Thermal Hydraulics Design Limits
Class Note II

Professor Neil E. Todreas

The following discussion of steady state and transient design limits is extracted from the theses of Carter Shuffler and Jarrod Trant. These limits are a simplified and narrower discussion than the relevant NRC standard review plan you will also be referred to.

- Shuffler, Carter Alexander. "Optimization of hydride fueled pressurized water reactor cores." S. M. Thesis, MIT Dept. of Nuclear Engineering, 2004.

- Trant, Jarrod Michael. "Transient analysis of hydride fueled pressurized water reactor cores." S. M. Thesis, MIT Dept. of Nuclear Engineering, 2004.

Steady State Limits

1 MDNBR

Departure from nucleate boiling (DNB) is the most limiting constraint on power for commercial PWRs. DNB occurs at the critical heat flux, which is a function of the geometry and operating conditions in the core. It is characterized by a sharp decline in the heat transfer coefficient at the coolant/cladding interface, as vapor blankets the fuel rod preventing fluid from reaching its outer surface. The result is an abrupt rise in the temperature of both the fuel and cladding, which can damage the fuel and/or cause a cladding breach.

The performance metric for DNB is the MDNBR, which is the minimum ratio of the critical to actual heat flux found in the core. In commercial design, significant margin exists in the MDNBR limit to account for transients, core anomalies (i.e, rod bow), process uncertainty (i.e, instrument error), and correlation uncertainty. While it is difficult to quantify the magnitude of each, a reasonable MDNBR limit can be obtained by executing VIPRE at the reference core geometry and operating conditions. The reference core's MDNBR limit already accounts for the needed margin. The use of the MDNBR given by VIPRE as the MDNBR limit for the steady-state thermal hydraulic analysis therefore ensures that all new designs will demonstrate the same level of DNB margin as the reference core. This limit is ~ 2.17.

One final note on the MDNBR limit is warranted. Using the limit, as described above, assumes that the margins built into the reference core's MDNBR limit are sufficient for all geometries considered in this study. This may not be true, however, for the transient contribution. Consider, for example, the loss of flow accident (LOFA). Designs that are tighter than the reference core will coast down more quickly, and therefore require additional margin for transients in the overall steady-state MDNBR limit. Ultimately, the final maximum achievable power will be the minimum power given by either the steady-state or transient analyses, at each geometry.

2 Pressure Drop

The maximum pressure drop sustainable through the primary system is determined by the capacity of the coolant pumps. Two separate pressure drop limits are used in the steady-state thermal hydraulic analysis to reflect the current and 5 year expected enhanced states of pumping technology. While losses occur throughout the entire primary coolant loop, the limit is based on the pressure drop across the fuel bundle, because it will vary most among the redesigned cores.

The lower pressure drop limit indicative of current PWR pumping capacity is determined in the same manner as the steady-state MDNBR limit: finding the pressure drop across the fuel bundle given by VIPRE for the reference core geometry and operating conditions. This pressure drop is approximately 29 psia. The enhanced pressure drop limit is based on examination of pumping capacities for the Westinghouse AP600 and AP1000 PWR designs, and a survey of industry experts. The pressure drop in the core nearly doubled between the design of the AP600 and AP1000, and so it is reasonable to believe that in the next 5 years the capacity could again double. The enhanced fuel bundle pressure drop limit is therefore 60 psia.

3 Fuel Temperature

Oxide fuels release non-negligible amounts of fission gas, which, if not limited, can pressurize and even burst the fuel pin. Based on fuel performance data for oxide fuels, the fission gas release fraction can be kept below 5% by limiting the average fuel temperature to 1400 C [4]. This is the temperature limit adopted for oxide fuel. Note that this is more limiting than imposing a peak centerline temperature limit of 2800 C, which is the melting point of UO_2. Note that this temperature limit only applies to steady-state operation.

4 Axial Flow Velocity

Because the enthalpy rise across the core is fixed, a specific geometry can only achieve higher powers by increasing the coolant flow through the core. As the bulk flow gets larger, the turbulent axial and cross-flow velocities increase, making a vibrationrelated rod failure more probable. It is therefore desirable to provide design limits to restrict rod vibrations, and resultant wear at the cladding/rod support interface.

In lieu of a detailed vibrations and wear analysis for each core design, a single limit on the hot channel axially averaged velocity can be imposed. The limit based on judgment is that vibration problems could be avoided in PWRs by limiting the axial velocity of coolant to 7 m/s. The limit adopted was 8 m/s, under the assumption that additional grid spacers would be added if deemed necessary by a separate fluid-elastic instability analysis of select, optimum geometries.

A more thorough analysis of relevant vibration and wear mechanisms is required.

5. Vibrations Analysis for Hydride and Oxide Fueled PWRs

5.1 Introduction

Dynamic forces generated by the turbulent flow of coolant in PWR cores cause fuel rods to vibrate. Flow-induced rod vibrations can generally be broken into two groups: large amplitude “resonance type” vibrations, which can cause immediate rod failure or severe damage to the rod and its support structure, and smaller amplitude vibrations, responsible for more gradual wear and fatigue at the contact surface between the fuel cladding and rod support. While the former group is typically prevented by adequate structural design of the fuel assembly, the latter is unavoidable. Sufficient wear resistance must therefore exist in the fuel assembly components to preclude excessive damage. Ultimately, both vibration types can result in a cladding breach, and therefore must be accounted for in the thermal hydraulic design of hydride and oxide fueled PWRs.

If a more thorough analysis of relevant vibration and wear mechanisms is needed, appropriate design limits are imposed for each mechanism as described below.

