A METHOD TO PREVENT SEVERE POWER AND FLOW OSCILLATIONS IN BOILING WATER REACTORS

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ABSTRACT

This paper introduces a new method for preventing boiling water reactor fuel damage due to the growth of unstable density wave oscillations to severely large magnitudes. The method limits the growth of the density waves by limiting the magnitude of the oscillation of the coolant mass flow rate at the inlet of at least some fuel bundle such that only upward flow is permitted. Further growth of the density wave beyond inlet flow reversal is thus prevented which limits the severity of the coolant flow conditions at the fuel clad surface in the entire fuel assembly such that dryout either does not occur or rewetting of the clad surface occurs every oscillation cycle and excessive high clad temperatures that may cause its failure do not occur. A device realizing this method, for which a patent application has been filed, is described and its effectiveness is numerically demonstrated. This hardware solution is particularly useful for limiting the consequences of unstable oscillation should the ability of the operator to shut down the reactor power with scram be lost as part of the hypothetical scenario known as anticipated transient without scram.

KEYWORDS
BWR oscillations, ATWS Instability, Reverse Flow Prevention, Hardware Solution

1. INTRODUCTION

The problem for which this article proposes a solution is the divergence of power and flow oscillations in the core of a Boiling Water Reactors should operation is destabilized without timely automatic intervention or operator action. This is the so-called anticipated transient without scram with instability (ATWSI). A full appreciation of this problem requires an introduction to the nature of the density wave instabilities and how plant operators successfully coped with it over the years, and what are the emerging problems as the plants evolve with higher power rating and operation schemes.

The unstable behavior of a BWR is associated with the density waves in the vertical boiling channels made of the individual fuel assemblies in the core. The mechanisms of the density wave instabilities are covered in many articles and reports, for a which a good example is the Ref. [1] monograph. The simplest density wave in a boiling channel can be described for a fixed power source distributed along the channel, the pressure drop across the channel is also fixed, and the inlet flow is subcooled. Assuming a random perturbation to the flow rate at the inlet of the channel, a corresponding enthalpy wave travels upward with the flow. Downstream from the elevation of boiling inception, the flow enthalpy is translated to a steam quality wave where more steam is generated per unit of flow rate to account for an enthalpy increase. All flow parameters, mainly flow rate and steam quality and void fraction, are subsequently perturbed and the perturbations travel upward in the boiling channel with a progressive phase lag.

The density wave alters the flow characteristics in two ways. The first one is that the total weight of the coolant in the channel, which is proportional to the integrated fluid density along the channel, is altered dynamically resulting in a net gravitational pressure head response. The second way is the change in friction pressure drop along the channel. The friction pressure drop in turn is affected in two ways: the first way is through the change in the flow rate itself (friction being proportional to the square of flow rate), and the second way through the change in the two-phase multiplier which accounts for the increase in frictional pressure drop for higher steam quality. In an idealized situation, the net pressure drop across the channel is kept constant, which leaves a residual component of force to compensate for the driving changes in density head and the changes in friction. This force acts to oppose the original flow perturbation, i.e. negative feedback, which is stabilizing in the quasi-steady state case. But since the feedback is delayed by the time the wave needs to traverse the channel, the net force reinforces the original flow perturbation if the perturbation frequency is resonant, that is the delayed force accelerates the flow further with a phase-lag of 180 degrees. A delayed feedback process is unstable only if its magnitude is sufficiently strong. The density wave degree of stability is reduced for higher power-to-flow ratios and for bottom-peaked axial power distribution as they tend to increase the void content and subsequently the density head feedback which drives the instability. High friction pressure drop at the channel inlet increases kinetic energy dissipation and helps to stabilize density waves, while high friction at higher elevations is destabilizing due to the phase lag of their effect which tends to reinforce the original perturbation at the resonant frequency. Density wave stability is strongly affected by the inlet flow subcooling.

The effect of inlet subcooling on stability of density waves is not monotonic. In the limit of very high subcooling, the boiling boundary is shifted to high elevation in the channel leaving little space for evaporation processes to take place and the density head response is diminished. Therefore, when the inlet subcooling is very high, further increase is stabilizing. This is the opposite effect when considering the other extreme. For very low subcooling, when the inlet flow is nearly saturated liquid, the total vapor generation rate is constant for constant power regardless of the flow changes, which diminishes the density head response to inlet flow oscillations and the channel is stabilized. Increasing inlet subcooling from a low subcooling point is destabilizing because the vapor generation rate is forced to oscillate in response to inlet flow oscillation as the total heating power is divided between a component needed to supply the sensible heat and overcome the subcooling (which oscillates with the inlet flow rate) and the remaining component used to generate vapor. The strength of the vapor generation feedback increases with inlet subcooling and the density wave is thus destabilized by it.

In a BWR, the oscillation of flow rate in the fuel bundles resulting from density waves is complicated by the double role the water plays in the operation of the reactor. The density wave results in a corresponding neutron moderation effectiveness which in turn results in nuclear reactivity and fission power responses. The fission energy generated inside the fuel rods is transferred to the coolant through heat conduction in the fuel rods through the clad surface. The fluctuation of the heat flux through the clad surface is filtered through the heat conduction processes through the fuel rods and the clad surface heat flux experiences a damped and delayed response relative to the fission power itself. The fluctuation of the heat flux results in corresponding fluctuations in the boiling rate and the coolant density where such feedback tends to further destabilize the density waves in the boiling channels.

The various modes of instabilities in BWR and their consequences and the long term solutions are discussed next.

