Discussion and Issues in the “NISA Advisory Committee on the Technological Assessment of Aging in Nuclear Reactors”

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Launch of the “NISA Advisory Committee on the Technological Assessment of Aging in Nuclear Reactors”

Last November the Nuclear Industrial and Safety Agency (NISA) initiated the NISA Advisory Committee on the Technological Assessment of Aging in Nuclear Reactors. As it turned out, I was invited to become a member of the committee. Hitherto, NISA has ignored our ideas. I decided to participate in the Hearings because I believed it was necessary to have a forum in which to communicate our thoughts about the issue of aging nuclear power plants, in particular concerning the extraordinary embrittlement of the Genkai-1 plant. However, these Hearings are, as their name implies, a forum in which committee members’ views are heard and debate takes place, but in the end NISA takes responsibility for writing the report. I was aware of this limitation when I decided to become a committee member.

The following three issues have been considered during the Hearings:

(1) Assessment of the aging of individual plants:
Technical assessment reports on ageing have to be submitted to NISA for nuclear power plants that have been in operation for over 30 years, and every 10 years after that. If the review confirms their safety they can continue to operate. Assessment reports were submitted for Ikata Unit 2 (commenced operation 19 March 1982) and Fukushima Daini Unit 1 (commenced operation 20 April 1982) for the first time last year. A 40-year report was also submitted for Mihama Unit 2 (commenced operation 25 July 1972).

(2) Relation between aging and the Fukushima Daiichi accident:
This refers to consideration of the question of whether aging (deterioration of equipment and materials) contributed to or exacerbated the Fukushima Daiichi accident.

(3) Cause of the greater than predicted embrittlement of Genkai-1:
Consideration of how to interpret the results of the monitoring tests of the Genkai-1 ductile-brittle transition temperature (DBTT), which exceeded the predicted 98°C, and whether the equation for predicting embrittlement is appropriate.

So far 16 meetings of the NISA Advisory Committee on the Technological Assessment of Aging in Nuclear Reactors have been held (mid-June 2012). NISA’s intention was to disband the committee at the end of March 2012, but due to the delay in the establishment of the new
Nuclear Regulatory Commission, the Hearings are continuing unchanged.

Theme (1) relates to life extensions for aging nuclear power plants and was the province of the Aging Countermeasures Examination Committee Working Group of the Agency for Natural Resources and Energy (ANRE), which is part of the Ministry of Economy, Trade and Industry (METI). After the Fukushima accident occurred on March 11, 2011 this working group was disbanded and the role was shifted to the NISA Advisory Committee on the Technological Assessment of Aging in Nuclear Reactors.

Consideration of Ikata-2 has already finished and NISA has announced the conclusion that it is possible to extend operation. Regarding Fukushima Daini-1, an investigation was carried out into whether or not a state of cold shutdown has been safely maintained. The debate about Mihama-2 is approaching the final stages. The life extension of Mihama-2 impinges on the amendment to the regulations, which states that in principle the period for which nuclear power plants may be operated is 40 years calculated from commencement of operation. However NISA is of the opinion that these are separate issues. It says, “The technical assessment of aging … is a matter required by law … which must be solemnly undertaken.” It compiled an investigation report which accepted a life extension beyond 40 years based on the argument that “if a new system which limits operation to 40 years comes into effect, regardless of the results of the technical assessment of aging, just those reactors which clear the new standard to be established in the future will be able, as an exception, to have their lives extended.” My proposals that these Hearings should debate the details of how to close down aging reactors such as these with advanced irradiation embrittlement and that a conclusion should be deferred until a new nuclear regulatory agency is established were not included.

Theme (2) is already finished. A report was compiled (February 16, 2012) which said, “The conclusion was that it is difficult to believe that aging of equipment contributed to or exacerbated the accident.” However, “The assessment of the effects of aging was a desktop assessment, so it is necessary to carry out further studies in future through on-site confirmation, etc.” The contents are sloppy, based on technical assessment methods of aging and past results, and simply adding on an assessment of the 3.11 seismic movement. The original draft drew the conclusion, “It is believed that [aging] did not cause or exacerbate the accident.” However, even committee members besides myself expressed the view that this was odd. They pointed out that without even seeing the scene of the accident such a conclusion was premature, and that it was unclear whether the object of the investigation was clarification of the causes of the accident or future improvement. Consequently these words were deleted and replaced by the underlined words above.

