**Engineering Science**
2023; 8(1): 1-5
http://www.sciencepublishinggroup.com/j/es
doi: 10.11648/j.es.20230801.11
ISSN: 2578-9260 (Print); ISSN: 2578-9279 (Online)

# Review of Inaccuracies in the Analysis of the Flow Stability Specific of the LW-SMR Modular Design

**Aleksey Rezvoi**

NuCon.US, Woodridge, USA

**Email address:**
nucon.2001@gmail.com

**To cite this article:**
Aleksey Rezvoi. Review of Inaccuracies in the Analysis of the Flow Stability Specific of the LW-SMR Modular Design. *Engineering Science*. Vol. 8, No. 1, 2023, pp. 1-5. doi: 10.11648/j.es.20230801.11

**Received**: September 25, 2022; **Accepted**: November 9, 2022; **Published**: February 28, 2023

**Abstract:** The presented analysis has been issued to express doubts about the correctness of the engineering and operational safety assessment, which arises from the modeling of transient modes and methodologically should help light water small modular nuclear reactor designers/developers to correct the model they are usually creating for studying the stability of the thermal-hydraulic circuit of the light water small modular nuclear reactor with the natural circulation of primary coolant. After the NuScale report publication and the following presentation review, additional questions arise regarding the analysis methodology, which was carried out and presented as part of the licensing package presented to NRC. After having carefully and critically read the available part of the presented report on the study of instabilities and the presentation issued by NuScale, the answer to the NRC safety committee request could be concluded that the instability analysis has not been performed correctly not only technically, but theoretically. Some clarification of the problem of analysis of instabilities is required additional explanations for further integral light water small modular nuclear reactor design developments and correct analysis implementations.

**Keywords:** SMR, Natural Circulation, Primary Circuit Instabilities, Two-Phase Flow, Once-Through Steam Generator

## 1. Introduction

The brief considerations and some ideas presented below have been extracted from the author' extended analytical report on the study of two-phase flow instabilities of such (similar) systems and include:

1) Review, analysis, conclusions and recommendations on the phenomenological analysis of various types and causes of two-phase flow instabilities;
2) Simplified evaluations of the interaction and mutual influence of various types of local instabilities on the over-circuit instability of the primary circuit system (PCS) and possible analogies with the occurrence of instabilities in the secondary circuit, and in the once-through steam generator (SG) especially;
3) Consideration and analysis, justification of possible simplifications, assumptions, and boundary conditions (BC) for further modeling the PCS of the light water small modular nuclear reactor (LW-SMR) integral design with natural circulation (NC) of the primary coolant (Figure 1) and studying the instabilities arising during operation, which can significantly affect anticipated and unanticipated transients;
4) Conclusions and resulting influence of specific design features of such a system on the following design of control algorithms and system maneuverability. LW-SMR w/NC operational safety justification.

## 2. Observations

The reviewed documents [1] and [2], and multiple scientific discussions allow us to conclude that first of all, LW-SMR core and PCS designers does do not have an adequate understanding of the specifics of the LW-SMR w/NC driving force. It's quite not normal for such specific designed systems.

As usual, the presented disturbance/instabilities characters scheme [1] has a general, academically undeveloped, and documental not correctly confirmed idea only, and can be taken only very general as an initial basis, but cannot be used without adjustments for a specific case considered in the LW-SMR w/NC analysis for the following reasons:

1) The assumption about the "unperturbed heat flux" generated from the core is incorrect since the heat flux disturbances always exist in the core, even during steady

state operations. This statement is especially true and important for the specifics of systems w/NC the coolant. Such disturbances can be decreasing or increasing in the amplitudes of parameters (coolant flow rate, temperature, level, etc.), which strongly depends on the system behavior;

2) Accordingly, the presented report [1] does not contain a substantiated explanation of the behavior of the hot coolant flow above the core, on "overflow edge" level variations, and the corresponding response to subsequent disturbances and changes in the heat transfer conditions to the secondary side in the SG;
3) The influence on the over-circuit instability of a long rising section (chimney) and the appearance of even insignificant steam (second phase) in it not being considered in the report [1];
4) The influence of the PCS pressure fluctuations can affect the PCS over-circuit behavior and make it (more or less) stiff due to the inertial of the built-in pressure compensator - pressurizer (PRZ) response not considered in the report [1] and presentation [2]. Consequently, changes in circuit/PCS pressure would be critical in power transients in both anticipated and unanticipated scenarios;
5) As a result, the report [1] does not clearly explain the primary/initiating causes of persistent disturbances in the feed water (FW) flow also. The appearance of such disturbances means that these are either the consequences of changes in heat exchange, or failures in the FW mass flow control system (even due to uncertain operating and control algorithms), or as consequence of the poor-quality design of the once-through SG, for example, in terms of the use of flow restrictors or orifices at the SG sections and separate SG pipes inlets;
6) The presented report [1] do not have a complete and joint understanding that the "steam output quality" for a once-through SG will always be constant, more precisely, "not worse" (the worst value of the output steam quality is observed in the full power when the so-called "ballast section" is not present in the SG). The power-loading-temperature (PLT) diagram could be used for better understanding. The other PCS parameters should be considered the joint only analysis of the core, circuit, and SG behavior's operating modes.

