Autonomous Reactivity Control

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Abstract. The Autonomous Reactivity Control (ARC) system was developed to ensure inherent safety of fast reactors while having a minimal impact on reactor performance and economic viability. The ARC system is a modification to a standard fast reactor fuel assembly, in which two liquid-filled reservoirs, one above and one below the core, are connected by a tube which replaces one of the fuel rods in the assembly. The system has a near-negligible impact on core operation and performance during standard conditions, but will act to passively introduce negative reactivity if temperatures rise above a pre-determined level. Properly designed, the ARC-system will act as a thermostat in the core, autonomously controlling temperature without the need for any operator action, electrical systems or any moving mechanical parts. This actuation responds to temperature and relies solely on the laws of physics, and is therefore an inherent feedback mechanism. The ARC system is in active development at the University of California Berkeley & Argonne National Laboratory in the US and at Uppsala University in Sweden. This paper summarizes the state-of-the-art of these development efforts of the system itself as well as the results of full transient analysis of ARC-equipped fast reactor cores.

Key Words: Inherent safety, ARC, ATWS, Unprotected transients

1. Introduction

The Autonomous Reactivity Control (ARC) system was developed to ensure inherent safety of fast 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 [1] [2] [3] [4], and the principles of the design, operation and manufacturing of ARC systems is presented in great detail in [5]. Ref. [6] presents a detailed analysis on the transient performance and the design principles to avoid oscillatory behaviour in ARC-equipped fast reactor cores. This paper serves as a brief summary review of the state of development of the ARC concept up to then of 2016.

The ARC system is one of the latest of a long line of systems and solutions developed specifically for the purpose increasing inherent and passive safety of fast reactors. One of the first systems specifically designed to reduce reactivity through leakage in accident scenarios is the GEM system developed at FFTF in the 1980s [7]. Core design concepts such as the “diabolo” design with an axially shorter central core region have shown great promise [8] [9] [10]. The use of ^{6}Li for reactivity control was introduced along with the original travelling wave reactor (TWR) design by Teller et. al [11]. In 1998, *Kambe et. al* developed the Lithium Expansion Module (LEM) system for reactivity control for the RAPID cores [12], and the LEM system design is the inspiration for the ARC system itself. Another approach is flow levitated absorbers (FLAs), which typically consists of balls or plates held in a separate assembly at or just above the axial level of the top of the active core by the coolant flow [13]. Efforts have also been made to design passive systems that increase the expansion of standard reactor control rods in to the core upon coolant temperature increases [14].

The ARC system in its standard configuration is installed by a number of internal modifications to a conventional fast reactor nuclear fuel assembly. 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 (henceforth the ‘‘expansion” liquid), while the lower reservoir contains the same expansion liquid and, floating on top of it, a separate immiscible liquid (henceforth the ‘‘absorber” liquid). The remaining free volume between the two concentric tubes in the closed system is filled with an inert gas. 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. The design, components and operational states of a fuel assembly with an ARC-installation is shown in Fig. 1. A full-detail 3D version of a ARC-equipped fuel assembly is shown in Fig 2.

