Siemens Digital Industries Software

The virtual nuclear reactor

Using a comprehensive digital twin to develop cost-effective nuclear plants

Executive summary

In this white paper, we give examples of how digital twin technology is being used to support the growth and adoption of nuclear power. We explore the specific challenges the nuclear industry is facing and how the nuclear engineering community is increasingly addressing these challenges using virtual reactor models and a comprehensive digital twin.

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Abstract

The current fleet of nuclear reactors are based in huge imposing facilities generally located in isolated locations away from population centers.

This need not be the case. In the near future nuclear reactors will be regarded as portable, modular sources of safe and clean energy. Rather than being located in remote facilities hundreds of miles from cities, they will be in convenient locations near where the demand for power is the greatest.

This prediction poses a couple of difficult questions: How do we get to this future and why have we not already delivered these types of facilities?

Although there are many possible answers to these questions, we believe that an overreliance on old simulation tools is one of the biggest contributors to maintaining the status quo in the nuclear power industry. Digital twin technology is the only way of changing that status quo and delivering reliable and affordable nuclear energy.

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Figure 1. The current fleet of nuclear reactors are located in imposing remote locations far from population centers.

A new paradigm for developing and deploying nuclear technology

In the 21st century world governments are faced with the challenge of drastically reducing emissions of greenhouse gases while simultaneously expanding energy access and economic opportunity for billions of people. Last year the Massachusetts Institute of Technology (MIT) delivered a new interdisciplinary study that involved many contributors that explored *"The Future of Nuclear Energy in a Carbon-Constrained World."*[1] The report concluded there is plenty of space for cheap zero-carbon energy, and that, *"Without that contribution [of nuclear energy], the cost of achieving deep decarbonization targets increases significantly."*

One of the most striking conclusions of the MIT study is we need to act fast if we want to meet decarbonization targets. The data shows if we are serious about mitigating the worst effects of climate change then we need to put clean energy into the grid in less than 20 years, and probably in less than 10.

This is a significant issue: The MIT report states that "while other energy generation technologies have become cheaper in recent decades, new nuclear plants have only become costlier" observing that "recent experience of nuclear construction projects in the United States and Europe has demonstrated repeated failures of construction management practices in terms of their ability to deliver products on time and within budget."

Amongst many other measures, the report proposed a new paradigm for new reactor technology development and deployment that includes greater reliance on virtual reactors and the digital twin, including a proposal to shorten the development process by 10 to 12 years by using integrated computer simulation and modeling rather than building expensive demonstration reactors.

In this white paper we will explore how digital twin capabilities that have been successfully deployed across other industries can be employed in the nuclear industry in spite of its exceptional requirements for validation, the accurate representation of physics and the quantification of uncertainty. We contend that by adopting a comprehensive digital twin (or virtual reactor) methodology it is possible both to cut in half the design cycle for new nuclear technology and greatly reduce the cost of testing required to support licensing. Moreover, without the extensive use of digital twin technology, many of the next generation reactor designs will never make it through the licensing and commissioning phase.

We are not alone in this conviction: the United States Government's Department of Energy recently announced a $35 million investment in the GEMINA program that is aimed at developing digital twin technology for advanced nuclear reactors to create tools that "introduce greater flexibility in nuclear reactor systems, increased autonomy in operations, and faster design iteration." The expectation is "the development of these digital twins will work towards a 10x reduction of operating and management costs at advanced reactor power plants."[2] Those targets are aggressive because the aim is to reduce the cost of maintenance from $13 per megawatt hour, which is normal for the current fleet, down to $2 per megawatt hour. This represents a massive reduction in the operation and maintenance cost of nuclear technology.

