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Modular High Temperature Gas Reactor Core Modeling with RELAP5-3D/PHISICS – Optimization Schemes for Load Following

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Abstract – The objective of this study is to develop a 3D neutron kinetic (NK) and thermal hydraulic (TH) coupled model using the INL developed code RELAP5-3D©/PHISICS to study the load following operation of a Modular High-Temperature Gas-Cooled Reactor (MHTGR). The selected design is the 350 MW prismatic, graphite moderated, helium cooled thermal reactor based on the MHTGR-350 transient benchmark led by the High-Temperature Gas-Cooled Reactor (HTGR) Methods Core Simulation Group at Idaho National Laboratory (INL) in the framework of the Organization for Economic Cooperation and Development Nuclear Energy Agency (OECD/NEA).
This kind of reactor usually reacts very slowly to the perturbation of the core parameters due to the large amount of graphite in the core. This kind of behavior promotes the reactor stability but on the other hand limits the reactor load-following operability. Recently advances in gas reactor designs have made load-following a feasible and achievable goal. Modern nuclear reactors (such as the MHTGR-350) are designed to withstand the structural stresses associated with load-following. Operating the reactor in load-following mode will inevitably reduce the load factor. Although a higher load factor means more revenue and the best usage of the fuel, following the variable energy demand will increase the maximum achievable fraction of generated nuclear power, being no more limited to the base load power generation. In general, if low impact on material aging and the safe operability are demonstrated, the plant economics will be minimally affected. In order to ensure that the system can be safely operated in a load-following mode, an extensively study has been carried out. Some tests with linear change in coolant mass flow rate demonstrated that the reactor behavior is suitable for operation in load following mode. This assumption has been confirmed by a 4 days load following transient test in which the reactor supplied the requested power with a negligible error.

Keywords – MHTGR-350, Load following, RELAP5/PHISICS, Criticality search

I. INTRODUCTION

In the last few years the load following mode operability has become an attractive feature for the new reactor designs to improve their competiveness. Recently advances in gas reactor designs have made load-following in gas reactors a possible application. With the aim of checking the flexibility and the safety margins of this type of reactors a preliminary study using the MHTGR-350 design [1] has been carried out through a senior design project at Nuclear Engineering Department of North Carolina State University (NCSU) in collaboration with INL [2]. For this analysis, the model developed by INL [3] has been used, reducing the number of groups in the cross section library to perform transient simulations longer than a day in an acceptable runtime. A steady state calculation using nominal conditions has been performed to assess the modifications in the model. After that, to avoid exceeding 100% of the nominal power during the daily load oscillations the 65% power operative point has been studied. Some tests have been carried out to understand how to efficiently control the reactor power. Finally, the model has been used to simulate four days of operation in load following mode using a typical load profile. The results show that this design can be operated in load following mode without concerns for the safety between 65% and 100% using the coolant mass flow rate to regulate the power. The codes selected for this study and the modifications to the existing model have been described in section II. In the same section, a rapid description of the MHTGR-350 model is reported. In section III a detailed description of the approach used for the steady state analysis and the obtained results are presented. The sensitivity analysis and the model load following scenario transient results are described in section IV.

II. CODES & MODELS

As shown in Fig. 1, starting from the center the MHTGR-350 core consists of three reflector blocks rings, three hexagonal fuel elements rings surrounded by two rings of replaceable reflector elements, followed by a permanent reflector elements region. The active core consists of 660 hexagonal graphite fuel blocks containing holes for the fuel compacts the coolant flow and the burnable absorber pins. six of the reflector columns in the first three internal rings contain startup control rods (CRs) holes (fully withdrawn during normal operation) and 24 columns of the outer reflector ring contain holes for the CRs. Finally, there are six fuel columns with holes for the reserve shut down CRs.

