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Tailoring the response of Autonomous Reactivity Control (ARC) systems

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ABSTRACT

The Autonomous Reactivity Control (ARC) system was developed to ensure inherent safety of Generation-IV reactors while having a minimal impact on reactor performance and economic viability. In this study we present the transient response of fast reactor cores to postulated accident scenarios with and without ARC systems installed. Using a combination of analytical methods and numerical simulation, the principles of ARC system design that assure stability and avoids oscillatory behavior have been identified. A comprehensive transient analysis study for ARC-equipped cores, including a series of Unprotected Loss of Flow (ULOF) and Unprotected Loss of Heat Sink (ULOHS) simulations, were performed for Argonne National Laboratory (ANL) Advanced Burner Reactor (ABR) designs. With carefully designed ARC-systems installed in the fuel assemblies, the cores exhibit a smooth non-oscillatory transition to stabilization at acceptable temperatures following all postulated transients. To avoid oscillations in power and temperature, the reactivity introduced per degree of temperature change in the ARC system needs to be kept below a certain threshold the value of which is system dependent, the temperature span of actuation needs to be as large as possible.

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1. Introduction

The Autonomous Reactivity Control (ARC) system was developed to ensure inherent safety performance of Generation-IV reactors while having a minimal impact on reactor performance and economic viability. The motivation and inspiration for the development of ARC systems have been covered in earlier publications (Qvist and Greenspan, 2014a; Qvist and Greenspan, 2014b; Qvist and Greenspan, 2012; Qvist, 2013), and the principles of the design, operation and manufacturing of ARC systems has been presented in great detail in Qvist et al. (2016). We refer the reader interested in detailed information about the design and operational principles of the system to these previous publications.

In its standard configuration, the ARC system is installed as a modification to a conventional nuclear fuel assembly design. The "system" consists of two reservoirs, located at the top and bottom of the assembly, and two concentric tubes that link the reservoirs. The inner tube is open at both ends and connects the insides of both reservoirs, while the outer tube is open at the bottom (connected to the lower reservoir) and at the top connects to a closed gas-filled reservoir. During operation, the upper reservoir is completely filled with a liquid (Potassium), while the lower reservoir contains the same expansion liquid and, floating on top of it, a separate immiscible liquid (Potassium and Lithium). The remaining free volume between the two concentric tubes in the closed system is filled with an inert gas (Argon). The outer ARC-tube has the same outer dimension as the fuel rods. Installing an ARC-tube therefore implies replacing one of the fuel rods in the assembly. A schematic view of the operation of an ARC-installation is shown in Fig. 1. During an accident/transient scenario in the reactor, the ARC-system responds in the following way, starting from standard operating conditions:

1. Some event raises the temperature in the core, which heats up the coolant.
2. The heated coolant flows to the top of the assembly and transfers heat to the expansion liquid inside the upper reservoir.
3. The expansion liquid in the upper reservoir thermally expands. Since the reservoir is completely filled and sealed at the top, this expansion is directed down the inner ARC-tube that connects the two reservoirs.