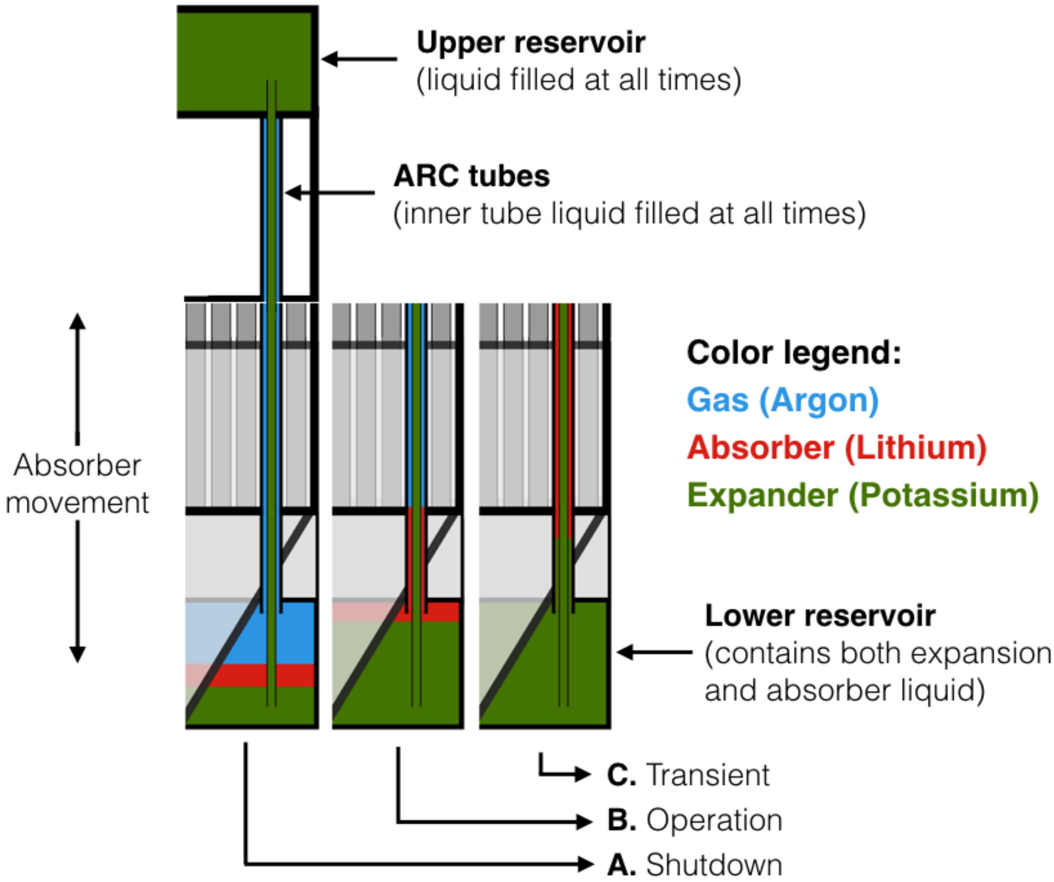

Figure 1, Schematic view of the ARC system at different states/temperatures (not to scale)