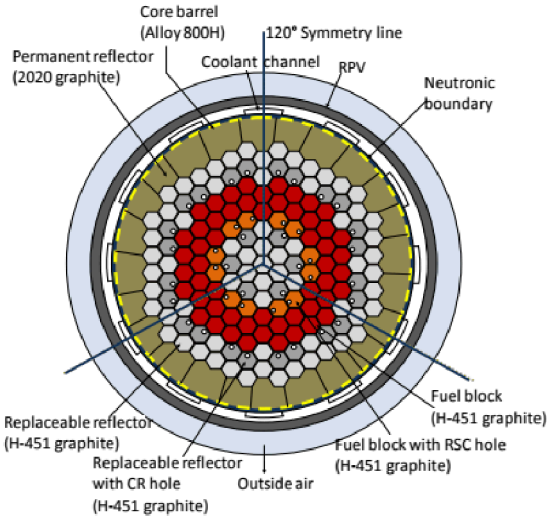

Fig. 1: MHTGR-350 Core radial layout

To perform this study, the RELAP5-3D©/PHISICS coupled model developed in [3, 4, 5] have been used. The "Parallel and Highly Innovative Simulation for INL Code System" PHISICS [6, 7] is an advanced simulation code suite, developed and validated for the existing light water reactor (LWR) fleet and for the advanced reactor designs [8, 9]. PHISICS is based on many different modules such as the "Intelligent Nodal and Semi structured Treatment for Advanced Neutron Transport" INSTANT [10] which is a PN hybrid finite element transport solver or the "Multi-Reactor Transmutation Analysis Utility" MRTAU [11] used to perform depletion evolution calculations. They both rely on the micro/macro cross sections manager module MIXER used to interpolate the cross section libraries. The code is coupled with the extensively verified and validated system code RELAP5-3D© [12], allowing advanced core design coupled simulations. The MHTGR-350 RELAP5-3D© model has been developed as stand-alone Thermal Hydraulic (TH) model first, and then coupled with PHISICS to provide a blockwide power profile based on the temperatures feedback to fully capture the dynamics of the MHTGR-350 core design. The

Neutronic model is based on a P1 approximation including the first order anisotropic scattering terms and the feedback includes moderator temperature, fuel temperature, and ^{135}Xe concentration. The PHISICS and RELAP5-3D© codes are both developed and maintained by the respective developer teams at INL.

II.A. Cross Section Library collapsing

The MHTGR-350 Benchmark [1] original cross section library is based on the 26 energy group structure. Since the load following transients time scale is longer than a day, the requested computational time for coupled simulations with 26 energy groups is still prohibitive especially for steady states calculations in which all the feedback parameters have to perfectly stabilize to restart a transient without including any residual reactivity oscillation due to a non perfect steady state condition.

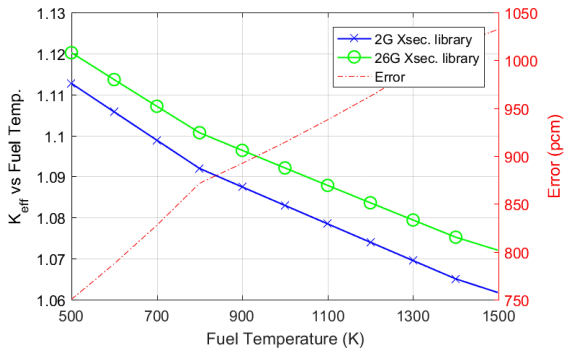

Fig. 2: K_{eff} vs Fuel Temperature, 2G and 26G cross section library (constant 900 K moderator temperature and no ^{135}Xe).

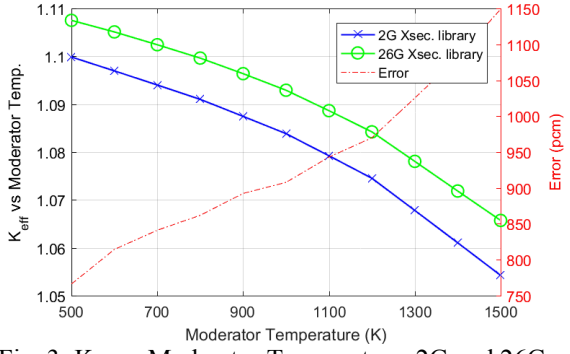

Fig. 3: K_{eff} vs Moderator Temperature, 2G and 26G cross section library (constant 900 K fuel temperature and no ^{135}Xe).

