**BEFORE THE PUBLIC UTILITIES COMMISSION**
**OF THE STATE OF SOUTH DAKOTA**

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| **IN THE MATTER OF THE APPLICATION OF NAVIGATOR HEARTLAND GREENWAY, LLC FOR A PERMIT UNDER THE SOUTH DAKOTA ENERGY CONSERVATION AND TRANSMISSION FACILITIES ACT TO CONSTRUCT THE HEARTLAND GREENWAY PIPELINE IN SOUTH DAKOTA** | **HP22-002**<br><br>**DR. JOHN ABRAHAM SURREBUTTAL TESTIMONY IN SUPPORT OF LANDOWNER INTERVENORS** |

**1. Please state your name, position, and business address.**

Answer: My name is John Abraham. I am a Professor of Mechanical Engineering at the University of St. Thomas, 2115 Summit Avenue, St. Paul, MN 55105.

**2. Have you previously submitted testimony in this proceeding?**

Answer: Yes. I submitted direct testimony dated May 26, 2023, on behalf of Landowner Intervenors.

**3. To whose testimony are you responding in surrebuttal?**

Answer: I am responding to the June 23rd, 2023, rebuttal testimony of John Godfrey and Stephen Lee, both of whom submitted rebuttal testimony to my direct testimony. Since Mr. Godfrey relies on the Direct Testimony of Staff witness Mr. Byrd, I also discuss Mr. Byrd's testimony.

**4. Please summarize your testimony.**

Answer: In brief, it is my opinion that computational fluid dynamics ("CFD") calculations are more able to accurately calculate the extent of a carbon dioxide pipeline rupture plume, compared to PHAST modeling. It is further my opinion that pipeline safety should be assessed using CFD modeling. and that reasonably accurate CFD modeling is readily available and can be completed at reasonable cost and effort for Navigator Heartland Greenway's ("NHG") proposed carbon dioxide pipeline.

**5. Do you agree with Mr. Godfrey's characterization that CFD is "a catch-all term," the use of which is "problematic," especially with respect to its application to the proposed carbon dioxide pipeline?**

Answer: Mr. Godfrey states that CFD is a "comprehensive scientific and engineering approach to model a variety of fluid flow scenarios, which for CO2 would include transport and dispersion." I agree with this statement. Mr. Godfrey also states that it is "problematic to refer to CFD as a "catch-all term," and in this, he is incorrect. CFD is not a catch all term, it refers to calculations of the momentum, pressure, temperature, turbulence levels, *etc.* in a flowing fluid. In this regard, the term "fluid dynamics" means flows of gaseous, liquid, and supercritical substances. The term CFD is well known in the scientific community and its usage is not problematic. I have published perhaps 200 studies involving CFD – it is a ubiquitous tool in use by the scientific community.

Mr. Godfrey also states that there are "multiple methods, models, and computer programs available for its application. Each has its own strengths and weaknesses." While it is true that a number of computer models exist that have strengths and weaknesses, this diversity does not make the use of CFD problematic, but rather it is a matter of exercising judgment about which models to use and how to use them to accomplish specific tasks. With regard to carbon dioxide pipeline public safety, the task is to provide a reasonable estimate of the maximum distance that hazardous concentrations of carbon dioxide may spread following a rupture of a carbon dioxide pipeline. While development of a highly accurate model that takes account of all factors that influence carbon dioxide dispersion with great precision is certainly a useful undertaking, first responders and citizens who would live and/or work near a proposed carbon dioxide pipeline do not need a perfect CFD model. They need a model that will generate a reasonable estimate of the maximum extent of the danger zone for their planning purposes. Likewise, the South Dakota Public Utilities Commission ("Commission") needs and should require NHG to conduct CFD modeling before a siting permit is granted so that the Commission has a reasonable estimate of the persons, livestock, and businesses potentially put at risk by a rupture. In the event of a rupture, real world factors will determine the actual hazard zone for each rupture, and no two will be the same. Citizens, first responders, and the Commission do not need a large number of model runs conducted for many locations and conditions. They need a reasonable estimate of the hazard zone for a limited set of representative locations and a limited set of high consequence areas.