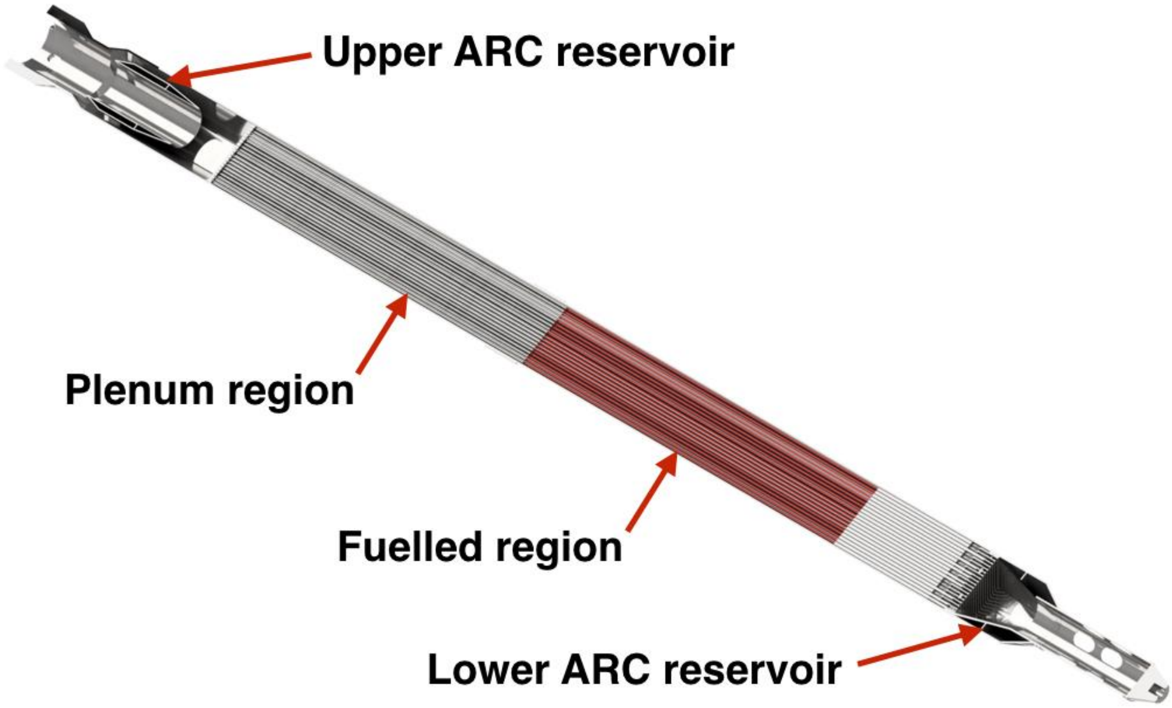

Figure 2, Cut-through view of an ARC-equipped fuel assembly (to scale)

The uppermost section of the assembly, containing the upper ARC liquid and gas reservoir, is shown in Figure 3. The lowermost section, with the lower ARC reservoir and its shielding, is shown in Figure 4.

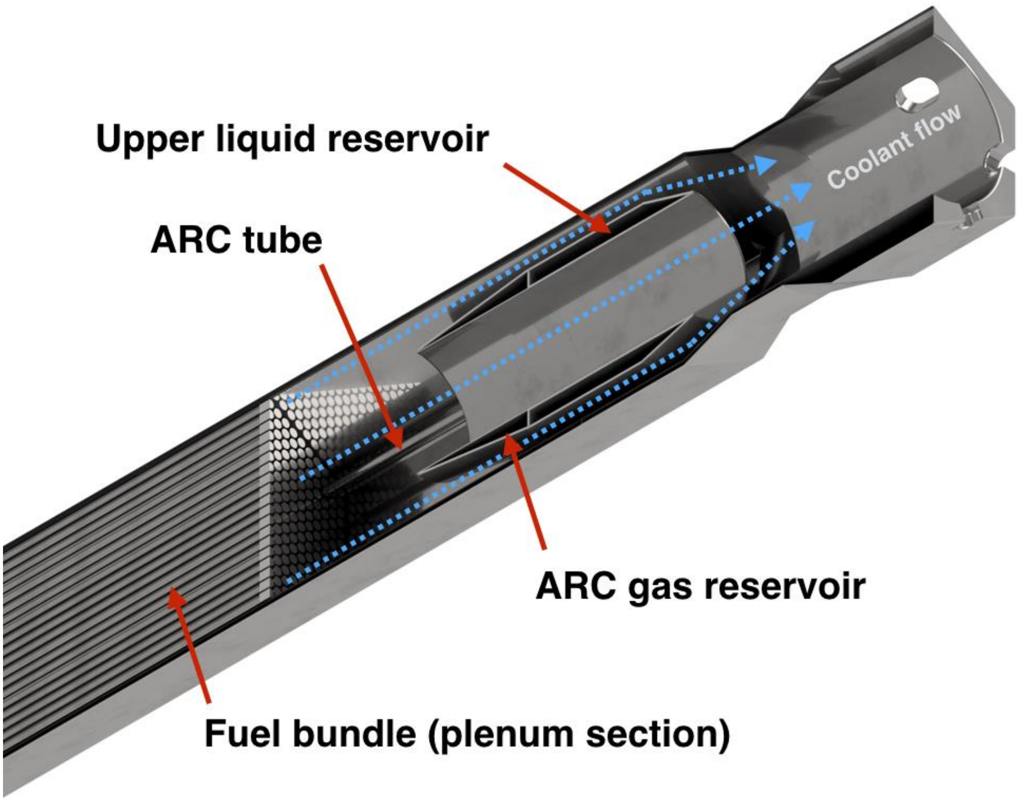

Figure 3, Top section of the fuel assembly, with components of the ARC system marked

