livermore as might be expected but rather in Seattle. Unfortunately I was quite busy at the time and could not accept the invitation. In May of 2009, however, I was introduced to John Gilleland, the CEO of TerraPower, at the ICAPP conference held in Tokyo that year, by my old friend Ning Li of Xiamen University in China. There I learned that the nuclear reactor proposed by Dr. Teller and his colleagues had become the subject of research and development by Dr. Wood and others at TerraPower, as the TWR. I learned also that it was being sponsored by Bill Gates, and that the development of a new reactor in China was envisioned. The organization as described to me seemed to have a deeply amateur quality, but I knew that any aspects in which it was lacking could be well remedied by addition of outstanding personnel, and I felt that an organizational system of this nature might indeed be needed in order to bring the CANDLE reactor to reality. I was invited to join as a consultant, and pleased to accept.

In the arrangements for the consultancy, the procedures at Tokyo Tech were quite lengthy and the formal signing was not completed until July of 2009. In September, I was able to schedule a visit to TerraPower in Bellevue, Washington. On my way there, I stopped in at my alma mater University of California, Berkeley, where I had been asked

to speak in relation to CANDLE. Though word had not yet reached Japan, the latest issue of Nuclear News contained a feature article on the TWR. Neither my name nor the name CANDLE appeared in the article, but people obviously knew that the CANDLE reactor and the TWR represented the same kind of nuclear reactor. The title of my speech at Berkeley was simply CANDLE, but the lecture hall was packed to overflowing.

The surroundings of the TerraPower research facility were luxurious, with towering trees and a deep green ambience. I was pleasantly surprised to find that not only Dr. Gilleland but also Dr. Wood and many researchers and graduates of MIT that I knew quite well were working at TerraPower. In the morning of the first day, I spoke to those who gathered there about the CANDLE reactor. Throughout the afternoon and the following day, they described to me the TerraPower organization and facilities, and the TWR.

In November, I received an urgent email message from my friend Ning Li asking me to come to China right away. He wrote that Bill Gates, Dr. Gilleland, and their associates had visited China in early November, and that he wanted me to visit the same institutions that they had. I hastened to adjust my schedule, and arrived in China at the end of November. I visited the China Institute of Atomic Energy (CIAE), the China National Nuclear Corporation (CNNC), the State Nuclear Power Technology Corporation Ltd. (SNPTC), Tsinghua University, and the Shanghai Nuclear Engineering Research and Design Institute (SNERDI). At each location, Ning Li first spoke about the TWR and I then spoke about CANDLE. Many young people were in each audience. In the conference at CNNC in Beijing, I was surprised to meet one of my old students who was then working at a laboratory in Chengdu. He had simply been told to travel to Beijing for a conference, and hadn't even imagined that I would be speaking there.

It was at that time that I had received from Ning Li the internet article about the visit of Bill Gates to China and also Toshiba.

Present status

Whenever I speak about CANDLE at international conferences, the lecture halls are now filled to overflowing, where once the audiences were quite small or nearly non-existent. This, I think, may be part of the "Bill Gates effect". What I am doing now has changed very little from my previous work. It is true that many people have advised me to adopt a more attention-getting approach, but I think the present course is fine. I

am in truth most gladdened to see that innovative reactors are now becoming the focus of highly active research efforts. If the TWR someday proves successful, I will be delighted to know that many people are aware of its origins in the nuclear reactor named the CANDLE reactor that was first conceived and researched here in Japan.

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