Integrated Nuclear Web-based Digital Twin Platform for the NETL TRIGA Reactor

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Abstract—**Digital twin technologies, which couple physical systems with their virtual representations for monitoring, prediction, and analysis, have advanced significantly in many engineering domains. However, their deployment in nuclear systems remains limited due to stringent requirements on safety, validation, and system-level integration. Existing efforts often focus on individual components such as high-fidelity simulation or data-driven models, while practical implementations that unify these elements into an accessible and operational framework remain scarce. In response, this work presents the Nuclear Twins Website (NTW), a web-based digital twin platform developed for the NETL TRIGA reactor. The NTW is designed as a centralized and integrated hub that unifies data, simulation, and user interaction. The platform integrates five core components: core configuration analysis, operational data access, a natural-language-based data query interface, an interactive reactor simulator, and a high-fidelity prediction module. By connecting historical data, physics-based models, and user interaction, the NTW enables intuitive exploration, training, and analysis of reactor behavior. Rather than introducing a standalone software tool, this work demonstrates a structured approach for deploying nuclear digital twins that emphasizes integration, accessibility, and validation. The NTW provides a scalable foundation for bridging high-fidelity reactor simulations with practical operational and research workflows.**

Keywords: Digital Twin, Nuclear Engineering, TRIGA Reactor, Web Platform, Reactor Analysis, Human-Interactive System

I. INTRODUCTION

The concept of the digital twin has evolved from a virtual representation of engineered systems into an integrated framework that combines physical assets, computational models, and data streams for monitoring, prediction, and decision support. Early formulations of the digital twin were introduced in the context of product lifecycle management by Grieves [1], [2], where the focus was primarily on virtual representation for design and manufacturing processes. Subsequent developments expanded this concept to more complex systems, including aerospace applications, where digital twins have been used for structural health monitoring and lifecycle prediction [3]. NASA further advanced the paradigm by integrating real-time sensor data with physics-based models to support mission safety and system reliability [4]. More recent studies have emphasized the role of digital twins as system-level frameworks for integrating simulation, data, and decision-making processes [5].

With the advancement of large-scale sensing, cloud infrastructure, and artificial intelligence, digital twins have become key enabling technologies for predictive maintenance and operational optimization across multiple industries [6]. Industrial applications have demonstrated the effectiveness of digital twins in manufacturing and smart systems, particularly in combining data-driven and physics-based approaches [7].

Despite these developments, the direct transfer of digital twin methodologies to nuclear engineering is non-trivial. Nuclear systems impose strict requirements on safety, reliability, and validation, which constrain the adoption of emerging digital twin technologies. While essential components such as high-fidelity neutronics and thermal-hydraulics simulations have reached a high level of maturity, their integration into a coherent and operationally meaningful digital twin remains an open challenge. Similarly, data-driven approaches and advanced instrumentation have enabled improved monitoring and diagnostics in nuclear systems, but these developments are often implemented independently rather than within a unified framework [8].

Recent studies and reports have emphasized the existence of technical gaps in coupling simulation, data, and validation within realistic reactor environments. For example, the ORNL report highlights challenges in integrating sensing, modeling, and computational infrastructure for nuclear digital twin applications [9], while OECD-NEA studies emphasize the need

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for system-level digital transformation across the nuclear lifecycle [10]. Additional efforts focusing on AI-driven nuclear platforms further underscore the importance of combining data and physics-based models in a consistent and validated manner [11]. Recent academic studies similarly point out that achieving both high-fidelity prediction and real-time interaction remains a key unresolved challenge in nuclear digital twin development [8], [9].