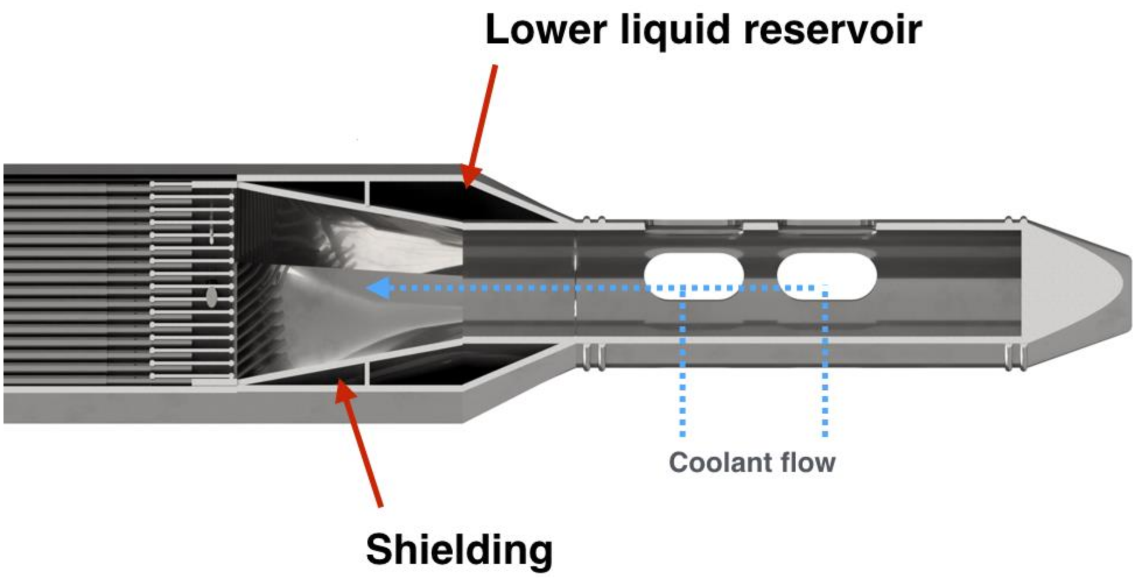

Figure 4. Lowermost section of the fuel assembly

During an accident/transient scenario in the reactor, the ARC- system responds in the following way:

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 in 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.
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 axial level of 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.

Properly designed, the ARC-system will act as a thermostat in the core, autonomously controlling temperature without the need for any operator action, electrical systems or any moving mechanical parts. This actuation responds to temperature and relies solely on the laws of physics, and is therefore an inherent feedback mechanism (akin to the core thermal expansion feedbacks).

2. Quasi-static reactivity balance analysis

While accurate analysis of the operation of an ARC system requires transient coupled neutronic and thermal-hydraulic analysis (as presented in the following section), quasi-static reactivity balance methods are exceptionally useful for scoping out the design requirements for the system and determining the total required reactivity worth. If ARC systems are to provide long-term reactivity compensation following an unprotected transient, the required reactivity worth of such systems can be calculated using the quasi-static reactivity balance method. The general reactivity balance for the core can be defined as *[15] [16]*:

$$\Delta\rho = (P - 1)A + (\frac{P}{F} - 1)B + C\delta T_{in} + \rho_{ext} \qquad (1)$$

where *A*, *B* and *C* are measurable integral reactivity parameters defined according to convention [16], Δp is reactivity, *P* is the normalized power (*P* = 1.0 is full operational power), *F* is the normalized coolant flow rate (*F* = 1.0 is forced-flow at full pumping power), δT_{in} is the change in the coolant inlet temperature and ρ_{ext} is reactivity introduced by, for example, the motion of control rods. This method is exact for transitions between steady states, and approximately valid in transients slow enough to preclude non-equilibrium stored energy in the fuel pins.

Due to the non-linear nature of the ARC-system response (which essentially follows the axial reactivity worth profile in the core), a "linearized" ARC-term cannot be added as another term inside the integral parameters of eq. (1). Instead we treat the reactivity from the ARC system as an independent parameter called U_{ARC}. Eq. (1) can then be modified to include an ARC system as:

$$\Delta\rho = (P - 1)A + (\frac{P}{F} - 1)B + C\delta T_{in} + x_{transient} * U_{ARC} + \rho_{ext} \qquad (2)$$

where $x_{transient}$ is a multiplier defining the fraction of total possible actuation that the ARC system experiences in the quasi-static state following a specific transient scenario. In whatever transient that is the limiting (most challenging or serious) event for a specific core, $x_{transient}$ will by design be exactly equal to unity. In other, non-limiting transients for the same core, $x_{transient}$ is somewhere in the range $0 \leq x_{transient} < 1.0$.