In the benchmark cross section file the flux for each material and branch is provided, therefore an automatic tool to collapse the energy structure from 26 energy group to a 2 group energy structure described in [13] has been developed. The python tool use the flux as a weighting function to collapse the group constants and preserve the reaction rates. Particular attention has been devoted to the scattering matrix in which a two step collapsing procedure has been performed and the prompt and delayed neutron have been considered all to born in the fast group to avoid unnecessary problem complexity addition. A comparison of the two library using the MHTGR-350 neutronic model and the perturbation theory module developed in [14] has been performed. As show in Fig. 2 and Fig. 3 the keff collapsing error is ranging from 700 to >1000 pcm. This error is mainly because only the scalar flux is available and it has been used to collapse the first order anisotropic scattering matrix. The introduced error is significant if considered absolutely, but as shown in Fig. 4 and Fig. 5 if we consider the reactivity excursion from a homogenous 900K temperature without ^{135}Xe in the range of interest is under the 10% that is perfectly fine for the purpose of this work.

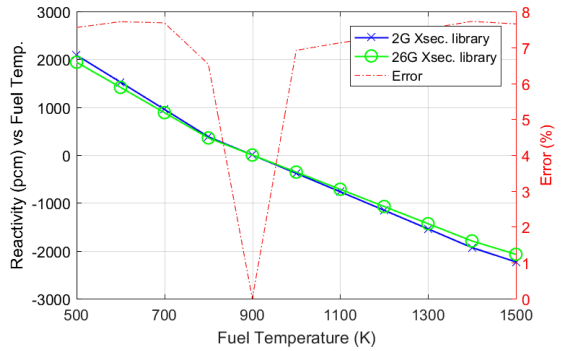

Fig. 4: Reactivity vs Fuel Temperature, 2G and 26G cross section library (900 K moderator and fuel temperature, and no ^{135}Xe reference state).

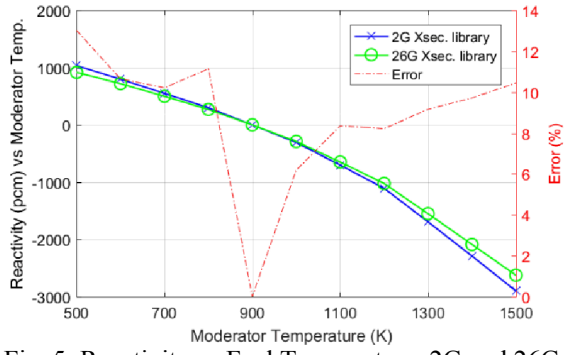

Fig. 5: Reactivity vs Fuel Temperature, 2G and 26G cross section library (900 K moderator and fuel temperature, and no ^{135}Xe reference state).

III. STEADY STATE ANALYSIS RESULTS

The first steady state analysis has been performed to assess the model in nominal conditions. After that, in order to operate the reactor in load following mode, the 65% of nominal power

operative point was studied to avoid exceeding the 100% of the nominal power during the daily load oscillations. Also if the cross sections have been calculated for an End of Equilibrium cycle (EOEC), there is still a lot of excess in reactivity (> 8000 pcm without 135Xe) and is for this reason that a criticality search controller has been introduced in the model to find the critical CR position. All of the 24 CRs are moved simultaneously to get a keff equal to 1.0 ± 1 pcm (see Fig. 6).

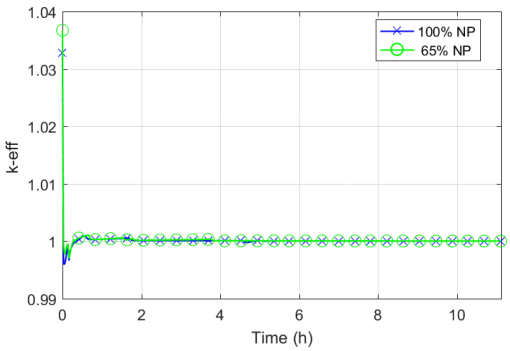

Fig. 6: keff steady state calculation.

As shown in Fig. 7 the 65% nominal power steady state requires a bigger insertion level of the CRs because a lower average fuel and moderator temperature as shown in Fig. 11 and because the average ^{135}Xe concentration decrease from 2.236e-10 cm^{-1} $barn^{-1}$ to 1.802e-10 cm^{-1} $barn^{-1}$. The inserted CRs in both cases improves the axial power shape, which was extremely peaked on the top without CRs. This is because the reactor top is cooler than the bottom (The helium coolant flows from the top to the bottom) and the temperature reactivity feedbacks are both negatives. The radial peaking factor for the unrodded configuration is 1.24 and is unchanged (see Fig. 8). It naturally increase in the 65% power configuration (see Fig. 8 Fig. 9) because of the deeply inserted CRs in the first external reflector ring which reduce more the power in the closest fuel ring.