1.1. Instability Modes

There are three recognized instability modes in a BWR core. The first one is the single channel instability where power feedback is not important and thermalhydraulic processes are dominant. This type of instability may occur only in the case of unusually high power in a single bundle, or strong bottom-skewed power distribution, or in the case of flow blockages or improperly seated fuel bundles.

The more common mode of instability is the core-wide mode, where the flow in all the bundles oscillate in-phase. This phase-locking is imposed by the neutron kinetics where the total power affecting all the channels oscillate at the same frequency. The net flow through the reactor core is also forced to oscillate which brings into play the damping effects due to friction in the recirculation loop.

For large BWR cores, the regional oscillation mode may become dominant [2]. In that case, the phase locking mechanism is connected to the excitation of the first azimuthal neutron flux mode which forces the flow in half the bundles to oscillate out-of-phase with the flow in the other half. The net flow and power of the core do not oscillate in this case, provided the oscillation magnitude remains sufficiently small and nonlinear effects are not important. Detection of this oscillation mode is not possible using the average power range monitors (APRM) signals, and must rely on the local power range monitors (LPRM).

1.2. Consequences of Growing Oscillations

For any of the instability modes identified above, the common consequence of the resulting growth of oscillations is the reduction of the critical heat flux margin. The main cause of the critical heat flux margin is the flow oscillation which creates regions of high steam quality and heat transfer degradation as a consequence of dryout. Post-dryout operation is associated with high clad temperature and is not allowed.

There are differences in the critical heat flux response for the respective instability modes due to the relative magnitude of the power oscillation for a given flow oscillation magnitude. For single channel instability, the power is essentially constant and the CHF response is due to the flow oscillation alone. For the global oscillation mode, the power response is significant. For the regional mode of oscillation, the power response is less than the case of core-wide oscillation due to the first azimuthal neutron flux mode subcriticality. The effect of power oscillation on CHF is minimal compared with the effect of flow oscillation, but is important to note as flow oscillations cannot be measured and oscillation detection is accomplished by monitoring power. For that reason, actions to terminate instabilities are taken at lower detected power oscillation magnitude to protect against the regional mode of oscillation than for the global mode.

1.3. Long Term Stability Solutions

There are two types of long term stability solutions. The first one is "region exclusion" which relies on conservative calculations to identify regions in the power-flow operating map for which instabilities are possible. Operator actions are prescribed to exit the regions for which stability margin is small, and immediate exit or even scram upon entry in the exclusion region. The more popular long term solution is the detect-and-suppress where signals from individual or grouped LPRMs are processed online for evidence of coherent oscillations, and automatic scram terminates to instability prior to reaching oscillation magnitude that is sufficient to challenge the critical heat flux limits.

In either case, the stability solution relies on the ability to accomplish instability termination by reactor scram. A hypothetical loss of the ability to scram to terminate instabilities is the core of the problem under consideration in this article.

1.4. Nonlinear Effects in BWR Oscillations

Once the system is destabilized, the oscillation magnitude grows at exponential rate starting from the low amplitude representative of the prevailing noise. The exponential growth rate is limited to the linear case where the oscillation magnitude is small. Once the oscillation magnitude grows sufficiently, nonlinear effects become important and the characteristics of the oscillation is altered. According to Ref. [3], nonlinearities in the neutron kinetics generate a damping effect for the global mode where the growth rate decreases with the increase of power oscillation magnitude until a limit cycle is reached. This is the opposite for the regional mode [4], where the rate of oscillation growth actually increases with the increase of power oscillation magnitude for the regional mode. This shows that the neutron reactivity feedback effect is not self-limiting for the regional mode. However, when the hydraulic nonlinearity is taken into account, all oscillation modes are self-limiting. The growth of the inlet flow cannot continue without limits, but stops at a relatively large magnitude where significant flow reversal at the inlet is evident.

As the inlet flow oscillation magnitude is increased, steam quality waves traveling through the channel will also increase in magnitude and eventually dryout will occur. However, due to the oscillatory nature of the flow rate and the steam quality response, dryout is not irreversible and cycles of dryout and rewetting result in periodic pulses of clad temperature that do not necessarily reach the levels required to cause fuel damage. However, as the oscillation magnitude grows further, dryout may become irreversible and failure to rewet causes escalation of the clad temperature excursion potentially beyond clad damage limits.

2. ANTICIPATED TRANSIENT WITHOUT SCRAM WITH INSTABILITY

The hypothetical event of a transient leading to core instability without the ability to terminate the event by scram is described in the literature, for example Ref. [5]. Such transient can be initiated by a turbine trip, for the which the plant control system responds by opening the turbine bypass valve and trip the recirculation pumps. The reactor operating point shifts to lower flow rate corresponding to natural circulation and power is also reduced due to the negative reactivity introduced by increasing the void fraction in the core. However, the power-to-flow ratio at the end point of natural circulation is sufficiently high and core instability is expected. The situation is made worse by the isolation of the turbine as the steam bleeding to the feedwater heaters stops and the core inlet flow subcooling is gradually increased. The increase of the core inlet subcooling is strongly destabilizing.

Normally, the inception of instabilities is detected by the detect & suppress system and a timely scram signal is issued to the effect of terminating the instability before reaching any appreciable oscillation magnitude. The loss of the ability to scram allows the oscillation to grow until other measures are taken by the operator. According to Ref. [6], the operator action to lower the water level below the feedwater spargers results in bringing the feedwater in contact with steam and the resulting reduction in core inlet flow subcooling restores stability. The ultimate intervention measure is the boron injection. The effectiveness of these protection measures depends on acting before the oscillation magnitude reaches the high levels that can cause fuel damage.

