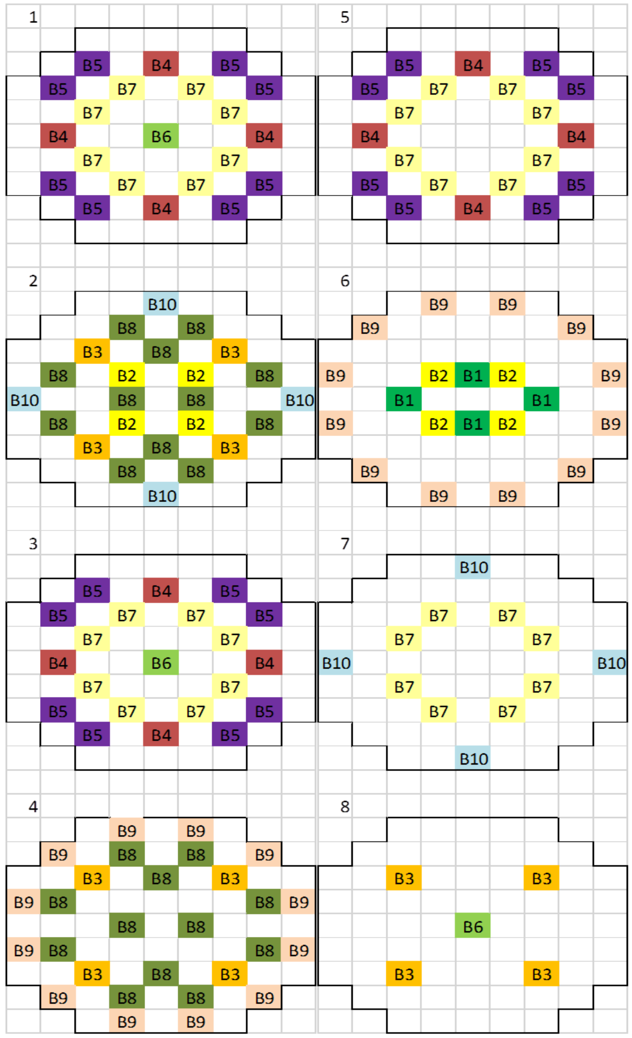
Illustration of VERA Capability to Model a Typical SMR

Small modular reactors (SMRs) such as the one illustrated in Figure 1 are being considered by the commercial nuclear power industry as an option for more distributed generation and for replacement of older fossil fuel generating facilities. SMRs are more compact than operating pressurized water reactors (PWRs), producing from 50 MWe to 200 MWe as compared to 1000 MWe or higher for their full-sized cousins, and are offered as “expandable” units; that is, their modular design allows the utility to add more units progressively at the same site.

Over the past year, TVA, UT-K, ORNL and B&W researchers completed several simulations of a typical integral PWR SMR using VERA. The work included development of fuel assembly lattice designs, core cycle designs, and control rod management simulations, progressing from simple 2D lattice calculations to a single 3D fuel assembly and finally to full core 3D simulations with control rod bank moves. The work exercised a majority of the VERA core simulator components.

1. Pressurizer
2. Once-Through Steam Generator
3. Feedwater Inlet / Steam Outlet
4. Reactor Coolant Pumps
5. Electro- Hydraulic CRDMs
6. Upper Internals
7. Reactor Core

Figure 1 Illustration of a typical iPWR



Move	EFPD	Bank	Steps
1	0	4	15
		5	15
		6	15
		7	15
2	150	2	20
		3	20
		8	0
		10	20
3	300	4	0
		5	0
		6	0
		7	0
4	450	3	0
		8	0
		9	0
5	600	4	30
		5	30
		7	50
6	750	1	60
		2	0
		9	0
7	900	7	50
		10	50
8	1050	3	50
		6	50
9	1200	ARO	228
Rods not shown are fully withdrawn			

Figure 2 Proposed Ten-Bank Control Rod Management Scheme Rod Bank Move Sequence and Insertion Depth.