Oak Ridge National Laboratory is also working on a Transformational Challenge Reactor" that aims to revolutionize the construction of nuclear reactors using 3D printing and additive manufacturing techniques: "the goal is simple: build an additively manufactured microreactor using the latest scientific innovation and allow nuclear industry to adopt the technology."[3]

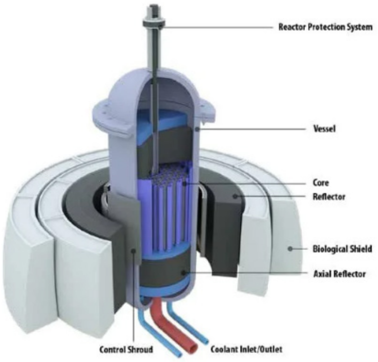

Figure 2. Oak Ridge National Laboratory's "Transformational Challenge Reactor" is constructed using additive manufacture and 3D printing.

Thomas Zacharia, the director of Oak Ridge National Laboratory, is explicit about the role the digital twin will play in this project: "In parallel with core development and fabrication, the TCR team will develop a 'digital twin' of each physical part of the core. These digital twins will have access to all of the data streams captured before, during and after the manufacturing, characterization, and testing of each part, and to the results of sophisticated monitoring of parts in operation."[4]

The digital twin can take many different forms. In this white paper our focus is on the high-fidelity digital twin that is a living breathing facsimile of your nuclear reactor. This digital twin is not only useful in the design phase, but it can evolve alongside the physical reactor throughout its operational lifetime. In this mode of operation, the digital twin can be used to control predictive maintenance and develop model-based full detection systems.

There are lots of great innovative ideas for advanced reactor designs, and it would be impossible to cover them all in a single paper. We have selected three examples that illustrate the value and potential of digital twin technology applied to nuclear reactors.

- The **X-energy** concept is a pebble bed reactor that uses tri-structural isotropic (TRISO) fuel particles in a helium cooled reactor with high exit temperatures (from 650 to 700 Celsius), which can be delivered in small modules and have a power generation capability of up to 300 megawatts (MW)
- **Kairos Power** uses a similar type of pebble fuel, but in this case it adopts a novel molten salt fluoride coolant, which can again have high outlet temperatures and efficiencies
- **TerraPower** is developing a liquid metal cooled traveling wave reactor as well as a molten chloride fast spectrum reactor

Although each of these concepts uses different technology, each has the potential to be much lower cost, much simpler to construct and, most importantly, more inherently safe than the current fleet of nuclear reactors.

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The challenge

All these proposed reactors face a common challenge. They need to be both cost-competitive and quickly operational. In the past, design and licensing cycles have taken 10 to 20 years and cost around $10 billion. That is not feasible in the current market.

The traditional approach to commissioning was highly dependent on the usage of one-dimensional system tools that were used to demonstrate the performance of the proposed reactor through the design phase. This took place before the construction of demonstration reactors to help resolve the many uncertainties associated with a new nuclear concept involving new combinations of fuel, coolant and moderator. The MIT study concluded: “Given the simplicity of most new reactor designs and today’s computational capabilities proof of concept could be established (and much of the technical risk could be removed) by using computation as a direct tool to shorten the development cycle. Developing a computer system to simulate the coupled response of the reactor (fuel, coolant, structure, balance of plant, safety response) will be a significant challenge but is clearly less costly than constructing an extra demonstration facility.”

The digital twin is the only solution that can eliminate the enormous cost of full-scale testing. However, in order to perform that role, the digital twin needs to have full predictive capabilities, encompassing all the physical models involved. The unique challenges of the nuclear licensing process mean that our understanding of the physical processes involved, and their representation in the digital twin, must be much better than in other industries.

Unlike other industries we cannot go back and test our concepts using a full-scale model. For example, during the licensing phase of a new airliner, you can do all your design work on the structural performance of the wings using a digital twin, but ultimately the licensing authority will take those wings and test them until they break. Quite reasonably, no one is keen to test a full-scale nuclear reactor until destruction. The requirements for a high-fidelity digital twin is therefore much greater.

If we can deliver a high-fidelity digital twin or virtual reactors, then we will be able to shorten the design cycle not by years, but by a decade or more, while simultaneously reducing the commissioning costs.