The mixed mean coolant outlet temperature in the quasi-static state following any transient must remain below a predefined level, often given by the cladding material long-term temperature limit. If the Unprotected Loss of Flow (ULOF) event is the limiting transient of the given system ($x_{ULOF} = 1.0$) and we define a maximum allowable long-term coolant outlet temperature of T_{LC}, it is possible to define the total required worth of the ARC actuation (U_{ARC}) as:

$$U_{ARC} = U_{ULOF} = A + B + (□□_{□} + □)[\frac{□_{□□□□} - □_{□□}}{\Delta □_{□}} - 1] \qquad (3)$$

where $□_{□□□□}$ is the mixed-mean coolant outlet temperature before the transient initiates, F_n is the normalized natural circulation flow rate and $\Delta □_{□}$ is the pre-transient coolant temperature rise through the core. If the value of U_{ARC} computed from eq. (3) is positive for a given value of $T_{LC,}$ the core will only need to make use of the ARC systems in the early phase of the ULOF transient. If the Unprotected Loss of Heat Sink (ULOHS) scenario is limiting for the system, the value of U_{ARC} is defined by:

$$U_{ARC} = U_{ULOHS} = (1 - □_{□}) * (A + B) + C * (□_{□□□} - □_{□□}) \qquad (4)$$

where P_d is the power level matching the capacity of the passive (decay) heat removal systems. Applying a maximum allowable long-term fuel peak centerline temperature of T_{LF}, the required worth of the ARC system (setting $x_{UTOP} = 1.0$) in an Unprotected Transient Overpower (UTOP) event to limit the maximum fuel centerline temperature to a set value (T_{LF}) is:

$$\square_{\square\square\square} = \square_{\square\square\square\square\square} = 2 * (\square + \square) \times (\frac{\square_{\square\square\square} - \frac{\square_{\square\square}}{\square_{\square}}}{\Delta\square_{\square\square} + 2\Delta\square_{\square\square}}) - \square_{\square\square\square} + \square + \square \qquad (5)$$

where p_r is a peak-to-average fuel temperature multiplier and $\Delta\square_{\square\square}$ is the average fuel temperature rise over the coolant. If UTOP is the limiting scenario ($x_{UTOP} = 1.0$), the required ARC system reactivity worth to limit the coolant outlet temperature to T_{LC} is:

$$\square_{\square\square\square} = \square_{\square\square\square\square\square} = (\square + \square)(\frac{\square_{\square\square\square} - \square_{\square\square}}{\Delta\square_{\square\square}} + 1) - \square_{\square\square\square} \qquad (6)$$

When UTOP is the limiting quasi-static state, whichever value of eq. (5) and (6) is the largest will determine the required ARC worth. Equations 3-6 can be used to dimension an ARC installation for an existing core design. Analytical methods have also been developed for partial actuations of ARC systems following various types of transients, the results of which are summarized in ref. [6]. The predictions of core behavior using the equations above (and the analytical partial actuation results) have been independently validated using transient analysis codes. In all cases, the quasi-static temperatures predicted matched those reported by the code-based simulation within an error margin of ±1K.

3. ARC-equipped core transient analysis results

The transient behavior of ARC-equipped cores was studied using as a reference system the oxide-fuelled cores developed in the Argonne National Laboratory (ANL) Advanced Burner Reactor (ABR) study [17] [18]. The reactivity worth of the ARC absorber (99% ^{6}Li enriched lithium) was calculated for the ABR CR=0.75 MOX-fuelled core using the Serpent v.2.1.24 monte-carlo reactor physics code [19] with ENDF/B-VII.0 [20] neutron cross-sections. The system was modeled heterogeneously (no homogenization of materials) using the automated core design and analysis code ADOPT [21], separated into nine axial regions in the active core. In the calculations, one fuel rod was replaced by an ARC rod in each assembly. The detailed geometry of the ARC system installation was calculated using the ARCAD code, the function and structure of which is described in ref. [5].