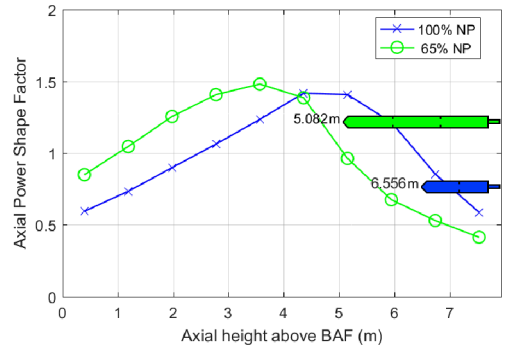

Fig. 7: Axial power shape factor, 100% nominal power vs 65 % nominal power and CR insertion Depth.

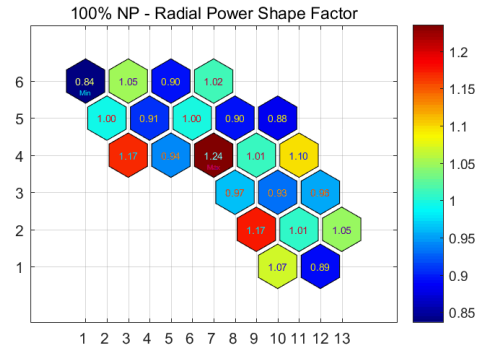

Fig. 8: 100% nominal power radial power shape factor.

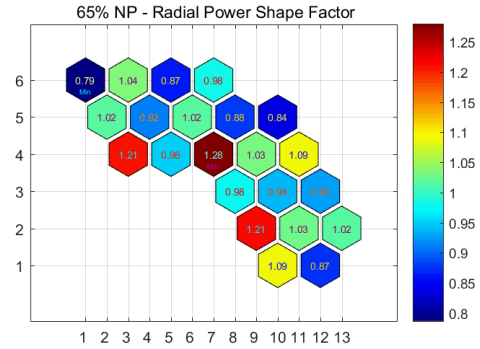

Fig. 9: 65% nominal power radial power shape
As shown

Before starting with the transient calculations, maximum and average values of the moderator and fuel temperature have been checked to determine if they exceed the safety margins and if the number of iterations is sufficient to stabilize the parameters. Fig. 10 and Fig. 11 shows that the temperature values are well below the maximum allowed values (1520 K for fuel and 2370 K for the graphite block) and the parameters are stable after 11 h.

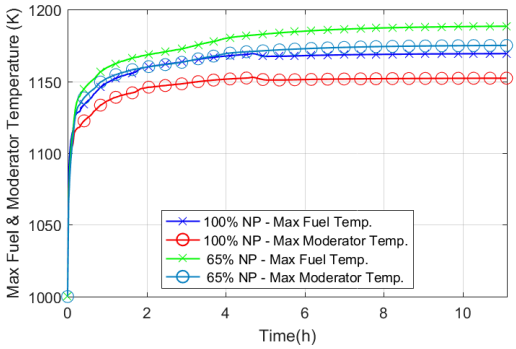

Fig. 10: Maximum fuel and moderator temperature steady state calculation.

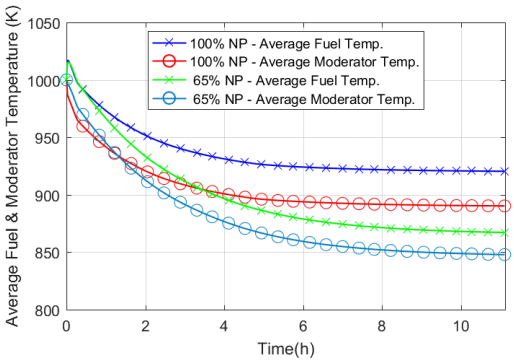

Fig. 11: Average fuel and moderator temperature steady state calculation.