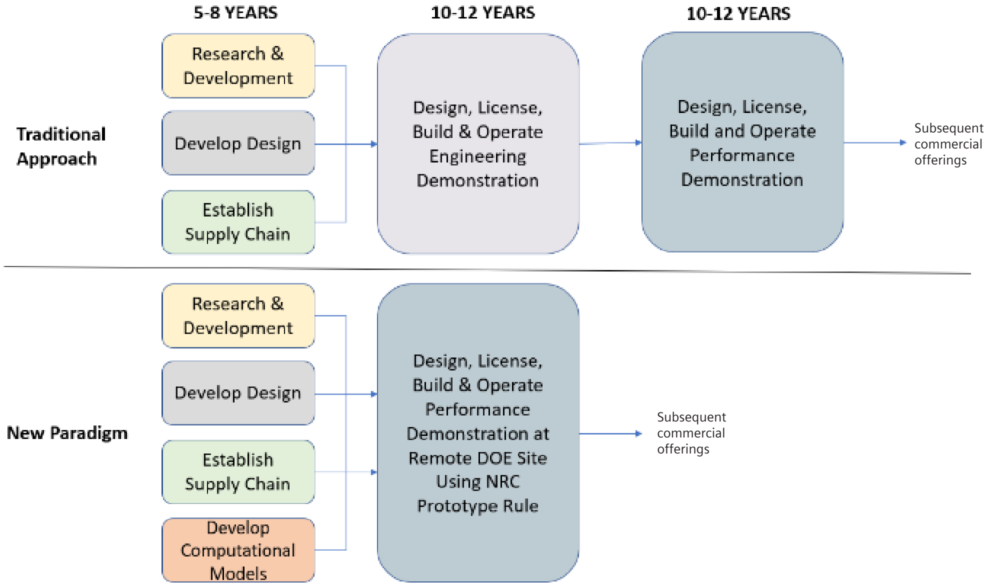

Figure 3. MIT is proposing a new paradigm in which the digital twin eliminates the need for engineering demonstration reactors, removing 10-to-12 years from the commissioning timeline.

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The digital twin in action: novel coolants

In the illustration below from X-Energy, you can see how many components have been virtually designed using Simcenter™ STAR-CCM+™ software, a part of the Xcelerator™ portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software. One of the main advantages of the X-Energy reactor is its strong safety capability. Its low power density combined with the large amount of graphite present in the core means the system has high thermal inertia in the event of an accident (such as the loss of coolant). However, there are concerns the presence of "hot spots" in the pebble bed might negatively influence the integrity of the pebbles and the fuel.

During the design phase it was critical that X-Energy was able to predict the temperature in both fluids and solids simultaneously, including the influence of all modes of heat transfer: conduction, convection and radiation.

Using traditional one-dimensional network techniques, it would be simply impossible to optimize all these components, as the temperature uncertainty in the components would be much too high to satisfy the licensing authorities (without massive factors of safety that would compromise the financial viability of the reactor).

In order to satisfy licensing requirement both x-energy and Kairos Power (which also uses a pebble bed reactor) have to be able to demonstrate they can accurately predict the temperature in the thousands of individual fuel pebbles, which are not static but move through (and are eventually expelled from) the reactor as they become depleted. This means the fuel life of individual pebbles varies at different positions in the reactor. There are lots of uncertainties regarding the power of each pebble, and therefore how accurately their temperature can be predicted and ultimately how they can be cooled.

The only way of eliminating these uncertainties (short of building an expensive full-scale demonstrator) is by using a high-fidelity three dimensional twin, such as the one illustrated below, which resolves individual pebbles in full detail, and allows us to gain an understanding of how the temperature of individual pebbles varies throughout the reactor core; something that would be nearly impossible to do even in a real life experimental demonstration reactor.

However, providing an accurate and digital model of the pebble was also a nontrivial endeavor. We began a collaboration with NRG in the Netherlands, first to build an extremely high-fidelity simulation of the pebble bed, and then to use that as a testbed to validate more practical lower-order models that could be deployed in a digital twin.

