ViBRANT: A Light Physics-Driven Surrogate Reactor

Product/category

- Process/Prototyping
- Analytical/Test
- Mechanical/Materials
- IT/Electrical

Primary submitting organization:
Idaho National Laboratory

Product/services brand name:
ViBRANT

When product was introduced to the market:
July 2024

Abstract:
ViBRANT is a surrogate nuclear reactor that replaces neutrons with photons to accelerate advanced reactor development. ViBRANT uses an LED-driven core, photodiodes, thermocouples and high-performance software interfaces to help mature advanced reactor instrumentation and control systems, validate models, and facilitate system integration prior to deployment in real-world reactor prototypes.

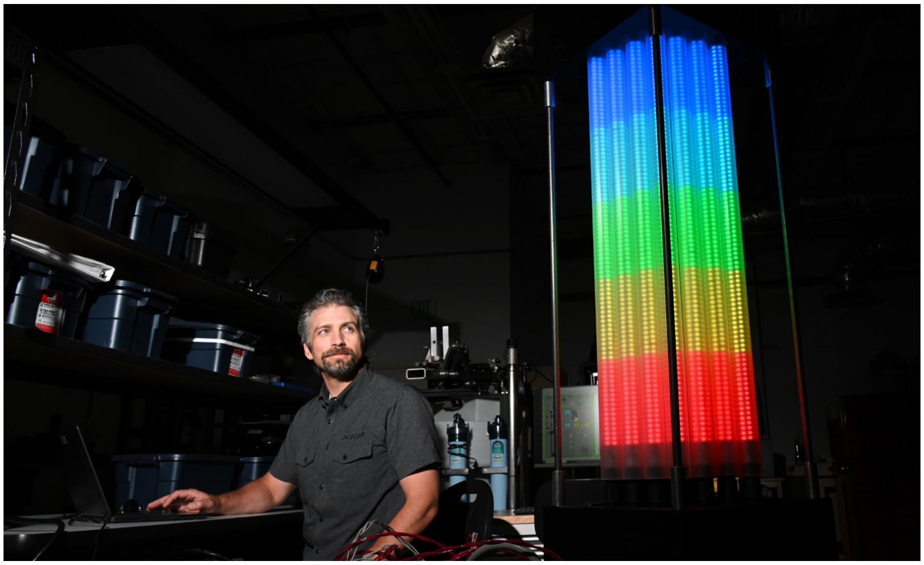

Figure 1: ViBRANT's initial 36-pin configuration shownning individual LED and light spectrum control.

Executive summary:
As the U.S. demand for reliable domestic energy increases, nuclear is one of the best options for powering data centers, national security infrastructure, industry and communities.

Reactor developers have produced dozens of advanced nuclear reactor designs, but before they can move from concept to prototype, they need a cost-effective and safe way to test and refine these vital reactor systems.

ViBRANT is a surrogate nuclear reactor platform that uses photons — particles of light emitted from thousands of LEDs — to represent the phenomena that take place in a nuclear reactor core.

By equipping the system with an accessible LED-driven surrogate flux, photodiodes, thermocouples and high-performance software interfaces, ViBRANT provides a flexible yet high-fidelity capability that connects detailed reactor physics models with real-world hardware.

ViBRANT leverages the same computer software programs used to develop next-generation nuclear reactors — codes that describe the complex interactions between neutrons, reactor materials, coolant flow and other phenomena in a reactor core.

ViBRANT allows researchers and reactor developers to apply these state-of-the-art, highly detailed reactor physics models to simulate a real nuclear reactor core, observe flux, temperature and reactivity feedback in real time, and test and refine reactor control strategies before nuclear prototype deployment. Currently configured to support the MARVEL microreactor program, ViBRANT serves as a nonnuclear validation environment for MARVEL's reactivity control system.

However, its hexagon pattern core is ubiquitous in the nuclear industry. This geometry makes it applicable to any similar core, but the ability to independently control its 60,000-plus LEDs makes it tunable to represent the function of nearly any reactor configuration.

By bridging computer models and reactor hardware in a safe and accessible environment, ViBRANT is accelerating the development and deployment of tomorrow's fleet of advanced reactors.

Additional supporting materials:
[ViBRANT pptx]

[ViBRANT report]

Video:
[Link]

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What does this product or technology do?