Another parameter to take into account is the core pressure drop, which induce vibrations that can compromise the integrity of the core. The core pressure drop is well below the 68 kPa limit [15] in both cases as shown in Fig. 12.

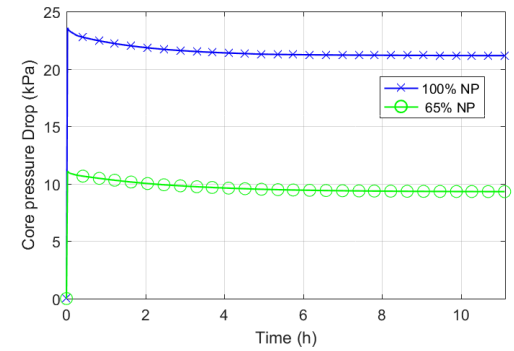

Fig. 12: Core pressure drop steady state calculation.

Since the power has been reduced to the 65% simultaneously with the mass flow rate, the outlet helium temperature (at the bottom of the reactor) is the same in both cases, as shown in Fig. 15. The fuel and moderator temperatures axial profiles are instead very different (see Fig. 13 and Fig. 14). This difference is mainly due to the greater CRs insertion level in the 65% nominal power steady state case which moves the main power production through the bottom of the reactor as shown in Fig. 7 and also to a lower heat exchange coefficient between helium and graphite due to a lower Reynold number.

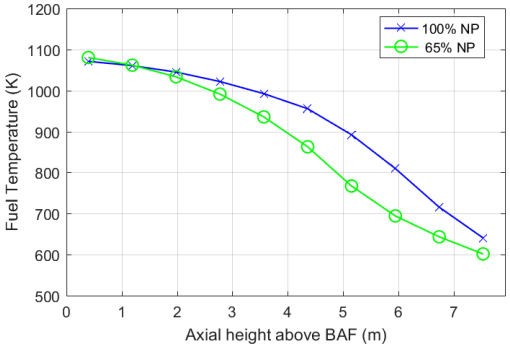

Fig. 13: Axial fuel temperature, 100% nominal power vs 65 % nominal power.

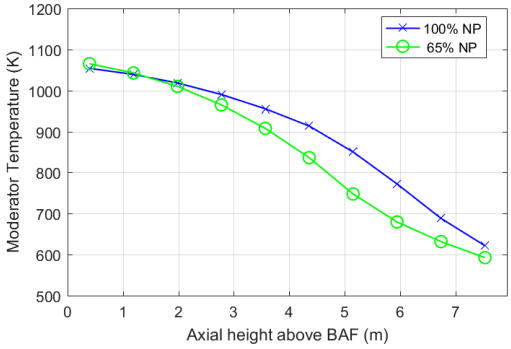

Fig. 14: Axial moderator temperature, 100% nominal power vs 65 % nominal power.

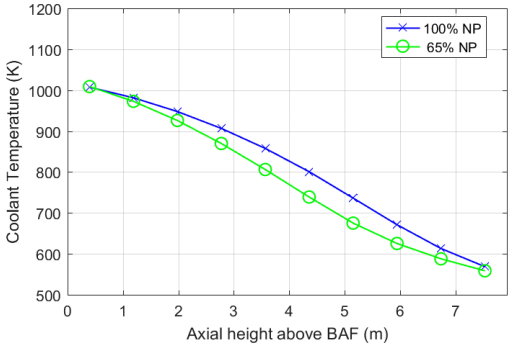

Fig. 15: Axial coolant temperature, 100% nominal power vs 65 % nominal power.

IV. TRANSIENT ANALYSIS RESULTS

IV.A. Model sensitivity assessment

After the steady state calculations, the first study was devoted to determine how fast the power can change by modifying the coolant mass flow rate without exceeding the temperature safety margins and to characterize the relation between power and mass flow rate. The 65% nominal power steady state has been selected because of the load curve (Carolinas regional power load from the 1 May to the 4 May) maximum excursion of the 35%. In this way, the total power will never go over the 100% of the rated power. The first four transient calculations are triggered by a mass flow rate ramp change of 100s (reasonably achievable by a circulating systems) of ±35% and ±10%. In Fig. 16 is possible to see that the correlation between mass flow rate and power is almost linear and the linearity decrease with the magnitude of the perturbation. From a stability point of view instead, the overshoot is very small for a 100s ramp and the reactor power completely stabilizes in less than 100 s from the end of the perturbation.

