BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE APPLICATION OF NAVIGATOR HEARTLAND GREENWAY, LLC FOR A PERMIT UNDER THE SOUTH DAKOTA ENERGY CONVERSION AND TRANSMISSION FACILITIES ACT TO CONSTRUCT THE HEARTLAND GREENWAY PIPELINE IN SOUTH DAKOTA	**HP22-002** **DR. JOHN ABRAHAM INITIAL PRE-FILED TESTIMONY IN SUPPORT OF LANDOWNER INTERVENORS**

Q: Please state your name and purpose for providing testimony in this proceeding.

A: My name is Dr. John Abraham. The purpose of my testimony is to provide the South Dakota Public Utilities Commission (Commission) with information that will be helpful when it considers Navigator's proposed hazardous carbon dioxide (CO_2) pipeline in South Dakota. Specifically, I have reviewed Navigator's "Heartland Greenway System Plume Modeling and Buffer Overview" and provide testimony regarding the shortcomings of the PHAST computer model used by Navigator in its preparation of this overview. I caution the Commission not to rely upon conclusions drawn from PHAST modeling, specifically as it relates to the "buffer" distances Navigator provides. My ultimate opinion is that PHAST modeling is not the gold standard, and should not be relied upon by the Commission for its review and decision making. It is not wise to rely upon PHAST modeling for assessments of risk or to determine impacts to safety, land use, or economic, environmental, social or general welfare concerns. Doing so would be a disservice to the people of South

Dakota. Relatedly, I provide opinions concerning the diffusion of CO_2 following a leak or rupture or other unintended release event.

Q: How did you become involved in these proceedings?

A: I was contacted by Brian Jorde who represented himself as legal counsel for many concerned South Dakota citizens and landowners. Mr. Jorde asked if I would review the Navigator "Plume Modeling and Buffer Overview" and provide an opinion on the methodology employed by Navigator in that report, discuss its shortcomings, if any, related to Navigator's analysis, and render an opinion to a reasonable degree of scientific certainty on whether or not the "Plume Modeling and Buffer Overview" contains accurate information that the Commission can rely upon. Mr. Jorde asked me to provide a general opinion on whether the Commission should consider PHAST modeling to be reasonably reliable, as well as a more specific opinion on whether the Commission should rely on and give weight to Navigator's Plume Modeling and Buffer Overview when it considers the potential impacts of a pipeline rupture on community safety, land use development, and economic, environmental, social and general welfare concerns of the directly affected current landowners, persons and businesses in proximity to the proposed pipeline route, as well as expected future inhabitants of the region. Additionally, I was told by Mr. Jorde that, to his knowledge, Navigator has not shared this overview with the public or first responders or others, so I do not divulge Navigator's specific buffer areas or amounts here and instead construct my testimony and render opinions without divulging Navigator's claimed "Confidential" buffer areas.

I will discuss different approaches for calculating plumes from CO_2 pipeline leaks. The calculations provide insight regarding how far a particular plume of CO_2 may reach given environmental conditions and local topography. I will discuss the origins, strengths, and weaknesses of two competing approaches (PHAST modeling and computational fluid dynamics (CFD) modeling), and why PHAST should not be used to assess the risk of harm from the rupture of a CO_2 pipeline.

Q: What experience, education, training, or background qualify you to provide opinions and your concerns as you have hearing?

A: In my professional capacity, I teach, consult with companies, and carry out research on a wide-range of engineering topics, in particular thermal-fluid sciences. The descriptor thermal-fluid sciences refers to the flow of heat and fluids (fluids include liquids, such as water; gases, such as air or other vapors; and supercritical fluids, such as supercritical CO_2).

I teach courses to both undergraduate and graduate students on topics related to thermal sciences; among my regular teaching duties are Heat Transfer (a senior-level engineering course) and Advanced Thermal Design (a graduate-level course).

As a researcher, I have produced 272 scientific journal publications, given approximately 150 scientific presentations, written 37 book chapters, obtained 16 patents, with 5 applications in process. I have also edited 21 major works and written 3 books.

I am the Editor in Chief at two scientific journals (Numerical Heat Transfer part A and Numerical Heat Transfer part B) that specialize in numerical modeling of thermal fluid problems. I am the series editor of Advances in Heat Transfer, which is the most prestigious book series in heat transfer. I am also the series editor of Advances in Numerical Heat Transfer. I have won numerous awards that are listed in my CV and I serve on multiple editorial advisory boards

My education, experience, training, and background is fully described in my CV of which a true and accurate copy is found in **Attachment No. 1**.

