March 20, 2023

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Project Number 99902100

U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
ATTN: Document Control Desk

Subject: Submittal of Nascent Thermal Hydraulic Model White Paper

This letter transmits the TerraPower, LLC (TerraPower) "Nascent Thermal Hydraulic Model White Paper," which provides an overview and description of the Natrium Simplified Coolant Energy Transport (Nascent) model used to predict the steady-state peak coolant temperature in fuel assembly subchannels.

TerraPower requests that the U.S. Nuclear Regulatory Commission (NRC) staff review the subject white paper and provide documented feedback regarding topics for which additional discussion or consideration may be beneficial. TerraPower requests that a nominal review duration of 6 months be considered.

The white paper contains proprietary information and as such, it is requested that Enclosure 3 be withheld from public disclosure in accordance with 10 CFR 2.390, "Public inspections, exemptions, requests for withholding." An affidavit certifying the basis for the request to withhold Enclosure 3 from public disclosure is included as Enclosure 1. Enclosure 3 also contains ECI which can be disclosed to Foreign Nationals only in accordance with the requirements of 15 CFR 730 and 10 CFR 810, as applicable. Proprietary and ECI materials have been redacted from the white paper provided in Enclosure 2; redacted information is identified using [[ ]]$^{(a)(4)}$, [[ ]]$^{(ECI)}$, or [[ ]]$^{(a)(4),(ECI)}$.

This letter and enclosures make no new or revised regulatory commitments.

If you have any questions regarding this submittal, please contact Ryan Sprengel at rsprengel@terrapower.com or (425) 324-2888.

Sincerely,

Ryan Sprengel

Ryan Sprengel
Director of Licensing, Natrium
TerraPower, LLC

Enclosure:
1. TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))
2. TerraPower, LLC White Paper, NAT-3049 *Nascent Thermal Hydraulic Model White Paper* – Non-Proprietary (Public)
3. TerraPower, LLC White Paper, NAT-3049 *Nascent Thermal Hydraulic Model White Paper* – Proprietary (Non-Public)

cc:
Mallecia Sutton, NRC
William Jessup, NRC
Nathan Howard, DOE
Jeff Ciocco, DOE

ENCLOSURE 1

TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))

Enclosure 1
TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))

I, George Wilson, hereby state:

1. I am the Vice President, Regulatory Affairs and I have been authorized by TerraPower, LLC (TerraPower) to review information sought to be withheld from public disclosure in connection with the development, testing, licensing, and deployment of the Natrium^{TM} reactor and its associated fuel, structures, systems, and components, and to apply for its withholding from public disclosure on behalf of TerraPower.
2. The information sought to be withheld, in its entirety, is contained in Enclosure 3, which accompanies this Affidavit.
3. I am making this request for withholding, and executing this Affidavit as required by 10 CFR 2.390(b)(1).
4. I have personal knowledge of the criteria and procedures utilized by TerraPower in designating information as a trade secret, privileged, or as confidential commercial or financial information that would be protected from public disclosure under 10 CFR 2.390(a)(4).
5. The information contained in Enclosure 3 accompanying this Affidavit contains non-public details of the TerraPower regulatory and developmental strategies intended to support NRC staff review.
6. Pursuant to 10 CFR 2.390(b)(4), the following is furnished for consideration by the Commission in determining whether the information in Enclosure 3 should be withheld:
    a. The information has been held in confidence by TerraPower.

    b. The information is of a type customarily held in confidence by TerraPower and not customarily disclosed to the public. TerraPower has a rational basis for determining the types of information that it customarily holds in confidence and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application and substance of that system constitute TerraPower policy and provide the rational basis required.

    c. The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR 2.390, it is received in confidence by the Commission.

    d. This information is not available in public sources.

    e. TerraPower asserts that public disclosure of this non-public information is likely to cause substantial harm to the competitive position of TerraPower, because it would enhance the ability of competitors to provide similar products and services by reducing their expenditure of resources using similar project methods, equipment, testing approach, contractors, or licensing approaches.

