Application of the Post-BT standard to future BWR licensing assessment

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The core of light water reactors has been designed so as not to cause boiling transition during both normal operation and transient phenomena as a means to guarantee the integrity of fuel. This is one restriction for maintaining the fuel integrity. However, research in recent years has shown that the boiling transition itself does not directly affect the fuel integrity rather it is the increased fuel cladding temperature. Based on these facts, a standard that includes the criteria and evaluation method of fuel integrity after boiling transition was made by the Standards Committee of Atomic Energy Society of Japan. If this standard is applied to the present boiling water reactors, the operational limited minimum critical power ratio (OLMCPR) can be decreased during the end of cycle. If this standard is applied to plants to be built from now on, there are possibilities to rationalize the facilities, to uprate and to reduce the workload of control room operators.

KEYWORDS: BWR, Post-BT, Dryout, Rewet, PCT, OLMCPR, AOO

I. Introduction

The core design of the present light water reactors (LWRs) does not allow boiling transition during both normal operation and transient phenomena. This has guaranteed the integrity of fuel. However, the fuel temperature increases by the decreased capacity for heat removal caused by boiling transition. Therefore, the boiling transition itself does not directly affect the fuel integrity. That is, avoiding boiling transition is a conservative restriction to keep the fuel integrity from damage caused by overheating of fuel.

Generally, in the boiling water reactor (BWR) core, heat from the fuel rods is taken from the core by forced convection boiling heat transfer of water mainly in the high flow quality region. Therefore, in the BWR core, boiling transition means dryout phenomenon and does not departure from nucleate boiling (DNB) phenomenon. Dryout phenomenon means lost of the liquid film flow in the annular dispersed flow pattern in the high quality region.

Under such conditions, occurrences of boiling transition are necessarily connected with fuel damage. Many transient phenomena occur with immediate scram or an increase of the void fraction that suppresses the increase of the core thermal power. In these transient phenomena, the dryout state on the fuel surface does not last long, and rewet phenomenon occurs. After rewetting, the fuel surface is covered by a liquid film flow again. In this condition, the increase of the fuel cladding temperature is small. This small temperature increase of fuel surface does not affect the fuel integrity.

Many studies about dryout and rewet phenomena have been done and these phenomena are now well understood. Moreover, methods for predicting the fuel cladding temperature etc. have also been established.

In BWRs, experimental knowledge has shown that fuel integrity is not affected by boiling transition on the fuel surface. Then the standard17 that includes the criteria and the evaluation method of fuel integrity after boiling transition is going to be made by the Standards Committee of the Atomic Energy Society of Japan (AESJ).

In this paper, an outline of this standard is described and the possible advantages when applying this standard to actual BWRs are shown.

II. The Post-BT Standard in Japan

1. The Standards Committee of AESJ

The Standards Committee of AESJ is a committee that decides upon nongovernmental standards. The basic principles of the Standards Committee are to be just, neutral, and transparent in its dealings. Furthermore people who have special knowledge and concerns can participate in the work. The procedure of public examination that asks widely for opinions is also carried out.

The flowchart to establish the standard by the Standards Committee of AESJ is shown in Fig. 1.

<table>
<thead>
<tr>
<th>A draft of the standard is made by the Standards Committee in AESJ</th>
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<tbody>
<tr>
<td>Examination by the general public</td>
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<tr>
<td>The standard is established</td>
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</table>

Fig.1 Flowchart to establish the standard in AESJ
2. The Post-BT standard

The standard consists of three parts. The first part is the criterion to judge the integrity of the fuel which has experienced boiling transition by using dryout duration and the peak cladding temperature (PCT). The second one is the criterion to judge the re-use possibility of the fuel which has experienced boiling transition by using dryout duration and the PCT. The third one is the method to determine the dryout duration and PCT.

Regarding fuel integrity, the cause of fuel damage when boiling transition occurs is due to brittleness by too much oxidation. And it may be considered the integrity during fuel handling. The maximum temperature is set as 800°C considering mechanical property decrease by Î£ phase to (Î£ + Îµ) phase transformation temperature of zircarloy and dryout duration is set as 100s in consideration of safety margin for experimental data. This criterion is shown in Fig.2.

The criterion for the re-use of the fuel which has experienced boiling transition is that over 0.1% deformation is not allowed. This is almost equal to the 10 Îµm deformation that is allowed for normal full-use fuel. This criterion is shown in fig.3. Normally fuel cladding deformation is about 10 Îµm and the standard for the re-use of the fuel is set as shown.

