The Impact of Xenon-135 on Load Following Transatomic Power Molten Salt Reactor

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INTRODUCTION

First-of-kind civil Molten Salt Reactor (MSR) was developed, built and operated in Oak Ridge National Laboratory (ORNL) in the 1960s. It was called Molten Salt Reactor Experiment (MSRE) and at the moment is the only one operated MSR worldwide. Based on experience from this experiment, the first commercial Molten Salt Breeder Reactor (MSBR) was designed in early the 1970s. In the thermal spectrum MSR, fluorides of fissile and/or fertile materials (i.e., UF_4 and/or ThF_4) are mixed with carrier salts (i.e., LiF) to form a liquid fuel which is circulated in a loop-type primary circuit and leads to following advantages over traditional solid-fueled reactors: (1) low pressure in the primary loop; (2) strong negative thermal feedback; (3) passive decay heat cooling; (4) reduced fuel fabrication costs; (5) online refueling and reprocessing [1].

Nevertheless, cost-competitiveness of such innovative designs in the current domestic energy market may only be feasible with load-following operation. Load following operation has the potential to increase the commercial competitiveness of nuclear power dramatically. Due to increasing penetration of renewables on the electric grid, base-load operation carries the risk of correspondingly frequent negative electric energy pricing. Thus, responsiveness to net electricity demand is essential to market relevance for new designs [2].

The main physical effect that limits the possibilities of power variations in a conventional Light Water Reactor (LWR) is fission product poisoning, especially the xenon effect (a few hours after the change in the reactor power level). The ^{135}Xe is the most powerful known neutron absorber (average cross section for thermal neutrons approximately 10^6 barns) with a half-life $\tau_{1/2} = 9.17h$ and yield for ^{235}U fission about 6.3%. The vast majority of xenon-135 (6.1%) is produced from another fission product - ^{135}I ($\tau_{1/2} = 6.6h$) [3]. Under normal operating conditions, the ^{135}Xe is being transmuted to ^{136}Xe ('burned') in the reactor core as it is produced, so while it harms the neutron economy, balancing the reactor controls can compensate for its effect. The difficulty comes when the reactor power is reduced, and there are fewer neutrons to burn out the ^{135}Xe, so its concentration increases and further suppresses reactor power. In this case, the core takes some time to recover from the power reduction impact of ^{135}Xe. This response to changing power levels, particularly from higher to lower power levels, dramatically slows the reactor's response to power demands. Potentially, ^{135}Xe removal during reactor operation would allow more flexibly vary power levels to follow power demands, typically referred to as 'load following.'

The Transatomic Power (TAP) MSR design is a 1250 MW_{th} liquid-fueled reactor which has been selected as a prototype of modern MSR. The TAP is an intermediate spectrum reactor designed to be started with high-assay low-enriched uranium (LEU) as initial fissile load. This work presents modeling and simulation of load following transient operation of the TAP MSR. We compared these results with well-studied Pressurized Water Reactor (PWR) behavior. This study focuses on the ^{135}Xe/^{135}I balance in the TAP core and its effect on the reactor performance. Herein we assumed that the TAP online fuel reprocessing system is inactive. Another feature of the MSR, its circulating liquid fuel and corresponding delayed neutron precursor drift, is also not treated here.

Much of the analysis herein used a full-core 3-D model of the TAP developed using the continuous-energy Serpent 2 Monte Carlo reactor physics software. The PWR transient analysis has been done for a single-assembly model with burnable poison (gadolinium) provided with Serpent [4]. All calculations presented in this paper were performed using the Serpent 2 version 2.1.31 with JEFF-3.1.2 nuclear data [5].