A dynamic model for transient analysis of the ABR (CR = 0.75) with an ARC system installed was made using the CHD code. A description of the code together with comparative benchmark of other established codes and experimental results can be found in [22]. The transient analysis performed here with the CHD code is currently being validated by simulations with the well-known SAS4A/SASSYS-1 code system [23] for further validation of these results. The CHD code uses a standard point-kinetic model with eight groups of delayed neutrons to calculate the core fission power. Delayed neutrons are calculated for each system analyzed using the 8 groups results obtained from Serpent calculations [19], and decay heat is calculated using the 23-group model for plutonium in ANSI/ANS [24]. Rather than explicitly calculating the heat transfer to the ARC liquids inside the CHD code at each time step, the heat transfer characteristics are pre-calculated using a full-detail computational fluid dynamics model for each specific ARC-equipped fuel assembly. In order to compare various design alternatives for the upper ARC reservoir, a “time-lag parameter” (τ) was defined as:

$$T_{l}(t) = T_{co} + (T_{l}(0) - T_{co}) \times e^{-\frac{t}{\tau}} \quad (7)$$

At full flow conditions in a typical fast reactor, the volume-averaged liquid temperature in an upper ARC reservoir will follow the coolant temperature with of approximately 1.4s.

Figure 5 shows the results of an unprotected “station blackout” scenario (SBO), which is essentially a combination of the ULOF and ULOHS events, for the ABR CR=0.75 MOX-fuelled reactor. In the reference case without ARC systems, the station blackout scenario leads to coolant boiling after 87 seconds in hottest channel. With the ARC system installed, the coolant temperature retains a ~80K margin to boiling throughout the transient, and stabilizes with a mixed mean coolant outlet temperature of around 720°C. Since the coolant inlet temperature increases in the SBO event, more negative reactivity is introduced than in the typical ULOF event (in which inlet temperature is typically assumed to remain constant). Because of this, the peak coolant temperature reached in the SBO event is about 30°C lower in the ULOF event. Through an extensive series of transient analysis events on ARC equipped ABR cores, it has been shown that a carefully designed ARC system, installed by replacing just a single fuel rod per assembly by an ARC tube, can provide comprehensive inherent safety across a wide range of transients while avoiding oscillatory behavior altogether.