A central limitation arises from the fragmented nature of current implementations. Simulation tools, experimental measurements, and data-driven models are often developed and applied independently, resulting in partial and disconnected representations of the underlying physical system. For instance, several studies focus exclusively on high-fidelity simulation for reactor analysis, while others emphasize data-driven monitoring or machine-learning-based prediction without tight coupling to physics models [6]. While these approaches enable individual capabilities, they hinder the realization of consistent and integrated prediction, validation, and operational insight across the system. The primary challenge is therefore not only the advancement of individual technologies, but also their systematic integration into a unified environment that supports interaction, interpretation, and validation in a physically meaningful manner.

Direct deployment of such integrated digital twin frameworks in commercial power reactors or advanced reactor systems remains challenging due to strict regulatory requirements, limited accessibility, and the high cost of experimentation and validation. As a result, an intermediate testbed is required to develop, evaluate, and validate integrated digital twin architectures under controlled and accessible conditions before full-scale implementation.

Research reactors provide a practical pathway for addressing this challenge. The NETL TRIGA reactor at the University of Texas at Austin offers a unique combination of inherent safety, operational flexibility, and experimental accessibility. Its strong negative temperature feedback ensures stable behavior, while its pulse and transient operating modes enable detailed observation of reactor kinetics and dynamic responses [12]. These characteristics make the TRIGA reactor an effective testbed for exploring integrated digital twin architectures that connect reactor physics, operational data, and user interaction [13], [14]. Prior efforts have explored various components of such systems, including real-time digital twin development [15], state estimation and control [16], and reduced-order modeling approaches [17], [18].

Building on this testbed environment, the Nuclear Twins Website (NTW) has been developed as a web-based digital twin platform for the NETL TRIGA reactor, publicly accessible at nuclear-twins.tacc.utexas.edu or nucleartwins.online. The NTW builds upon a series of prior efforts within this research program, including the development of web-based reactor simulators [19], and validation of real-time digital twin frameworks [20]. The NTW is designed as a unified environment that integrates data, modeling, and user interaction within a single coherent interface. The platform consists of five primary components: a data module for accessing operational records, a core module for reactor configuration analysis, an interactive reactor simulator for operational training and exploration, a high-fidelity prediction module, referred to as Shadowcaster, and an experiments module for investigating and validating reactor behavior. This approach is consistent with prior work on reduced-order modeling and digital twin–based prediction methods for TRIGA reactors [17], [18].

Among these components, the high-fidelity prediction module plays a distinct role in extending the analytical capability of the platform. Unlike the real-time predictive paradigm typically associated with digital twins, the Shadowcaster module incorporates a digital shadow approach based on high-fidelity reactor physics simulations. The term "digital shadow" is used to describe a representation that is derived from the physical system through high-fidelity simulation, without requiring continuous real-time coupling or bidirectional synchronization.

Rather than performing instantaneous predictions, this approach involves executing detailed computational analyses to reconstruct and evaluate reactor states. As a result, it provides access to rich physical information such as neutron flux distributions, isotopic compositions, and depletion histories that are not directly observable through real-time interfaces. The term "Shadowcaster" is used to describe the process of generating, aggregating, and presenting these high-fidelity simulation results within the platform.

Through the integration of these five components, the NTW enables a cohesive workflow in which data access, core analysis, interactive operation, high-fidelity prediction, and experimental validation are interconnected. This unified structure allows information generated in one module to inform and enhance others, supporting a consistent and physically grounded representation of reactor behavior within the digital twin environment.

The main contributions of this work are summarized as follows:

1. An integrated digital twin platform for a research reactor is presented, unifying data access, core analysis, interactive operation, predictive modeling, and experimental validation within a single web-based environment.
2. A framework is established for exposing high-fidelity reactor physics capabilities through an accessible interface, enabling interactive analysis without decoupling from underlying physical models.
3. A prediction module based on advanced simulation tools is incorporated to support detailed reactor analysis, including depletion behavior and criticality estimation within the digital twin environment.
4. A practical pathway is demonstrated for connecting analysis, training, and validation, providing a scalable approach to digital twin deployment in nuclear engineering.