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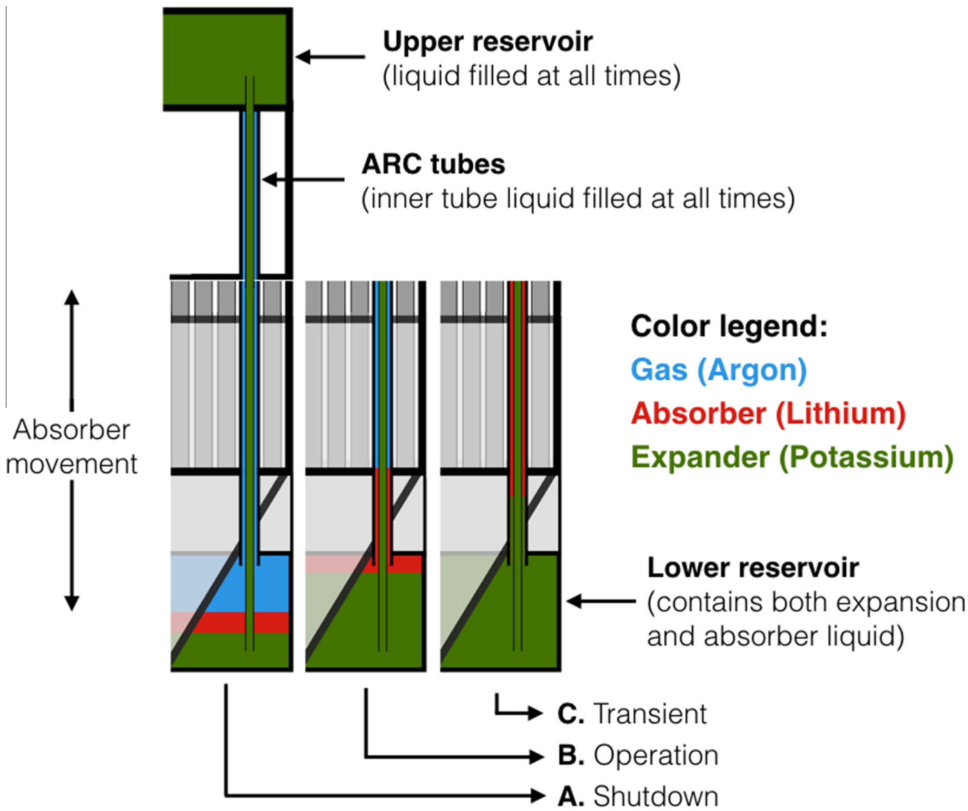

Fig. 1. Schematic view of the ARC system at different states/temperatures.

4. As expansion liquid enters the lower reservoir from the upper reservoir (through the inner ARC-tube), the level of absorber liquid rises toward (and finally into) the active core, while compressing the inert gas above.
5. The absorber liquid, which has a high neutron capture cross-section, introduces negative reactivity by absorbing neutrons in the core, which in turn causes a reduction in power and temperature.
6. As the core cools down, the temperature of the expansion liquid starts to fall. Thermal contraction combined with the pressure of the inert gas again lowers the axial level of the absorber liquid until the system reaches a stable critical configuration.

The focus of this study is the transient behavior of ARC-equipped fast reactor cores, and their stability during and following accident scenarios. Using a combination of analytical methods and numerical simulation, the principles that avoid oscillatory behavior and assure stability of fast reactor cores with ARC systems installed have been identified and defined.

The design of any ARC-system starts with an informed guess on a number of parameters, which are then iteratively improved after obtaining simulation results. The parameters of the ARC-system depend primarily on the relative importance of different accident scenarios in the specific core in which it is to be implemented. The core state assumed following three general types of Anticipated Transients Without Scram[*] (ATWS) are summarized in Table 1.

Other events that may occur can be defined as combinations of the events above. For instance, the loss of all external power (station blackout) event is effectively the LOF and LOHS events happening simultaneously. For these three general types of transients, there are essentially three different time-scales of importance:

1. *Early phase*
This phase typically spans the first few minutes of the transient. It is typically in this phase that the highest temperatures (and possible coolant boiling and/or fuel melting) will occur in the ULOF and UTOP scenarios. It is primarily to limit temperatures during this phase of the transients that the ARC-system was ini-

Table 1
Definitions of core states following main ATWS events.

Loss of flow (ULOF)	Loss of heat sink (ULOHS)	Transient overpower (UTOP)
Primary system pumps are tripped and the flow rate transitions to an asymptotic state of lower flow. If all pumps fail, the flow rate transitions to that driven by natural circulation ($F = F_n$). The coolant inlet temperature is assumed to remain constant (i.e., $\delta T_{in} = 0$) and there is no external reactivity introduced ($\rho_{ext} = 0$)	The main path for heat removal from the primary cycle is lost. Power is reduced to the level matching passive heat removal systems ($P = P_d$), external reactivity is zero ($\rho_{ext} = 0$) and the primary coolant flow rate remains unchanged ($F = 1.0$)	A positive external reactivity ($\rho_{ext} > 0$) is introduced, the coolant inlet temperature remains unchanged ($\delta T_{in} = 0$) and the primary coolant flow rate remains unchanged ($F = 1.0$)

F = Normalized primary coolant flow rate.
P = Normalized power.
δT_{in} = Change in the coolant inlet temperature.
ρ_{ext} = External reactivity.

[*] Unprotected here means that active shutdown (or Scram) systems do not function.

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