Theme (3), which relates to irradiation embrittlement in Genkai-1 and
whether the existing prediction equation is appropriate, is the issue that interests me most. Debate about the cause of the high DBTT (98℃) observed in the Genkai-1 pressure vessel monitoring tests revolved around two theories: [i] was it caused by poor quality pressure vessel material or a bad manufacturing method, or [ii] was it because the embrittlement prediction equation does not accurately reflect reality in the high irradiation range?

Kyushu Electric claimed that the results of chemical analysis of the steel materials showed that there were no irregularities and that uniformity was maintained. They also claimed that examinations carried out by the Central Research Institute of Electric Power Industry (CRIEPI) and others into micro-organization in the monitoring samples showed a good correlation between embrittlement and the formation of impurity clusters, so there was no abnormal embrittlement. However, to confirm the accuracy of this judgment and form a conclusion about whether or not the material of the pressure vessel is sound, instead of getting a research organization like CRIEPI, which is part of the nuclear industry, to assess the samples, they should be given to fair and trustworthy university researchers to examine their micro-organization.

To support Kyushu Electric’s claim, a report entitled “Preliminary Consideration towards Improvement of the Accuracy of the Embrittlement Prediction Method ” jointly produced by CRIEPI and the Federation of Electric Power Companies (FEPC) was submitted to the eighth meeting (February 22, 2012, document 10). It concluded that it is not necessary to change the thinking behind the embrittlement model and the reaction rate equation, which form the basis of the current prediction equation, and that the variation from reality arose due to the lack of data in the high irradiation range. Further, by giving importance to the high irradiation range data (applying a weighting) and resetting the parameters of the equation (impurity cluster formation rate equation coefficient) the Genkai-1 data fit was improved. In fact, however, the fourth data point of 98℃ is still above the standard deviation margin and the second and third data points drop below, making the curve look very suspicious. In other words, they were unable to draw a meaningful curve connecting the third (56℃) and fourth (98℃) data points.

It is problematic that in order to improve the fit in the high irradiation range the coefficients for the reaction rate equation etc. were greatly changed. These reaction rate equations are the master equations that determine the whole method, so for the parameters to change greatly depending on the data sets that are used indicates the brittleness of the model itself. The reliability of the embrittlement prediction equation model, which is the basis of JEAC4201-2007, is therefore called into question. The problem goes beyond the Genkai Nuclear Power Plant. It extends to all aging nuclear power plants.
Looking at the diagram in which NISA compared the prediction equation for aging nuclear power plants with the observed data (Hearing number 5, 23 January 2012, document 2), a large gap between the predicted figure and the observed figure can be seen in the high irradiation region. It is a fact that the prediction equation is unable to predict reality. However, the inaccuracy for Genkai-1 is particularly striking. The inaccuracy for other reactors is within 20°C, but the data from the fourth monitoring sample for Genkai-1 is out by 42°C. Besides the fact that the embrittlement prediction equation does not match the pressure vessel of Genkai-1 (see [ii] above), we must consider that the extraordinary embrittlement is due to the materials or the manufacturing method ([i]).

Another surprising thing was that when we investigated CRIEPI's embrittlement prediction equation, we discovered an elementary but important error in the equation itself. This prediction equation expresses changes in the micro-organization, namely the formation of impurity clusters and lattice defect clusters, which are the cause of irradiation embrittlement, as a reaction equation set, by tracing impurity atoms (copper atoms, etc.) and point flaw reaction (combination and disappearance) processes, and relating this to the rise in DBTT. This can be said to be an epoch-making change, compared to the rough and ready 2004 equation that just tried to fit the data, ignoring the rate of irradiation. However, there was a vital error in the reaction rate equation.

The main cause of irradiation embrittlement is the formation of copper clusters (or impurity clusters in general). In the model there are two types, irradiation induced clusters and irradiation promoted clusters. Irradiation induced clusters are accumulations of copper atoms in lattice defects caused by neutron irradiation. The rate of formation is proportional to the concentration of copper atoms and the rate of diffusion of copper atoms (the speed at which they move). Physically this is an appropriate assumption. However, CRIEPI's report says, "Because the formation of irradiation-enhanced clusters is a process in which copper atoms that exceed the solid solubility limit form a nucleus together, it is described by the square of the quantity of copper above the solid solubility limit and also the square of the diffusion coefficient." It must be said that this is a mistake. Because two (or more) copper atoms come together to form a cluster, it is appropriate to the think that it is proportional to the square of the concentration of copper atoms, but it is a mistake to say that it is proportional to the square of the dispersion coefficient. [Footnote] Because two atoms move, at first sight it might seem that it would be proportional to the square of the speed, but that is not the case. Whether one atom is moving or stationary at one point, the rate at which they come together is the same. This can be proved mathematically. For example, the chance of two people meeting in a crowd in a stadium is the same whether one of the two is moving or stationary.