The U.S. is entering a period of unprecedented energy demand. Homes and industry require more reliable and resilient domestic power.

To secure the nation's energy future, the nuclear energy industry has produced more than a dozen advanced nuclear reactor designs. Soon, these reactors will power the AI revolution, strengthen national security, and provide electricity and heat for businesses and communities.

Now, the United States has reached a critical juncture in the nuclear renaissance: Reactor developers are preparing to prove their concepts by building reactor prototypes.

ViBRANT — or Visual Benign Reactor as Analog for Nuclear Testing — is helping reactor developers bridge the gap between computer models and real-world reactors by replacing high-hazard neutronic physics with a highly-controllable surrogate light physics network. By using light emitted from thousands of individually controllable LEDs, ViBRANT provides a comprehensive and accessible physical representation of the phenomena that take place in a nuclear reactor core.

During startup and operation, ViBRANT's LEDs increase in intensity and change color as the core's temperature and neutronics evolve. Using its LED-driven core, photodiodes, thermocouples and interfaces for high-performance software control, ViBRANT provides a flexible, high-fidelity capability that wholistically represents primary reactor behaviors.

In the past, reactor developers designed, analyzed, fabricated and assembled the reactor prior to any significant testing and software development. This process made reactor design or assembly problems extremely costly and difficult — if not impossible — to fix since the final reactor is built before testing begins.

Even modern solutions, such as digital twins, can still lead to costly errors. With digital twins, researchers create and virtually test digital model of the real-world reactor and its software before building a reactor prototype. However, digital twins are riddled with approximations that compound problems that may not be detected until the reactor is deployed.

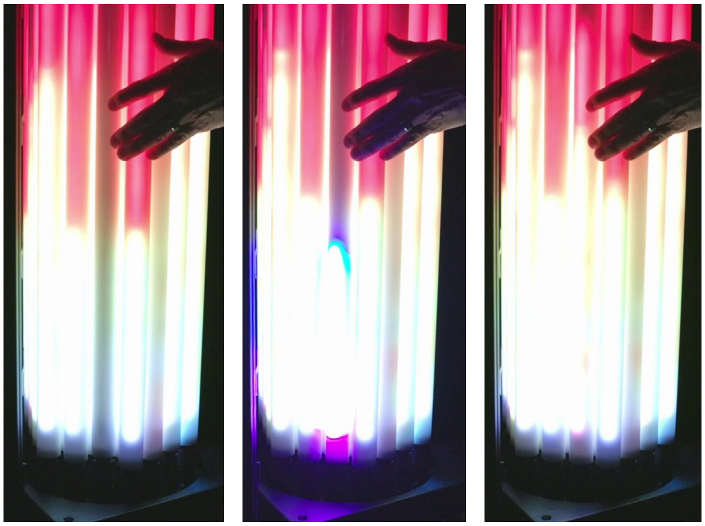

Figure 2: ViBRANT performing a thermal study with sufficient accessibility and scaled thermal distributions to perform a live pin insertion. (left: pre connection, center: mid-connection, right: full-connection)

ViBRANT allows scientists and engineers to iterate and integrate complex advanced reactor instrumentation and control systems, reactor physics models, and real-world hardware in an accessible, hazard-free environment prior to deployment in a real reactor. In other words, through iterative testing, ViBRANT enables reactor developers to assess the design's performance at each stage of the development process.

This capability allows software to be developed and refined from the beginning, and hardware problems are detected and corrected before they are encased in the reactor core, surrounded by coolant and bombarded with radiation, making them difficult or impossible to fix. Instead of an afterthought, instrumentation and control software is a development tool because the software design is iterated along with the reactor design itself.

Recently, researchers demonstrated ViBRANT's capabilities with the Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor program, an 85-kilowatt, sodium-potassium-cooled microreactor being developed at the Idaho National Laboratory.

The ViBRANT capability served as a nonnuclear, light-physics validation environment for MARVEL's reactivity control system — the combination of software and hardware responsible for controlling MARVEL's reactor core during startup, operation, shutdown and scram.

Beyond MARVEL, ViBRANT's ability to rapidly customize its features to represent a wide range of alternative reactor core conditions such as different power levels, drum configurations and sensor placements, enables developers to evaluate advanced reactor control architectures, including artificial intelligence and autonomous operations, before deployment in a nuclear environment at tracking infrastructure at all hours.