The remainder of this paper is organized as follows. Section II presents the design philosophy and system framework underlying the NTW. Section III describes the platform implementation and its core capabilities. Section IV discusses application scenarios and the role of the NTW in nuclear digital twin deployment. Finally, Section V concludes the paper and outlines directions for future research.

II. DESIGN PHILOSOPHY AND SYSTEM FRAMEWORK

The NTW is designed not as a collection of independent tools, but as an integrated framework for deploying and evaluating nuclear digital twin architectures in a research reactor environment. The design of the platform is guided by several core principles that address the limitations identified in current digital twin implementations, particularly the fragmentation between data, simulation, and user interaction.

First, integration is treated as a primary design objective. Rather than developing isolated capabilities, the NTW is structured to ensure that data, core analysis, interactive operation, and high-fidelity simulation are interconnected within a single environment. Each component is designed to both consume and generate information that can be utilized by other modules, enabling a coherent representation of reactor behavior across multiple levels of fidelity.

Second, the platform emphasizes accessibility without sacrificing physical fidelity. High-fidelity nuclear simulation tools such as MCNP [21] and MPACT [22] provide detailed and accurate predictions but are often inaccessible to non-expert users due to their complexity and computational cost. The NTW addresses this challenge by exposing these capabilities through user-facing interfaces, enabling interactive exploration while maintaining a connection to underlying physics-based models. This balance allows the platform to serve both educational and engineering purposes.

Third, validation is embedded as a central design requirement. In nuclear engineering, predictive capability must be supported by rigorous comparison with experimental observations. The NTW incorporates experimental modules and data access capabilities that enable systematic validation of computational predictions, thereby reducing the gap between simulation and physical reality. This validation-oriented design distinguishes the platform from purely visualization- or simulation-driven digital twin implementations.

Fourth, the platform adopts a multi-fidelity modeling strategy that combines real-time interaction with high-fidelity analysis. Interactive components, such as the reactor simulator and surrogate-based models, provide near-instantaneous feedback for exploration and training. In parallel, high-fidelity simulation tools are integrated through the Shadowcaster module, enabling detailed analysis of reactor states. This combination allows the platform to support both rapid interaction and in-depth investigation within a unified framework.

Fifth, the NTW is designed with a reactor-specific and deployment-oriented perspective. Rather than aiming to directly replicate a full-scale digital twin of a commercial reactor, the platform focuses on a staged development approach using a research reactor as a testbed. This enables iterative development, validation, and refinement of digital twin capabilities under controlled and accessible conditions, while maintaining a clear pathway toward future deployment in larger and more complex nuclear systems.

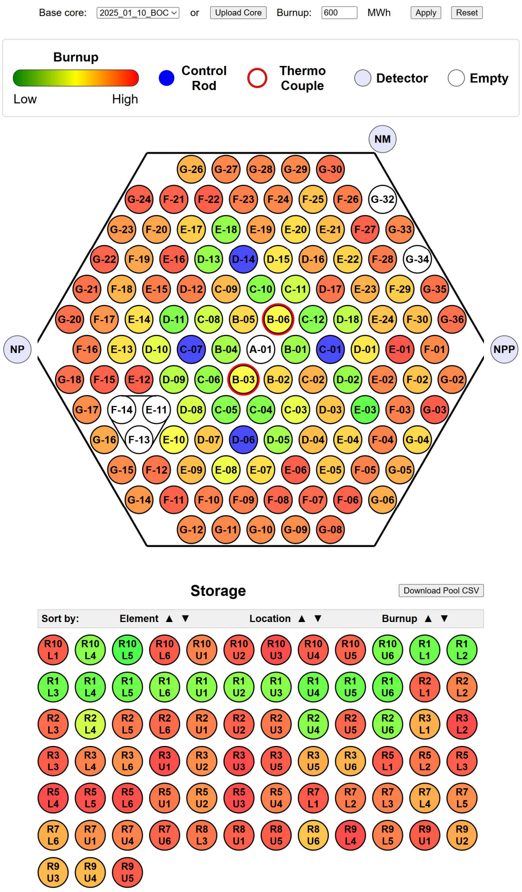
Together, these design principles define the NTW as a structured framework for integrating data, simulation, and user interaction, providing a foundation for the development of practical and validated nuclear digital twin systems.

