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Aging Nuclear Power Plants

focusing in particular on irradiation embrittlement of pressure vessels

Japan’s Aging Nuclear Power Plants

Japan began generating nuclear power in 1970. The Tsuruga-1 plant began operations on March 14, 1970, just in time to provide atomic energy for the Osaka Expo. At the time most people were not aware of the dangers associated with nuclear power. It is fair to say that they hoped that scientific and technical progress would enable the same nuclear energy that brought about the tragedy of Hiroshima and Nagasaki to be used for peaceful purposes.

After Tsuruga-1, which was a boiling water reactor (BWR), on November 28 of the same year the Mihama-1 pressurized water reactor (PWR) began operations. Thereafter, as can be seen in Figure 1(1), the number of nuclear power plants in Japan increased rapidly. By the 1990s Japan was third in the global nuclear energy stakes after the United States and France. In 2005 the Higashidori and Shika-2 reactors came on line bringing the number of reactors to 55, with a total generating capacity of 49.58 GW. Since then, Hamaoka Units 1 and 2 were permanently closed down (January 2009), Tomari-3 came on line (December 2009), and six reactors at the Fukushima Daiichi Nuclear Power Station were effectively knocked out by the Great East Japan Earthquake, bringing the number of “surviving” reactors to 48. (As of the end of March 2012, TEPCO has officially recognized the permanent shutdown of Fukushima Daiichi Units 1 to 4.) However, of those there is no indication that eleven reactors will restart: three reactors (Units 2, 3, 4) of the seven-reactor Kashiwazaki-Kariwa Nuclear Power Station have not restarted since the Chuetsu-oki Earthquake in July 2007; the three Onagawa reactors, the four Fukushima Daini reactors and the Tokai Daini reactor were all shut down by the Great East Japan Earthquake. Besides these, Japan’s other nuclear reactors have not yet passed stress tests, so all Japan’s reactors are likely to be out of action by early May 2012.

Japan’s nuclear power plants began commercial operations over ten years later than the first plant in the United States. With the exception of two reactors (USA) started up in 1969, the power plants which began operations in the 1960s in countries such as the United States and Germany have been decommissioned, so Japan is now a world leader in the operation of aging reactors(2). Unlike when the plants were built, there is no model for managing aging plants.

Before nuclear power plants reach 30 years of operations, and every ten years thereafter, utilities are required to produce a technical assessment for the operation of aging plants. Utilities may be granted approval to continue operating aging plants on the basis of a review by The Ministry of Economy Trade and Industry’s (METI) Aging Response Review Committee. At the moment there are over 20 reactors in Japan which have been operating in excess of 30 years, including Tsuruga-1, Mihama-1~3, Fukushima Daiichi-1~6, Shimane-1, Takahama-1&2, Genkai-1. Of those, Tsuruga-1, Mihama-1 and Fukushima Daiichi-1 have already been operating for 40 years and been granted approval to operate for a further 10 years.

How long were nuclear power plants designed to operate? These days utilities and METI claim that no life expectancy was determined, but in fact Japan’s nuclear power plants were designed with an expected life of 40 years. That is evident if one looks at the pressure vessel. In the 1970s the utilities’ license applications included an evaluation of neutron irradiation embrittlement (see below) based on an assumed operating life of 40 years. Furthermore, monitoring specimens placed in the reactors assume 40 years of inspections. In most cases only five or six sets of specimens were placed in the reactors. This became a problem when the issue of life extensions arose, so in 2007 a rule (JEAC 4201-2007) was hurriedly introduced which allowed the specimens to be cut and re-used.

It is thought that the reason why Japan’s reactors were designed to last 40 years was because the license to operate nuclear power plants in the United States was for 40 years. However, these is evidence that at first the estimated life was 30 years. According to a Toshiba engineer who worked on nuclear power plants, Shiro Ogura (personal correspondence), the design life written in specifications at the time when GE was prime contractor for Fukushima Daiichi-1&2 was 30 years. He said that when Toshiba became the prime contractor for Fukushima Daiichi Unit 3 the design life was changed to 40 years.

