Title: Achieving passive safety in even large SFR cores through the use of Autonomous Reactivity Control systems

Description: For decades, designers of fast reactors have struggled to achieve the passive safety characteristics of small cores when scaling up to larger power reactor scales due to the possibility of a strongly positive coolant-density coefficient. To meet this challenge, the Autonomous Reactivity Control (ARC) system has been recently devised to allow for excellent passive safety performance in the case of major protected and unprotected transients in standard assembly-type fast reactors, even when the coolant density reactivity coefficient is positive. The ARC system can be included into any standard linear-assembly fast reactor core with minimal modification to the assemblies, and provides an additional engineered, passive negative reactivity insertion in response to an increase in reactor outlet temperature over nominal conditions. In this way, a strong overall negative feedback can be assured in response to a large variety of transients, even when control rods fail to actuate. The ARC system can be tuned very easily to a multitude of core designs and reactivity requirements, and has been shown through mechanistic simulation to provide a smooth, reliable, and strong mechanism for shutdown during all examined transients in both medium and large SFR cores. Additional studies have shown the potential to use the ARC system as a means for passive load following and method for providing long term reactivity control in compensation of burnup.

Article: The favorable transient characteristics of small fast reactor cores have been understood since early in the development of nuclear power. High leakage, already present in small cores due to long mean free paths, is exacerbated when the coolant heats up and expands, leading to even higher amounts of leakage. This phenomenon is utilized in small cores to provide a negative feedback effect in response to reactor transients in which the core power increases and temperatures go up. The increased leakage, coupled with other negative feedbacks such as fuel expansion, grid plate expansion, and control rod drive expansion, contributes to an overall favorable response, where transients are self-arrested before substantial negative consequences can occur.

While most negative feedbacks, like fuel and grid plate expansion, are agnostic to the power level of the reactor, the coolant-density feedback is not. As power level is increased, typically the number of assemblies and core diameter is increased to allow for proper cooling of the fuel. As the core size is increased, the leakage component is decreased in importance, and in fact most all neutrons born away from the periphery will be captured in either the fuel or the coolant. As the coolant heats up in response to a transient, instead of the increased leakage playing the dominant role as was the case in a smaller core, two different phenomena are elevated in importance in larger cores: a hardening of the spectrum and a decrease in parasitic neutron losses in the coolant. Both of these phenomena have effects that can lead to a positive feedback in large cores. If the magnitude of this positive feedback is large enough to outweigh the negative feedbacks of the core, a transient that would be benign in a small core could lead to catastrophic failure in a large core.

Researchers have proposed many ideas in order to overcome this issue and enable inherent safety properties in commercial scale fast reactors, but many of these work-arounds have consequences of their own. Much work was done early on to slightly soften the spectrum through the introduction of small of amounts of moderators. This was meant to enable most of the benefits of a fast spectrum while enhancing the negative Doppler feedback and lessening the impact of increasing average number of neutrons produced per fission. This could thus overcome a potentially positive coolant feedback. However, doing so has detrimental impacts on breeding ratios. Furthermore, enhancing the Doppler feedback is not always beneficial, as is seen in comparisons of oxide and metallic fuels.

Another strategy for overcoming the positive coolant-density issue is to manipulate the core geometry to be very flat and wide, keeping the core power high by spreading it over larger diameter with shorter assemblies. This “pancake core” method allows for leakage to be increased, similar again to small cores, by letting neutrons leak axially. This however is suboptimal in normal operation, as it is widely known that optimal core geometry is one that approximates a right cylinder that has equal height and diameter. This means that excessive neutrons are being lost during normal operation, again negating some of the most prominent benefits offered by fast systems.

Alternatively, the core geometry can be kept near optimal height by artificially increasing neutron “leakage” by placing internal blankets in the core, as in a heterogeneous core. This allows for excess neutrons to be absorbed in the internal blankets when parasitic coolant capture is reduced, as opposed to being absorbed in the fissile fuel where further multiplication will take place. While this method has worked very well for standard fast reactor designs, it introduces a number of different assembly designs into the core, possibly complicating core design and shuffling patterns. Furthermore, for concepts such as the standing-wave breed-and-burn which has recently gained traction, all assemblies must be of the same design and geometry to enable them to be placed at any position in the core.

Drawbacks with all of these methods have led to the recent introduction of the Autonomous Reactivity Control (ARC) system [1]. The aim of the ARC system design was to allow for passive safety to be achieved in virtually all fast reactor designs that utilize standard assemblies (i.e. SFR, LFR, GFR designs are included, but designs such as the recent molten chloride fast reactor are not considered), regardless of the core feedback coefficients inherent to the core design. This is to be accomplished through the inclusion of an engineered system into the design of a standard assembly which is able to produce a negative feedback response when faced with an increasing coolant temperature. In general concept, the ARC design is meant to function similar to a gas expansion module (GEM) [2], except instead of only responding to a loss of flow as a GEM does, an ARC system is meant to react to a change in coolant temperature. Therefore, the ARC system should be able to arrest any transient scenario which causes temperatures to increase, which encompasses all transients with potential safety impact. Furthermore, it is desirable that the ARC system response should be reversible as in a GEM, so that system actuation does not necessarily imply a reactor shutdown as does a SCRAM or actuation of other safety systems based on material curie points or similar phenomena [3].