How does the product operate?

ViBRANT replaces nuclear fuel, hazardous reflector materials and neutron-driven physics with light physics. The hazards of a real reactor are reduced to safe levels, allowing developers to iterate and refine reactor instrumentation and control system hardware software before building expensive prototypes.

The platform consists of:

- Thousands of LEDs that generate surrogate neutron flux using photons
- An accessible illuminated reactor core
- Photodiodes that measure light intensity as a proxy for neutron flux
- Thermocouples that measure the heat generated by LEDs in the reactor core
- High-performance software interfaces that couple light physics with validated nuclear reactor codes

Over the past four years, researchers have employed ViBRANT to accelerate MARVEL's design.

During the demonstrations, ViBRANT was paired with the microreactor automated control system (MACS) to create a hybrid that contains all the real-life electromechanical capabilities that will soon control MARVEL. Together, the MACS/ViBRANT capability served as a nonnuclear, light-physics validation environment for MARVEL's reactivity control system — the combination of software and hardware responsible for controlling MARVEL's reactor core during startup, operation, shutdown, abnormal conditions, and a scram event.

This configuration employed MARVEL's two mechanical reactivity control mechanisms: a single translating control rod and four control drums — rotating cylinders — that absorb or reflect neutrons to control the fission chain reaction. By employing these subsystems, the MACS/ViBRANT configuration, with surrogate rods and drums around ViBRANT's LED-driven core, captured MARVEL's ability to position the reflector/absorber components for precise power control during operation and rapidly turn the absorber material toward the core to stop the chain reaction during a scram event.

The system has provided engineers with an invaluable tool: the ability to tinker.

The studies resulting from the MARVEL-inspired MACS/ViBRANT configuration have yielded numerous refinements to its hardware and software designs. For example, one study revealed that MARVEL's control drum actuator clutch, spring and damper components were improperly sized and the design parameters were too stringent. Both operating and scram movements were interrupted by too much friction with bearings. Using the data and accessibility provided by ViBRANT, researchers were able to resize and provide sufficient tunability to satisfy the MARVEL demands and be more adaptable to other reactor designs that might include such horizontal applications, alternate drum inertias, different system resistances, etc. The control drum actuators were one of several control system components that were fine-tuned based on insights gleaned from the MACS/ViBRANT system.

ViBRANT has demonstrated its utility using many software configurations, with several leveraging the same computer software programs used to develop next-generation nuclear reactors like MARVEL. These codes include RELAP, Monte Carlo N-Particle and the Multiphysics Object-Oriented Simulation Environment (MOOSE) — software tools that describe the complex interactions between neutrons, reactor materials, coolant flow and other phenomena that take place in a reactor. Reactor developers can modify the suite of software tools interacting with ViBRANT to meet their specific requirements.

To translate the differential equations that govern neutron behavior into light particle physics, researchers developed complex algorithms that relate ViBRANT's light physics to nuclear physics. These algorithms take heat, light and other information from ViBRANT's sensors and translate that information into data that feeds complex reactor codes. The output from those codes governs the behavior of LEDs in the reactor core, closing the feedback loop.

ViBRANT takes light physics and relates it to behavior that developers would expect to see with the reactor, so the surrogate reactor is calibrated to act like the real reactor.

As a learning and validation tool, ViBRANT can be calibrated to act almost identically to the MARVEL reactor through elegant tuning methods. The tool can also speed up time frames. Where the MARVEL reactor will take a day to get up to normal operating conditions, the surrogate system mimics the same processes in 10 minutes.

"The ViBRANT technology will be a key resource in helping us to appreciate reactor operation nuances and optimize our pre-deployment efforts while enabling rapid refinements during deployment."

— Jules Messaoudi & Paolo Venneri, Amazon Web Services (AWS), World Wide Public Sector – Federal Civilian

How does the product improve upon competitive products or technologies?

ViBRANT improves upon existing reactor development tools by occupying a space that neither digital twins nor full-scale hardware testing can address. At present, there are no direct analogs to ViBRANT.

The closest comparisons are digital twin environments and advanced nuclear physics modeling platforms. Digital twins communicate information — they simulate behavior numerically — but do not communicate physics through the natural world. ViBRANT does. Instead of relying solely on approximations embedded in millions of lines of code, ViBRANT translates reactor neutronics and thermal behavior into photon-based physics that operate in real space, through measurable physical phenomena. Information is not merely computed; it is expressed and fed back through light, sensors and thermally responsive systems.