2.1. ATWSI under MELLLA+

Power uprated plants can be operated with flexibility if a flow window is allowed rated power for reactivity management between control rod pattern changes. Such scheme is the Maximum Extended Load Line Limit Analysis Plus (MELLLA+). Compared with operation before power uprate, the even of pump trip brings the operation to higher power at natural circulation, which is less stable, as explained in Ref. [7]. The higher decay ratio at natural circulation associated with MELLLA+ is translated to a quicker escalation of the instability event and the expectation of higher oscillation amplitudes. This resulted in the need for fresh examination of ATWSI as shown for example in Ref. [8].

Analysis such as given in Ref. [8] for ATWSI events under MELLLA+ may be too conservative in predicting peak clad temperatures in excess of 1500 K, yet the message is clear that a generic resolution of such hypothetical events is not expected and extra analysis and/or more elaborate protection measures are needed.

3. A HARDWARE SOLUTION FOR ATWSI

As stated above, all the current solutions to the stability problem depend on the ability of the operator, or automatic protection systems, to terminate the event. Long term solutions rely on reactor scram. In the case of ATWSI where the ability to scram is lost by definition, the ability to terminate the event depends on timely operator recognition of the situation and the ability to interfere by cutting off feedwater flow to lower the water level in the reactor vessel, and ultimately boron injection. Inherent protection by hardware modification to the fuel design is a new solution concept.

The ideal hardware solution at the level of fuel design is creating an unconditionally stable bundle. This ideal solution continues to be elusive, if not impossible, given the design constraints any new fuel type must conform to for operating in existing plants. The proposed fuel hardware modification is a compromise, which preserves the stability characteristics of the host fuel type where the inception of instability is not prevented; only the extent of the growth of the oscillations is limited.

A device is introduced to the lower tie plate structure to act as a check valve. The valve is open and the hydraulic characteristics of the fuel is unchanged as long as the flow direction is the normal upward direction. The device blocks, or substantially reduces, the flow in the reverse direction thus limiting the oscillation amplitude to swings between zero and nearly twice the initial flow rate. This limitation of the flow oscillation magnitude at the inlet of the fuel bundle also limits the severity of the flow conditions at higher elevations where critical heat flux may be exceeded. Thus, even if dryout momentarily occurs, rewetting also occurs every oscillation cycle and the clad never reaches the high temperatures associated with failure to rewet.

It is important to note that preventing further growth of the oscillation at the inlet of a few fuel bundles (the limiting ones with highest power peaking) has the effect of preventing the growth of the oscillation in all other bundles. It is therefore not necessary that the device is implemented in all fuel bundles.

3.1. Description of a Reverse Flow Preventer Device

The concept of limiting flow oscillation magnitude by preventing inlet flow reversal can be accomplished using the device described here.

Figure 1 shows an isometric cut drawing of the lower tie plate component of a fuel assembly including the structure of the proposed device. The drawing shows two parallel plates with holes forming a cavity inside which a screen module is free to move and rest against the upper plate when lifted up by the normal coolant flow in the upward direction or rests against the lower plate upon flow reversal or stagnation. Figure 2 shows an isometric sketch of the screen which is a grid structure attached to which an array of concave disks aligned with the holes in the plates. The grid has tabs to prevent blocking the upper holes under normal flow direction, while the disks rest on the lower plate blocking its matching holes if the flow stagnates or reverses.

Figure 1   Isometric cut drawing of the lower tie plate including the reverse flow preventer structure

Figure 3 is a vertical cut drawing of the lower tie plate structure including the floating screen between two holed plates identified as detail (C). The screen is shown in the up position which is the normal position when flow in the upward direction lifts the screen. The up and down positions are detailed in Figures 4a and 4b respectively.

The distance traveled by the screen between the up (open) and down (closed) positions is too small for building up of high speed movement and therefore the opening and closure of the flow path are not abrupt but rather smooth.