III. PLATFORM IMPLEMENTATION AND CAPABILITIES

The NTW platform is composed of five primary components that collectively implement the design principles: the Data module, Core module, interactive reactor Simulator, Shadowcaster module, and Experiments module. Each component provides a distinct capability while remaining tightly coupled with the others, enabling an integrated digital twin environment.

A. Core Module: Interactive Core Analysis and Surrogate-Based Prediction

The Core module enables interactive analysis of both historical and user-defined reactor core configurations, as shown in Figure 1. Users can reconstruct existing core layouts, explore hypothetical configurations, and evaluate depletion-driven changes in fuel composition under specified operating conditions.



Base core: 2025_01_10_BOC or Upload Core Burnup: 600 MWh Apply Reset

Figure 1. Core module interface of the NTW platform, enabling interactive reconstruction and analysis of TRIGA reactor core configurations. The interface integrates core visualization, fuel inventory management, burnup tracking, and surrogate-based prediction of neutronic parameters within a single environment.

To support rapid analysis, the module incorporates a neural-network-based surrogate model trained on approximately 20,000 precomputed MCNP simulations. While high-fidelity MCNP calculations typically require several hours to complete, the surrogate model enables near–real-time estimation of key neutronic parameters, including effective multiplication factor and fuel composition changes. This approach allows users to explore a wide range of core configurations without repeatedly performing computationally expensive simulations.

In addition to predictive capability, the Core module provides an intuitive visualization of the reactor core and associated fuel inventory. Users can modify fuel arrangements, examine depletion states, and assess the impact of control rod positions on reactor behavior. By combining interactive manipulation with physics-informed prediction, the module supports both educational exploration and engineering analysis of reactor configurations.

B. Data Module: Operational Data Access and Time-Resolved Analysis

The Data module provides access to historical operational data collected from the NETL TRIGA reactor, enabling systematic analysis of reactor behavior over time. The module consists of two primary interfaces, Data by Date and Data Playground, which together support both structured inspection and flexible data-driven analysis.

The Data by Date interface allows users to explore reactor operational data on a day-by-day basis, as illustrated in Figure 2. The upper section presents synchronized time-series plots in a static format, enabling detailed and precise analysis of reactor parameters. Key quantities, including reactor power, control rod positions, detector signals, and temperature measurements, can be examined with high resolution to identify trends and transient behaviors.

The lower section provides a dynamic replay of the same dataset, allowing users to experience reactor operation in a time-progressive manner. This replay functionality enables intuitive understanding of operator actions and system responses, effectively bridging quantitative data analysis with experiential interpretation of reactor behavior.

In addition to date-based exploration, the Data Playground interface enables users to query and analyze data directly from the underlying database, as shown in Figure 3. Users can construct customized queries and generate up to eight simultaneous plots, allowing flexible investigation of correlations, trends, and event-driven behaviors across multiple operational parameters. This capability extends the platform beyond visualization, providing a user-driven analytical environment for exploratory research.

Year: 2026 Month: 04 Day: 10

Or load bookmark: -- Select Bookmark --

Save bookmark: from HH:MM:SS to HH:MM:SS

- **Bookmarks:** Use the dropdown to quickly load saved time ranges, or enter a start/end time and click "Save" to create a new bookmark for the selected date.
- **Operational Mode:** In the generated plots, you can click **"Mode On"** or **"Mode Off"** in the legend to toggle the visibility of the reactor's operational status.
- **Before vs. After:** "Before" is the raw signal from the console including electronic noise and testing signals. "After" is filtered to remove that noise and testing artifacts; it is not used to remove spikes caused by technical specification violations.