The presentation slides [2] of the density wave (DW) oscillation phenomenon illustration also does not correctly explain the once through SG disturbances concerning the LW-SMR w/NC integral design specifics. This diagram is presented in very general form and cannot relate to systems with the coolant NC because:

1) Assumes sinusoidal (regular) oscillations in the flow with a constant period. However, no explanation has been proved as to why this assumption has been made. In reality, the resulting oscillations will be aperiodic and with various amplitudes;
2) Is the increase in the volume of the steam phase implied in the entire volume of SG or only at the outlet? Let's note that there will always be only the vapor phase at the exit from the once-through SG, and it is determined by the problem statement, the flow rate of the coolant, and the corresponding parameters of the heated channel in the core outlet. If it does not provide these parameters during the operations, it is being incorrect designed;
3) As rightly noted in the NRC letter [3], the DW is not a "void phase" movement as mentioned in the presented report [1]. In the considering case, this is exactly the DW of one phase in the coolant or FW flow, of which it moves at a certain speed. However, oscillations of the liquid/steam boundary are related to hydrodynamic instability in parallel heated channels, which occurs in the secondary side of the once-through SG also [4, 5].

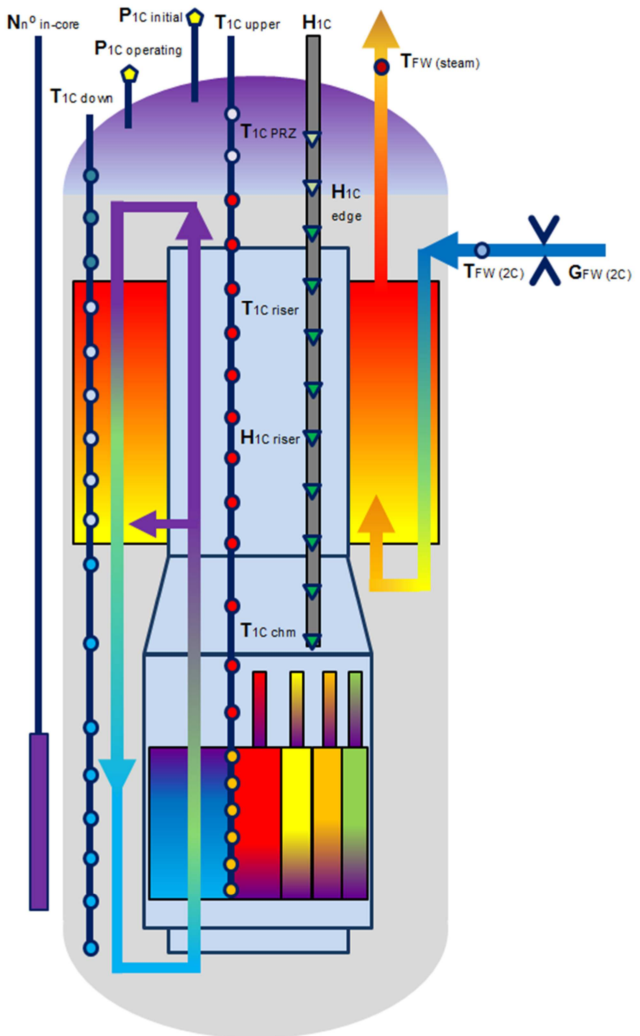


***Figure. 1.*** *The analytical scheme of the LW-SMR integral design w/NC primary coolant. The flow directions of the primary and secondary coolants. Approximate scheme of the I and C of sensors locations.*

Many remaining types of disturbances are not considered in any way in the analysis of instabilities of the DW type in SG (probably, the question of these effects was not presented in the instabilities problem analysis [1]). Simultaneously, their number, cumulative influence, and the result of the analysis are very critical for such LW-SMR safe operation and, accordingly, are important for the licensing process of similar systems.