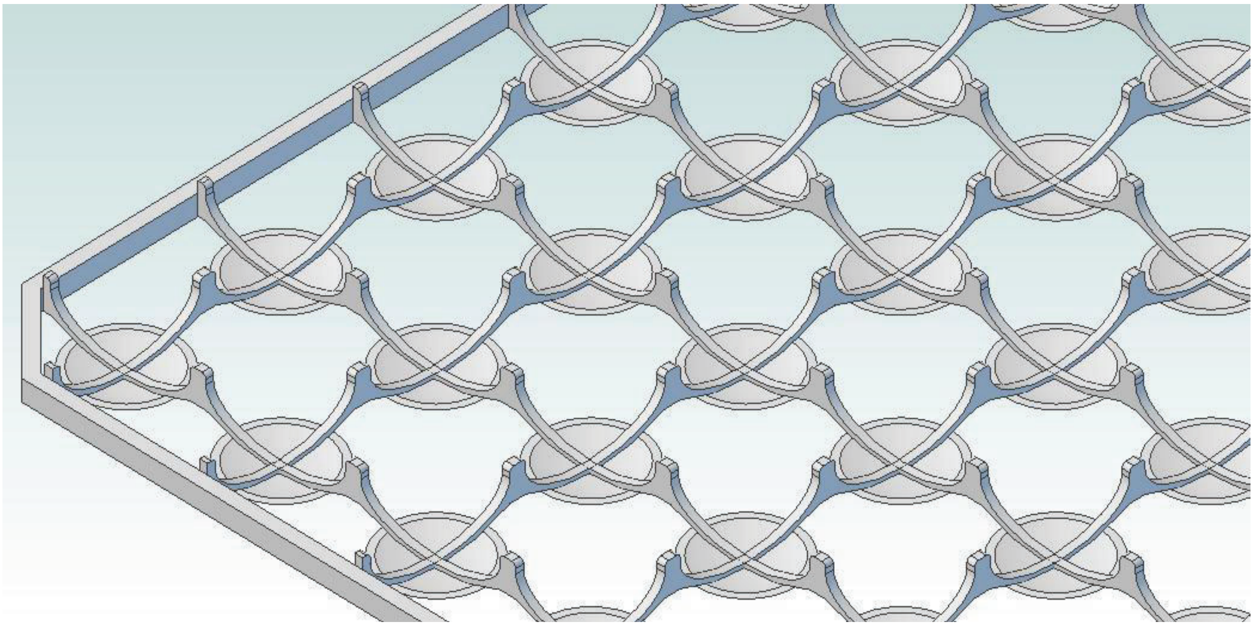

Figure 2 Isometric drawing showing a zoom of the screen structure in the lower tie plate of Figure 1.

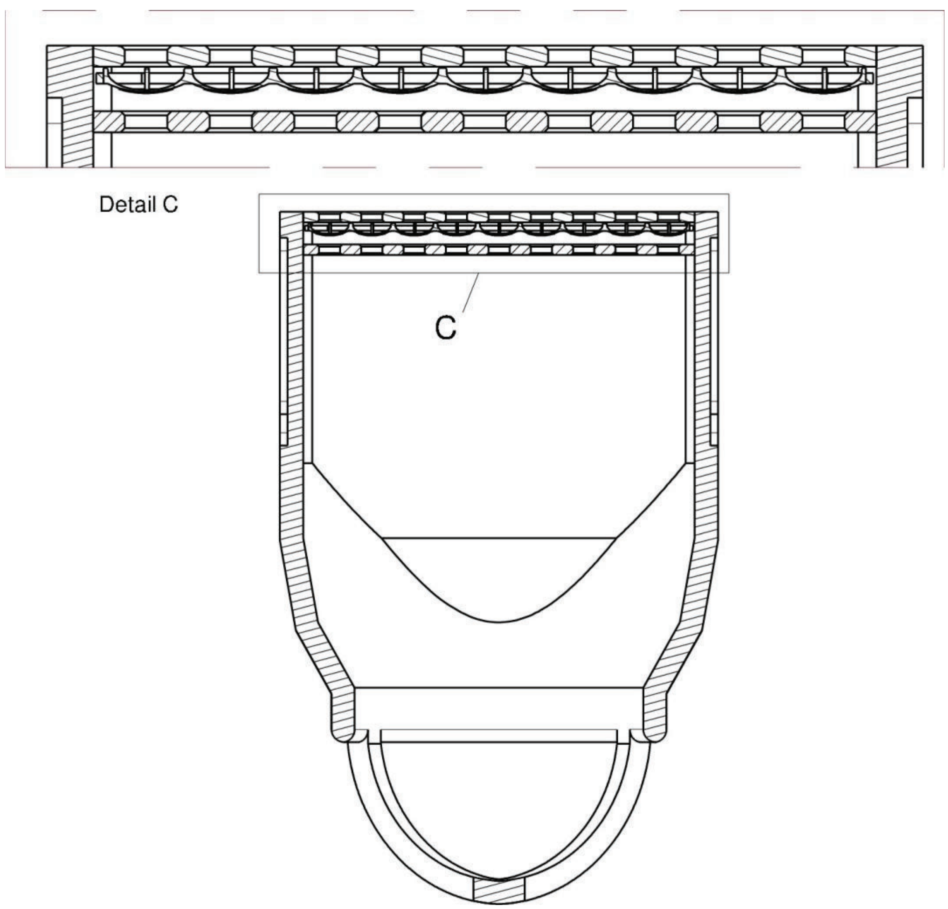

Figure 3 Vertical cut drawing of the lower tie plate structure including the floating screen between two holed plates identified as detail (C).

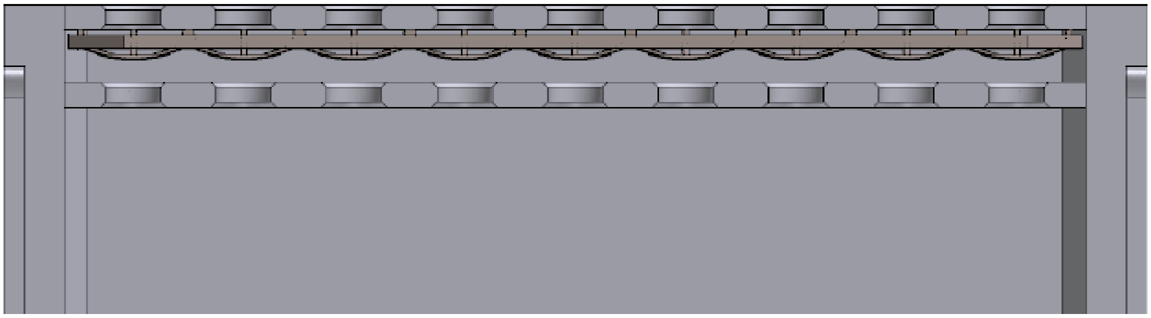

Figure 4a   The screen is shown in the up position and the upward flow is unobstructed.