DESCRIPTION OF THE ACTUAL WORK

Transatomic Power Reactor Design

The TAP MSR concept is very similar to original MSRE design developed by ORNL [1] but has two major innovations: the fuel salt composition and the moderator. The MSRE's LiF-BeF_2-ZrF_4-UF_4 salt has been substituted with LiF-UF_4 salt which allows for an increase in the uranium concentration within the fuel salt from 0.9 to 27.5% while maintaining a relatively low melting point (490°C compared with 434°C for the original MSRE's salt) [6]. The graphite has a very high thermal scattering cross section which makes it a perfect moderator but has a few major drawbacks: (1) the low lethargy gain per collision requires a large volume of moderator to be present to reach criticality, which leads to a larger core and obstructs the core power density; (2) even special reactor-grade graphite has relatively high porosity, consequently, it holds gaseous Fission Products (FPs) (e.g., tritium, xenon) in pores; (3) the reactor graphite lifespan in a commercial reactor is about 10 years [7]. To resolve these issues, the TAP concept uses another moderator, namely, zirconium hydride ($ZrH_{1.66}$), allowing for a more compact core and a significant increase in power density. These two innovative design choices, together with a configurable moderator (the moderator-to-fuel ratio can be changed during regular maintenance shutdown), facilitate the commercial deployment of this conceptual design in the current commercially available 5% LEU fuel cycle.

The TAP MSR primary loop contains the reactor core volume (including the zirconium hydride moderator rods with silicone carbide cladding), pumps, and primary heat exchanger. Pumps circulate the LiF-(Act)F_4 fuel salt through the primary loop. The pumps, vessels, tanks, and piping are made of a

nickel-based alloy (similar to Hastelloy-N[1]), which is highly resistant to corrosion in various molten salt environments. Inside the reactor vessel, near the zirconium hydride moderator rods, the fuel salt is in a critical configuration and generates heat. Table I contains details of the TAP system design.

TABLE I: Summary of principal data for the TAP MSR [8, 9]).

Thermal power	1250 MW_{th}
Electric power	520 MW_e
Gross thermal efficiency	44%
Outlet temperature	620°C
Fuel salt components	LiF-UF_4
Fuel salt composition	72.5-27.5 mole%
Uranium enrichment	5% ^{235}U
Moderator	Zirconium Hydride (ZrH) with SiC cladding
Neutron spectrum	thermal/epithermal

TAP Full-core Model

Advanced geometry surfaces and transformation capabilities of Serpent are employed to represent the TAP core. Fig. 1 shows the XY section of whole-core configuration at the expected reactor operational level when all control rods are fully withdrawn. This model contains the moderator rods with silicon carbide cladding, pressure vessel, inlet and outlet plena (Table II). Fuel salt flows around rectangular moderator assemblies consisting of lattices of small-diameter zirconium hydride rods in a corrosion-resistant material. Moderator rods configuration is selected to obtain salt volume fraction (SVF) ($SVF = V_{fuel}/(V_{fuel} + V_{moder})$) approximately 0.9 [6].

TABLE II: Geometric parameters for the full-core 3D model of the TAP [6].

Component	**Parameter**	Value	Unit
Moderator rod	Cladding thickness	0.10	cm
	Radius	1.15	cm
	Length	3.0	m
	Pitch	3.0	cm
Moderator assembly	Array	5 × 5	rods×rods
	Pitch	15.0	cm
Core	Assemblies	268	pcs/core
	Inner radius	1.5	m
	Plenum height	25.0	cm
	Vessel wall thickness	5.0	cm

To represent reactivity control system the model has: (1) control rod guide tubes made of nickel-based alloy; (2) control rods represented as hollow 70-30% Gd_2O_3-Al_2O_3 cylinders with a thin Hastelloy-N coating [6]; (3) air inside guide tube and control rod. Control rods design has yielded a cluster of 25 rods that provide a total reactivity worth of 1121 ± 26 pcm[2].

[1]Hastelloy-N is very common in reactors now but have been studied and developed at ORNL in a program that started in the 1950s.

