INL/CON-07-12657
PREPRINT

An Innovative Hybrid Loop-Pool Design for Sodium Cooled Fast Reactor

2007 ANS/ENS International Meeting

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November 2007

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INTRODUCTION

The existing sodium cooled fast reactors (SFR) have two types of designs – loop type and pool type. In the loop type design, such as JOYO (Japan) [1] and MONJU (Japan), the primary coolant is circulated through intermediate heat exchangers (IHX) external to the reactor tank. The major advantages of loop design include compactness and easy maintenance. The disadvantage is higher possibility of sodium leakage. In the pool type design such as EBR-II (USA), BN-600M(Russia), Superphénix (France) and European Fast Reactor [2], the reactor core, primary pumps, IHXs and direct reactor auxiliary cooling system (DRACS) heat exchangers (DHX) all are immersed in a pool of sodium coolant within the reactor vessel, making a loss of primary coolant extremely unlikely. However, the pool type design makes primary system large. In the latest ANL's Advanced Burner Test Reactor (ABTR) design [3], the primary system is configured in a pool-type arrangement. The hot sodium at core outlet temperature in hot pool is separated from the cold sodium at core inlet temperature in cold pool by a single integrated structure called Redan. Redan provides the exchange of the hot sodium from hot pool to cold pool through IHXs. The IHXs were chosen as the traditional tube-shell design. This type of IHXs is large in size and hence large reactor vessel is needed.

In this investigation, we propose a hybrid loop-pool design with the goal of reducing capital cost and improving safety. The design takes advantage of the compactness of loop design and the inherent safety of pool design. Primary loops are formed by connecting hot sodium at reactor outlet plenum (hot pool), IHXs, primary pumps and reactor inlet plenum with pipes. The primary loops are immersed in the cold pool (buffer pool). During accidents, modular Pool Reactor Auxiliary Cooling Systems (PRACS) transfer heat from the reactor core to the cold pool. Similar design was used for liquid salt cooled advanced high temperature reactor (AHTR) systems [4].

DESIGN DESCRIPTION

Fig. 1 compares conventional pool design and our hybrid loop-pool design configurations. Under normal operations, the primary loops operate in forced circulation driven by primary pumps which could be located either in the reactor hot leg or in the cold leg. The IHXs could be either traditional tube-shell heat exchangers or compact heat exchangers. Compact heat exchangers have much higher power density (5 to 10 times higher) and are much smaller than tube-shell type heat exchangers.

The primary systems and the cold pool are thermally coupled by the PRACS, which is composed of PRACS heat exchangers (PHX), fluidic diodes and connecting pipes. A fluidic diode reduces leakage flows under primary loop forced circulation. Fluidic diodes are simple, passive devices that provide large flow resistance in one direction and small flow resistance in reverse direction. The simplest fluidic diode devices generate an irreversible loss of kinetic energy by creating a strong vortex flow in one direction, while flow in the opposite direction does not have this effect. Both DHX and PHX modules use conventional tube bundles to reduce flow resistance and are in baffles to enhance natural circulation as shown in Fig. 1.

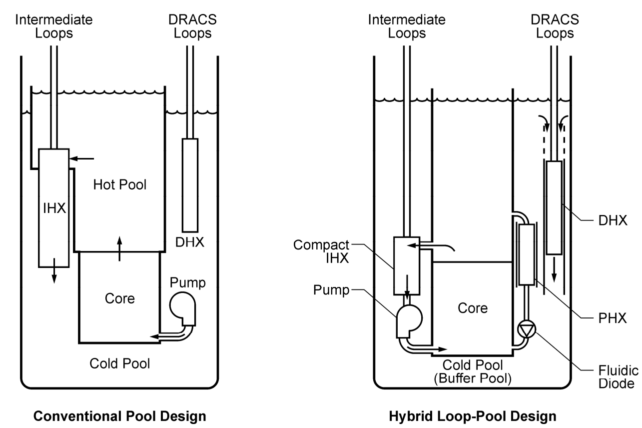

Fig. 1. Comparison of conventional pool design and innovative hybrid loop-pool design for SFR.