Additionally, I have consulted for industry for approximately three decades. In total, I have been retained by approximately 60 companies on a variety of subject matters in engineering, including the use of CFD modeling. CFD refers to a technique of flow prediction. The process involves the placement of computational grid cells throughout the fluid region, then fluid parameters such as velocity, pressure, turbulence level, temperature, density, etc. are calculated at each of these computational grid cells. When the elements are reviewed as a whole, the picture of the real flow patterns becomes apparent. I have authored two recent book chapters on CFD modeling that provide a background to the method:

- *J.P. Abraham, S. Bhattacharya, L. Cheng, and J.M. Gorman, A Brief History of and Introduction to Computational Fluid Dynamics, in Computational Fluid Dynamics, edited by: Suvanjan Bhattacharya, published by IntechOpen, 2021.*

- *J. Gorman, S. Bhattacharya, J.P. Abraham,, L. Cheng, Turbulence Models Commonly used in CFD, in: Computational Fluid Dynamics, edited by: Suvanjan Bhattacharya, published by IntechOpen, 2021.*

I have also published many dozens of studies that use CFD modeling; these studies are listed in my CV. CFD is a mature science, it is easily accessible to trained enginees and the software is easily available.

Finally, I have been involved in numerous litigations and have been recognized multiple times as an expert in CFD modeling.

Q: What materials and data did you review and consider prior to rendering your expert opinions provided here?

A: I reviewed the following documents for this testimony:

Documents related to the Satartia rupture:

Navigator Heartland Greenway System Plume Modeling and Buffer Overview (undated)

PHMSA Failure Investigation Report - Denbury Gulf Coast Pipelines, LLC (May 26, 2022)

PHMSA Notice of Probable Violation (May 26, 2022)

PHMSA Notice of Probable Violation and Proposed Compliance Order (January 31, 2023)

Response of Denbury LLC to Proposed Compliance Order (March 2, 2023)

PHMSA Consent Order and Consent Agreement (March 24, 2023)

PHMSA Incident Database Entry for February 22, 2020 Rupture of Denbury Pipeline Near Satartia, Mississippi (last updated by Denbury on March 21, 2020)

Wunderground.com weather data for Jackson-Evers International Airport Station on February 22, 2020 (nearest National Weather Service Station to Satartia)

Scientific Papers:

Godbole, A., X. Liu, G. Michal, B. Davis, C. Lu, K. Armstrong, C. Medina, *Atmospheric Dispersion of CO2 following Full-Scale Burst Tests,* 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, October 21-25, 2018, Melbourne, Australia.

Huiru, W., Y. Zhanping, M. Fan, L. Bin, H. Peng, *Study on Dispersion of Carbon Dioxide over the Shrubbery Region*, Frontiers in Energy Research, Vol. 9, article 695224, 2021.

Liu, X., A.R. Godbole, C. Lu, G. Michal, *Investigation of Terrain Effects on the Consequence of Distance of CO2 Released from High-Pressure Pipelines*, Faculty of Engineering and Information Sciences – Papers: Part B, 995, 2017

Liu, X., A. Godhole, C. Lu, G. Michal, P. Venton, *Optimisation of Dispersion Parameters of Gaussian Plume Model for CO2 Dispersion*, Environmental Science and Pollution Research, Vol. 22, pp. 18288-18299, 2015.

Mack, A., M.P.N. Spruijt, *CFD Dispersion Investigation of CO2 Worst Case Scenarios Including Terrain and Release Effects*, 7th Trondheim CCS Conference TCSS-7, June 5-6, 2013, Trondheim, Norway.

Witlox, H.W.M., A. Holt, *A Unified Model for Jet, Heavy and Passive Dispersion Including Droplet Rainout and Re-evaporation*, CCPS 1999, UDM paper.

Witlox, H.W.M., M. Harper, A. Oke, *Modelling of Discharge and Atmospheric Dispersion for Carbon Dioxide Releases*, Journal of Loss Prevention in the Process Industries, Vol. 22, pp. 795-802, 2009.

Witlox, H.W.M., M. Harper, A. Oke, *PHAST Validation of Discharge and Atmospheric Dispersion for Pressurized Carbon Dioxide Releases*, Hazards XXIII Symposium Series 158, pp. 172-182, 2012.