Start Time: 12:15:30 End Time: 13:15:30 Speed: 5x

Figure 2. Data by Date interface of the NTW platform. The upper panel provides synchronized time-series visualizations for detailed analysis of reactor operational data, while the lower panel enables dynamic replay of reactor behavior, allowing users to examine transient responses and operator actions in a time-resolved manner.

All datasets can be exported for external analysis, enabling integration with independent research workflows. By combining structured data access, interactive replay, and flexible querying, the Data module serves as a critical component for validation, supporting direct comparison between measured data and model-based predictions within the digital twin framework.

TRIGA Reactor Real-time Plotly Playground

Number of plots: 4

Plot 1

Y-axis variables: LinPower

Y-axis Scale: ☑ Log Scale

Start Datetime: 2026-04-08 13:00:00

End Datetime: 2026-04-08 15:00:00

Plot 2

Y-axis variables: Tran, Shim1, Shim2, Reg (4 selected)

Y-axis Scale: ☐ Log Scale

Start Datetime: 2026-04-08 13:00:00

End Datetime: 2026-04-08 15:00:00

Plot 3

Y-axis variables: NM, NPP, NP (3 selected)

Y-axis Scale: ☐ Log Scale

Start Datetime: 2026-04-08 13:00:00

End Datetime: 2026-04-08 15:00:00

Plot 4

Y-axis variables: FuelTemp1, FuelTemp2, WaterTemp (3 selected)

Y-axis Scale: ☐ Log Scale

Start Datetime: 2026-04-08 13:00:00

End Datetime: 2026-04-08 15:00:00

Figure 3. Data Playground interface of the NTW platform, enabling user-defined querying and visualization of reactor operational data. Multiple plots can be generated simultaneously to support flexible analysis of correlations and trends across different reactor parameters.

C. *Interactive Reactor Simulator: State-Aware Operational Modeling*

The interactive reactor simulator, referred to as Doppelganger, provides a virtual operating environment that reproduces the behavior of the NETL TRIGA reactor, as shown in Figure 4. The simulator is designed to bridge the gap between theoretical knowledge and hands-on experience by enabling users to perform reactor operations in an interactive and visually immersive setting.

To ensure a consistent and realistic user experience, the simulator interface closely replicates the actual NETL TRIGA control panel, as illustrated in Figure 4. Key operational elements, including control rod indicators, reactor status displays, and control switches, are reproduced within the interface, allowing users to interact with the system in a manner that closely resembles real reactor operation. This design approach enhances both familiarity and usability, particularly for users undergoing training or transitioning from theoretical study to practical operation.

TRIGA Doppelganger

Reactor Reference Time

Date: 2025-11-04

Hr: 6 Min: 0

Speed: 3.0

Demand: 50 W

Simulator status

Demand:	50 W	Pow:	560.3 kW
Speed:	3.0x	Xe(%):	39.0242
Pump:	ON	I (%):	29.5747
Source:	IN	BU (MWh):	516.240
Mode:	Manual	keff:	1.00018
Tran:	687	Period:	457.36
Shim1:	750	F.Temp1:	265.82
Shim2:	714	F.Temp2:	295.08
Reg:	741	W.Temp:	18.00

Chatbot

Chatbot type: --- select type ---

Simulator mode: --- select mode ---

This Chatbot provides brief instructions for each mode.

If you want to see the full description at once, select **Full description**.
If you want a step-by-step guide, select **Step by step**.

Please make a selection from the dropdown menus above.

ρ calc

Tran: 0

Shim1: 0

Shim2: 0

Reg: 0

Total(¢):

Tran	Shim1	Shim2	Reg
AIR	MAGNET	MAGNET	MAGNET
▲ (q)	▲ (w)	▲ (e)	▲ (r)
▼ (a)	▼ (s)	▼ (d)	▼ (f)

Figure 4. Interactive reactor simulator of the NTW platform. The interface replicates the NETL TRIGA control panel and integrates real-time visualization of reactor state, control rod positions, and system parameters, along with auxiliary components such as a status panel and chatbot interface to support interactive operation and training.