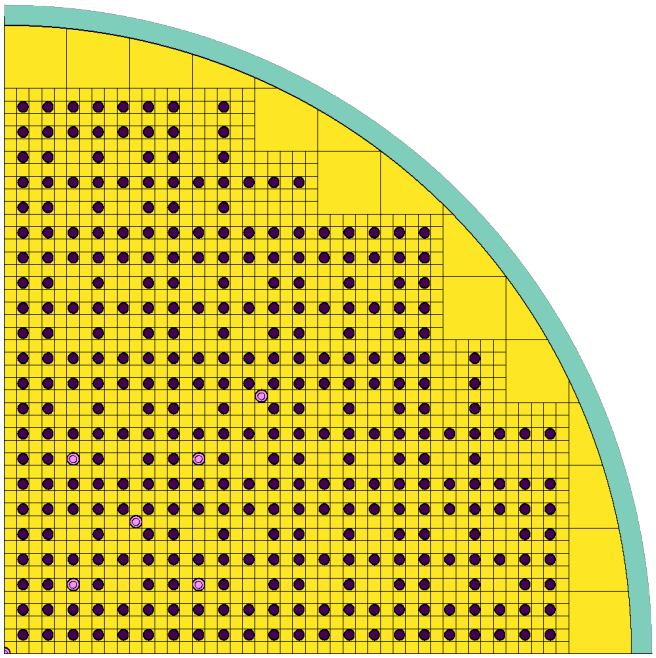

Fig. 1: An XY section of the TAP model at the horizontal midplane with fully withdrawn control rods. The violet color represents zirconium hydride, and the yellow represents fuel salt. The blue color shows Hastelloy-N, a material used for the vessel wall, and the pink color is the air.

Load Following Transient

Generic PWR during steady-state operation at a constant neutron flux level reaches ^{135}Xe/^{135}I equilibrium for that reactor power in about 40 to 60 hours. When the power level is decreased, the neutron flux is reduced, less ^{135}Xe is transmuted ('burned') to ^{136}Xe, and the balance shifts to the larger ^{135}Xe concentration. For the worst-case scenario for the PWR (power was reduced to 0%) the xenon concentration peaks in about 8-9 hours after shutdown (depends on the neutron spectrum). Based on this knowledge of PWR poisoning, we selected following worst-case load curve (see figure 2, 3; red line):

1. Startup with fresh fuel and operating on 100% power level for 96 hours to reach ^{135}Xe/^{135}I balance;
2. Instantaneous variation of the power from 100% to 0%;
3. Shutdown for 7.66 hours to reach the ^{135}Xe peak;
4. Instantaneous power boost from 0% to 100%, then operation on this level for 16 hours.

This scenario can be considered as backing up solar power with nuclear on a high-solar penetration grid (e.g., in California).

[2]1 pcm = $10^{-5}\Delta k_{eff}/k_{eff}$.

RESULTS AND ANALYSIS

Using the methodology described previously, the PWR assembly and the TAP full core depletion analysis was performed. We used 15-min power load curve resolution during the active phase of the transient to capture rapid changes in multiplication factor and isotopic composition. All results herein were obtained using built-in Serpent 2 capabilities for fuel depletion calculations.

Multiplication Factor and Xenon Equilibrium

Fig. 2 shows the infinite multiplication factor (k_∞) evolution for the PWR assembly during postulated transient. As expected, k_∞ dropped after shutdown from 1.120 to 1.105 (−1500 pcm) because ^{135}I decayed to ^{135}Xe, and xenon poisoned the core. The multiplication factor reached local minimum ≈ 7 hours after shutdown. Notably, after power level growth from 0% back to 100%, k_∞ reached even larger value than it was before shutdown (≈ 1.1234, +300 pcm). The imbalance between ^{135}I production and ^{135}Xe 'burning' is a main reason of this reactivity boost.

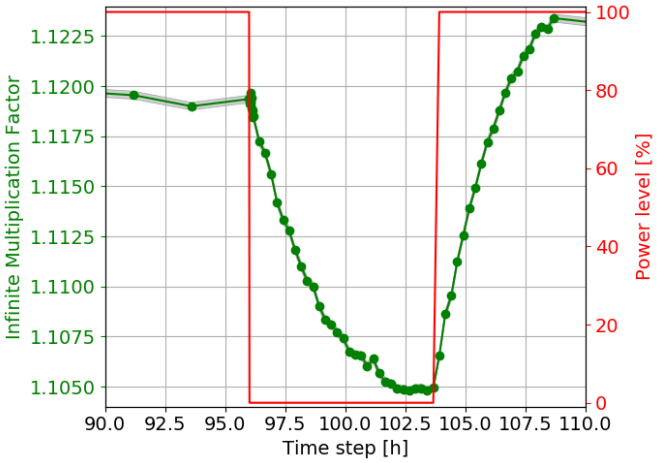

Fig. 2: Multiplication factor for worst-case load curve for the PWR immediately after shutdown (confidence interval $\sigma \pm 20$pcm shaded).