Articles(3) about changes due to aging written in the 1980s by researchers at the Japan Atomic Energy Research Institute were based on the assumption of a 40-year life, so it can be assumed that at the time the shared understanding was that the life expectancy of nuclear power plants was 40 years.

　No matter what the equipment or machinery, as it gets older the frequency of breakages and other problems increases, making maintenance difficult. Associated costs and labor also increase. Nuclear power plants are no exception. Rather, it is normally assumed that damage will occur sooner in nuclear power plants because of their high technology nature, which pushes design capabilities to the limit.

　In 2003, immediately after revelations of cover-ups of cracks at Tokyo Electric Power Company’s (TEPCO) nuclear power plants, we set up the Nuclear Aging Research Team to focus on issues associated with aging of nuclear power plants. The pamphlet “Rokyuka suru genpatsu: gijutsu wo tou” (Aging Nuclear Power Plants: Questioning Technology)(5), which we published in 2005, raised the alarm about the dangers of aging nuclear power plants. Thereafter, in July 2007 the Kashiwazaki-Kariwa Nuclear Power Station was struck by the Chuetsu-oki Earthquake and then in March 2011 the Great East Japan Earthquake caused a severe accident at the Fukushima Daiichi Nuclear Power Station. As a consequence the world is now concerned about the seismic resistance of nuclear power plants, but accidents can be caused by other things besides earthquakes. Even if there is no earthquake, or else in combination with an earthquake, deterioration of equipment and machinery could trigger a severe accident. We cannot relax our vigilance towards nuclear power plants whose lives have been extended beyond their use-by date.

　The above mentioned “technical assessment for the operation of aging plants” contains headings related to aging, such as stress corrosion cracking and reduction of insulation of electrical equipment and instruments, but most importance is placed on the neutron irradiation embrittlement specimens in the pressure vessel. This is the issue that I will focus on in the rest of this article.

Outline of Neutron Irradiation Embrittlement in Aging Nuclear Power Plants

Destruction of the reactor pressure vessel due to neutron irradiation embrittlement should be called an *extreme* severe accident. If the pressure vessel breaks, there is almost no way of preventing a runaway chain reaction. There is also no way of preventing melt down of the nuclear fuel. Such extreme damage must be avoided at all costs.

The benchmark for irradiation embrittlement is the ductile-brittle transition temperature (DBTT). If an extreme situation arises such as pipe rupture due to an earthquake, it is necessary to cool the core using the emergency core cooling system (ECCS). However, if the DBTT is high, this is a dangerous operation. When cooled suddenly, a temperature difference arises between the inner and outer walls of the pressure vessel and strong tensile stress is brought to bear on the inner wall. If such tensile stress is applied when the temperature is below the DBTT range, there is a danger that the pressure vessel could suddenly break completely.

Table 1 shows Japanese nuclear power plants in descending order of the DBTT of their pressure vessels. (\*Recently the DBTT of Takahama-1 was reported to have been measured at 95℃, making it the second worst.) The table shows seven reactors in which DBTT exceeds 50℃. They are all old reactors that began operating in the 1970s.



Genkai-1 is the worst. The DBTT for this reactor was announced in October 2010. The figure comes from the most recent test of monitoring specimens in April 2009. The DBTT rose 42℃ since the previous test result of 56℃ in February 1993. This is a new record for Japan. This reactor is discussed in detail in the next section.

All the reactors listed from second to fifth place in the table are located in Fukui Prefecture and owned by Kansai Electric Power Company (KEPCO). In particular, we have been concerned about the continued operation of Mihama-1&2, where high DBTTs have been observed since the beginning of the 1990s. KEPCO asserts that results of pressurized thermal shock (PTS) analysis show that even if the ECCS was used in the event of a pipe rupture the pressure vessel would not fail.(6) However, the evaluation methodology for the stress arising *KI* has not been released, so it is not possible to know whether this analysis is reliable.