For normal power operation with forced cooling, the primary loops transfer heat to modular IHXs located in the cold pool. A small bypass with reactor inlet temperature flows upward through PHXs. This bypass flow heats up the cold pool. This added heat is mainly removed by the DRACS to the environment so that the cold pool temperature remains constant.

Under the loss of forced cooling (LOFC) transient with reactor scram, reduced heat transfer in the reactor core causes the core temperatures to rise. Natural circulation establishes quickly and flow reversal happens through PRACS loops. Due to higher flow resistance in IHXs and stopped pumps, and usually loss of secondary heat sink, natural circulation through IHXs is not important for decay heat removal compared to that by the PRACS. Decay heat removal mainly occurs through the PHX modules. The PHX heat transfer area is sized to match decay heat generation approximately 2 to 3 hours after loss of LOFC occurs. The DRACS heat removal systems are sized to match decay heat generation approximately 4 to 6 hours after LOFC occurs.

PRELIMINARY LOFC ANALYSIS

While detailed transient flow analysis is still in progress and has not been completed, simplified calculations which treat the primary loops and the cold pool as two interconnected lumped masses provide a first-order estimate for the transient response that follows LOFC. The total masses and thermal capacities of the primary loops and cold pool are referred to the ANL ABTR design. Figure 2 shows the resulting temperature and power histories, for the case where the PHX modules are sized with a nominal heat removal ability at 1.3% of normal reactor power , and the DHX with a capacity of 0.7% of normal reactor power. The effects of the large thermal capacity provided by hot pool in the primary loop and by the cold pool are readily seen, with the volume averaged temperature of the primary loop rising less than 50°C above the initial value of T_c = 488°C during the transient.

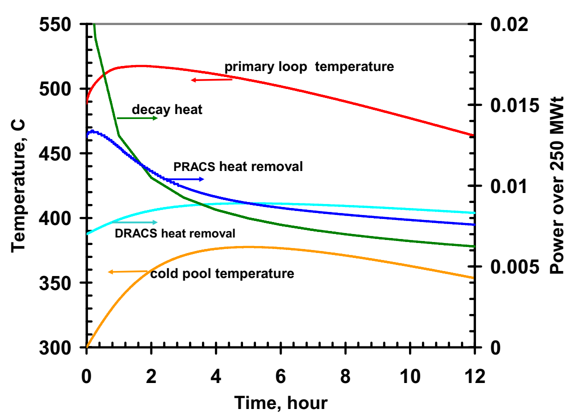

Fig. 2. Lumped-mass transient temperature response of the 250 MW(t) hybrid SFR to LOFC.

CONCLUDING REMARKS

This design has the following potential benefits:

- Utilizing compact IHXs allows reduction of the reactor vessel size which in turn reduces the capital cost of building a SFR.
- PHXs transfer heat from reactor to the cold pool more effectively than the conventional pool designs using natural circulation through IHXs and pumps. Hence, both core inlet and outlet temperatures could be increased which yields higher thermal efficiency for electricity generation.
- Reactor inlet temperature and cold pool temperature are decoupled, so are the primary loops and passive safety system. This provides more freedom to optimize the design by balancing economics and safety.
- The modularity of the IHXs and PHXs allows the plant design to be easily scaled up to large power. The economical advantage of this hybrid design is more significant for large SFR plants.
- The closed primary loops provide an extra barrier to prevent sodium leakage. With the primary loops immersed in cold pool, the possibility of core uncover severe accident is further reduced.
- Cold pool temperature can be set at a lower value than conventional pool design, hence thermal inertia is increased.

In summary, the proposed hybrid loop-pool design for sodium cooled fast reactors has large potential to improve the economics and safety of SFR, which warrants serious considerations for further detailed investigations.

ACKNOWLEDGEMENTS

This work was supported through INL Laboratory Directed Research and Development program under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

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