These criteria are applicable to the fuels already used in Japan and the phenomena that are considered based on the current system and construction.

There are two premises for these criteria. The first one is that the pressure boundaries of core coolant are sound and there is no large pressure decrease of the core. The second one is that there is no reactivity insertion over 1$. To put it concretely, the loss of coolant accident and the reactivity insertion accident are not applicable.

The representative phenomena that these criteria will be applied to are as follows:

- the occurrence of boiling transition by the sudden core thermal power increase and quick rewetting by the decrease of the thermal power by the scram of core; and
- the occurrence of boiling transition by the sudden decrease of core flow and quick rewetting by the void reactivity feedback or the scram.

So these criteria will be mainly used for the anticipated operational occurrences (AOOs). The AOOs are shown in table 1 with applicability of this standard. Except for the loss of feedwater heating, this standard is applicable for all AOOs. Most important AOOs for core design are load rejection without bypass and loss of core coolant flow. Regarding loss of feedwater heating, this phenomenon is quasi-steady, so it is impossible presently to apply this standard.

3. Evaluation method in the standard

In the standard, it is necessary to determine the onset time of boiling transition, rewetting time and the PCT.

In evaluation of the onset time of boiling transition time at
AOOs, it is appropriate to use the correlation that is used in the present BWR core thermal-hydraulic design. The correlation, expressed in the most general terms, is,

\[ x_e = f\left[L_B \cdot D_Q \cdot G, L, P, R\right]. \quad \text{(1)} \]

- \( x_e \): bundle average critical quality
- \( L_B \): boiling length
- \( D_Q \): thermal diameter (i.e., four times the ratio of total flow area to total rod perimeter)
- \( G \): mass flux
- \( L \): heated length
- \( P \): core pressure
- \( R \): a parameter which characterizes the local peaking pattern

In evaluation of the rewet time of the fuel cladding, it is appropriate to use either of the two correlations shown below.

- Modified Dougall-Rohsenow correlation

\[ \frac{hD}{k_{g,f}} = 0.023 \left\{ \frac{GD_H}{\mu_{g,f}} \left[ x_e + \frac{\rho_{g,s}}{\rho_{l,s}} (1 - x_e) \right] \right\}^{0.8} \frac{P_{r,0.4}}{r_{g,f}} \quad \text{(2)} \]

*In the upper correlation, steam film temperature (average temperature of fuel cladding surface temperature and saturation temperature) is used for the temperature of superheated steam.*

- Groeneveld 5.9 correlation

\[ \frac{hD}{k_{g,s}} = 0.00327 \left\{ \frac{GD_H}{\mu_{g,s}} \left[ x_e + \frac{\rho_{g,s}}{\rho_{l,s}} (1 - x_e) \right] \right\}^{0.901} \times P_{r,1.32} \left[ 1.0 - 0.1 \left( \frac{\rho_{l,s}}{\rho_{g,s}} - 1 \right) \right]^{0.4} \left( 1 - x_e \right)^{0.4} \quad \text{\textsuperscript{-1.50}} \quad \text{(3)} \]

- \( x_{rewet} \): rewet quality
- \( P \): core pressure [MPa]
- \( G \): mass flux [kg/(m² · s)]
- \( \xi \): heat flux distribution [W/m²]
- \( q''_E \): equilibrium heat flux [W/m²]
- \( \xi \): position along main flow [m]
- \( L_B \): boiling length [m]
- \( \lambda \): start point of boiling [m]

\[ m(P) = \frac{10^{-4}}{\left( 1 - 0.204(P - 6.86) \right)} \quad 6.9 \leq P \leq 7.8 \text{[MPa]} \quad \text{(6)} \]

The second is

\[ x_{rewet} = x_e + \Delta x \quad \text{(7)} \]

\( \Delta x \) is the deviation from the critical quality at the transient phenomena. The evaluated \( \Delta x \) is as follows.