Much of the proposed route of the NHG project would pass through crop and grazing land with limited topographical variation. Applying CFD modeling to a location that is generally representative of such land would provide a reasonable estimate of the hazard zone for much of the pipeline route. This being said, there may be particular locations that due to topography and/or population density require site-specific modeling. Given the rural nature of the proposed route, it is likely that few if any locations along it would require site-specific modeling. However, the need for site-specific modeling in high consequence areas should be carefully evaluated to avoid a risk of mass casualties.

In response to the Satartia rupture, Denbury agreed to conduct an "overland spread analysis" for all route locations within two miles of all "high consequence areas." Pipeline and Hazardous Materials Safety Administration ("PHMSA") Consent Agreement and Order (March 24, 2023) at page 5, para. 19 (Attachment 1). That is, after that rupture, PHMSA determined that a future rupture of that pipeline "could affect" high consequence areas up to two miles from the pipeline. Given that CFD modeling can take account of topography and other types of dispersion modeling does not, it is likely that the term "overland spread analysis" used in the Consent Agreement refers to CFD modeling. If the term "overland spread analysis" does in fact refer to CFD modeling, then PHMSA's requirement for such modeling indicates that application of CFD modeling is practical and necessary for identifying high consequence areas near carbon dioxide pipelines. Since the proposed NHG pipelines would be constructed from six and eight-inch diameter pipe, NHG Application at 1, whereas the Denbury pipeline was 24-inch pipe, the "could affect" area for the NHG project would likely be substantially smaller, but nonetheless this area should be determined by use of CFD modeling for both for public safety and pipeline safety purposes.

While it would be theoretically possible to conduct high resolution modeling at each milepost along the pipeline route, such modeling would be time consuming, expensive, and unnecessarily precise. Instead, first responders, citizens, and the Commission need a reasonable estimate of worst-case plume dispersion. The perfect should not be the enemy of the good.

It also should be noted that the assumptions made in applying any dispersion modeling to a pipeline rupture may have as great or even greater impact on identification of the size of a hazard zone. For example, assumptions about the mass of carbon dioxide that would be released upon rupture depend on a number of factors, such as the distance between isolation valves and operating pressure and temperature. What should be modeled is a worst-case scenario based on worst-case assumptions, because to protect public safety, citizens and responders should assume the worst with regard to the size of a hazard zone. Modeling for a worst-case release would ensure that citizens evacuate to a safe distance, first responders don protective gear at a safe distance, and the

Commission understands the possible risks to human and animal life and economic interests along the route. To ensure that NHG's modeling is reasonable, it should disclose all of its assumptions so that citizens, first responders, and the Commission can confirm that NHG's modeling is reasonable, both with regard to the type of modeling and its inputs.

**6. With regard to Mr. Godfrey's statement that "comparison of a specific computer model to a general engineering approach, PHAST to CFD, has the potential to be misleading," do you agree with it?**

Answer: Mr. Godfrey states that it is misleading to compare PHAST to CFD, because PHAST is a specific form of computer model, whereas "CFD refers to a much broader scientific approach to such modeling." As I have already opined, both PHAST and CFD can be used to predict the dispersion of carbon dioxide in an airflow. PHAST is the result of very limiting mathematical simplifications. CFD models do not require use of these simplifications, such that they have the capacity to be more accurate. For example, CFD models are able to accurately model the effects of topography and the turbulent mixing of carbon dioxide and air. PHAST calculations, on the other hand, are highly idealized, result in unrealistic calculations, and produce results that should not be relied on to protect public safety. I have provided examples of the fatal flaws of PHAST modeling in my initial report, and I adopt that discussion here. To the extent I have compared CFD and PHAST, it is to highlight the weaknesses of PHAST and its inappropriateness for calculating dispersion of carbon dioxide from pipeline ruptures. Mr. Godfrey presents no basis for his claim that a comparison between more accurate CFD modeling with less accurate PHAST is "misleading."

Mr. Godfrey also generally describes the PHAST model and claims that DNV updates and validates its software based on the results of carbon dioxide release experiments. Such updates do not change the fact that the mathematical underpinnings of the PHAST model are overly simplistic. Mr. Godfrey also states that Navigator worked with DNV to determine the inputs to the PHAST modeling effort, but does not state what these inputs were, such that he provides no evidence that NHG and DNV selected reasonable worst-case inputs. As a consequence, Mr. Godfrey's testimony provides no empirical support for the quality of DNV's modeling for NHG. Poor modeling assumptions generally result in poor modeling results.