Woolley, R.M., M. Fairweather, C.J. Wareing, et al., *CO@PipeHaz: Quantitative Hazard Assessment for Next Generation CO2 Pipeline*, GHGT-12, October, 2014, Austin, USA.

Q: Please describe PHAST modeling and its weaknesses as a predictive tool, if any.

A: PHAST modeling is a simplified approach to estimate where a plume will travel following a rupture or a leak. The method is discussed in publications such as Witlox and Holt, (1999). While parts of PHAST originated earlier than this publication, the 1999 paper provides a thorough discussion.

As revealed in the 1999 paper, the PHAST model is based on wind tunnel experiments from other researchers. These wind tunnel experiments were needed to obtain parameters that were used to force the model to match experimental results (termed “tunable parameters”). It is noteworthy that actual ruptures, such as the February 22, 2020 rupture of the Denbury pipeline near Satartia, Mississippi, are not in wind tunnels and so any wind-tunnel experiments would be irrelevant for Satartia or other real-world ruptures.

PHAST was also premised assuming a horizontal release, not a rupture like Satartia where a significant portion of the CO_2 was released vertically.

PHAST assumes that some plumes can take and maintain a perfectly spherical shape and that other plumes can maintain circular cross sections as they move downstream; this does not occur in real life.

Another weakness of PHAST is that it cannot account for changes in topography, which is an important factor for dense gases like CO_2 or for locations like Satartia that are in hilly topography.

Another feature of PHAST is that the cloud moves with a single velocity as it travels with the wind – this too is an unrealistic assumption.

It is noteworthy that when Witlox and Holt compared their calculations with experiments, they found errors of ~ 500% less than half a mile from the release site – with PHAST dramatically underestimating the concentration of released gases.

Other studies confirm that PHAST cannot be used to provide high fidelity plume calculations. In Witlox, Harper, and Oke, (2012), the calculations diverged from experiments after a distance of only about 30 m. Clearly, PHAST would be unable to calculate concentrations for a very different situation, for example over long distances (of about 1000 meters or more).

Based on my review of the enforcement documents prepared by the Pipeline and Hazardous Materials Safety Administration (PHMSA) for the Satartia rupture, I learned that a PHAST calculation was performed by Denbury prior to the Satartia rupture to determine if its pipeline posed a risk to the village. In its March 24, 2023 Consent Agreement with Denbury (available at:

https://primis.phmsa.dot.gov/Comm/reports/enforce/documents/42022017NOPV/42022017NOPV_Consent%20Agreement%20and%20Order_03242023_(20-176125).pdf), PHMSA reported that "the earlier PHAST dispersion analysis was wrong." Denbury's reliance on this pre-rupture dispersion model is also confirmed in PHMSA's May 26, 2022 Notice of Probable Violation (available at: https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/42022017NOPV_PCO%20PCP_0526022_%2820-176125%29%20-%20Denbury%20Pipeline.pdf), and in PHMSA's May 26, 2022 Failure Investigation Report (available at: https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf).
Consequently, from the information available to me, I conclude that Denbury – and unfortunately, every community where this particular pipeline was located – inappropriately relied upon a calculation approach that should have been known by Denbury, and its consultants, to be unable to incorporate critical factors necessary to determine the risks that its pipeline posed to Satartia and to vastly under-predict downstream gas concentrations.

Q: Is there a superior or preferred alternative to PHAST that is more accurate and reliable, and if so, please describe that superior modeling technique.

A: Yes, there is. The gold-standard and more accurate modeling technique and tool is known as CFD modeling, the computational fluid dynamics modeling referenced previously.

CFD modeling is becoming increasingly used in CO_2 pipeline rupture dispersion calculations (Huiru et al., 2021). This method has been effectively used and is able, for example, to handle different terrains (Godbole et la., 2018; Woolley et al., 2014; Mack and Sprujit, 2013; Liu, Godbole, Lu, and Michal, 2017).