\[ \Delta x = \left\{ 0.0635 \frac{D_w F_h f_g}{u_0^g} \left[ \left( \frac{G(x - x_e)}{q''} \right)_{t = t_w} \right] \times \frac{G_0 \left( \Delta T_w - 30 \right)}{30} \frac{dx}{dt} \right\} \quad \text{(8)} \]
x: quality
$\Delta x$: deviation of rewet quality between steady and transient states
$\Delta T_w$: superheating of wall [K]
$q^\prime$: heat flux at the dryout occurred [W/m$^2$]
$F$: peaking factor by the fuel rod powers
$G$: mass flux \([kg/(m^2 \cdot s)]\)
$D_w$: thermal diameter [m]
$h_{lf}$: latent heat \([J/kg]\)
$t_m$: time becomes $x-x_c$ maximum
$\Delta t_0$: time from $x-x_c$ maximum to $x=x_c$ [s]
$\frac{dx}{dt}$: average changing rate \(x\) of from becoming
\[x = x_c\] to rewet [1/s]
$G_0$: base value of mass flux \((= 1356)\) \([kg/(m^2 \cdot s)]\)
$d_{lf}^0$: base value of film flow moving velocity \((= 1)\) [m/s]

4. Verification of the evaluation correlations
For evaluation of the onset time of boiling transition, the Post-BT standard uses the current design method, so the verification has been done for already used fuel.

The applicability of the correlations for heat transfer coefficient and rewet time were well examined in the Standards Committee of AESJ.

Representative examination results by using correlations (2) and (7) are shown in Figs. 4 and 5. Fig. 4 compares calculated and measured PCTs, and shows that the calculated values are conservative against the measured values. Fig. 5 compares calculated and measured dryout durations and shows that for dryout durations the calculated values are also conservative.

The Standards Committee made many examinations for the correlations and these correlations were judged applicable for already used fuels.

III. Application for BWR design
1. Influences on design concepts
Since present plant design and present fuel design are based on the precondition of not causing boiling transition, when this standard is applied, the future design of BWRs will be affected.

First, the way of thinking about minimum critical power ratio (MCPR) may be changed. Now, the operational limit minimum critical power ratio (OLMCPR) is determined by adding the largest $\Delta$MCPR to safety limit minimum critical power ratio (SLMCPR). If this standard is applied, it may be permitted that MCPR becomes less than SLMCPR during transient phenomena. By using this standard, it may be possible that at first the lowest critical power ratio is set which only satisfies the standard in Fig. 2 and then the largest $\Delta$MCPR is added to the lowest critical power ratio (Fig. 6). However, it is considered that determining the lowest critical power ratio is very difficult. So it will be realistic to set the OLMCPR by the AOOs that this standard can not be applied to. After that, the AOOs that this standard can be applied to are evaluated by the criterion in Fig. 2.

Considering plant design, there is some possibility that currently installed equipment to prevent boiling transition will be rationed.

Furthermore, the void reactivity coefficient is set to negative value. This causes self-control of core thermal power. However, in the pressure transient that causes a sudden pressure increase and void fraction decrease in a BWR core, the void reactivity causes the thermal power increase of the core, so normally the absolute value of the void reactivity is set not too large. For the pressure transient, this standard will be applied, so fuels or cores that have a larger absolute value of the void reactivity may be designed.
2. Application to current BWRs

In many current BWRs, one of the AOOs, the loss of feedwater heating that this standard cannot be applied to, is limiting the OLMCPR during beginning and middle of the cycle (BOC and MOC). But during the end of the cycle (EOC), the load rejection without bypass that this standard can be applied is limiting the OLMCPR (Fig.7).

So, by using the Post-BT standard, the limiting phenomenon changes from the load rejection without bypass to the loss of feedwater heating and the OLMCPR will be decrease. From the decrease of the OLMCPR, the design margin will increase. By using this increased margin, uprating of the current BWRs will become possible technically.

In addition, now, PCT during the all pump trip accident (APTA) of ABWR is calculated without rewetting. If it is possible to use the rewet model of this standard, there is some possibility that the PCT of APTA decreases.

3. Application to BWRs that will be built in the near future

In Japan, from now on, most BWRs that will be built will be ABWRs. If all pump trip accident (APTA) is calculated using the method of this standard, it may be possible to increase design margin.

In ABWR, the MG-set that consists of a motor and generator is used to prevent the sudden core flow decrease during the loss of AC power. If this standard is applied, there is some possibility that the design criteria may be satisfied without the MG-set.

IV. Application for Future BWRs

1. ABWR-II

The next generation ABWR, the ABWR-II\(^2\rightarrow10^1\), has been under development for more than a decade in Japan by Japanese utilities, three BWR plant vendors and a BWR fuel vendor. This new ABWR will offer improved plant economy, greater safety, easiness of operation and maintenance, and flexibility in fuel cycle strategy.