**7. Mr. Godfrey asserts that the fact that CFD modeling will produce more comprehensive results is an "academic argument," and that your direct testimony failed to address the time and effort needed to produce just one CFD model for the proposed pipeline. He asserted that a single scenario will take days to model using CFD, and that modeling multiple locations would exponentially increase time and effort, such that PHAST modeling is more practical. How do you respond?**

Answer: Mr. Godfrey admits that CFD will produce more comprehensive results compared to PHAST and I agree with him on this issue. However, Mr. Godfrey goes on to claim that the time, effort, and presumably cost to produce CFD calculations is too large to be practical. He is incorrect. The modeling time, effort, and cost of CFD modeling depends on the number of model runs conducted, the range of scenarios modeled, and the precision of the model, with more precise modeling requiring substantially more computer time than less precise modeling. The CFD modeling needed by citizens, first responders, and the Commission need not be highly accurate, because what is needed is a reasonable estimate of the worst-case hazard zone. A reasonable estimate of the hazard zone size may be produced by a less time and effort-intensive model. Further, the hazard area for most of the route through South Dakota could be assessed based on a representative flatland scenario. While CFD modeling would take time, it would take a fraction of the time needed for preconstruction development and permitting.

Some of my prior CFD modeling efforts have required remarkably high precision, whereas other modeling efforts have not. Determination of the need for precision is a matter of scientific and professional judgement based on a thorough understanding of a model, its underlying mathematics, and the purpose for the modeling.

Mr. Godfrey also claims that PHAST, even though it is less accurate, is “more practical.” I disagree. A “practical” approach is one that balances accuracy and effort. That is, a “practical” solution should be accurate enough to be useful and should be able to be performed with reasonable effort. Since PHAST is not accurate, it cannot be considered “practical,” regardless of its ease-of-use.

Highly accurate CFD calculations can easily be done to assess the risks of ruptures either in the planning phase of a pipeline or after a pipeline has been constructed. When pipelines pass close to inhabited locations, CFD calculations can easily be performed to determine whether such locations are at risk given the topography and a range of weather conditions. Such calculations could be routinely performed. Mr. Godfrey has no basis to support his claims that CFD is not practical.

Mr. Godfrey implies that the time and effort to conduct CFD modeling would be unduly burdensome in terms of cost. The cost of CFD modeling is highly dependent on the need for precision and the number of scenarios modeled. I note that Mr. Godfrey has not provided any cost estimate for performing CFD modeling for the proposed NHG pipeline or the specifications for such estimate. In the absence of such estimate, the Commission should find his opinions about time, effort, and burden to be unfounded. I also note that the cost of the proposed project is estimated to be $3.2 billion, with $142 million of that to be expended in South Dakota. NHG

Application at 4. The cost of performing CFD modeling should be considered in light of total project costs. Also, a representative flatland scenario could be applicable along most of the NHG route in the states through which the pipeline would pass, which would further reduce costs. Moreover, the cost of CFD modeling should be considered in light of the potential cost in lives and property damage that could result from a pipeline rupture. CFD modeling would cost a small fraction of project costs and is justified by the public safety risks the project would create.

**8. Mr. Godfrey relies on the testimony of William Byrd, a staff expert, for the proposition that "site specific modeling is expensive and time consuming and can't be performed until a site is selected." How do you respond?**

Answer: Mr. Byrd states that CFD modeling "can't be performed until a site is selected" (emphasis added) and that "[o]nce the route is determined, based on a variety of considerations, site-specific modeling can be performed for pipeline segments in proximity to important or vulnerable areas." This statement is clearly erroneous. In fact, CFD can be performed at any stage in the development and planning of a pipeline project. Mr. Godfrey's rebuttal testimony expressly states that DNV has already conducted PHAST modeling for NHG. If NHG has already performed PHAST modeling, then for the reasons discussed above, there is no practical reason it could not have instead performed higher quality worst-case scenario CFD modeling in a representative location and also in locations where the pipelines travel close to higher population density areas. That is, NHG could have used CFD modeling instead of PHAST modeling to estimate its buffer zones and inform its pipeline design, integrity, and emergency planning efforts.