CFD modeling does not suffer the same weaknesses as PHAST. There are no tunable parameters that need to be carefully set. It can handle the impacts of variable terrain and non-horizontal leaks; it is able to simulate plumes that are not perfectly spherical or that have non-circular cross sections. With CFD modeling, the cloud does not move with a single velocity. Since CFD modeling can account for these variables, whereas PHAST does not, CFD modeling can yield more accurate calculations and predictions than PHAST. The advantages of CFD over PHAST are known in the scientific community and are expressed, for example, by Liu et al., 2015, as follows:

> The above studies represent examples of the application of the three categories of dispersion models—Gaussian-based, similarity-profile and CFD-based. In general, CFD models are the most adaptable and are able to produce better prediction, as they use more detailed mathematical descriptions of the conservation principles. This allows the simulation of complex physical processes involving heat and mass transport in complicated computational domains (Pontiggia et al. 2009). The main drawback of CFD models is that they are often difficult and time-consuming to set up and run. Furthermore, detailed meteorological measurements and topographic data, which are essential inputs to the CFD model, are often unavailable. Gaussian and similarity-profile models are unable to model the flow over obstacles or across complex terrains (Sklavounos and Rigas 2004). However, their main advantage is that they are relatively easy to use and provide quick estimates of dispersion.

From Liu et al., 2015

Q: Given that Navigator is requesting Commission approval for a perpetual location of their proposed hazardous CO_2 pipeline, do you have an opinion as

to whether the Commission should rely when deciding on the Navigator Application upon Navigator's PHAST modeling data and the buffer areas it generated as discussed and described in Navigator's "Heartland Greenway System Plume Modeling and Buffer Overview", and if so, what is your opinion?

A: My opinion, which is provided to a reasonable degree of professional scientific certainty, is that the Commission should not rely upon Navigator's PHAST modeling or the data and buffers that such flawed modeling provides. CFD modeling should occur and that modeling should be further scrutinized. The Commission would be wise to take more robust, accurate and dynamic CFD modeling into account before approving or denying Navigator's Application. PHAST modeling is known to underestimate gas concentrations and is unable to deal with a number of critical factors including but not limited to topography and turbulence. Furthermore, newer, more accurate methods are available that can provide more accurate concentration calculations.

Had such CFD modeling been performed prior to construction of the Denbury Satartia pipeline, the citizens, landowners, local and state governments, and decision makers would have had more accurate data when considering the proposed location of the pipeline and when evaluating possible mitigation conditions. Further, the surrounding communities, first responders, and residents would have been empowered with the most reliable data and information available to prepare for a rupture and protect themselves by mitigating the known, predictable risks resulting from a rupture of this pipeline. CFD modeling calculations would have provided more accurate knowledge and awareness of the actual danger zones, such that the negative fallout and effects of a rupture on the residents and community would have been greatly minimized or prevented.

Translating this analysis to the current proposed Navigator CO_2 pipeline at issue here, the Commission, if empowered with accurate CFD modeling, would be in a position to determine whether the actual risks associated with the proposed pipeline are simply too great for the landowners, other residents, and businesses near the proposed route, and the State of South Dakota as whole, to bear.

Q: Do you have an opinion as to Navigator's buffer distances as listed in its "Heartland Greenway System Plume Modeling and Buffer Overview" and, if so, what are your opinions?

A: Yes, based on Navigator's modeling, it is more likely than not that all of Navigator's stated buffer distances including, initial routing, design and operations, emergency response, and public awareness are under reported, inaccurate, and unreliable for use in the major decisions the Commission will make.

Q: Do you have an opinion as to concepts of "aspirational buffers" applied "where feasible and practical" in relation to a pipeline company's proposed pipeline locating decisions, and specifically in relation to your review of Navigator's buffers, and if so, what are those opinions?

A: Buffer distances and setbacks should be driven by the best available scientific means and modeling. If the goal is to evaluate the potential impacts of a pipeline rupture on current and future residents, land uses, businesses, and other uses, the buffers and setbacks should not be "aspirational;" they should be grounded in science and established to best protect both existing and future inhabitants and land uses. The concept of "where feasible and practical," when defined in terms of a pipeline company's perspective, is not a best practice. I encourage the Commission to consider Navigator's Application in light of the most accurate scientific information available including CFD modeling, and to evaluate the proposed project based on consideration of whether or not all buffer zones and setbacks are supported by CFD modeling, and not based on Navigator's self-interested judgment about whether a buffer zone or setback is "feasible and practical."

Q: Have all of your opinions expressed herein been provided to a reasonable degree of scientific professional certainty and been informed by your education, training, background, and experience?

A: Yes, they have, and I reserve the right to amend or modify these opinions upon presentation of any additional information that may justify such a change, if any.

/s/ Dr. John Abraham
Dr. John Abraham