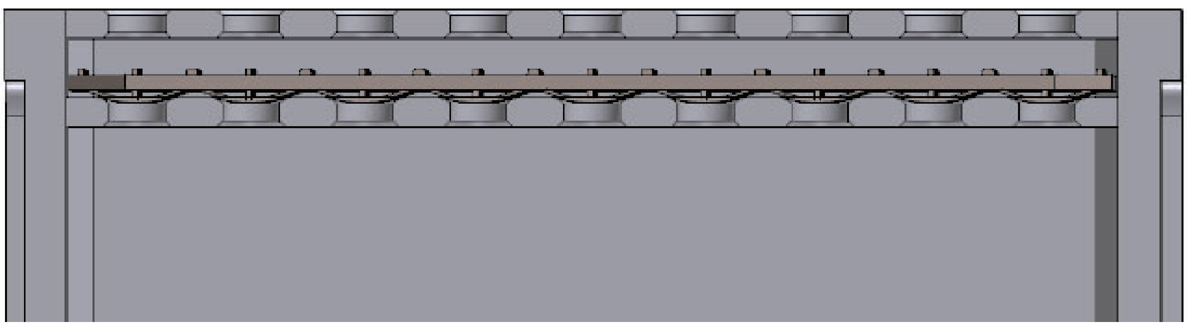

Figure 4b   The screen is shown in the down position and the downward flow is obstructed.

It is important to note that certain constraints must apply when designing a device to achieve this function. First, the possibility of device failure in the blocked position must be excluded by assuring that sufficient clearance exists for free motion of the screen inside the cavity. Second, the screen design shall not introduce a new problem of loose parts that may escape the cavity. Third, the operation of the device must be tested to exclude flow-induced vibrations. Finally, the introduction of this or similarly acting devices should not adversely affect other aspects of the plant operation. Upon reflection on this issue the impact of imposing no flow reversal seems to be helpful in the case of loss-of-coolant-accidents (LOCA); emergency core cooling spray on top of the core would be of maximal benefit if leakage of this coolant source through the bottom of the core is substantially reduced and the spray is more available for its intended purpose of core cooling.

3.2. Numerical Demonstration of the Principle of Operation

When the reactor is operated in an unstable state, the inlet mass flow of the coolant entering each fuel bundle will start to oscillate about its average value. Flow swings take a sinusoidal shape as function of time where the peaks and valleys of the oscillation are both positive. As the oscillation magnitude grows, the screen remains in the up position as long as the flow at its minimum remains in the upward direction and exerting the small pressure needed to lift the screen and maintain the flow path through the holes open. When the oscillation magnitude of the inlet flow grows such that the flow is not sufficient to maintain the hydraulic force that lifts the screen, i.e. approaches flow direction reversal, the screen drops to the down position with the disks blocking the flow holes beneath them. As the flow oscillation magnitude continues, the hydraulic forces bring the flow back in the upward direction which lifts the screen and the flow in the upward direction is allowed unobstructed. The largest flow oscillation magnitude through the inlet of a fuel assembly is limited as further oscillation growth is prevented by the flow path closure upon the onset of flow reversal.

The performance demonstrating the effectiveness of the method has been simulated numerically using a model capable of calculating the flow oscillations and unstable density waves in BWR fuel bundles and the associated thermal and hydraulic parameters. The results of such simulation in the absence of the beneficial effects of the new device are shown in Figures (5) and (6). Figure (5a) shows the inlet flow oscillation growing to substantial magnitudes where significant flow reversal occurs. Figure (5b) is a zoom of Figure (5a) in a time interval of 20 seconds in order to show the oscillating inlet mass flow rate more clearly. The resulting steam quality corresponding to these conditions are shown in Figure (6) demonstrating that the steam quality reaches unity for part of the oscillation cycle which means the fuel rods are totally deprived of the cooling effects of the liquid coolant for a relatively long duration. By contrast, the simulation of the same event is performed with the only difference that the lower tie plate with the new device is used and the results are shown in Figures (7) and (8). As shown in Figure (7a), the inlet mass flow rate oscillation continues to grow, similar to Figure (5a), until the flow reversal of small magnitude occurs upon which further growth of the oscillation magnitude is halted. A zoom of Figure (7a) is shown in Figure (7b) over a 20 second interval for better clarity. The corresponding effect on the steam quality is shown in Figure (8) which is demonstrated to remain well below unity thus guaranteeing the presence of liquid coolant to either prevent dryout or cause rewetting of the fuel cladding surface in case dryout occurs briefly. Thus the fuel cladding temperature remains low and fuel damage is prevented when the current invention is used.

As calculating clad temperature requires fuel-design-specific correlations, which is outside the scope of this work, the results will remain qualitative.