PTS analysis(7) assesses the pressurized thermal shock to the core of the pressure vessels of PWRs in the case of accidents such as loss of coolant accidents and main steam pipe ruptures. If sudden cooling occurs in the case of accidents such as these, temperature differences arise between the inner and outer surfaces of the pressure vessel and strong tensile stress arises on the inner surface. If the pressure vessel has become brittle (below DBTT), cracks progress and the pressure vessel fails causing a severe accident. It is necessary to confirm that the stress intensity factor *KI*does not exceed the fracture toughness *KIC*.

The reactors listed in sixth and seventh places in Table 1 are BWRs. The inner diameter of BWR pressure vessels is large compared to PWRs and the amount (flux) of neutron irradiation received in a given time is one or two orders of magnitude less than in PWRs. From the table it can be seen that the total amount (fluence) of irradiation received by Tsuruga-1 is about one thirtieth of that of Mihama-1, even though they began operating at much the same time. (There is a slight difference in operating time and also in the date the specimens were taken.) Consequently, it was thought that neutron radiation embrittlement was not such a big problem in BWRs as it was in PWRs. (Even now many researchers and engineers are still in the grips of that “common sense”.) However, after many years of operation, as we came to know the reality of irradiation embrittlement in BWRs, this “common sense” was overturned. The total amount (fluence) of irradiation is not the only determining factor for irradiation embrittlement. It has become clear that the rate (flux) at which irradiation occurs is also a determining factor. As will be discussed later, this led to an amendment to the monitoring specimen method JEAC-4201 and led to the situation where two BWRs are now listed among the worst seven, besides other BWRs with high levels of irradiation.

Why Does Irradiation Embrittlement Occur? - Basic Concept

Metal materials are degraded for all sorts of reasons. One reason is “radiation damage”. This phenomenon is investigated at the atomic level by means of the concept of lattice defects. The Physical Society of Japan has had a section on lattice defects for over 50 years. Pardon me for speaking of my personal involvement in this field, but I have devoted myself to this field of research since becoming interested in it as a university student. I became a tutor at Osaka University and experienced the student uprisings of the 1960s. In hindsight I can see that this field of research, which originated in America, developed in tandem with nuclear energy. Nevertheless, that fact did not lead me to abandon the field. I was eager to carry out materials research using radiation as a guest researcher of the Kyoto University Research Reactor Institute.. However it was difficult to see a connection between this research and the social problems associated with nuclear energy.

　The reason why irradiation defects became an important research theme was because when neutrons generated by nuclear fission hit reactor vessels and pipes they damage metal materials. This is called “neutron radiation damage”. If it causes materials to become brittle, it is called “neutron irradiation embrittlement”. Of particular importance is neutron irradiation embrittlement of the steel of the reactor pressure vessel, which is the heart of a nuclear power plant. If this is damaged it can lead directly to an uncontrollable severe accident.

What type of lattice defects arise from neutron radiation? Atoms in their crystals are precisely aligned in lattices, but if they are struck by a neutron they are displaced, leaving a hole. This is called a “vacancy”. Displaced atoms are called “interstitial atoms”. This phenomenon is called a “lattice defect”. In addition, secondary defects result when vacancies and interstitial atoms move about and accumulate, creating “vacancy clusters” and “interstitial atom clusters, respectively. Impurities within the metal (copper atoms etc.) move to form “impurity clusters”. These “secondary lattice defects” cause metals to lose their characteristic ductility (plasticity) and make them brittle. To compare it to the human body, it is like the hardening of the arteries which makes blood vessels vulnerable to rupture.