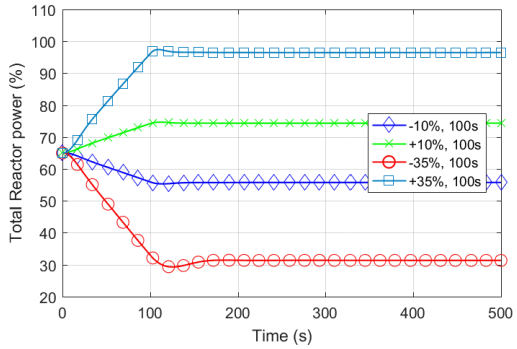

Fig. 16: Total reactor power for different linear mass flow rate change (±35% ±10% in 100 s).

Since the reactor model seems to work pretty well with a 100s ramp and a 35% amplitude mass flow rate change, in order to investigate which is the reactor limit the ±35% transients have been studied reducing the ramp time from 100 s, first to 50 s, than to 1s. It is worth to mention that the 1 s ramp change is just an extreme scenario studied to check the limit of the model. Fig. 17 shows that also for the 50 s ramp, the overshoot of the power is minimal and disappears rapidly. The situation is different for the 1 s ramp in which the overshoot is stronger, and the power exceeds the 100% of the nominal power but this is just an extreme scenario.

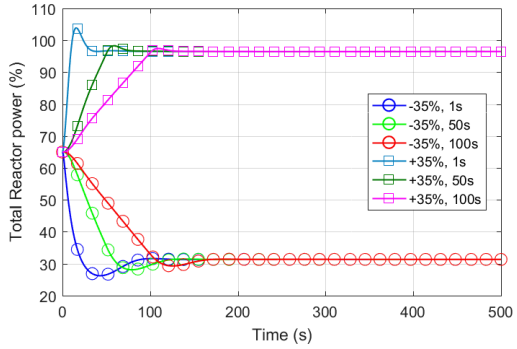

Fig. 17: Total reactor power for different linear mass flow rate change (±35% in 1 s 50 s 100 s).

More interesting are the conclusions drawn from the comparison of the power change and the average moderator and fuel temperature. As shown in Fig. 18 and Fig. 19, when the power increases the fuel temperature increases but the moderator one decreases and vice versa when the power decrease. The fuel and moderator average temperature absolute values excursion is comparable and since the temperature reactivity coefficients are of the same order of magnitude and sign (see Fig. 4 and Fig. 5) the reactor find a new stable point compensating the fuel introduced reactivity with the moderator one assuming no change in the ^{135}Xe composition. Another interesting conclusion is that when the power decreases, the system needs more time to stabilize again as shown in Fig. 17. This is probably due to fact that the decrease in power is driven by the negative reactivity introduced by the moderator warming up which exceeds the fuel cool down positive reactivity. Since the moderator graphite block has a bigger thermal inertia respect to the fuel, the transient lasts longer respect to the one driven by the fuel temperature.

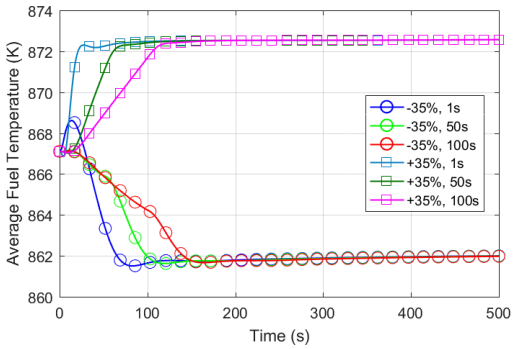

Fig. 18: Average fuel temperature for different linear mass flow rate change (±35% in 1 s 50 s 100 s).