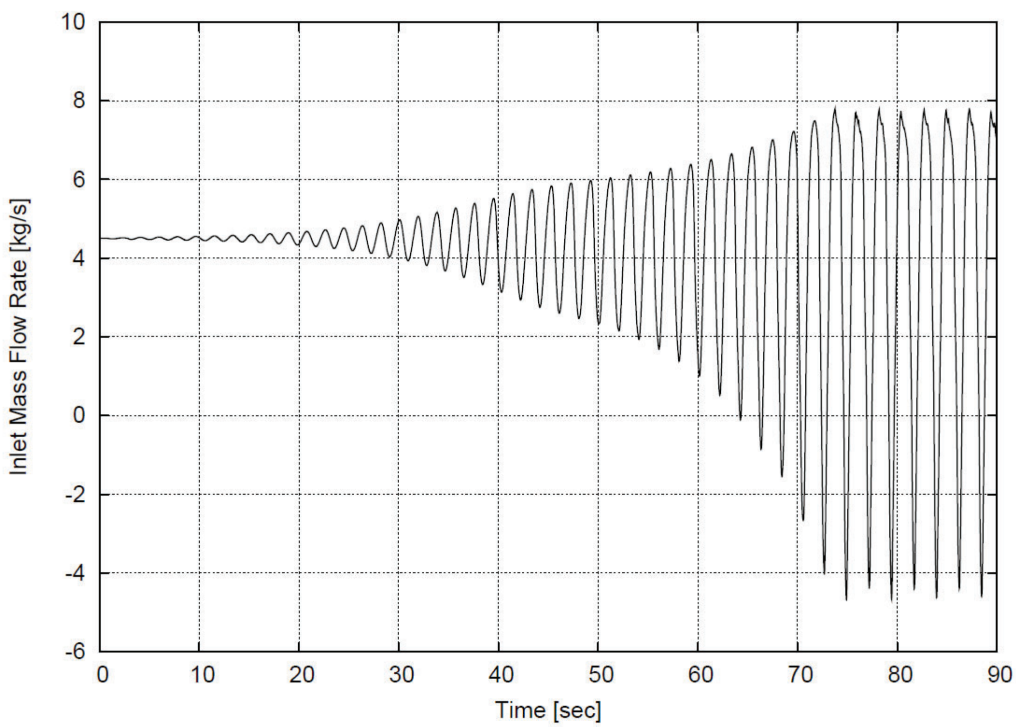

Figure 5a   Calculated example of unmitigated severe inlet flow oscillation with reverse flow

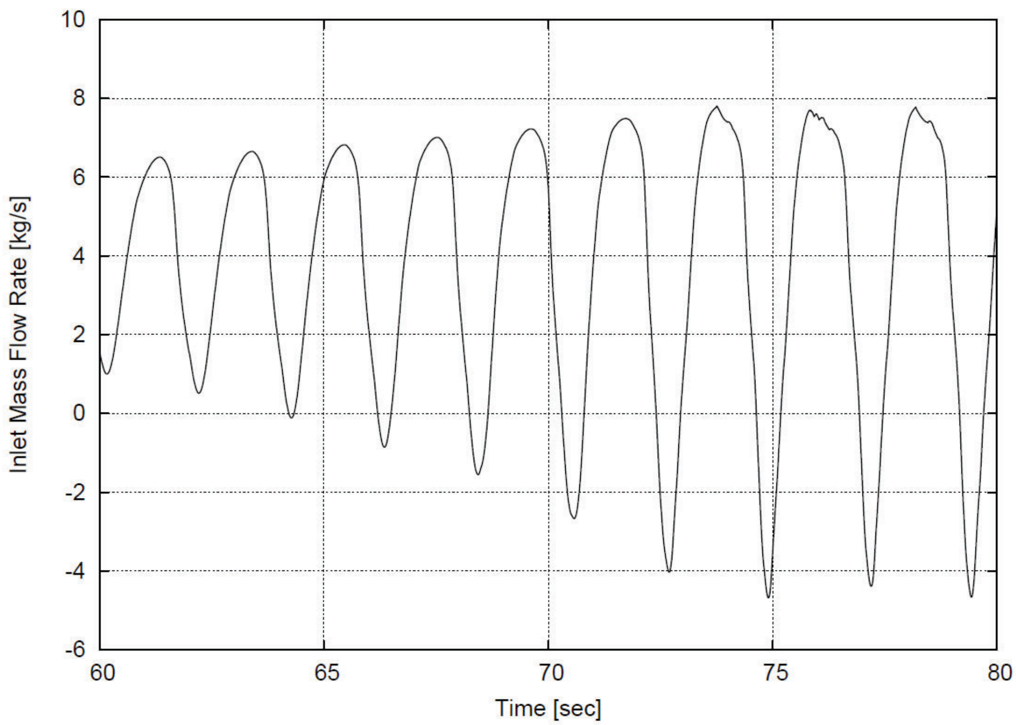

Figure 5b   Zoom of the Figure 5a calculated example of unmitigated severe inlet flow oscillation