Traditional digital twins interpret outputs from models that may contain assumptions, approximations or discretization errors. ViBRANT replaces that abstraction with closed-loop, physics-based interaction. Reactor inputs can be tuned physically to achieve required outcomes, allowing developers to observe how modeled behavior manifests in a tangible system. This reduces reliance on purely numerical approximations and enables direct validation of model-to-hardware integration.

Conventional hardware-in-the-loop testing, by contrast, typically occurs on full-scale reactor systems and involves nuclear materials, radiation hazards and significant operational risk. Developers often validate instrumentation and control systems only after a reactor is constructed, limiting opportunities for iterative refinement. ViBRANT normalizes the scale of multiple coupled physics phenomena — neutronics, thermal response and control system dynamics — to safe and accessible levels. It enables real electromechanical hardware to operate within a physically representative environment without the hazards associated with nuclear fuel.

Figure 3: ViBRANT controlled using robust high level commands thus making it amenable to rapid implementation.

"As a surrogate reactor device… it has all the aptitudes necessary to support ANS's endeavors to clarify common misconceptions, build understanding, and inspire future careers in the nuclear field."

— Uchenna Ezibe, Senior Manager, ANS STEM Programs American Nuclear Society

The platform also maintains sufficient fidelity to support advanced multiphysics codes such as MOOSE, RELAP and Monte Carlo N-Particle. ViBRANT's volumetric grid structure within its surrogate fuel pins allows real-world light physics to represent neutronic distributions. This provides a physically realized analog to modeled behavior rather than a purely mathematical one.

In effect, ViBRANT bridges the gap between computer models and nuclear prototypes. It is not solely a model, and it is not a real-world reactor system. By combining hardware integration with physics-based feedback in a benign environment, ViBRANT enables earlier validation, faster iteration and reduced development risk for advanced reactor technologies — capabilities not currently available in any other platform.

Provide a matrix demonstrating how key features compare to other products:

Reactor Development Improvement Tools (Aspect/Method)	"Separate Effects Testing (Single Physics Phenomena)"	"Hardware-in-the-Loop (HIL) (Hardware, Software, and Digital Models)"	"ViBRANT (HIL with Surrogate Physics Reactor)"	"Digital Twins (DT) (Digital Models)"
PERFORMANCE IMPROVEMENT				
High fidelity test control	3	3	10	10
Multiple variables	2	5	8	10
Model Validation	10	7	8	3
Predictive tool	1	5	7	10
Rapid Investigation	2	4	10	7
Min Computational Burden	10	6	8	1
Predictive tool	1	5	8	10
AI Development tool	1	5	9	10
I&C architecture	1	5	9	7
Robotics Integration	1	6	10	10
TRAINING AND EDUCATION				
Intuitive configuration	3	5	10	8
Improved outreach	1	2	10	8
Process rehersal	4	10	8	6
Hardware appreciation	6	9	8	2
Accessibility	2	5	9	8
Improved Training	2	6	8	8
TIME REDUCTION				
Time/Benefit Ratio	3	5	8	10
COST REDUCTION				
Capital Investment	2	5	10	3
Operation Optimization	1	7	8	10
SAFETY				
Low-Hazard	1	4	9	10
OPERATING IMPROVEMENT	2	5	8	10

What are the limitations of the product/service?

ViBRANT's surrogate control rod and control drums do not yet incorporate fully optimized absorber and reflector materials. Although the system successfully models reactivity feedback using LED-driven light physics and calibrated control algorithms, improved reflector and absorber materials would provide a wider bandwidth to represent real-world neutronic behavior, providing more comprehensive studies.

In one study, inserting a surrogate central control rod wrapped in a semi-absorbing material in the center of the core produced a 22% reduction at the surrogate neutronic sensor at the edge of the core when only the six internal surrogate fuel pins were activated. However, when all 36 pins were activated, the reduction was only approximately 2.2%. Although presented as a physical shortcoming, the exercise of addressing the problem is providing researchers with the opportunity to address real-world conditions such as optimized material selection, sensor placement and noise attenuation. The example demonstrates that even the system's limitations provide beneficial consequences.