A key feature of the simulator is its ability to initialize reactor conditions based on historical operational states. This includes the effects of xenon transients and fuel depletion, allowing simulations to reflect realistic reactor behavior over both short- and long-time scales. Users can control reactor parameters, manipulate control rods, and observe resulting changes in reactor power, reactivity, and kinetics in real time.

The simulator further integrates multiple auxiliary components to enhance situational awareness and user interaction. A real-time status panel provides continuous feedback on reactor conditions, including power level, reactor period, and operational state. In addition, a lightweight chatbot interface is incorporated to assist users during operation, providing guidance on control actions and reactor behavior. These features collectively support both guided learning and independent exploration.

By combining state-aware initialization, realistic interface design, and interactive control, the simulator supports both operator training and analysis of reactor dynamics. This capability enables users to explore operational scenarios that would be difficult or impractical to perform in a physical reactor environment, while maintaining a close connection to actual reactor behavior.

D. *Shadowcaster Module: High-Fidelity Digital Shadow and Predictive Analysis*

The Shadowcaster module extends the analytical capability of the NTW by integrating high-fidelity reactor physics simulations within the platform. Unlike the interactive components, which prioritize responsiveness, this module adopts a digital shadow approach that emphasizes detailed reconstruction and analysis of reactor states.

The module leverages advanced simulation tools, including MPACT, to perform high-resolution calculations of reactor behavior. These simulations enable refined fuel depletion tracking, neutron flux distribution estimation, and prediction of critical operating conditions. As a result, the module provides access to detailed physical information that cannot be directly obtained from real-time interfaces or simplified models.

This capability is particularly important for the NETL TRIGA reactor, which is operated through daily startup and shutdown cycles. Unlike commercial power reactors that operate continuously and approach equilibrium conditions, the TRIGA reactor does not allow key reactor poisons, such as xenon, to reach steady-state concentrations. Consequently, the reactor state varies significantly from day to day, and accurate prediction of daily operating conditions becomes a critical task.

To address this challenge, the Shadowcaster module reconstructs reactor conditions based on historical operational data and performs high-fidelity simulations to estimate parameters such as reactivity, neutron flux distributions, and poison concentrations. This enables users to evaluate the reactor state prior to operation, supporting tasks such as predicting critical control rod positions and assessing excess reactivity under evolving conditions.

The results of these simulations are systematically stored in a database, forming a structured repository of high-fidelity reactor state information. These data are then integrated into a dashboard environment developed using Apache Superset [23], allowing users to visualize and analyze simulation outputs through an interactive interface. As shown in Figure 5, the dashboard presents a comprehensive view of reactor behavior, including key parameters, trends, and correlations derived from high-fidelity simulations.