Usually, when a force is applied to steel it just deforms without breaking, but below a given temperature, if the slightest force is applied, rather than deforming plastically it breaks like pottery. This critical temperature is called the ductile-brittle transition temperature (DBTT). This brittleness of steel used to be the bane of shipbuilders. Many ships sank due to this phenomenon. The Titanic, which sank exactly 100 years ago in 1912 when it struck an iceberg while crossing the North Atlantic Ocean, is a famous example. Subsequent studies showed that poor quality steel plate was used and that the DBTT was 27℃.

When reactor pressure vessels are bombarded by neutrons the DBTT rises. When designing nuclear reactors it is necessary to predict how high the DBTT will rise and whether they can survive for the period of their design lives. However, assuming a design life for nuclear reactors of 40 years, it is impossible to know how they will be after 40 years until 40 years has elapsed. That presents a problem, so accelerated experiments are conducted. Accelerated experiments are commonly used tests to assess endurance by, for example, applying beyond normal load, or operating plants at greater than normal speed.

　Likewise, when conducting tests for neutron irradiation embrittlement, the amount(flux) of neutron exposure in a given period of time is increased far above normal amounts. Materials test reactors can radiate materials at a rate of 1012n/cm2. The “n” standards for “neutron”. This rate (flux) of exposure is between 100 and 10,000 times the rate of exposure in normal reactors, given that the rate of exposure for PWRs is 1010n/cm2, while the rate for BWRs is 108n/cm2. That means the amount of irradiation a BWR would sustain in 40 years can be applied in one or two days. Using such data a formula predicting embrittlement was produced. Furthermore, besides the normal monitoring specimens, accelerated monitoring specimens are also placed in BWR reactor vessels. They are placed not on walls of the vessel itself, but nearer to the core, where the rate (flux) of radiation is an order of magnitude higher. The idea is to predict the future state of the reactor. Likewise monitoring specimens are placed deeper inside PWRs than the walls of the reactor vessel. For example, in the case of Genkai-1 discussed below, the rate of radiation is about double the normal rate. It is an attempt to read the future.

　However, there is an assumption underlying the notion that the future can be predicted. That is that regardless of the rate (flux) of irradiation, or, to put it another way, regardless of the period of exposure, if the total amount (fluence) of radiation is the same, the result will be the same. The formula for this assumption is as follows:

　Rise in DBTT = material factor x F(*f*)(8)

The material factor is determined by the type and the concentration of impurities in the steel. For example, if there is a lot of copper, the material factor will rise. F(*f*) is the irradiation factor. It is postulated to be a function of the fluence of neutron irradiation “*f*” alone.

With accumulated experience of operating nuclear power plants, it became possible to obtain long-term data of monitoring tests in real life conditions and it became clear that this formula was suspect. In particular, with regard to BWRs, for which the rate of irradiation is slower, it became clear that the results for the normal monitoring specimens and the accelerated monitoring specimens placed in reactors did not agree. This trend is particularly pronounced in reactors like Tsuruga-1 and Fukushima Daiichi-1 where there is a lot of copper impurity in the steel of the reactor pressure vessels. It can be seen from this that the irradiation factor F(*f*) is dependent not only on the fluence of neutron irradiation “*f*”, but also on the flux of irradiation.(9)

We noticed this over ten years ago and alerted researchers to the issue.(10) However, at the time, the results of American research refuting dependence on the flux of irradiation held sway, so Japanese researchers refused to take the matter seriously and they did not alter the embrittlement prediction formula.(8) Faced with data from Tsuruga-1 showing unpredicted high levels of DBTT, METI’s Aging Response Review Committee dismissed the results saying they were due to data scatter.(11,12)

Thereafter, analysis of the micro-formation of copper progressed, and it became clear that when the rate of radiation is slow mainly clusters of copper atoms (obstructions) form, whereas in accelerated irradiation tests mainly clusters of vacancies form, so the cause of the hardening (embrittlement) is different. The results of this micro-analysis backed up our computer simulations.(13) The outdated thinking described above was forced to change and now the dependence of radiation embrittlement on the flux of irradiation is the shared academic understanding. The irradiation embrittlement prediction formula used in monitoring test methodology was changed and a new methodology (JEAC 4201-2007) was produced.(14) From mid-2011 assessment of pressure vessels shifted to the 2007 formula, but when the increase of DBTT using this formula is smaller than that using the previous 2004 formula, the 2004 formula is included as a reference.