The specifications of the ABWR-II core are listed in Table 2 and core configuration is displayed in Fig. 8. The thermal power of the ABWR-II core is 4960MW, which is 1.26 times larger than that of the ABWR core. The ABWR-II core consists of 424 bundles and the bundle has a 1.5 times larger bundle pitch compared to the conventional BWR bundle. This large bundle comprises four sub-bundles, which are separated by partitions and each consists of an 8 x 8 fuel arrangement. Targeted operation cycle length and average discharge burnup are set to be 18 months and 60GWd/t, respectively.

Fig.9 shows the reference design fuel bundle. The four sub-bundles are separated by a partition and there is a large water box in the center, formed by parts of the partition, which occupies 24 fuel rod positions. In addition, there are eight small water rods, each equivalent in size to the fuel rod.

In ABWR-II, the number of fuel rods per unit area in the reactor core is increased by loading fuel rods tightly and adopting the 1.5 times pitch lattice. This makes the H/U ratio small and the absolute value of the void coefficient is large. Although this creates a tendency for pressure transient to become severe in the ABWR-II, it is possible to solve this problem by modifying equipment specifications.

But if this Post-BT standard is adopted, these equipment specifications for pressure transients are not needed, so the further rationalization of the equipment may be possible.

If the Post-BT standard is adopted, further optimization of ABWR-II core and plant design may be possible. These optimizations are presented next.

2. Further prospective view

For the Post-BT standard, improvement in the prediction accuracy of dryout duration and PCT are important subjects. The further rationalization may be attained if there is a high-speed prediction technique with high precision. Advancement of the subchannel analysis technique to solve flow in a fuel bundle in detail is desired.

Moreover, if pressure transient is no longer a problem with the Post-BT standard, the design target value of the void coefficient may change. From the point of pressure...
Table 2 Main Parameters for ABWR-II Core

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>ABWR-II</th>
<th>ABWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power</td>
<td>MWe</td>
<td>1700</td>
<td>1356</td>
</tr>
<tr>
<td>Reactor thermal power</td>
<td>MWt</td>
<td>4960</td>
<td>3926</td>
</tr>
<tr>
<td>Operating cycle length</td>
<td>months</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Average discharge burnup</td>
<td>GWd/t</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Maximum core flow rate</td>
<td>t/h</td>
<td>62.1x10³</td>
<td>57.9x10³</td>
</tr>
<tr>
<td>Active core height</td>
<td>m</td>
<td>3.71</td>
<td>3.71</td>
</tr>
<tr>
<td>Fuel bundle pitch</td>
<td>cm</td>
<td>23.3</td>
<td>15.5</td>
</tr>
<tr>
<td>Number of control rods</td>
<td></td>
<td>-</td>
<td>197</td>
</tr>
<tr>
<td>Number of fuel bundles</td>
<td></td>
<td>-</td>
<td>424</td>
</tr>
</tbody>
</table>

Fig. 8 ABWR-II core configuration

Fig. 9 ABWR-II bundle configuration

transient and core stability, the absolute value of the void coefficient may not become so large. If this restriction disappears with the Post-BT standard, it is possible to make the absolute value of the void coefficient larger than the present design. The void coefficient tends to become large, if many fuel rods are generally loaded and H/U ratio becomes small. The optimal point of the H/U ratio was conventionally determined from the viewpoint of pressure transient or stability. If the Post-BT standard is used, the H/U ratio may be able to be made smaller than present.

There are some advantages of the increase of the absolute value of void coefficient. One is that it is possible to increase the number of fuel rods that can be loaded in the unit area of the reactor core. This leads to increased thermal margin and there is the possibility to uprate the BWR plant without many equipment changes.

Another is that a larger absolute value of void coefficient allows the reactivity control range to be increased by the core flow rate change. By using this merit fully, it is possible to reduce the control rod operation. Furthermore, there is the possibility that all control rod withdrawn operations through one cycle may be able to be carried out by extending the flow window or using spectral shift rods. This leads to a reduction of workload for operators.

V. Conclusion

In Japan, the Post-BT standard is going to be published by AESJ. In this paper, the standard was explained and its merit were shown.

Using this standard on current BWRs, OLMCPR during the EOC may decrease and increase the design margin. This increased margin can be used for uprating and so on.

For BWRs built in the near future, the rationalization of the equipment may be possible by using this standard. For future BWRs, it may be possible to optimize the absolute value of the void coefficient. This would lead to uprating of plants without large equipment changes. Furthermore, the ability of reactivity control by core flow rate change would be increased. This would lead to reduced control rods operations and reduced workload of plant operators.

References