As stated above, there is an error in the basic model of CRIEPI's
prediction equation. Naturally, any arithmetical calculation using this equation will produce the wrong result. Since the JEAC4201-2007 embrittlement prediction equation includes this fundamental error, it is a useless equation for predictions.

In addition to the abovementioned brittleness of the embrittlement prediction equation, a mistake in the derivation of the equation itself was discovered. The JEAC4201-2007 embrittlement prediction equation must be discarded. The current situation is that there is no reliable prediction equation.

Is Genkai-1 Pressure Vessel Sound? NISA's Predictable Assessment

At the 12th Hearing, held on March 29, NISA submitted a draft report entitled “Concerning Neutron Irradiation Embrittlement of Reactor Pressure Vessels (Draft)” (referred to hereon as “Draft Report”) (17). The purpose was to bring to a close the debate since January this year about “the cause of embrittlement in excess of predictions in the Genkai-1 reactor.” I strongly opposed the Draft Report and listed the problems. In the end the report was not finalized in March as planned and debate continued.

I strongly opposed the report because even though the reason why a high DBTT of 98°C was observed was hardly explained, the conclusion was drawn that the pressure vessel of Genkai-1 was sound, and the fact that the DBTT failed to agree with predictions was blamed on flaws in the prediction equation. Furthermore, NISA concluded that the pressurized thermal shock (PTS) assessment carried out by Kyushu Electric was appropriate and that the pressure vessel was in sound condition. However this type of assessment is totally inappropriate.

Figure 4 shows the results of Kyushu Electric’s PTS assessment (18). The curve that looks like a mountain in the bottom right hand corner is called the PTS state transition curve ($K_I$ curve). In the case of a sudden large loss of coolant (Loss of Coolant Accident = LOCA), the Emergency Core Cooling System (ECCS) kicks in and coolant is fed into the reactor. The $K_I$ curve shows the change over time in the force (strictly speaking the stress intensity factor $K_I$) applied under those circumstances to the leading end of cracks that are presumed to exist in the inner surface of the pressure vessel. As a result of inserting cooling water, the temperature of the internal surface drops. At the same time a temperature difference arises across the thickness of the pressure vessel and tensile stress is applied to the inner wall. Eventually the temperature difference of the pressure vessel becomes smaller and the value of the $K_I$ curve decreases towards the bottom left.
On the other hand, the curve rising to the right from the bottom left of Figure 4 is called the fracture toughness transition curve ($K_{IC}$ curve). It shows how the fracture toughness $K_{IC}$ changes depending on the temperature. If the material becomes brittle the curve shifts to the right.

How is this curve derived? Besides Charpy shock test specimens, specimens are placed inside the pressure vessel to measure fracture toughness. These are extracted and the fracture toughness is measured at various temperatures. A curve is drawn as an envelope around the bottom limit of the measurements, in other words below which there is no data. In the Japan Electric Association’s standard JEAC4206-2007 this curve is derived using the following equation:

$$K_{IC} = 20.16 + 129.9 \exp \left[ 0.0161 \left( T - T_p \right) \right] \quad \cdots \quad \text{(C8)}$$

Parameter $T_p$ is determined so as to draw an envelope around the measured data (i.e. so that all the data falls above the curve).

As the amount of neutron irradiation increases, the fracture toughness reduces and breakage due to embrittlement occurs at higher temperatures. In order to derive a fracture toughness transition curve that corresponds to amounts of irradiation embrittlement other than those given by the measurement test specimens, with the measurement data on the horizontal axis the curve is shifted an amount $\Delta T_{KIC}$ parallel to this axis in the higher temperature direction. In that case, $\Delta T_{KIC} = \Delta RT_{NDT}$ is said to hold. $\Delta RT_{NDT}$ is the difference in the DBTT (the amount by which DBTT shifts). In other words, it is assumed that if the temperature at which the fracture toughness value was measured is shifted by the same amount that the DBTT increased, the same fracture toughness value will
be obtained. There is no theoretical basis for this relationship, but since it more or less works experimentally, JEAC4206 used this assumption.