What you see in the figure below is the simple idealized structure of pebbles, used as an initial proof of concept validation point. From this we then moved into limited-size random beds ,and finally, onto fully random beds that include the wall effects. For each of these cases, we created high fidelity, quasi direct numerical simulation, which was then used to validate the lower fidelity models that can be deployed with confidence during the design of the reactor (in this case much less computationally expensive hybrid Reynolds-averaged Navier–Stokes (RANS) simulations.

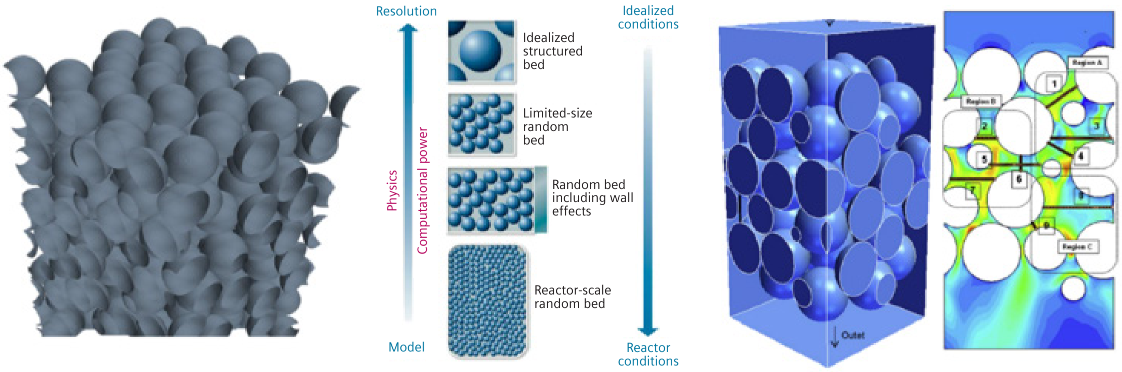


Figure 4. Evolution of pebble bed reactor modeling.

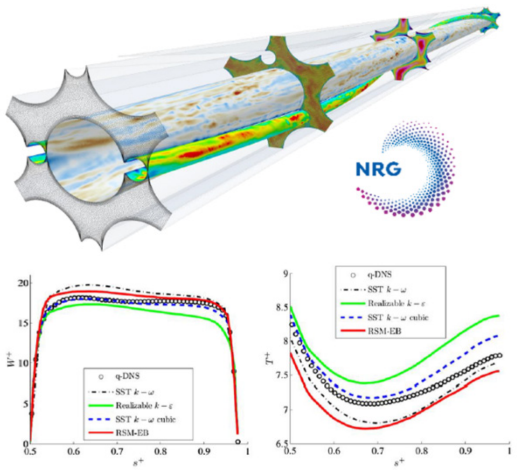
For the designers of a pebble bed reactor, this is a great starting point. You know what the state-of-the-art is, but you also have a range of lower-fidelity tools that can be deployed as part of a responsive digital twin. You also know what the time and computational cost is for the models, and you also have the data that allows you to extend the models to reflect any peculiarities of your reactor. And most importantly, you have the validation data (compiled by a large community of your peers) that can be used to satisfy the regulator on the veracity of your models, and eventually the safety of your reactor.

All of this is available at a fraction of the cost of a full-scale demonstration reactor that would have delivered less information than the digital twin.

The digital twin in action: thermal striping

Liquid metal cooled reactors, which are popular in Europe, are the basis of many Generation IV designs. Examples are the MYRRHA reactor in Belgium, TerraPower in the United States and LeadCold in Sweden. Liquid metals are excellent coolants, but once again introduce some new thermal-hydraulic challenges related to the high temperature operation.

One problem is "thermal striping," which is a consequence of the incomplete mixing of hot and cold liquid metal. This is of concern in the upper structures of the reactor, where striping can cause accelerated thermal fatigue, thermal stratification and fluid-structure-interaction induced oscillation. As with the pebble bed example above, we collaborated with NRG to develop quasi direct numerical databases of validation examples.



Dovizio et al. (2019 and 2020) NE&D

Figure 5. Wire wrapped fuel bundle simulations, Shams et al.

