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An Autonomous Reactivity Control system for improved fast reactor safety

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A B S T R A C T

The Autonomous Reactivity Control (ARC) system is a new safety device that can passively provide negative reactivity feedback in fast reactors that is sufficient to compensate for the positive coolant density reactivity feedback even in large low-leakage cores. The ARC system is actuated by the inherent physical property of thermal expansion, and has a very small effect on core neutronics at standard operating conditions. Additionally, the ARC system does not have an identified failure mode that can introduce positive reactivity in to the core. An ARC system can be installed in conventional fuel assemblies by replacing a limited number of fuel rods with rods that fill a safety function, providing negative reactivity to the core in the event of coolant temperature rise above nominal. These rods are of the same outer dimensions as the fuel rods, but contain smaller-diameter inner rods that are connected to liquid-filled reservoirs at the top and bottom of the assemblies. The reservoirs are filled with two separate liquids that stay liquid and immiscible throughout the applicable temperature range of fast reactor operation. The lower reservoir contains a "neutron poison" liquid with a high neutron absorption cross-section. The upper reservoir is filled with a separate liquid with a small neutron absorption cross-section. As the temperature in the assembly increases, the liquids in the reservoirs thermally expand, effectively pushing the absorbing liquid up toward the active core region while compressing the inert gas that fills the volume above the liquid between the inner and outer tubes of the ARC rods. The ARC system can be installed, or retrofitted in to existing systems, in every fuel assembly in the core. Since ARC installations in individual fuel assemblies operate independently, the system has a high level of redundancy. ARC-systems respond to local transients as well as core-wide accident scenarios. After actuation, the system automatically returns to its initial state as temperatures decrease, without the need for intervention by reactor operators. The ARC system concept and design considerations are described and illustrated.

1. Introduction

Much of the current focus of safety design for new nuclear reactors is on *inherent safety* features. Inherent safety means that the reactor design is such that the plant remains in a safe condition solely on the basis of the laws of nature; these laws ensure that all performance characteristics remain within safe bounds under all conceivable circumstances. This implies that no human intervention, no triggering signals and no supply of external energy are required for the reactor to remain in a safe condition (Van Dam, 1992). Inherent safety features are especially important when engineered systems such as the SCRAM-systems for reactor shutdown are not functioning.

Thermal reactor cores are designed to be slightly undermoderated to ensure that a decrease of the coolant density reduces the reactivity of the system. Thus, in a properly designed Light Water Reactor (LWR) there are no positive temperature reactivity feedbacks. In contrast, in most fast reactor cores coolant density reduction – due to increased temperature or voiding, has a positive reactivity feedback. This is because the core-averaged number of fission neutrons produced per absorption (η) increases because of neutron spectrum hardening. Coolant density decrease also causes an enhancement of the neutron leakage probability, which, in turn, introduces negative reactivity feedback. In most fast reactors the positive reactivity added by spectrum hardening (and,

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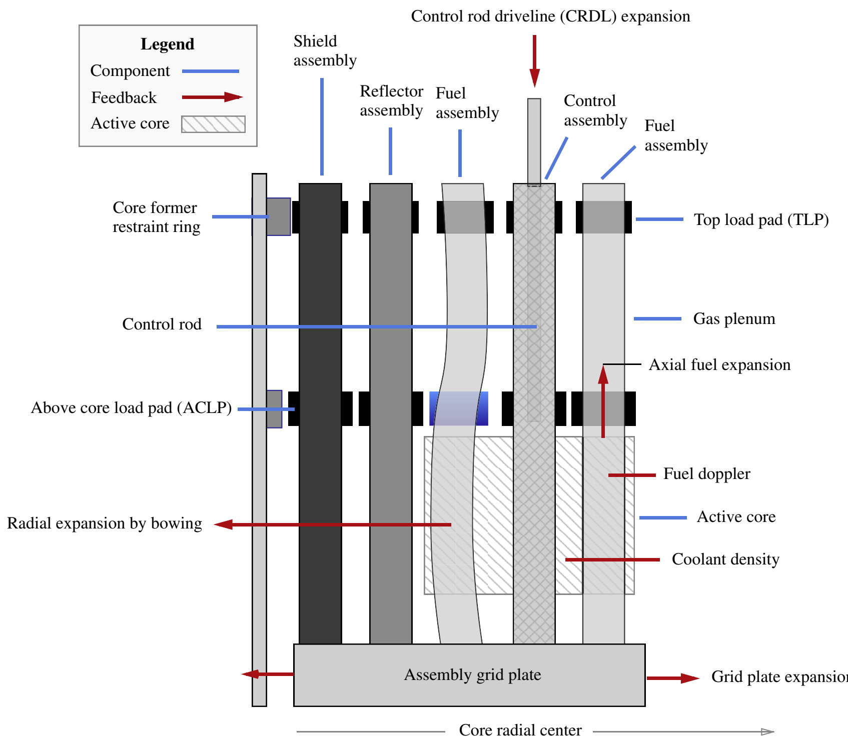