Theoretically, an enveloping curve can therefore be drawn using all the observed test data from the first to the fourth test at Genkai-1, as well as data measured before irradiation. Also, for an arbitrary amount of neutron irradiation, a fracture toughness transition curve (C8) can be drawn. In this way the two curves in Figure 4 show the current $K_{IC}$ curve and the $K_{IC}$ curve 60 years after commencement of operation for estimated amounts of irradiation of the inner surface of the pressure vessel.

According to NISA’s draft, “The fracture toughness measurement for accumulated irradiation equivalent to that in 22 years from now (60 years from commencement of operations) was approximately double (over 50°C in terms of temperature) the critical stress intensity factor. This fracture toughness measurement is a directly measured value not related to the accuracy and correlation equations of the prediction method. Even bearing in mind that in general there is a variation of $\pm$ 25% in fracture toughness for materials within the transition temperature range, it was confirmed that at this point in time there is sufficient margin for operation of Genkai-1.” (p. 11)

Is this true?

The first problem is the qualification, “Even bearing in mind that ... there is a variation of $\pm$ 25% in fracture toughness.” Is not the variation in the fracture toughness larger within the transition temperature range? Is it not said that it is from double to half? If there is a variation of 50% in the 80°C measurement of the fourth monitoring test, what will happen to the $K_{IC}$ curve? I drew this in Figure 5. The result is that the $K_{IC}$ curve approaches much closer to the $K_I$ curve.

The second problem follows on from the above quote, “In regard to the variation in the monitoring measurement values, although the measurements each time are few in number, they are carried out continuously for fracture toughness for temperatures which take into account the increase in temperature (which can be thought of as the DBTT) for each monitoring test and it is considered rational to take the overall lower limit.” This is on page 11. This sentence refers to a shift in the fracture toughness $\Delta RT_{NDT}$ based on the abovementioned assumption that $\Delta T_{KIC} = \Delta RT_{NDT}$. However, I submitted an opinion (19) to the Hearings with an analysis that specifically showed that for Genkai-1, at least, this assumption does not hold. It is unacceptable that NISA compiled this draft with no reference to my analysis.
Figure 5: Results of Authors’ Examination of Genkai-1 Pressurized Thermal Shock (PTS) Assessment. JEAC4206-2007 Appendix C and Appendix A, using references (17) and (20).

If this assumption does not hold, the shifted data point is not valid and the only two data points that can be used to draw the $K_{1C}$ curve are those from the fourth monitoring test. With such limited data it is hard to claim that a reliable value for fracture toughness can be derived. I therefore presented the curve in Figure 5 taking into account a variation of 50%.

However, in appendix A to JEAC4206-2007 there is a rule about what should be done “in the case where the value for fracture toughness is not derived.” This is an instruction to use the following equation to derive the $K_{1C}$ curve from the DBTT values.

$$K_{1C} = 36.48 + 22.78 \exp \left[ 0.036 \left( T - RT_{NDT} \right) \right] \cdots \ (A7)$$

Figure 5 shows the curve derived by inserting the fourth monitoring test values for DBTT $RT_{NDT} = 98\, ^\circ C$ into equation A7. This curve approaches almost to the point of touching the stress curve $K_1$. If the curves were to cross that would mean the pressure vessel would break.

Next I would like to consider the PTS state transition curve ($K_1$ curve), which shows the size of the stress arising. Are Kyushu Electric’s calculations sufficiently conservative? The assumption in JEAC4206 is for a semi-elliptical 10mm deep and 60mm long crack in the inner surface. It calculates the stress applied to the leading edge of this crack (stress
intensity factor $K$.) Figure 4 shows the PTS state transition curve derived by Kyushu Electric for Genkai-1. According to document 20 presented to the Hearings by Kyushu Electric, for the PTS assessment the most severe large rupture LOCA (loss of coolant accident) is assumed. Kyushu Electric said that it is a conservative assessment in which, without considering the temperature conditions of the inner surface or mixing with cooling water, the temperature would fall in steps from 291°C to 27°C. (Kyushu Electric gave a confusing explanation implying that the temperature of the inner surface also falls in steps.)