I declare under penalty of perjury that the foregoing is true
and correct. Executed on: March 17, 2023

George Wilson

George Wilson
Vice President, Regulatory Affairs
TerraPower, LLC

ENCLOSURE 2

TerraPower, LLC
White Paper, NAT-3049
Nascent Thermal Hydraulic Model White Paper

Non-Proprietary (Public)

Controlled Document - Verify Current Revision

Document Title: Nascent Thermal Hydraulic Model White Paper				
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REVISION HISTORY

Revision No.	Effective Date	Affected Section(s)	Description of Change(s)
0A	03/15/2023	Cover Page	Revised export control marking on cover page
0	03/01/2023	All	Initial Issue

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ACRONYMS

Acronym	Definition
ANL	Argonne National Laboratory
CTD	Cheng-Todreas Detailed friction factor model
CRBR	Clinch River Breeder Reactor
CFD	Computational Fluid Dynamics
CCH	Core Cooling Hydraulics
CTA	Core Thermal Analysis
DNS	Direct Numerical Simulation
FFTF	Fast Flux Test Facility
FoM	Figure of Merit
FCCI	Fuel-Cladding Chemical Interaction
GPU	Graphical Processing Unit
HCF	Hot channel Factors
IKE	Isokinetic Extraction
LES	Large Eddy Simulation
LDA	Laser Doppler Anemometer
OSU	Oregon State University
RANS	Reynold Averaged Navier-Stokes
SET	Separate Effects Tests
SFR	Sodium Fast Reactor
SEM	Spectral Element Method
T/H	Thermal Hydraulic

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SYMBOLS AND DEFINITIONS

Symbol	Definition
$A_{x,i}$	Axial flow area for subchannel i
C	Nascent model tuning parameter
C_{fbT}	Turbulent assembly friction factor coefficient [5]
C_{fbL}	Laminar assembly friction factor coefficient [5]
c_p	Coolant specific heat capacity
f_b	Darcy friction factor for an assembly
G_k	Conduction shape factor
L	Axial length of the fueled region of an assembly
l_k	Centroid-to-centroid distance between the subchannels that are joined by gap k
$\dot{m}_i$	Coolant axial mass flow rate in subchannel i
$\dot{m}_{\text{tot}}$	Coolant axial mass flow rate for an entire assembly
Q_i	Heat deposited in subchannel i
Re_b	Assembly Reynolds number
s_k	Width of gap k. For interior subchannels, this is the distance between two adjacent rods. For peripheral subchannels, this is the distance between a rod and the adjacent duct wall.
T	Coolant temperature
T^+	Dimensionless coolant temperature
$T^+_{i,\text{out}}$	Dimensionless coolant temperature at the top of the fueled length for subchannel i
T_{in}	Assembly inlet temperature
ΔT_{avg}	Assembly mixed-mean temperature rise
W_{dT}	Subchannel friction factor parameter [5]
W_{dL}	Subchannel friction factor parameter [5]
W_{sT}	Subchannel friction factor parameter [5]
W_{sL}	Subchannel friction factor parameter [5]
X	Flow split; the ratio of the axial coolant velocity in a subchannel to the average velocity for the assembly.
x	Axial coordinate
ϵ_k^{*H}	Effective eddy diffusivity for heat
λ	Coolant thermal conductivity
Ψ_i	The set of gaps that border subchannel i

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1 PURPOSE

This white paper presents TerraPower, LLC's (TerraPower) work in developing a Thermal Hydraulic (T/H) model, and a summary of the model's planned use within the analytical methods selected for use with the Natrium™ Reactor , a Terrapower and GE-Hitachi technology.

2 SUMMARY

This document describes the Natrium T/H methodology for predicting the coolant temperature distribution within core assemblies. Specifically, the Nascent (Natrium Simplified Coolant Energy Transport) model used to predict the steady-state peak coolant temperature in an assembly subchannels.

The discussion covers the method itself, the tuning process for model parameters, and the validation process.

This document provides information on:

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3 BACKGROUND / INTRODUCTION

This section provides context for the Nascent model. First, the Natrium fuel assemblies and the peak cladding temperature—an important figure of merit—are introduced as these topics are the focus of the Nascent model. Next, the role that the Nascent model meets in the Core Cooling Hydraulics methodology is described. Finally, the related topics of the Mongoose++ subchannel solver and Hot Channel Factors are briefly discussed.

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3.1 Natrium Fuel Assemblies

The initial fuel planned for use with the Natrium reactor is referred to as the Type 1 fuel design. The image below shows a cross section sketch of a Type 1 fuel assembly.

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Figure 1. Natrium Type 1 Assembly Sketch

The fuel assemblies include [[ ]]$^{(a)(4)(ECI)}$ fuel pins spaced in a triangular lattice and contained in a hexagonal duct. Spacing between the fuel pins is maintained by a helical wire wrap.