5.2 Goals of the Vibrations Analysis

The goal of the vibrations analysis is to develop and incorporate new design limits for flow-induced vibration and wear mechanisms into the existing thermal hydraulic programs, replacing the single limit on axial velocity.

5.3 Flow-Induced Vibration Mechanisms - Overview

Three primary types of flow-induced vibration are observed for cylindrical fuel elements subject to cross and axial flow:

- *Vortex-Induced Vibration:* Vortex-induced vibration can occur by two means: vortex shedding lock-in and vortex-induced acoustic resonance. In vortex shedding lock-in, the frequency of the vortices shed by cross-flow over the fuel rod "lock in" to the rod's structural frequencies, causing resonant vibration. In vortex-induced acoustic resonance, the shedding frequency excites standing acoustic waves created by the operation of fans, pumps, valves, etc. in the coolant loop[1]. Because the rules to avoid lock-in are more conservative than the rules to avoid acoustic resonance, only vortex shedding lock-in is considered in this analysis.

- *Fluid-Elastic Instability:* Fluid-elastic instability of a rod bundle occurs when the cross-flow velocity exceeds the critical velocity for the bundle configuration, at which point the rod response increases uncontrollably and without bound.

- *Turbulence-Induced Vibration in Cross and Axial Flow:* The fluctuating pressure fields generated by cross and axial flow turbulence in the core exert random forces on the fuel rods, causing vibration.

[1] Standing waves are required for the acoustic resonance condition. They are formed when acoustic waves traveling in opposite directions (as when an acoustic wave deflects off of fuel rods) superimpose onto one another.

The vibration amplitudes associated with vortex shedding lock-in and fluid-elastic instability are generally very large, and can quickly cause severe damage to the fuel rod and its support structure. If the pitch is tight enough, rod failure by tube-to-tube impaction is also possible. Fortunately, these devastating mechanisms can be prevented by adequate design of the fuel assembly structure for the flow conditions in the core (i.e. using an appropriate number of grid supports and providing adequate stiffness to the fuel rod).

Unlike vortex shedding lock-in and fluid-elastic instability, turbulence-induced vibration is generally of small amplitude and cannot be avoided. The principle design concern is therefore not the prevention of the vibration mechanism, but the limitation of resultant wear at the cladding/rod support interface.   Wear is a concern for two reasons. First, excessive wear can directly breach the clad or increase the likelihood of a breach from other rod damage mechanisms (i.e. impact stress and fatigue). Second, wear at the cladding/rod support interface lowers the structural frequencies of the rod, making it more susceptible to vortex-induced vibration and fluid-elastic instability.

The most common wear mechanism, and historically the most costly flow-induced vibration problem in the nuclear industry, is fretting wear. Fretting results from combined rubbing and impaction between the fuel rod support and the cladding surface. Sliding, or adhesive, wear also occurs where the grid support springs and rod rub against one another. Both wear types are considered in this study.

The mechanisms considered and their respective design concerns are summarized in Table 1.

Table 1 Flow-Induced Vibration Mechanisms

Flow-Induced Mechanism	***Design Concern***
Vortex-Induced Vibration	• Large amplitude vibrations occur when vortex shedding frequencies lock-in to the structural frequency of the rod
Fluid-Elastic Instability	• Large amplitude vibrations occur when cross-flows exceed the critical velocity for the rod bundle configuration
Turbulence-Induced Vibration in Cross and Axial Flow	• Small amplitude rod vibrations from turbulence generated pressure fields cause excessive fretting and sliding wear at the cladding/rod support interface

TRANSIENT LIMITS

The transients to be considered include a loss of coolant accident (LOCA), an overpower transient, and a loss of flow accident (LOFA). The LOCA and overpower transient will each yield the maximum achievable power for the given condition over the entire range of geometries.

Loss of Coolant Accident

The first transient to be considered is the loss of coolant accident (LOCA). There are two types of LOCA events that could be considered. The large break LOCA (LBLOCA) is an ANS condition IV transient, while the small break LOCA is an ANS condition III transient. The large break LOCA, being more restrictive, will be considered here.

A full scale LOCA evaluation over the entire design range is impractical. However, using the methodology of Catton, et.al [5] will allow use of the clad temperature history of the reference core as the bounding criteria for the entire range of geometries.

Overpower Transient

The second transient to be considered is an overpower transient. There are two ANS Condition II overpower transients which are considered in the South Texas Project Electric Generating Station (STPEGS) Final Safety Analysis Report (FSAR).

The first event is concerned with a main steam line break at power. The second event is rod bank withdrawal at power and the limit challenged is the minimum departure from nucleate boiling ratio (MDNBR).

The main steam line break overpower transient is constrained by the plant's 22.45 kW/ft linear heat rate limit. The rod withdrawal transient is limited by the 18% limit. This 18% overpower limit equates to a 16.03 kW/ft linear heat rate. Therefore, when considering a generic overpower transient, the 16.03 kW/ft limit will be breached prior to the 22.45 kW/ft limit. Therefore, the rod withdrawal will be treated here to cover both overpower transients over the entire geometry range. The limiting condition will be defined as the MDNBR of the reference core for this overpower transient.

Loss of Flow Accident

The third transient, the loss of flow accident, also consists of two categories, the complete loss of flow (CLOFA) and the partial loss of flow accident (PLOFA). The complete loss of flow is more limiting and will be considered here. The CLOFA is an ANS Condition III transient; however, in this paper as well as in the STPEGS FSAR the Condition II limits will be applied.

Figure 1 identifies the separate components of margin for MDNBR.

Figure 1: Separated Components of Margin for MDNBR