All of these goals are realized through the inclusion of a couple fluid reservoirs to the top and bottom of a standard assembly and two concentric tubes connecting the two, which together make up the ARC system. The connecting concentric tubes take the place of a single fuel pin in the assembly, and the two reservoirs are small enough in size to add very little overall length to an assembly [4]. The two reservoirs are filled with three fluids: (1) a neutronically-inert expander liquid, (2) a neutron poison liquid, and (3) an inert gas to account for the expansion and contraction of the expander liquid. During normal operation, the upper reservoir and inner concentric tube are filled with neutronically-inert expander fluid, the lower reservoir is filled with neutron poison fluid, and the outer concentric tube is backfilled with inert gas. As a transient scenario begins, the reactor coolant heats up and this temperature increase is communicated to the ARC system through convective heating of the upper reservoir. As the upper reservoir heats up, the expander present in the reservoir expands and pushes down through the inner concentric tube, causing the neutron poison in the lower reservoir to be expelled out of the lower reservoir and into the outer concentric tube within the active core. As the poison fills the connecting tube, the inert gas is compressed, allowing for the poison liquid to extend through the entire core length. As the poison is injected, the reactor power is decreased as if control rods were inserted from the bottom of the core, causing the reactor power to decrease and allowing for the transient to be controlled with no sort of operator intervention. Due to the passive nature of the response, relying only upon the inherent physical phenomena of fluid expansion and heat transfer, this type of system is referred to as an “engineered passive safety system.”

Detailed feasibility studies have shown that the inclusion of these additional pieces to the fuel assembly adds only minor complication to the manufacturing process, requiring only a handful of extra pieces and welds [5]. Furthermore, the ARC system does not significantly alter reactor operation, as the ARC system returns back to steady-state position once the reactor again reaches nominal power conditions, allowing for operation to continue. Additionally, the extra pressure drop introduced by the reservoir inclusions has been investigated using detailed CFD calculations and has been found to be ~1% of the total pressure drop without ARC systems installed [6].

By introducing a feedback that is so sensitive to reactor temperatures as the ARC system is, the question of stability comes into play. It is feasible to imagine that an actuation of the system could lead to rapid oscillations wherein the power first increases due to some transient initiator, the ARC system then quickly responds, causing the fuel to quickly cool back down, then allowing for the transient to flare back up, leading to another actuation, etc. However, detailed mechanistic transient simulations of the ARC system in established fast reactor designs have shown this concern to be unfounded [7]. This type of scenario has not been seen to occur for a couple of different reasons. The first reason is that, due to the layout of the fluids in the system, as the reactor is cooled down below nominal temperatures, positive reactivity is not inserted. This means that undercooling does not have an unfavorable impact on the core reactivity, from the perspective of ARC system response. The other reason is simply due to the thermal inertia of its components and the time that it takes to convect heat into the ARC reservoir fluids. Because it takes some finite time for coolant temperatures to be communicated to the ARC fluids, the system is actually not extremely sensitive to small fluctuations in coolant temperature. Rather, the ARC system response is smoothed out by the thermal inertia of the system, so that rapid oscillations by the ARC system are difficult to induce. Furthermore, because the design space of ARC systems is very large, the system parameters can be easily tuned to capitalize on this effect, ensuring that a smooth response is seen to all examined transient scenarios.

Simulations of existing reactor designs has shown much promise for ARC system performance in improving transient response. So far, it has been demonstrated that the margin to coolant boiling and fuel melting can be greatly extended through the inclusion of properly designed ARC systems for a wide variety of unprotected transients, including ULOF, UTOP, ULOHS, and flow blockages [7]. It has also been established that the design space for ARC systems is very broad, allowing for different system sensitivities and total worths to accomplish a variety of missions. Therefore, with the inclusion of ARC systems, no suboptimal designs such as “pancake cores” or internal blankets are necessary to design an inherently safe fast reactor core at commercial scales.

Other studies have shown that the ARC system has promise for other purposes as well, such as providing a means for passive load following [8] and passively holding down cycle excess reactivity without the use of control rods or other shim mechanisms [9]. Further work on the ARC system will focus on demonstrating the benefits of the ARC system in more challenging designs, such as large breed-and-burn cores, and on utilizing the safety benefits achieved through ARC system inclusion to extend the design space of existing reactor designs for economic gains. Therefore, in addition to overcoming the safety challenges with designing large-core fast reactors, the ARC system holds promise for improving the competitiveness of fast reactors as a whole.

Sources

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