Fig. 3 demonstrates the effective multiplication factor (k_{eff}) dynamics in the same transient for full-core TAP MSR model without any online FP removal. Surprisingly, k_{eff} slowly increased after shutdown from 1.0065 to 1.0078 (+130 pcm), and overall reactivity swing for the scenario is much smaller (270 pcm difference between maximum and minimum vs. 1750 pcm for the PWR). Similarly to the PWR case, k_{eff} for the TAP jumped after reactor power turned back to 100% but by 150 pcm only.

The analysis of the fuel composition variation gives clearer information about the ^{135}Xe/^{135}I equilibrium and the core state. Fig. 4 shows the normalized number density of isotopes influential to core neutronics. After 96 hours of operation on 100% power level xenon reached equilibrium concentration, and ^{135}I/^{135}Xe number density ratio is 2.3 and 0.9 for the PWR and TAP, respectively. After shutdown the ^{135}I decays to ^{135}Xe that is not burned up. The PWR had large

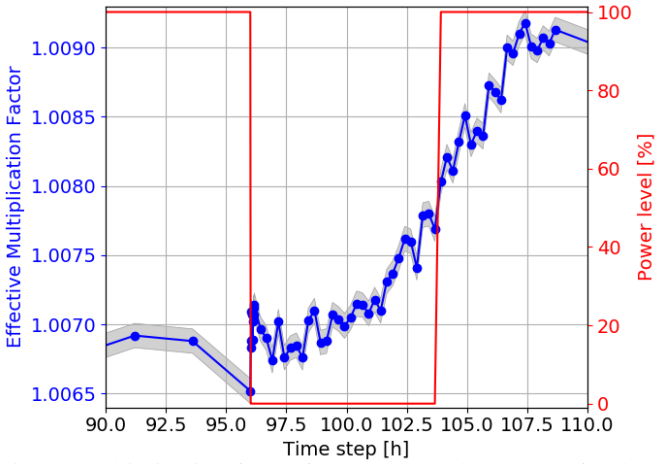

Fig. 3: Multiplication factor for worst-case load curve for the TAP immediately after shutdown ($\sigma \pm 7.5$pcm shaded).

^{135}I inventory which caused notable xenon concentration peak by 150% from equilibrium after about 7 hours due to shorter ^{135}I half-life (6.6h vs. 9.17h for ^{135}Xe). Contrarily, in the TAP ^{135}Xe concentration remained unchanged after shutdown because ^{135}I inventory was lower than ^{135}Xe. Thus, ^{135}Xe gain from ^{135}I decay did not overcome ^{135}Xe decay loss. In sum, the poisoning effect does not impact on the TAP core reactivity even in worst-case transient due to much lower than in the PWR ^{135}I/^{135}Xe ratio at equilibrium.

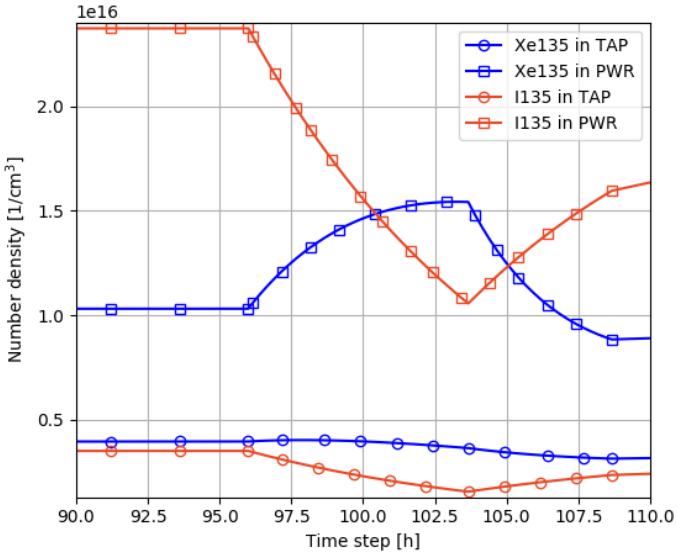

Fig. 4: Atomic density of ^{135}Xe and its precursor (^{135}I) immediately after shutdown for the TAP and PWR.