In general, the report [1] analyzes data and literature [6, 7, 8, 9, 5], and all reviewed flow disturbances are divided into static and dynamic, as well as thermo-hydraulic [4] and $n^0$-physical [10]. This analysis and classification of types of instabilities are relatively good, except for some inaccuracies and lag in theoretical understanding of the problem. However, a joint, comprehensive study of the problem of instability raises additional questions. Perhaps they arise due to the lack of access to the complete/full (not cropped) report, but the report is not available to the public.

For clarification, the author's alternative classification of thermo-hydraulic instabilities in two-phase flows presented in Figure 2.

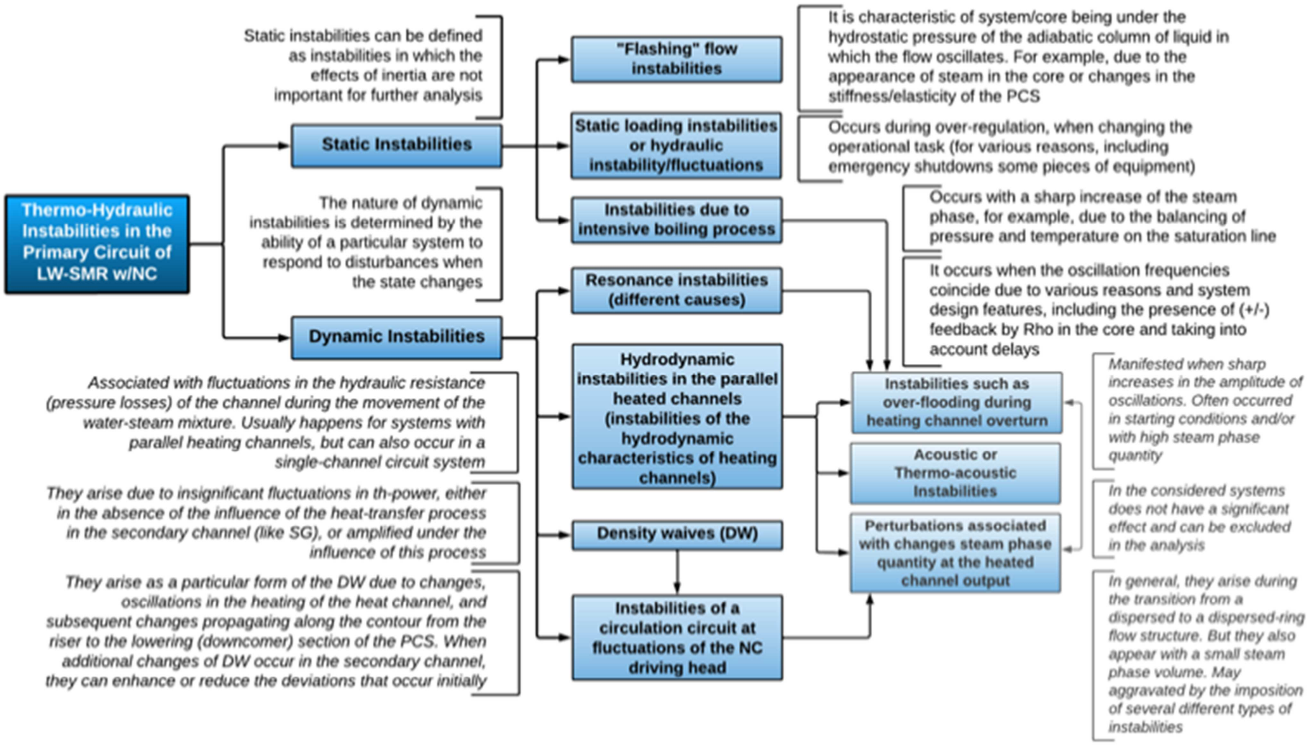


***Figure 2.*** *Thermo-hydraulic instabilities classification and co-influences.*

One cannot agree with the non-complex, simplified, and divided approach proposed for the phenomenological analysis [1]. It is quite apparent that the entire system will work only jointly, all potential disturbances can arise at any time, moments of operations and almost any preliminary exceptions and such conclusion about the insignificance of the influence of one or another type of instability on the general circulation circuit of the PCS is incorrect. Accordingly, the separation of the $n^0$-power feedback (FB) factor influences with the core thermo-hydraulic joint disturbances influence usually does not seem methodologically correct.

Even a seemingly insignificant disturbance, initially excluded from consideration, can shift the phase of the over-circuit oscillations in a positive or negative direction (more or less stable state). In other words, move the system into the area of resonant instabilities, which can be dangerous for the safe operation of the LW-SMR or cause failures leading to the shutdown of the nuclear reactor (NR) due to SCRAM by several signals (like: τ, Rho, $N_{set}$).