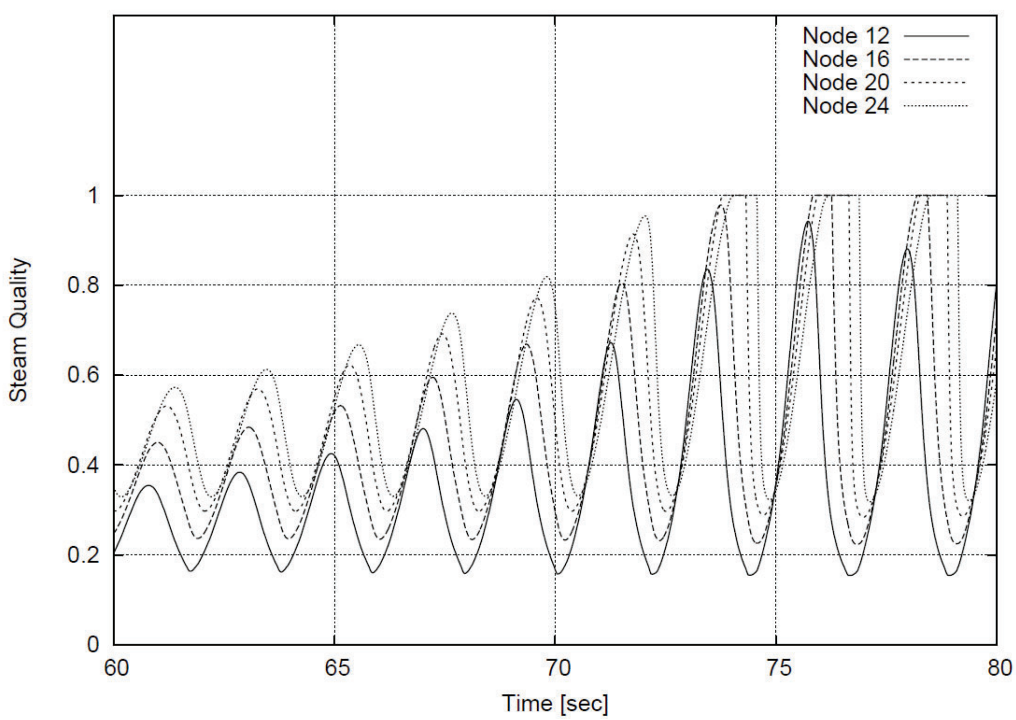

Figure 6   Steam quality calculated at different elevations (of 24 equal sized nodes) corresponding to the inlet flow shown in Figure 5b. for unmitigated severe inlet flow oscillation

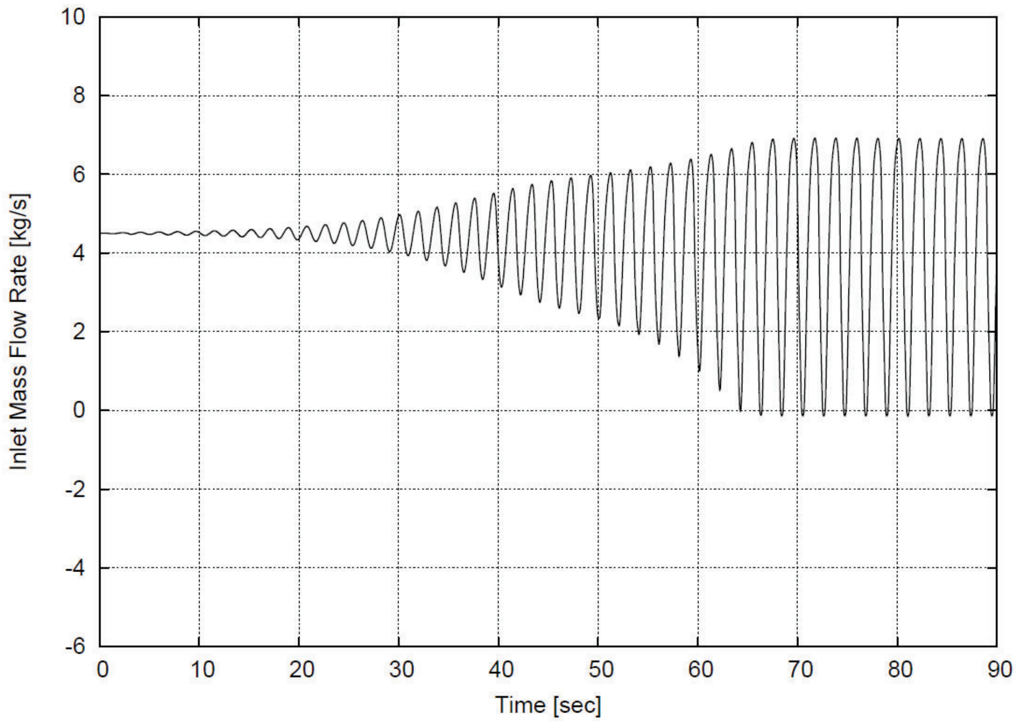

Figure 7a   Calculated example of inlet flow oscillation with reverse flow preventer