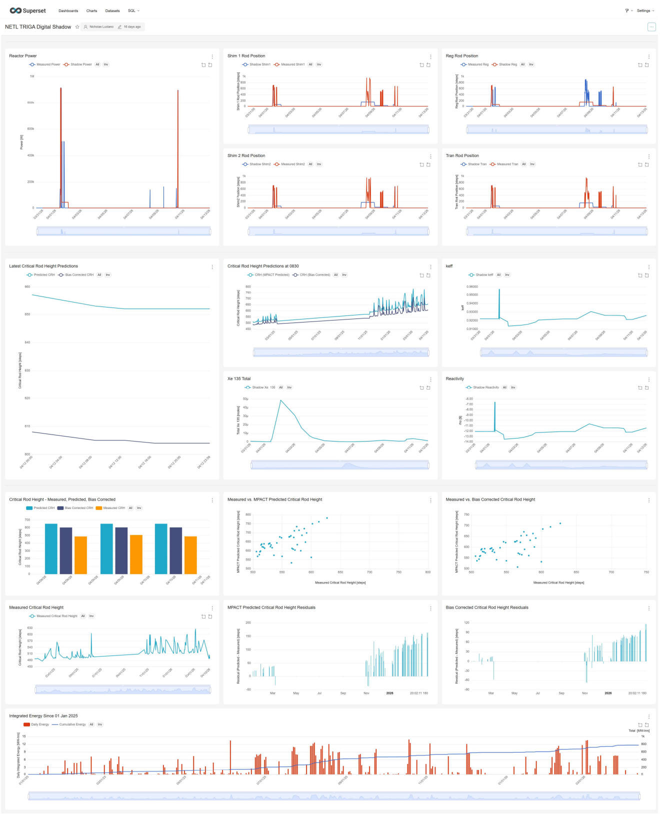


Figure 5. Interactive dashboard of the Shadowcaster module developed using Apache Superset, presenting aggregated high-fidelity simulation results.

By aggregating and presenting the results of these simulations in an accessible format, the Shadowcaster module connects high-fidelity computational analysis with user-facing workflows. This integration allows users to transition seamlessly from interactive exploration to in-depth reactor analysis within the same platform.

E. Experiments Module: Validation and Model Refinement

The Experiments module provides a validation-oriented component of the NTW, enabling systematic comparison between experimental observations and computational predictions. This module focuses on research activities that investigate reactor behavior and challenge conventional assumptions in reactor physics.

Several experimental studies are incorporated within the platform, including Cherenkov radiation–based power monitoring, control rod shadowing effects, and control rod worth calibration. The Cherenkov-based approach demonstrates a non-intrusive method for reactor power estimation using optical measurements, offering a complementary alternative to traditional detector-based systems [24]. The control rod shadowing study highlights the interaction effects between control rods, revealing deviations from assumptions of independent rod worth. Recent work has also explored improved calibration methodologies, including Gaussian process regression and rod swap techniques [25], [26]. These effects are quantified through high-fidelity simulations and surrogate modeling, enabling real-time exploration of reactivity interactions.

By integrating experimental data with simulation results, the Experiments module supports iterative model validation and refinement. This capability plays a critical role in ensuring that the digital twin remains physically consistent and grounded in observable reactor behavior.

The platform is implemented using a web-based architecture built on standard technologies, including HTML, CSS, JavaScript, and a Python-based backend (Flask), enabling scalable deployment and user accessibility [27].

IV. APPLICATIONS AND ROLE IN DIGITAL TWIN DEPLOYMENT

The NTW is designed not merely as a collection of independent modules, but as an integrated environment in which components interact to support a unified digital twin framework. This interconnected structure allows information generated in one module to propagate throughout the platform, thereby enhancing predictive capability, operational insight, and research utility.

One of the primary applications of this integrated structure lies in supporting reactor operation and planning workflows. The Core module enables rapid exploration of candidate core configurations and provides near–real-time estimates of neutronic parameters through surrogate modeling. These results can be further refined using the Shadowcaster module, where high-fidelity simulations provide detailed predictions of reactor behavior under specific operating conditions, particularly for non-equilibrium states encountered in daily reactor operation. In parallel, the Data module allows users to compare predicted quantities with historical operational data, supporting validation and adjustment of model assumptions. This workflow reduces the reliance on repeated full-scale simulations and enables more efficient preparation for daily reactor operation.

The platform also serves as a training and educational environment. The interactive reactor simulator allows users to perform virtual reactor operations under realistic conditions, including the effects of xenon transients and fuel depletion. By combining real-time interaction with data-driven replay of historical operations, the NTW bridges the gap between theoretical instruction and experiential learning. This capability is particularly valuable in nuclear engineering, where direct access to reactor operation is limited due to safety and regulatory constraints.