That is applied by LW-SMR analytical method of excluding phenomena from consideration by importance at the beginning of the analysis. As presented in [1], even before the study on a complex model, this also looks incorrect.

At the beginning of the phenomenological analysis, it was considered where (locally in the PCS), how, where, and why such disturbances could arise, appearance, and final effect were determined.

Obviously, the NR and PCS design and the methods, algorithms for controlling operational loading and power, and changing the flow rate of the supply FW have a serious impact on the occurrence of disturbances in the PCS and in the SG. The model for studying instabilities generally and seriously depends on the design features/elements of the object (LW-SMR integral design, Figure 1).

To simplification and correct problem understanding, the alternative diagram of the causes of disturbances in the PCS LW-SMR w/NC has been presented in Figure 3.

For example, in our work on a quite similar NR design development (similar thermal power), we presented a phenomenological diagram of the interactions of various types of instabilities and highlighted the causes of their occurrence, concerning the specific design of the NR, its separate PCS design elements. The previously developed diagram of the interrelationships of causes and possible mutual influences of various instabilities was adapted precisely in the contour of the considered type LW-SMR w/NC. After that, assumptions and simplifications were determined, and boundary conditions were formed to study and analyze the rising effects.

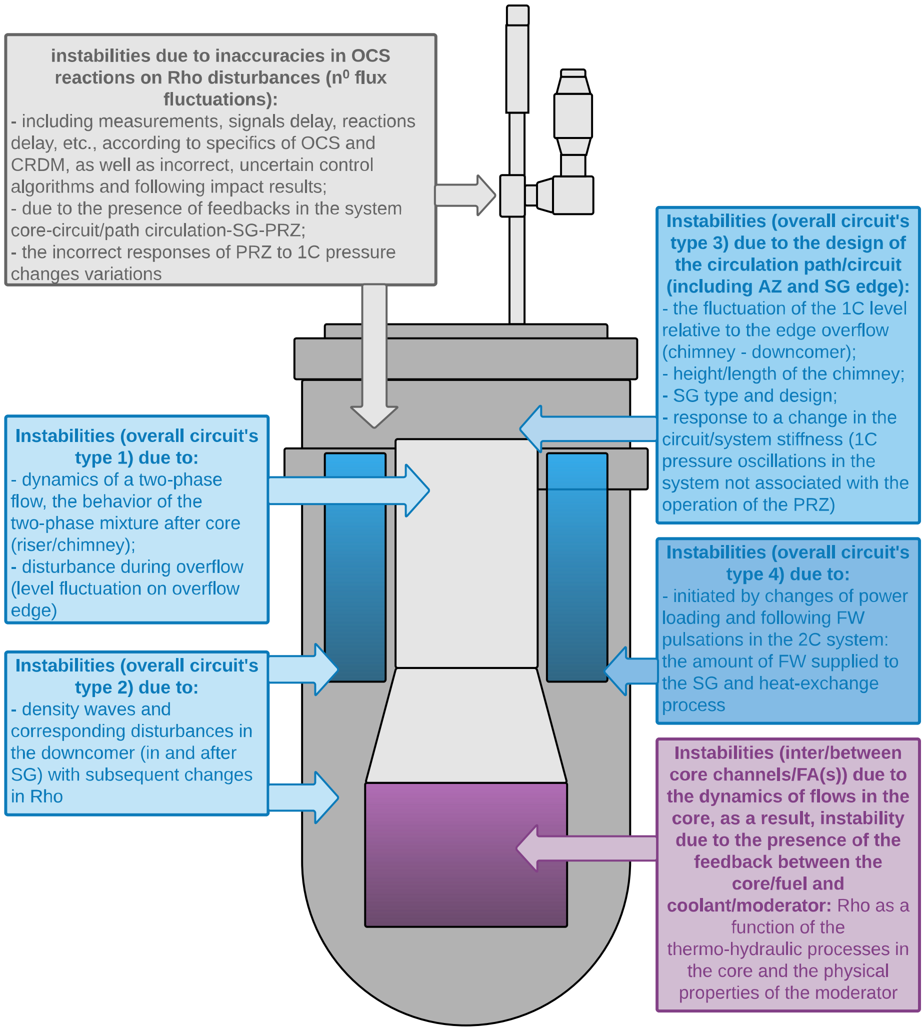


***Figure 3.*** *Thermo-hydraulic instabilities cause in the LW-SMR w/NC design.*

After developing an integrated approach to the study of the instabilities process, it is necessary to determine the BC for modeling [4]. It is convenient to consider flow fluctuations in PCS by dividing them according to the type of BC. Therefore, in general terms, there are three types of BC identified for such systems:

1) Thermo-hydraulic instability in a single heated channel operating at a fixed differential pressure, the instability of an isolated heated channel;
2) Thermo-hydraulic flow instability in the parallel heated channel system, or inter-channel instability;
3) Thermo-hydraulic coolant flows instability over the circulation loop or over-circuit instability.