However, even the 2007 formula cannot explain high DBTT for metal welds in Tsuruga-1 that we have drawn attention to. The metal welds in Tsuruga-1 have low levels of copper impurities, unlike the parent metal, so they shouldn’t have high DBTT. The amended JEAC-2007 was not able to adequately explain the complex reality.

Unpredicted Embrittlement in Genkai-1 Reactor Pressure Vessel

We looked into the “unpredicted” monitoring specimen data. The results were from Genkai-1. At the October 25, 2010 meeting of Karatsu City Municipal Assembly’s Pluthermal Special Committee, Kyushu Electric Power Company announced that the DBTT observed in Genkai-1’s fourth monitoring test specimen, which was taken during a periodic inspection in April 2009, had reached 98℃. Previously, the highest DBTT for a reactor pressure vessel had been 81℃ for metal taken from a weld at Mihama-1 (see Table 1). The Genkai-1 specimen exceeded this, so it would be fair to conclude that Genkai-1 is the most dangerous reactor pressure vessel in Japan.

　Furthermore, it is significant that this embrittlement was unpredicted. The DBTT observed in the previous (third) monitoring test (February 1993) was 56℃. That had increased by 42℃, which was contrary to the predicted result. Figure 2 is a diagram submitted by Kyushu Electric in its December 2003 Aging Technical Assessment, with a “×” added to the top right corner to show the result of the fourth monitoring test. Up until the third monitoring test the data points could be more or less plotted onto the predicted curve, but the latest data point is way above that curve. If you look closely at the diagram you will see that the broken line is the predicted curve and that a line is added above that showing the upper limit of the margin for error. However actual embrittlement is way above that upper limit.



Kyushu Electric says that 98℃ is the value predicted for 2060 (85 years after the start of operations), while the predicted DBTT for 2035 (60 years after the start of operations) is 91℃ and for August 2010 (35 years after the start of operations ) is 80℃. (\*If the 2007 formula is used the predicted DBTT is somewhat higher, so Kyushu Electric has amended it.) Let us consider whether this is correct.

We must first understand the data on which this is based. Table 2 shows the results for the first to fourth monitoring tests. The amount of neutron irradiation is the amount for the specimens, not for the pressure vessel itself. The specimens were placed deeper inside the reactor than the reactor walls, so they were irradiated by more neutrons. Since the specimens have been irradiated by more neutrons than the reactor walls in the same time, operating years are converted to “effective operating years”.

Effective operating years for the fourth monitoring test specimen was 66 years, meaning the reactor walls would be irradiated by the same amount of neutrons after 66 years. Since the reactors do not operate continuously, this amount of irradiation would not actually be reached until 85 years after the reactor began operating. How then are the present DBTT and the DBTT after 60-years estimated? Since DBTT is 98℃ after 85 years, bringing it back to 35 years and 60 years Kyushu Electric comes up with the lower temperatures of 80℃ and 91℃ respectively.

The method used to derive this estimate is to redraw the prediction curve, adding a margin of error so that it passes through data point “×” in the top right corner of Figure 2, then to read off the DBTT corresponding to the amount of irradiation after 35 years and 60 years respectively. But for such a method to have a basis, the embrittlement prediction curve in Figure 2 must have some legitimacy. However, as discussed above, the formula used in the past has been pronounced invalid.

So can the new 2007 prediction formula explain the DBTT of Genkai-1? The answer is no.