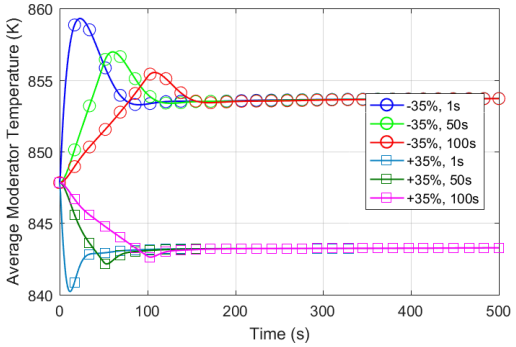

Fig. 19: Average moderator temperature for different linear mass flow rate change (±35% in 1 s 50 s 100 s).

The maximum fuel and moderator temperatures follow the same trend of the average ones (see Fig. 20 and Fig. 21), but in none of the cases are critical from the safety point of view.

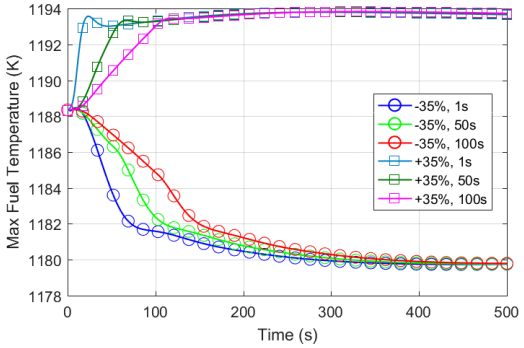

Fig. 20: Maximum fuel temperature for different linear mass flow rate change (±35% in 1 s 50 s 100 s).

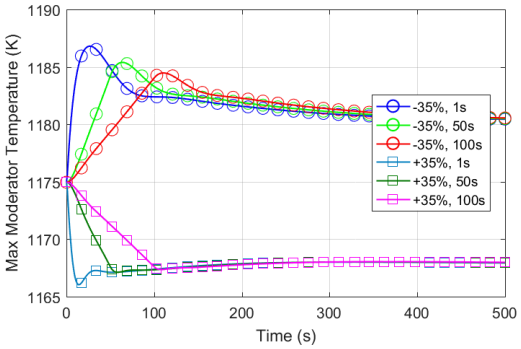

Fig. 21: Maximum moderator temperature for different linear mass flow rate change (±35% in 1 s 50 s 100 s).

IV.B. Load following transient study

Once the relation between coolant mass flow rate and the reactor power was assessed, the load following scenario has been studied. In order to reduce the computational time under the 48 h the decoupled time step module developed in [16] has been used imposing a 1e-2 s TH time step and a 1 s NK time step considering that power change slowly during the day. The selected case is the Carolinas energy demand from the May 2nd to the May 5th [17] (see blue line in Fig. 22).

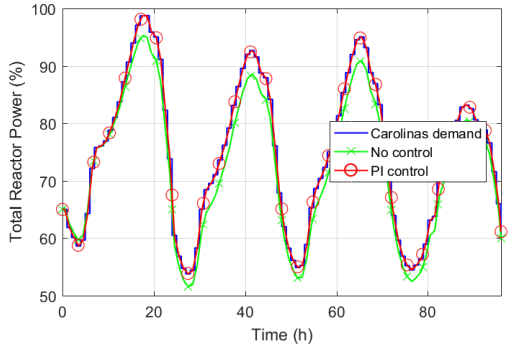

Fig. 22: Total reactor power with and without controller vs Carolinas regional demand power profile.

Since the relation between the power and the mass flow rate is almost linear, the first simulation has been performed using the relative demand profile as a boundary condition for the coolant mass flow rate. In this case, the model power follows the demand except for the minimums and the maximums as shown in Fig. 23. As demonstrated in the previous calculations, the linearity of the problem decreases far from the starting point.

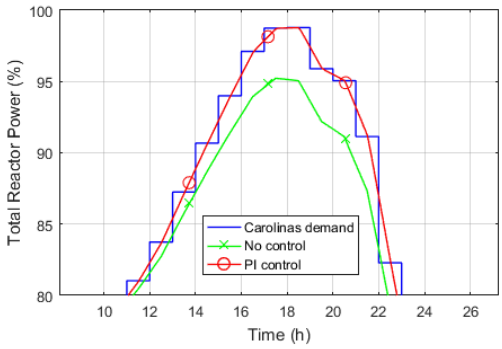

Fig. 23: Total reactor power with and without controller vs Carolinas regional demand power profile; focus on the first maximum.