Neutron spectrum

To understand the difference between ^{135}I/^{135}Xe gain and loss for two reactor types, we plotted the neutron flux per lethargy energy distribution (fig. 5). The spectrum for the TAP is harder than for the PWR due to lack of moderation in the TAP core (SVF≈ 0.9) and its type (ZrH). The harder neutron spectrum leads to accelerated ^{135}Xe loss rate because capture

cross section is declined rapidly with energy (fig. 5, solid red line, energy interval from 10^{-7} to 10^{-4}).

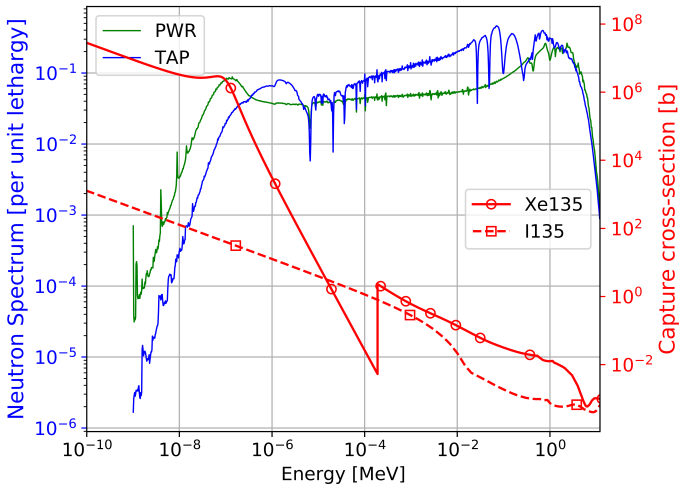

Fig. 5: Neutron spectra normalized by lethargy for the PWR and TAP vs. ^{135}Xe and ^{135}I caption cross-section.

CONCLUSIONS

The depletion calculations of the PWR assembly and the TAP full-core models for simple load following transient were performed using the Serpent 2 Monte Carlo code to illuminated impact of Xenon-135 poisoning on the MSR. The transient assumed for both reactor types following generated power dynamics: (1) 96-hour operation cycle on 100% power level; (2) instant power drop to 0% level for 7.66 hours (to reach ^{135}Xe concentration peak); (3) boost back to 100% power, and operation on this level for 16 hours. The results of this study indicate that from the depletion calculation, the multiplication factor for the PWR dropped rapidly after reactor shutdown and reached maximum poisoning effect (-1500pcm) $\approx$ 7 hours after shutdown. The drop happened because ^{135}I/^{135}Xe number density ratio at equilibrium in the PWR is about 2.3 and ^{135}I decays to ^{135}Xe faster than ^{135}Xe to ^{135}Cs.

Similar depletion calculation for the TAP MSR showed different result: k_{eff} rose a bit after the reactor shutdown, and no effect of xenon poisoning was observed. The reason for this behavior is different ^{135}I/^{135}Xe concentration ratio which is about 0.9. Thus, ^{135}I decay did not lead to the xenon peak in the TAP and the poisoning effect is negligible. The most obvious finding to emerge from the analysis is that the neutron energy spectrum is harder for the TAP. The reactor neutron energy spectrum significantly impacts ^{135}Xe 'burn' rate and shifts ^{135}I/^{135}Xe mass balance at equilibrium.

Continued research into the MSR load following and related topics could progress in many different directions. First and foremost, efforts will be made to investigate the impact of xenon poisoning on TAP in the end-of-life (EOL) state, which might have more thermal neutron spectrum. This might be performed with online reprocessing tool SaltProc [10, 11], which would simulate online fuel reprocessing and refueling to obtain realistic equilibrium fuel salt composition. Furthermore, the TAP design allows the moderator-to-fuel ratio adjustment during operation, which should be taken into consideration in future simulations.

Lastly, an additional area to explore is the multi-physics transient analysis, which requires the development of the TAP model with the coupled neutronics/thermal-hydraulics code, Moltres [12]. The final goal of this effort is to characterize neutronics, and thermal-hydraulics limits related to load following, and optimize control rod maneuver strategy that minimizes axial offset and maintains safety margins.

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