One key Figure of Merit (FoM) used in the analysis of Natrium fuel assemblies is the peak cladding temperature. This is an important FoM because the performance of the fuel cladding can be degraded by the temperature-dependent phenomena such as thermal creep and Fuel-Cladding Chemical Interaction (FCCI).

3.2 Use of the Nascent Model in T/H Analysis

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3.3 Relationship Between Mongoose++ and the Nascent Model

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3.4 Relationship Between the Nascent Model and Hot Channel Factors

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4 THE NASCENT MODEL

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4.1 Modeled phenomena

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4.2 Simplifications

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4.3 Model equations

In this model, temperatures are expressed in the dimensionless form,

$$T^{+} = \frac{T - T_{\text{in}}}{\Delta T_{\text{avg}}} \tag{4-1}$$

where T is the temperature of interest, T_{in} is the assembly inlet temperature, and ΔT_{avg} is the average assembly temperature rise which is computed from the assembly energy balance.

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5 TUNING AND VALIDATION PLAN

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5.1 Sources of Tuning and Validation Data

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5.1.1 Electrically-heated Rod Bundles

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5.1.2 High-fidelity CFD

High-fidelity CFD simulations will be used to produce both tuning and validation data for Natrium T/H tools. These simulations will be performed using the Nek5000 and/or NekRS CFD codes developed at Argonne National Laboratory (ANL). (For the purposes of this discussion, the Nek5000 and NekRS codes are practically interchangeable. NekRS is an evolution of Nek5000 that is designed explicitly for next-generation computers such as GPUs, but both tools share the same fundamental physics modeling).

The Nek series of CFD solvers offer many important features which together lead to a step change in predictive capability over more typical CFD methods. One important feature is the ability to analyze turbulent flows with the Large Eddy Simulation (LES) method. LES falls in the class of *turbulence simulation* methods as opposed to *turbulence modeling*, a distinction made by Pope [6], among others. In turbulence simulation methods some portion of the turbulent structures are resolved explicitly, and a realization of their time-dependent evolution is computed. Direct Numerical Simulation (DNS) is another example of a simulation method. The difference between these is that DNS calculations resolve turbulence at all spatial scales whereas LES only resolves turbulence on the larger scales. Specifically, LES resolves turbulence at the “inertial” scales which contain the bulk of the energy in the system and are most dependent on the problem geometry [7]. Turbulence at lower scales is expected to be more universal across problems and therefore more predictable via simple “subgrid” models [7]. Both LES and DNS are considered a sharp contrast from turbulence modeling approaches such as Reynold Averaged Navier-Stokes (RANS) which are more approximate and therefore less predictive.

LES is a broad category, and many LES methods have been devised with differing levels of predictive capability. One advantage of the Nek codes is that they offer *consistent* LES methods—methods that are consistent with DNS in that they do not add any artificial dissipation when the turbulence is fully resolved. This means that with sufficiently fine numerical discretization, consistent LES methods are exactly as predictive as DNS. This contrasts with some LES methods such as the Smagorinsky model which introduces some artificial dissipation regardless of the discretization [7].

Another important feature of the Nek codes is that they use the Spectral Element Method (SEM) for spatial discretization. In this method, the mesh is partitioned into many elements and the solution fields are represented with high-order polynomials on those elements. Because the domain is divided into elements, it is possible to represent complex geometries such as fuel assemblies. (This is contrast to some codes that use pseudo-spectral methods and are limited to simple domains like Cartesian boxes). Because high-order polynomials are used, the method provides the high-order convergence in terms of spatial resolution. The high-order convergence reduces the computational cost of high-resolution simulations and makes them feasible on existing computers.

Spatial resolution convergence studies are commonly employed with the Nek codes. Typically, a simulation is run at a given polynomial order for some number of time steps, then it is “restarted” at a higher polynomial order using the lower-order solution as the initial condition, and then it is run for more time steps. The convergence of the results can be assessed in post-processing by comparing the statistical solutions from the two different polynomial orders.

The points above can be summarized as follows:

- Any errors introduced by subgrid turbulence modeling decrease with increasing spatial resolution.
- SEM makes very high spatial resolution achievable.
- Spatial convergence can be practically assessed by polynomial refinement studies.