My understanding is that the Commission does not have routing authority, meaning that in South Dakota the entity that selects the route would be the company that proposes it, and no state agency could order a route change. Absent county action on route, this means that the route for the proposed project has already been "selected" by NHG. Conducting CFD modeling instead of PHAST modeling during the company's route selection process would have been practical and provided a more accurate estimate of hazard zones.  Rather than rely on NHG's inaccurate PHAST modeling, the Commission should instead rely upon CFD modeling so as to better understand the risks that carbon dioxide pipeline ruptures create, including their possible geographic scope of impact.

Mr. Byrd's argument might be better stated to be that CFD modeling should not be performed before a pipeline is constructed, because the route might change and/or because doing so at that time would be costly and/or inefficient. Since the Commission has no authority to order a route change, it is unlikely that the vast majority of the route would change. Moreover, a representative flatland model would adequately apply to most voluntary route changes. Therefore, the possibility of limited voluntary route changes would not make performance of CFD modeling during company route selection wasteful or inefficient. In any case, Mr. Byrd provided no time, effort, or cost estimates for CFD modeling to support his opinion that "[s]ite specific modeling is expensive and time consuming," such that Mr. Godfrey's opinion that "[w]ith respect to routing, the use of CFD for site-specific modeling is not practical" appears to be unsupported by Mr. Byrd's testimony.

Finally, I note that Mr. Godfrey references Mr. Lee's testimony to admit that NHG "intends to use CFD modeling in the manner described by Mr. Byrd," an admission that reveals that NHG does not consider CFD modeling to be overly expensive or burdensome, but rather that it objects to the timing of its use. Unsupported objections to the timing of use of CFD modeling do not justify use of PHAST, which is a clearly inferior modeling technology. The Commission should require NHG to perform CFD modeling so that the Commission, citizens, impacted landowners, and first responders have a clearly superior assessment of the risks of the proposed pipelines.

**9. Mr. Godfrey asserts that "PHAST and similar programs when properly applied and understood can be useful tools to evaluate a wide range of scenarios that are important to routing a $CO_2$ pipeline and that could not practically be done using CFD." Do you agree?**

Answer: No. PHAST is an inferior tool whose primary benefit is that it is faster, easier, and therefore cheaper to use. Since a better modeling tool exists, the Commission should require that it be used. While CFD modeling would likely require more time and money, the time and cost can be mitigated by selection of appropriate levels of precision and the use of representative locations. Moreover, the marginal increase in the time and cost needed for CFD modeling almost certainly would not be significant relative to the project's multi-year development schedule and $3.2 billion cost.

**10. Mr. Godfrey asserts that the PHAST modeling done for NHG by DNV is reliable and useful, because "not every rupture scenario can be foreseen or predicted." He also states that, "even with CFD, there will be situations that the engineers implementing the model could not foresee or predict." He claims that by "hyper-focusing on a gold-standard approach," that you suggest that the proposed pipeline cannot be constructed and operated without substantially impairing the health, safety, or welfare of the inhabitants of the siting area." How do you respond?**

Answer: Use of the PHAST model does not produce reliable predictions of potential consequences. This conclusion was demonstrated by Denbury's use of PHAST prior to the Satartia rupture. The PHMSA Consent Agreement with Denbury states: "the earlier PHAST dispersion analysis was wrong." To correct this wrong, Denbury agreed to perform a different "overland spread analysis." Attachment 1 at page 5, para. 19. Denbury's use of the PHAST model resulted in Denbury failing to determine that its pipeline "could affect" Satartia. *Id*. This failure, in turn, resulted in Denbury failure to include Satartia and its first responders in the company's emergency planning and public education efforts. These were real world adverse consequences of reliance on the PHAST model. Prior to the development and widespread use of CFD modeling, use of PHAST may have been better than nothing, but now there is no reason to use this simplistic model except to limit project expenses.

While CFD modeling, and for that matter no other type of modeling, can foresee and predict all rupture scenarios, this is no reason not to use the best computer modeling approach available.