Fig. 1. Dimensional changes and corresponding reactivity feedback mechanisms in a conventional fast reactor core.

to a smaller extent, by reduced neutron capture probability in the coolant) due to a coolant density decrease in the central region of the core is larger than the negative reactivity introduced by the enhanced neutron leakage. The extreme case of such an event is coolant voiding due to boiling or loss of coolant accidents. Reducing the positive feedback associated with coolant density reduction and increasing the magnitude of negative feedback of other mechanisms while maintaining acceptable core performance has been a major focus of fast reactor safety research. The main mechanisms that inherently provide negative reactivity feedback in fast reactor cores are defined in Fig. 1. The red arrows indicate the directions of motion of the component that causes the negative feedback.

Fig. 2 shows the possible event-initiating perturbations (blue boxes), the resulting component temperature changes (black squares), the main[1] resulting reactivity effects and the associated reactivity feedback definitions for a conventional fast reactor core.

The effects shown in Fig. 2 represent the largest and most important reactivity feedback effects; they do not represent all effects occurring in the core. A green-box indicates a negative temperature reactivity feedback and a red box a positive feedback. The black reactivity box shows an effect where the sign of the feedback is time-dependent as in case of control rod driveline expansion. Initially as the control rod driveline (CRDL) heats up, control rods are inserted into the active core causing a negative reactivity feedback. At a later stage, the reactor vessel heats up and expands, effectively pulling the control rods back out of the core, resulting in a positive feedback.

A combination of the inherent feedbacks shown in Fig. 2 should keep peak temperatures below safety margins in unprotected transients such as loss of flow (ULOF), loss of heat sink (ULOHS) and the inadvertent ejection of control rod(s) resulting in a transient overpower event (UTOP). However, it is very difficult to design a low-leakage reactor core, such as required for breed-and-burn reactors (Greenspan, 2012), to have a combination of inherent reactivity feedbacks to keep core component temperatures sufficiently low in accidents. If the nominal neutron leakage probability is small – a requirement for a good neutron economy, the negative feedbacks connected to changes in the relative leakage probability will have a small impact on the core reactivity. A low-leakage core does not only have smaller magnitude negative feedback, but larger magnitude positive feedbacks. This is because the negative component of the feedback, which is leakage-based, is reduced, while the positive spectral component remains essentially unchanged. This makes it extremely challenging, if not impossible, to design large low-leakage fast reactor cores to be inherently safe without use of passively actuated engineered reactivity control systems.

To objective of this work is to describe the Autonomous Reactivity Control (ARC) system that was invented to overcome the issue of too positive coolant temperature feedback and too large positive coolant void worth without significantly impairing the core neutron economy in standard operating conditions.

Section 2 defined a set of evaluation criteria for systems and solutions aimed at improving the reactivity feedback of fast reactor cores. Using these criteria, Sections 3–6 evaluate already proposed solutions based on leakage, moderation, solid absorbers and liquid absorbers respectively. The evaluation of existing solutions is summarized in Section 7. The Autonomous Reactivity Control (ARC) system is introduced in Section 8. Section 9 presents different approaches for designing the reactivity response of ARC-type systems. In Section 10, possible combinations of materials for ARC-systems are presented. The system design methodology, based on the approaches defined in Section 9, is briefly introduced in Section 11. Section 12 presents the characteristics and performance of an ARC-system installation in a large fast reactor core. Finally, Section 13

[1] Teller et al. (1996) propose the need of 1000 thermo-stat modules per GWe of core output.