The first two types of BC can be omitted if the LW-SMR core has a design that is expedient to be considered as a single heated channel ("unshrouded" fuel assemblies (FA) been used in the NuScale core design). That means that the instability will have only an over-circuit character or corresponded to type "c" BC only.

*BC type "c"**:** When considering the NC circuit's thermo-hydraulic stability, the interaction of the thermo-hydraulic parameters of all design components of the closed circulation loop should be investigated.*

Over-circuit instabilities can have variable periods and oscillation amplitudes, of which changes strongly depend on the circulation loop design. The appearance of additional local disturbances can cause interactions and superposition of different oscillations. Locally rising and disappearing instabilities can mutually reinforce or weaken each other; therefore, it is important to consider them together when analyzing. In real conditions, this type of BC appears in cases where the disturbance of the pressure drop in the system of heated channels (even with a single heated channel, LW-SMR core) is comparable to the pressure drop in the PCS circulation loop and affects the fluctuations in the over-circuit flow rate (which directly depends on heat flux in the core). And these are precisely the conditions for the existence of the EC in such type of NR.

As a result, over-circuit flow rate fluctuations lead to flow rate fluctuations along the entire loop, which causes enthalpy fluctuations. These fluctuations act on the flow rate as a lagging FB, similar to the action of "α", when the FB fluctuates in a circuit with a relatively long lifting chimney section, with fluctuations in the coolant level above the overflow edge (top of reactor vessel), with delayed responses to changes (fluctuations) in pressure in the PCS. All three of these circuit design elements/components are not considered in the LW-SMR analysis in the report [1].

The instability problem becomes much more complicated if we introduce into consideration the FB on the change in $n^0$-physical parameters (Rho as resulting parameter) in the core. Time delays associated with heat transfer from the fuel to the coolant flow and the instantaneous reaction of Rho (fission process) to changes in the parameters in the core cause additional disturbances in the core and circulation loop. Such disturbances can cause local evaporation, and the appearance of even a small volume of steam only enhances the instability of the circuit and initiates disturbances of the $n^0$-flow in the core.

The arising disturbances must be monitored and corrected by the NR control system, which inevitably automatically turns on with time delay in operation because of possible significant $n^0$-flux disturbances. The specifics of creating control algorithms without considering and understanding the interactions occurring in the PCS circulation loop entails errors in control and the possibility of transferring the NR into an unsafe operation mode.

# 3. Afterword and Conclusion

Our specialists developed a more detailed report on the reality of information importance for future operational safety provision and possible issues of modular LW-SMR design.

Thus, the obvious fact is that in the conditions of uncertainties in the NR component design and following misunderstanding and errors made in modeling LW-SMR instabilities the subsequent errors extend to the safety justification and creation of the control system, to the operational safety concept that has a huge price and cannot be ignored by the project designers/developers and especially licensing authority, the NRC. Further, it is likely that after these adjustments, additional review, and revision of specific chapter of the safety assurance report (SAR), for example, will be required even in the early stage of NR and especially LW-SMR design development.

Overview is provided above should clarify and initiate correct and understandable methods for further analytical process development and engineering problem solution.

The presented problem could not me limited of this observation and should be analyzed more precisely and accurate. The main problem for such analysis is correct and adequate understanding of theoretical aspects of two-phase flow instabilities and correct co-influence on NR core operations.

Presented analysis overview is just the first part of the theoretical overview of two-phase flow instabilities problem.

# Abbreviations

*LW: light water (reactor)*
*SMR: small modular reactor*
*NC: natural circulation*
*PCS: primary circuit system*
*SG: steam-generator (here once through)*
*PRZ: pressurizer*
*FW: feed water*
*PLT: power loading vs in-core temperature*
*DW: density waves*
*BC: boundary conditions*
*FA: fuel assembly*
*FB: feed-back*
*SAR: Safety Assurance Record*
*NR: nuclear reactor*
$n^0$*: neutronics*
*Rho: reactivity*
$\tau$*: power doubling period*
$N_{set}$*: set (reactor) power*
$\alpha$*: volumetric steam content*

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