Introducing a Proportional Integral (PI) controller to change the coolant mass flow rate (see Fig. 24) based on the error function calculated as the difference between the current demand and the actual model total power, the model meets perfectly the power demand as shown in Fig. 22 and Fig. 23.

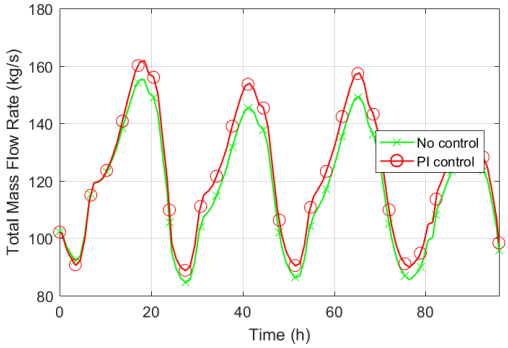

Fig. 24: Total coolant mass flow rate with and without controller.

The three main model feedbacks are shown in Fig. 25 and Fig. 26. After the first 20 hours in which the model is still influenced by the steady state configuration the feedbacks start to oscillate with a 24 h period driven by the coolant mass flow rate changes. The moderator and fuel average temperatures oscillate almost in phase; the ^{135}Xe concentration instead is out of phase thanks to the delay introduced by the decay of the ^{135}I ($T_{1/2}$ 6.57 h).

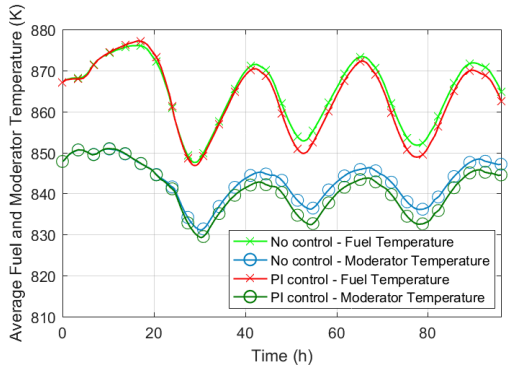

Fig. 25: Average fuel and moderator temperature with and without controller.

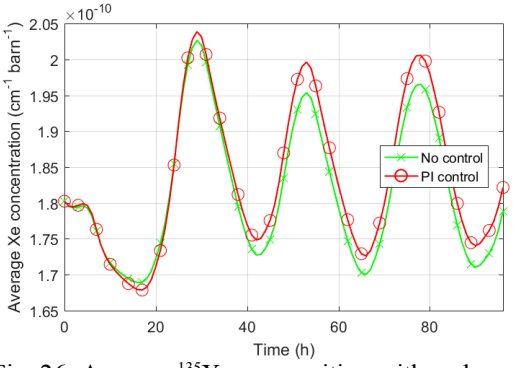

Fig. 26: Average ^{135}Xe composition with and without controller.

Finally, the maximum moderator and fuel temperature stay well below the limits during the transient as shown in Fig. 27.

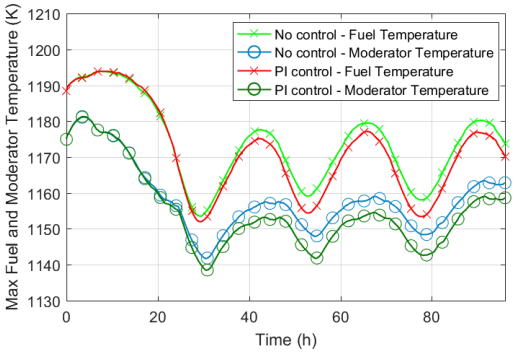

Fig. 27: Maximum fuel and moderator temperature with and without controller.

V. CONCLUSION AND FUTURE STEPS

A full procedure to study the MHTGR-350 reactor behavior using RELAP5-3D©/PHISICS in load following mode has been established. A full comprehension of the most important phenomena occurring when a high temperature reactor has to be operated in load following mode has been achieved. This study shows that it is possible to operate the MHTGR-350 reactor in load following mode without safety concerns. The next steps will be reducing the main approximations of the model such as the 2G cross section library which has to be recalculated using super homogenization factors to preserve the reaction rates; extending the validation domain to the beginning of equilibrium cycle.

VI. ACKNOWLEDGMENT

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