Another key application is in validation and model refinement. The Experiments module provides a structured environment for comparing computational predictions with experimental observations. For example, Cherenkov radiation–based power monitoring offers an alternative measurement approach that can be directly compared with detector-based signals, while control rod shadowing studies reveal interaction effects that challenge conventional assumptions. By integrating these experimental insights with simulation outputs, the NTW supports iterative improvement of both models and operational strategies, which is a critical requirement for ensuring the reliability and credibility of digital twin systems in nuclear applications.

From a broader perspective, the NTW illustrates a multi-fidelity digital twin architecture that combines real-time interaction with high-fidelity analysis. Interactive components, including the simulator and surrogate-based core analysis, provide rapid feedback and intuitive understanding, while the Shadowcaster module enables detailed physics-based prediction. This hybrid approach addresses the well-known trade-off between computational fidelity and real-time responsiveness in digital twin systems.

Finally, the NTW provides a pathway for staged deployment of nuclear digital twins. By leveraging a research reactor as a testbed, the platform enables development and validation of digital twin components under controlled conditions. Insights gained from this environment can be extended toward more complex systems, including advanced and commercial reactors. In this context, the NTW represents an intermediate step between isolated digital tools and fully coupled, real-time digital twin implementations, which remain a long-term goal in nuclear engineering.

Together, these applications demonstrate how the NTW integrates operational, educational, and research functionalities within a unified framework, providing both immediate practical utility and a scalable foundation for future nuclear digital twin deployment.

V. CONCLUSION

This work has presented the NTW, a web-based digital twin platform developed for the NETL TRIGA reactor. The platform integrates operational data, core configuration analysis, interactive reactor simulation, high-fidelity predictive modeling, and experimental validation within a unified environment. By connecting these components, the NTW moves beyond isolated digital tools and demonstrates a structured approach for implementing integrated digital twin systems in nuclear engineering.

A key contribution of this work lies in the integration of multiple modeling and interaction paradigms within a single platform. Surrogate-based models enable near–real-time estimation of reactor parameters, while the interactive simulator provides a state-aware environment for exploring reactor operation. In parallel, the Shadowcaster module supports high-fidelity analysis through detailed reactor physics simulations, allowing in-depth evaluation of reactor states. Together with the integration of experimental studies and operational data, this framework provides a pathway for systematic validation, which is essential for ensuring the reliability of digital twin methodologies in safety-critical systems.

The NTW also highlights the role of research reactors as effective testbeds for digital twin development. By leveraging the operational flexibility and accessibility of the NETL TRIGA reactor, the platform enables iterative development, validation, and refinement of digital twin components under realistic but controlled conditions. This approach provides a practical pathway toward the deployment of digital twin technologies in more complex nuclear systems, including advanced and commercial reactors.

In addition to its research applications, the NTW enhances educational accessibility and operational efficiency. The platform allows users to interact with reactor systems, analyze historical data, and evaluate predictive models within a single interface, thereby bridging the gap between theoretical knowledge, experimental observation, and engineering practice.

Future work will focus on further strengthening the integration between data, simulation, and user interaction. Planned developments include the expansion of high-fidelity predictive capabilities, improved data management infrastructure, and enhanced coupling between real-time operation and computational models. These efforts aim to advance the NTW toward a more comprehensive and continuously evolving digital twin framework.

Overall, the NTW demonstrates how digital twin concepts can be translated into a practical, validated, and user-accessible system for nuclear engineering. The platform provides both immediate utility and a scalable foundation for future digital twin deployment, contributing to the broader effort to integrate data, simulation, and validation in next-generation nuclear technologies.

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DATA / CODE AVAILABILITY STATEMENT

The NTW platform is publicly accessible at https://nuclear-twins.tacc.utexas.edu or https://nucleartwins.online, enabling direct interaction with the system described in this work. The platform provides downloadable access to core configurations, operational datasets, and simulation results across multiple modules, supporting independent analysis and reproducibility. Additional implementation details can be provided upon reasonable request.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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