In the picture below you can see some illustrations of the direct numerical simulation of flow in wire wrapped fuel bundles performed by Afaque Shams' group at NRG.[5] These simulations demonstrate that we can resolve the fine detail of the wires and in our computational meshes and predict the local distributions of temperatures around the bundles (something that would have been impossible 15 or 20 years ago).

With a database of quasi-DNS results (that explicitly represent turbulence rather than modeling it) we were able to validate lower-fidelity RANS approaches, which can be practically deployed in the context of a digital twin.

NRG has also demonstrated that the nonlinear SST k-omega model is able to predict local temperature distributions with an adequate degree of accuracy. The key insight here is the nonlinear version of the model can capture the entropy of turbulence, which directly influences the distributions of temperature, velocity and turbulence. This sort of information is useful to the designer of a nuclear reactor (or its digital twin) because it saves months of effort in validating the tools.

With an effective turbulence model in place, it was also possible to simulate fluid-structure-interaction and predict how the fuel assemblies move in response to flow and thermal effects (and in particular thermal striping). This is especially important for designs such as the TerraPower concept, in which the fuel will last the entire lifetime of the reactor and will be distorted by radiation and thermal effects. Using Simcenter STAR-CCM+, NRG were able to predict the oscillations in fuel bundles to within 0.2 percent,[6] which can provide real insight into the risk of fatigue over the lifetime of the power plant.

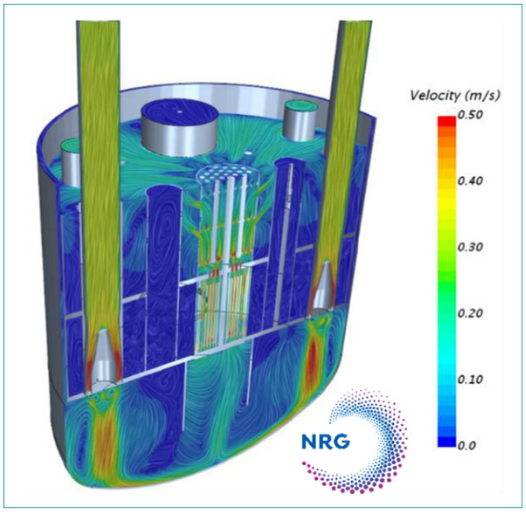


Figure 6. Simcenter STAR-CCM+ simulation of thermal stratification in ESCAPE experiment.

A constant theme here is that we are using high-fidelity models of complicated physics to validate less computationally expensive, lower order models that can be used as part of a practical digital twin. We found out early on the way in which the liquid metal mixes is chaotic and difficult to predict, especially using standard Reynolds averaged turbulence models that did not accurately predict the flow structures that govern mixing in liquid metal coolant. In response to this we have been developing hybrid models that produce large eddy simulation (LES) type results at a fraction of the computational cost.

These so-called second generation unsteady Reynolds average Navier Stokes (URANS) models of turbulence can predict these temperature distributions with cost savings that are almost two orders of magnitude better than LES approaches. For example, we can solve 50 times faster and have results that are practically the same in terms of accuracy. In a recent validation study presented by NRG, we were able to predict the thermal distribution throughout the reactor, including thermal striping and stratification effects in a real reactor without any tuning.

> *All of this is available at a fraction of the cost of a full-scale demonstration reactor that would have delivered less information than the digital twin.*

Conclusion

The adoption of a digital twin – a functional virtual model that is able to predict the performance of a nuclear reactor throughout design, licensing and operational stages – is a prerequisite for delivering the next generation of nuclear reactors in time to save the planet from the deleterious effects of climate change. Although much work is still to be done in developing physical models that account for all aspects of reactor performance, the cost of developing those models is several orders of magnitude lower than the current industry norm of constructing expensive demonstration reactors.

References

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5. Shams et al. *"High fidelity numerical simulations of an infinite wire-wrapped fuel assembly,"* Nuclear Engineering and Design Volume 335, 2018.
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