Figure 3 shows the irradiation embrittlement prediction curve drawn by us on the basis of the 2007 prediction formula, and the observed DBTT.(15) Like Figure 2, this diagram shows both the scale for DBTT and also for the increase in DBTT, the difference from the initial DBTT of minus 16℃.



It can be seen that the observed data of 98℃ is 42℃ above the predicted curve. This cannot be explained in terms of margin of error. Compared to Figure 2, if anything the deviation is greater. Thus the 2007 prediction formula fails completely to reproduce the irradiation embrittlement behavior of Genkai-1. Hence, there is no explanation why a high DBTT was observed in Genkai-1. Given that such high DBTTs are observed when there is a high amount of copper impurity, or there is phosphorous grain boundary segregation, we cannot rule out the possibility that the Genkai-1 pressure vessel contains, depending on the location of the monitoring specimens, low quality steel with high levels of impurities. In regard to Genkai-1, both the 2004 formula (Figure 2) and the 2007 formula (Figure 3) have lost their predictive power. It is meaningless to estimate based on these formulas that the current DBTT is 80℃, or that after 60 years operation it will be 91℃.

　So what should we suppose the DBTT to be now? There is no sound method of estimating it. In that case, Kyushu Electric should respect the observed data of 98℃, assume that the pressure vessel itself has already reached this high DBTT (that being a true safety margin) and consider what response should be taken. The response should be to carry out the abovementioned PTS assessment based on a DBTT of 98℃, reconsider the operating sequence based on the 98℃ figure, and also carry out pressure tests based on 98℃.

NISA’s Response and Public Comments

We were surprised at the observed high DBTT for Genkai-1. As soon as we found out about it we requested Social Democratic Party leader Mizuho Fukushima to arrange a hearing with officers of Nuclear Industrial and Safety Agency (NISA) to find out about the monitoring test methodology etc. To our amazement, at that point in time (December 15, 2010) NISA had received no information about the results of the fourth monitoring test for Genkai-1. The first they heard of it was from the questions in our letter. Kyushu Electric had not informed NISA of the strikingly high DBTT and NISA said they did not know because they had no obligation to inquire. What a careless and lax safety monitoring system. At the hearing we demanded that NISA pay great attention to Genkai-1’s DBTT, and that it publish raw data for the Charpy test.

It is a matter of great significance that the results of the fourth monitoring test for Genkai-1 cannot be accounted for by either the former prediction formula (JEAC 4201-1991), or the current formula (JEAC 4201-2007), and that the high DBTT cannot be accounted for. NISA called for opinions regarding the 2010 supplement to JEAC 4201-2007, so, in light of this serious situation, the Nuclear Aging Research Team submitted a public comment to NISA articulating fundamental questions about the monitoring test methodology.[[1]](#footnote-1)

The essence of our public comment was as follows (abbreviated):

* The 2007 prediction formula is totally unable to reproduce the results of the monitoring test on mother material in the Genkai-1 reactor and metal welds in the Tsuruga-1 reactor, so the monitoring test system cannot be implemented based on the 2007 prediction formula.
* It is necessary to make a decision to permanently shut down nuclear reactors in which a high DBTT that cannot be explained by the prediction formula is observed.
* A fundamental review of JEAC-4201 is necessary, including whether prediction is possible.

　This public comment calls for a fundamental review of JEAC-4201, which stipulates the monitoring test methodology for steel in pressure vessels, and for an explicit statement in the rule that there are cases where the option of permanent shutdown should be selected.

　NISA’s response to our public comment was published on its web site on May 6, 2011. There was no direct response to the points we made. The response made no reference to the striking deviation in the Genkai-1 data. It simply stated that where there is a deviation the margin for error should be reset and that there was no problem. NISA’s reply was an insult to our intelligence. What needs to be corrected is the thinking behind the monitoring test methodology that uses margin for error to paper over problems.

1. [↑](#footnote-ref-1)