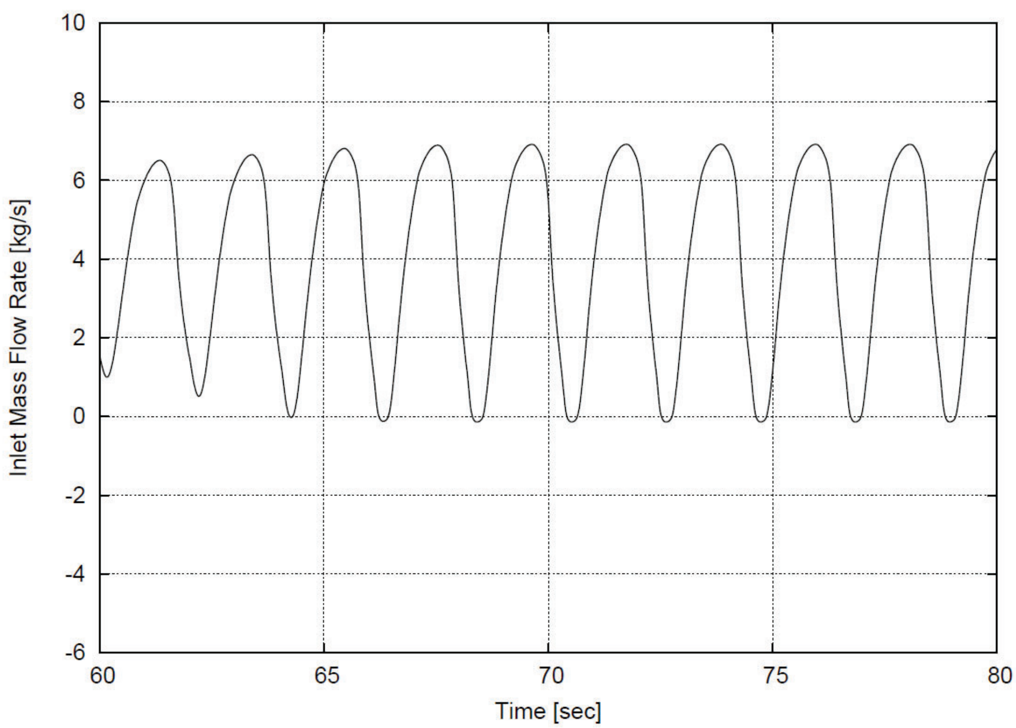

Figure 7b   Zoom of the Figure 7a calculated example of inlet flow oscillation with reverse flow preventer

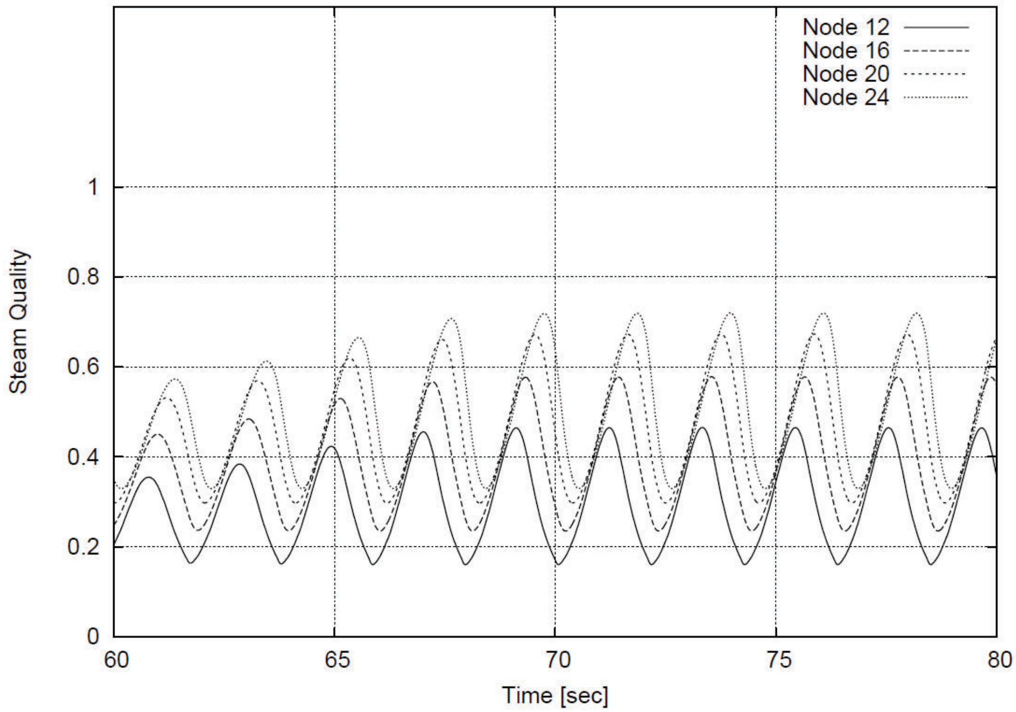

Figure 8 Steam quality calculated at different elevations with reverse flow preventer.

4. CONCLUSIONS

A proposed hardware solution is presented to address the problem of severe power and flow oscillations associated with hypothetical anticipated transients without scram in BWR. The hardware solution acts to limit the oscillation growth in the entire core by preventing flow reversal at the inlet of some fuel assemblies. This device is also helpful in the rare event of LOCA.

REFERENCES

1. J. March-Leuba, “Density-Wave Instabilities in Boiling Water Reactors,” Oak Ridge National Laboratory ORNL/TM-12130 NUREG/CR-6003, September (1992).
2. J. March-Leuba and E. D. Blakeman, "A Mechanism for Out-of-Phase Power Instabilities in Boiling Water Reactors," Nucl. Sci. and Eng. Technical Note, Vol. **107**, No. 2, 173-179 (1991).
3. Y. M. Farawila and D. W. Pruitt, "A Study of Nonlinear Oscillation and Limit Cycles in Boiling Water Reactors—II: The Global Mode," Nucl. Sci. Eng. **154**, 302–315 (2006)
4. Y. M. Farawila and D. W. Pruitt, "A Study of Nonlinear Oscillation and Limit Cycles in Boiling Water Reactors—II: The Regional Mode," Nucl. Sci. Eng. **154**, 316–327 (2006).
5. W. Wulff, H. S. Cheng, A. N. Mallen, and U.S. Rohatgi, "BWR Stability Analysis with the BNL Engineering Plant Analyzer," NUREG/CR-5816, October (1992).
6. NEDO-32047-A, “ATWS Rule Issues Relative to BWR Core Thermal-Hydraulic Stability,” June 1995.
7. P. Yarsky, Applicability of TRACE/PARCS to MELLLA+ BWR ATWS Analysis - Rev. 1," USNRC Office of Nuclear Regulatory Research, Nov. (2011).
8. Lap-Yan Cheng et al., "BWR Anticipated Transients without Scram in the MELLLA+ Expanded Operating Domain -- Part 2: Sensitivity Studies for Events Leading to Instability," BNL-98525-2012-IR, Sept. (2012).