Considering these advantages together, the Nek codes provide the user with powerful control over turbulence approximation errors. For this reason, Nek simulations utilizing the features discussed here are considered more trustworthy than typical CFD methods and appropriate for both the tuning and validation of other T/H methods when used alongside experimental data.

Published research results for both nuclear and non-nuclear applications provide confidence in the validity of the Nek codes. For example, El Khoury et al. report DNS calculations run with Nek5000 [8]. This study notes many features of the predicted flow that match both experimental observations and DNS results from other work. Walker et al. report a detailed study of Nek5000 LES results for channel flow and flow past a bare (not wire-wrapped) hexagonal rod bundle [9]. This study is noteworthy because it quantifies the effects of the LES models and demonstrates increasing accuracy with increasing spatial resolution. The channel results compare well with DNS results found by others, and the rod bundle results compare well against experimental measurements by Krauss and Meyer [10]. Nek5000 LES results also compared favorably against experimental LDV (Laser Doppler Velocimetry) and thermocouple temperature data in a blind benchmark exercise of fluid mixing in a T-junction [11, 12].

The previously discussed publications focus on relatively simple geometries (channels, pipes, and rod bundles), but others have demonstrated the utility of the Nek codes on more complex geometries as well. Goth et al. compare Nek5000 LES calculations to experimental PIV (Particle Image Velocimetry) results of a wire-wrapped hexagonal rod bundle [13]. Makarashvili et al. compare Nek5000 LES calculations to experimental PIV data of a square rod bundle with a spacer grid [14]. These examples along with many others not listed here indicate that the Nek codes are general CFD tools applicable to a wide variety of problems including those of interest to the Natrium project.

High-fidelity CFD calculations have some advantages and some disadvantages relative to the other data sources considered here that are worth noting. One advantage of these calculations is that they are not subject to the same measurement uncertainties seen in experiments. Physical experiments must rely on thermocouples, pressure taps, pitot tubes, and other instruments that are subject to inherent uncertainties. Physical limitations place constraints on the number of these instruments and the locations that they can sample. In contrast, flow variables from a CFD solution are represented to very high precision in the computer, and the values at any simulated location can be observed. There may be a bias caused by insufficient temporal/spatial refinement or statistical uncertainty due to a finite sampling window, but these artifacts can be controlled and reduced by procedure. Similarly, the problem geometry is defined precisely in a numerical experiment, and it is not subject to the same type of uncertainties introduced by the manufacturing process for parts of a physical experiment.

However, these calculations are subject to other sources of error. Like any computer program, an error in the source code can potentially go unnoticed and lead to biased results. Consequently, quality assurance controls must be applied to mitigate these. Discretization errors may also bias the results, and refinement procedures are needed to control these. The same is true for the simulation boundary conditions. Furthermore, some approximations to the physics and geometry will be applied to reduce the computational cost and make the simulations achievable. For example, all problems will likely assume a constant molecular viscosity rather than a temperature-dependent one. Similarly the coolant density will typically be assumed constant and the Boussinesq approximation may be applied for buoyancy. The extreme computational cost of these simulations also places a practical limit on the size of the problem that can be studied. [[ ]]$^{(a)(4),(ECI)}$ These limitations mean that the high-fidelity CFD calculations cannot supplant the

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role of experiments, but they can complement the experiments and serve a crucial role in the tuning and validation of the Nascent model.

5.1.3 RANS CFD

RANS CFD calculations will also be used in a limited fashion to provide tuning data for the Nascent model. RANS models are approximations and consequently introduce uncertainties, but these types of CFD calculations still have significant predictive capability because they explicitly resolve the problem geometry and the 3-dimensional mean flow field. They are also much more computationally efficient than high-fidelity CFD tools which allows for studies that cover large geometries and many flow conditions.

The Natrium project will use Simcenter STAR-CCM+ from Siemens to perform these calculations. [[

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5.1.4 Separate-Effects Experiment Tests (SETs)

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One challenge is that the legacy SETs of interest were not performed under 10 CFR Appendix B or NQA-1 programs. Therefore, an existing data qualification process will be applied to assess the quality of the output data. This process will focus on the "quality assurance program equivalency" and "data corroboration" methods. The equivalency method will consider documented controls used by the experiments such as test procedures, as-built measurements, equipment calibration, and uncertainty quantification activities. The data corroboration method will identify any agreement and disagreement between different tests that study similar systems.