The primary objective of the study was to establish a viable fuel design (<5% U235 enrichment) and core loading pattern that could reach the goal cycle length of 1400 EFPDs (Kenner, CASL-U-2014-0069-000). The initial simulations provided input to fuel economics studies as well.

Current PWRs typically operate throughout the entire cycle with almost all rods out (ARO), using soluble boron in the coolant for reactivity control. Conversely, boiling water reactors (BWRs) typically maneuver their control blades as often as every 2 GWd/mtU burnup (about 36 EFPD), with as many as 20 rod maneuvers in a 2-year cycle. The control rod maneuvers are used for gross adjustments and feed water flow rate is used for fine adjustments.

Flow control works for BWRs because the void reactivity coefficient is strong and a change in flow directly impacts the core average quality. PWRs are not designed to operate with substantial voids, so the sensitivity of reactivity to flow will be much less. Thus, the option of controlling reactivity through flow isn’t expected to be as useful for the iPWR. Therefore, although the iPWR SMR is essentially a short pressurized water reactor, for designs that do not utilize soluble boron it is envisioned that core power will be managed through manipulation of the control rods in a way that is more similar to current BWRs. It is likely that the iPWR SMR will need to maneuver the control rods as frequently as a typical BWR, with approximately 40 rod maneuvers over a 4-year cycle.

Since the initial VERA studies did not include control rod maneuvering, an additional set of simulations was completed to consider the effect of the control rods on cycle length while demonstrating VERA's capabilities for modeling control rod management. For simplicity, the VERA illustration assumed that rod maneuvers would be completed every 150 EFPD. The final maneuver at 1200 EFPD was assumed to be ARO. No other adjustments to the operating parameters (e.g., core coolant inlet temperature) were made for the study, although a single case was run to illustrate that VERA can handle changes to other operating conditions with rod moves throughout the cycle.

Since the proposed commercial iPWR reactors have control components in almost every fuel assembly, there are many combinations of "banks" possible. The 10-bank scheme used was formulated based on BWR plant schemes. The banks were assumed to be operated using a "deep/shallow" management approach, meaning that when possible a rod bank is either fully withdrawn or is inserted to greater than 60% depth. No bank is inserted for two consecutive maneuvers.

The goal for the simulation was to achieve a core average multiplication factor of 1.000 ± 0.003 over each 150 EFPD segment for a 1400 EPFD cycle length. Power peaking was compared against typical acceptance criteria ($F\Delta H < 1.55$, $FQ < 2.4$, and average assembly power < 1.45). The 10-bank control rod moves were iteratively simulated to arrive at a combination of banks and insertion depths that provided a core reactivity near the target. First, VERA was used to determine the hot excess reactivity for the core design with all rods out (ARO) and then the worth of each of the control rod banks was calculated using VERA. Using this information, the required control rod bank insertion depth was estimated and iterative VERA simulations were completed to arrive at the critical control rod bank positions.

Figure 2 provides the move sequence and insertion depths arrived at using VERA for the 10-bank scheme where 228 steps denotes full withdrawal. The predicted core power and coolant temperature distribution are shown for the maximum power peaking during the cycle at 150 EFPD. Unfortunately, the combination of assembly lattice, core loading pattern, and control rod management did not arrive at a successful solution, as the cycle length fell short of the targeted 1400 EFPD cycle and the power peaking exceeded the acceptance criteria.

However, the work did successfully illustrate VERA's capability to model this type of SMR. VERA's fuel shuffling functionality was not exercised, since the iPWR SMR features a once-through cycle. The VERA method of characteristics (MOC) neutronics subcomponent was used to predict power and reactivity with control rod maneuvering, both with and without thermal-hydraulic feedback. The problem was scaled from 35 to 3815 CPU cores, effectively demonstrating the solution time with respect to computing capacity. Computer clusters at Oak Ridge National Laboratory, Idaho National Laboratory and Tennessee Valley Authority were used.