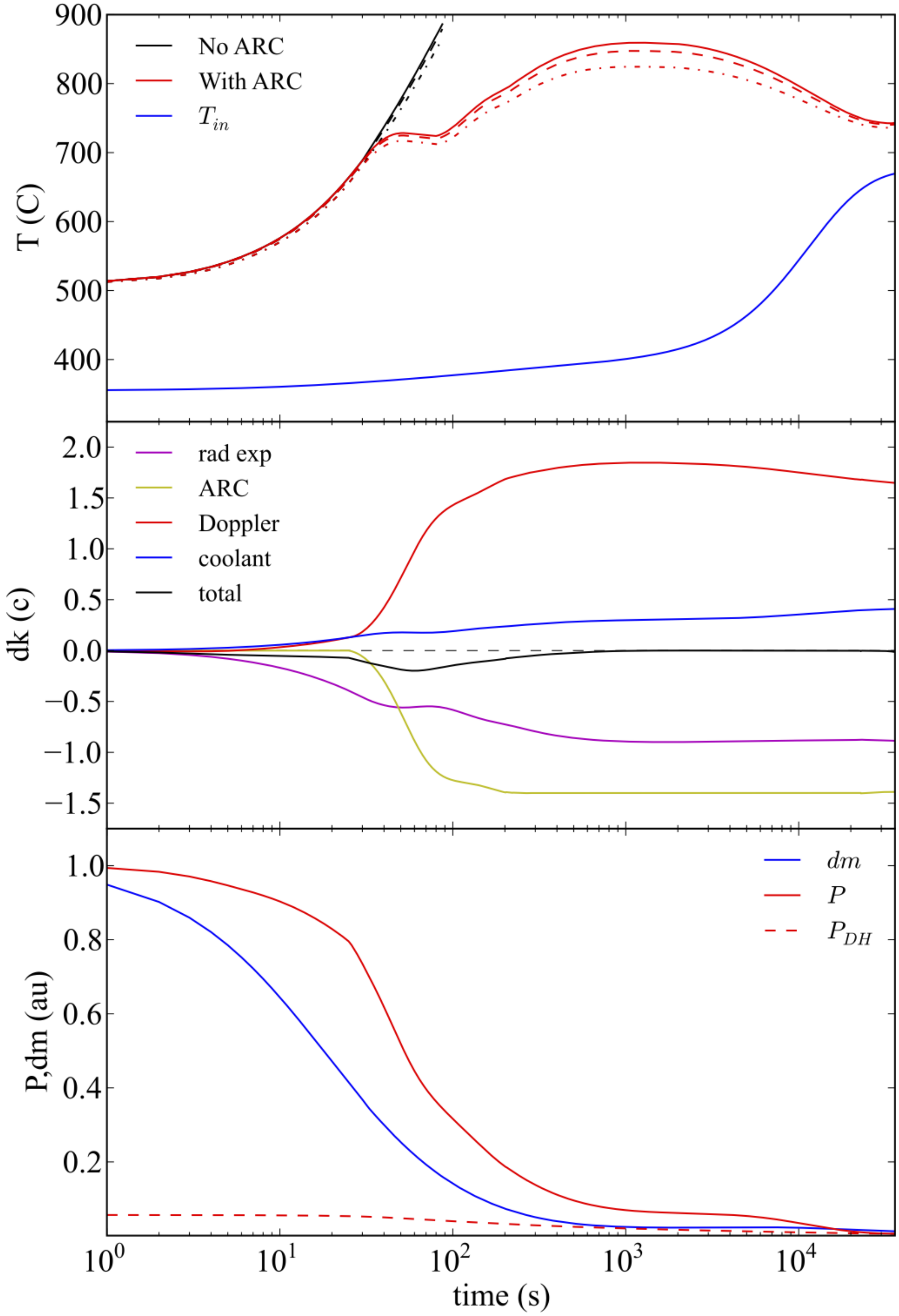

Figure 5, ABR CR=0.75 MOX-fuelled reactor station blackout simulation results. Upper panel: Coolant temperatures, the three red lines correspond to three separate core channels. Mid panel: Reactivity components, Lower Panel: Power and flow rate

4. Current state of development and future work

While significant further study and experimental verification is required, from our current analysis results it appears to be possible to design an ARC-system to respond to the most severe anticipated unprotected transients in a typical fast reactor core and maintain temperatures at acceptable levels throughout these events, without introducing any oscillatory behavior. A typical ARC installation constitutes a relatively minor adjustment to a fast reactor fuel assembly, replacing 1-2 fuel rods with ARC tubes, increasing the total axial assembly length by at most ~10% and the total primary coolant pressure drop by ~1%. Incorporating ARC-equipped fuel assemblies into design process of new fast reactor cores may open up a design space that was previously inaccessible due to the requirements of passive safety performance relying solely on existing reactivity feedback components.

Some of the main topics for future development efforts are:

- In systems with relatively large amounts of reactivity vested in control systems, there may be important and complex dynamics between the response of ARC systems and the reactivity introduced from the expansion (and contraction) of the control rod drivelines, which needs to be further analyzed in future work.
- The transient analysis results of ARC-equipped cores are currently being further validated against the results of established codes such as SASSYS-1/SAS4A in work carried out by the University of California Berkeley in collaboration with Argonne National Laboratory.
- The main material data uncertainty is that of the high-temperature mutual solubility of lithium and potassium. The liquid stratification must be tested more thoroughly experimentally throughout the temperature range of interest.
- The presence of lithium as the ARC system absorber increases the production of tritium. The production, migration and handling of tritium and its impact on reactor operations and shielding will need to be studied in more detailed for various types of systems.
- In the assembling steps of the components of an ARC equipped fuel assembly, the most challenging work appears to be the inner edge weld between the gas reservoir and the upper liquid reservoir. This may present a challenge to the welder if the upper ARC reservoir inner diameter is relatively small and the gas and liquid reservoirs are long, and may require further work. In addition, the methods and order of filling the system with liquids and gas needs to be further developed and tested experimentally.
- A satisfactory all-encompassing *analytical* analysis method that defines at what point a given system design will introduce un-acceptable oscillatory behavior has not yet been found, but is an interesting avenue for potential future work. This is currently being explored with excellent input and advice from external collaborators [25].

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