On the other hand, in Figure 5 the $K_1$ curve referred to as ‘Matsubara and Okamura’ shows the results of a PTS assessment for a pressure vessel of the same dimensions as Genkai-1 (plate thickness 168mm, diameter 3.37 m) (21). It is a diagram showing the case of a 10mm deep crack (a ratio of crack depth to plate thickness of 0.06). This curve gives a much larger $K_1$ curve than the curve in Kyushu Electric’s assessment. Matsubara and Okamura’s paper assumes a sufficiently long crack, so compared to assuming a crack of 60mm length the values are rather large, but that variation is about 15% based on stress calculations (personal correspondence from Dr. Aono). Even if that amount is subtracted it is above Kyushu Electric’s $K_1$ curve. There is therefore a possibility that Kyushu Electric’s assessment is not sufficiently conservative in regard to pressure conditions, etc.

On this point, committee member Meshii said that the $K_1$ curve changes greatly depending on the heat transfer coefficient $h$ of the inner surface. If the equation is taken as $h=1\text{kW/m}^2\text{K}$ the result is close to Kyushu Electric’s analysis, but if it is taken as $h=2\text{kW/m}^2\text{K}$ the result is about the same as the Matsubara and Okamura analysis, and for $h=\infty$ it crosses the $K_{1c}$ curve. From this result, Meshii concluded, “The PTS assessment carried out by Kyushu Electric was judged to be close to realistic, but not so conservative that it was not necessary for variation in the fracture toughness value to be taken into account.”(22). He is saying that the curve in the assessment is at the limit and that Kyushu Electric’s analysis does not have sufficient leeway.

Seen in this light, the conclusion in NISA’s draft report (17) that it has been confirmed that Genkai-1 is “sound enough” in regard to pressurized thermal shock must be seen as lacking foundation. At the sixteenth meeting of the Hearings NISA submitted a new draft (23) which to some extent took into account the various critical views expressed. Debate on this draft is set to begin. However, even though the wording is slightly changed and the data reinforced, the arguments and the conclusion in this draft are the same as before. The conclusion that the Genkai-1 pressure vessel is sound was there from the beginning. The new draft does no more than add all sorts of considerations.

For reactors with such extreme irradiation embrittlement that the
conclusion concerning whether or not they are safe varies depending on the analytical method and point of view, there is no other way to ensure people’s sense of security than to make a decision to shut these reactors down.

Destruction of the pressure vessel due to embrittlement is an accident that must not be allowed to happen. If the pressure vessel is destroyed the nuclear fuel will be spread over a wide area and there will be no way of cooling the nuclear fuel to remove the decay heat. Emergency response fire trucks and power supply trucks will all become ineffective. Reactors with even a small risk of being destroyed due to embrittlement should be shut down.

A bill to wind up NISA and NSC and establish a new Nuclear Regulatory Commission is now being debated in the Diet. The bill proposed by the government contains a clause saying, “The life of nuclear power plants will in principle be 40 years.” This condition allows a life extension of 20 years in exceptional circumstances, so there is the possibility that the 40-year condition will be gutted of meaning. It should state that nuclear power plants will, without exception, be decommissioned after 40 years.

All nuclear power plants that began operations in the 1970s will be over 40 years old by 2019. All these early reactors have numerous problems with manufacturing technology and quality of materials, and they are deteriorating. Of course Tsuruga-1 and Mihama-1&2, which are already over 40 years old, should be closed down, and Genkai-1 and Takahama-1, which have extreme irradiation embrittlement, should be closed down without waiting for them to turn 40.

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References


The $K_{IC}$ curve in this diagram is a revision of a diagram published on Kyushu Electric’s web site in July 2011. Furthermore, the diagram on the website, as noted in the August 2011 issue of Tsushin, is an incorrect curve with ductile brittle transition temperature substituted as $T_p$. 
However Kyushu Electric did not acknowledge this and gave a transparent excuse drawing an image freehand for the curve (transcript of meeting 5).

(19) Ino Hiromitsu, Hearings on Technological Assessment of the Aging meeting 11 document 9, March 19, 2012, diagrams 1 and 2.

(20) Kyushu Electric Power Company, “Responses to Committee Member Comments”, Hearings on Technological Assessment of the Aging meeting 8 document 6, February 22, 2012, pp. 3-5.


(22) Meshii Toshiyuki, “Genkai-1 PTS Analysis Calculation”, Hearings on Technological Assessment of the Aging meeting 14 document 8, May 9, 2012.


Figure 4: Kyushu Electric’s Pressurized Thermal Shock (PTS) Assessment for Genkai-1 Pressure Vessel.

Figure 5: Results of Authors’ Examination of Genkai-1 Pressurized Thermal Shock (PTS) Assessment. JEAC4206-2007 Appendix C and Appendix A, using references (17) and (20).