The work also underlines the need for additional VERA tools to search for critical control rod insertion depth. The recommended search capability will be extremely useful for not only this application, but also for BWRs as CASL develops BWR capability in Phase 2.

For more information, see CASL-U-2015-0041-000R and CASL-U-2014-0069-001 .

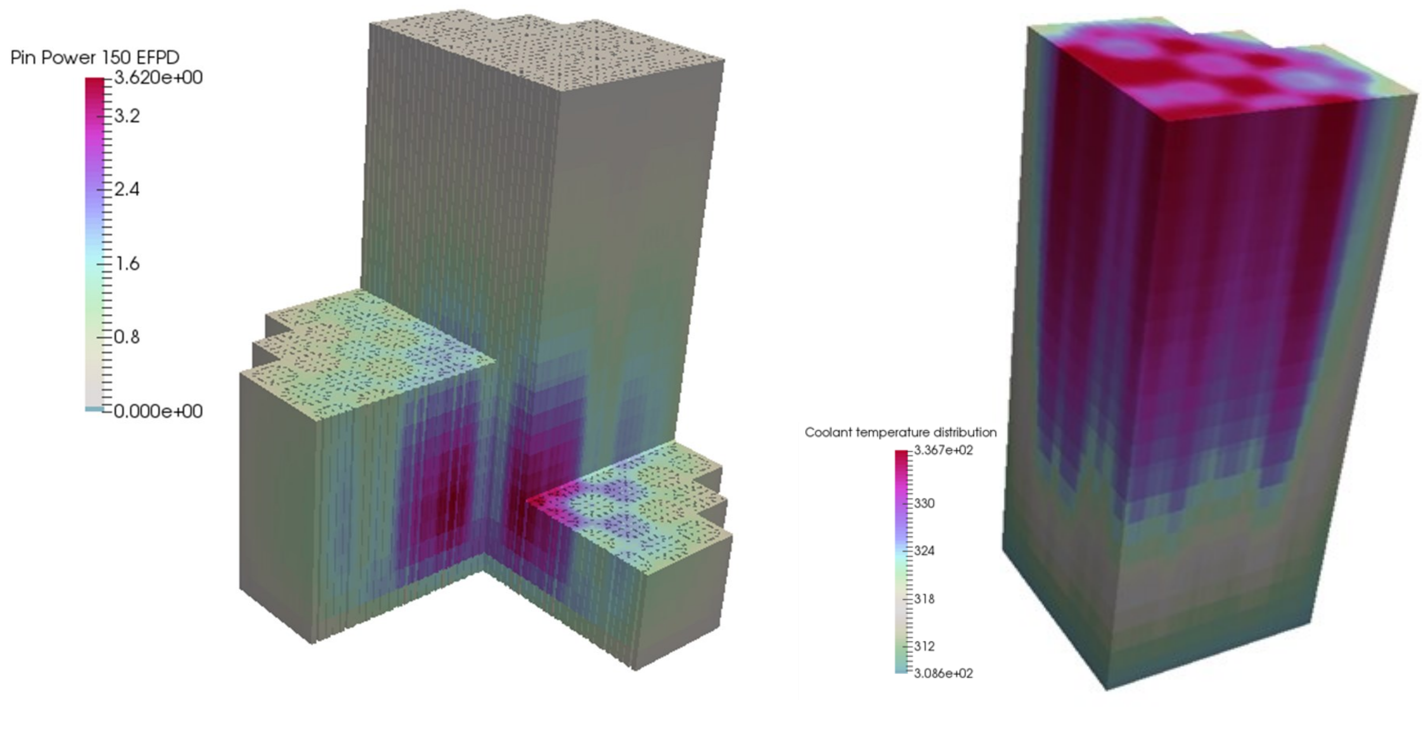


Figure 3 Results for a Ten-Bank Control Rod Management Scheme for a Typical iPWR SMR; Core Power Distribution at 150 EFPD [left]; Coolant Temperature Distribution [right].