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5.3 Parameter Tuning Process

5.3.1 Tuning Friction Factor Parameters

The friction factors are tuned by a variety of input data sources and provide versatility for multiple downstream applications. Friction factors that represent the assembly as a whole can be computed directly from pressure drop tests. Other applications—including the low order model—need different friction factors for each type of subchannel in an assembly (interior, edge, and corner). These require more detailed data sources that can resolve the intra-assembly velocity distribution, but the output subchannel friction factors must also be consistent with the assembly friction factors. The following diagram indicates the data dependencies in the tuning process.

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Figure 2. Data Dependencies Associated with Friction Factor Tuning

The details of tuning the assembly and subchannel friction coefficients are discussed in the following subsections.

5.3.1.1 Assembly Friction Coefficients

The equation forms from the Chen-Todreas family of friction factor correlations will be used here. In the turbulent range the assembly friction factor is represented as,

$$f_b = \frac{C_{fbT}}{\mathrm{Re}_b^{0.18}} \tag{5-1}$$

where C_{fbT} is a constant parameter and Re_b is the assembly Reynolds number. In the laminar range, it is instead represented as,

$$f_b = \frac{C_{fbL}}{\mathrm{Re}_b} \tag{5-2}$$

The friction factor for transitional flows is interpolated using both the laminar and turbulent expressions.

In the Chen-Todreas family of correlations the C_{fbT} and C_{fbL} coefficients are determined from subchannel-specific coefficients which are in turn rely on parameters such as W_{dT} , W_{dL} , W_{sT} , and W_{sL} . See Cheng and Todreas for a discussion of these parameters [5]. [[

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5.3.1.2 Subchannel Friction Coefficients

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5.4 Tuning wire-induced mixing parameters

The helical wire wraps traverse back-and-forth through rod-to-rod gaps, increasing the fluid mixing. Over sufficiently large axial distances (comparable to the axial wire pitch) this leads to an effective

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diffusion of energy and other transported quantities between the adjacent subchannels. In the Nascent model, this diffusion is modeled with the term that includes the ϵ_k^{*H} parameter, the dimensionless effective eddy diffusivity.

The Cheng-Todreas mixing correlation is proposed to evaluate this parameter for all Natrium assemblies [5]. This correlation will be assessed by a variety of data sources. The correlation coefficients may be updated using the same data sources if the assessment finds inaccuracy. The data sources are:

- Legacy tracer injection experiments: These experiments study the transport of salt or hot water injected into the coolant.
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- LES calculations: Mixing will [[ ]]$^{(a)(4)}$ be inferred from singly-heated rod simulations using prototypical pin and wire dimensions.

This phenomenon contrasts with the flow split phenomenon in that it is not expected to depend strongly on the number of pins in the assembly. A tracer injection study by Hanson and Todreas finds that ϵ_k^{*H} values are similar for both the interior and the edge regions of a wire-wrapped assembly [15]. Similarity between the edge and interior regions indicates that the different ratios of corner, edge, and interior subchannels caused by differing pin numbers will not have an impact on the coolant mixing. [[

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5.5 Tuning the C Parameter

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6 PRELIMINARY NASCENT MODEL PREDICTIONS

This section presents example results from the Nascent model and compares them to Mongoose++. The purpose of this exercise is to demonstrate that the Nascent model adequately reproduces the same peak fluid temperature predicted by Mongoose++ for cases of interest despite the fact that the Nascent model makes many simplifications relative to Mongoose++. This indicates that the Nascent

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model sufficiently accounts for the important phenomena. Note that the results presented here are preliminary given that the tuning and validation activities described above have not yet occurred.

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Figure 3. Example calculation with flat power distribution.

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Figure 4. Example calculation with skewed power distribution.

These figures demonstrate important characteristics of typical assembly temperature distributions. There is a large temperature difference between the interior and edge regions due to the vastly different power-to-flow ratios for the interior and edge subchannels. Subchannels adjacent to the edge subchannels have their temperature significantly depressed by mixing and conduction. As the second figure above demonstrates, a skewed power distribution can lead to a peak temperature which is near the periphery of the assembly. In this near-edge region, the skewed power distribution competes with the interior-to-edge diffusion to set the peak temperature. [[

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Figure 5. Nascent Model versus Mongoose++ Peak Temperatures for a 1/3-Core Reactor Model

[[ ]](a)(4) This suggests that the Nascent model provides similar performance to the Mongoose++ subchannel solver for this particular application while greatly reducing the computational burden and model complexity.

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