Contrary to Mr. Godfrey's claim, I do not suggest that "the proposed pipeline cannot be constructed and operated without substantially impairing the health, safety, or welfare of the inhabitants of the siting area." Pipelines do in fact rupture, and safety regulations are intended to mitigate the risk and consequences of such ruptures, but ruptures nonetheless happen. The Commission should consider the potential impacts of carbon dioxide pipeline ruptures, as well as NHG's risk and integrity management efforts to reduce their likelihood, as part of its determination of whether the proposed pipelines would substantially impair the health, safety, or welfare of South Dakotans. CFD modeling is a superior way to determine the potential impacts of a pipeline rupture, and it will provide superior information for emergency response planning purposes. Therefore, the Commission should rely on it instead of the PHAST model.

**11. Mr. Godfrey asserts that use of CFD modeling would not have made any difference in the response to the Satartia rupture. How do you respond?**

Answer: My understanding from review of PHMSA documents related to the Satartia rupture is that one of the purposes for Denbury's use of PHAST dispersion modeling was to determine the locations of high consequence areas along its pipeline that could be affected by a rupture of its pipeline. If a pipe segment "could affect" a high consequence area then additional pipeline safety requirements apply, including public education and first responder outreach requirements. The failure of the PHAST model to predict that Satartia was at risk appears to be the primary reason that local first responders and its citizens were unaware that a $CO_2$ pipeline was even in the county. If Denbury had used CFD modeling and it predicted that Satartia could be affected by a rupture, then Denbury would have been required by federal regulation to include Satartia in its public education and emergency response planning efforts. If Denbury had then conducted a public education program and outreach to local emergency responders describing how a rupture would look and smell, then the citizens and responders would have been less likely to think that a chemical release from some other source had occurred, instead of the chemical release from the pipeline. If local first responders had been informed of the risk and properly equipped with carbon dioxide detectors, then air monitoring could have started much sooner; instead, they had to wait for Denbury's air monitoring contractor to show up. The reason first responders were not forewarned and equipped in advance was because Denbury determined, based on its PHAST modeling, that Satartia was not at risk, so Denbury conducted no training with local first responders and provided no equipment or equipment recommendations to local first responders.

The purpose of plume dispersion modeling is to identify at-risk persons and communities and trigger appropriate pipeline design, integrity, and emergency response planning efforts. Mr. Godfrey seems to believe that the Denbury PHAST modeling failures were unrelated to the company's emergency response and public education deficiencies. As Mr. Godfrey has admitted, one purpose of dispersion modeling is to define the areas in which heightened pipeline integrity and emergency and risk management activities must be implemented. It follows that Denbury's reliance on the PHAST model was the root cause of all of the factors that Mr. Godfrey believes were more consequential than Denbury's use of PHAST dispersion modeling.

**12. Mr. Lee asserts that the PHAST model is reliable and is appropriate for use in modeling major carbon dioxide pipeline ruptures. Do you agree?**

Answer: Mr. Lee states that NHG conducted modeling using the PHAST and ALOHA models. The ALOHA model is a different Gaussian model that suffers from the same types of simplifications as the PHAST model. He also states that DNV validates the PHAST model by using "real world research data" including but not limited to data collected by DNV's Spadeadam planned release, which was an intentional rupture of a short test pipeline. Researchers have conducted a handful of test ruptures, some of which are described in the 2015 paper referenced by Mr. Lee's testimony: M. Ahmad *et al.*, *COSHER Joint Industry Project: Large Scale Pipeline Rupture Tests to Study CO2 Release and Dispersion*.

For a more recent list and description of test ruptures, see the July 2021 study, M. Vitali, *et al*., *Risks and Safety of CO2 Transport via Pipeline: A Review of Risk Analysis and Modeling Approaches for Accidental Releases*, Table 1 and related discussion, which study is available at: https://www.mdpi.com/1996-1073/14/15/4601. It reports that the COSHER JIP test rupture referenced by the paper cited by Mr. Lee involved the rupture of a 219 mm (8.6 inch) pipeline in low wind conditions and flat terrain. *Id*. at 6. The rupture released 136 metric tons of $CO_2$ over the course of 204 seconds. *Id*. The maximum plume height was 60 meters (197 feet), and it extended a maximum of 400 meters (1,312 feet). A video of this test rupture has been widely circulated.

In comparison, Denbury reported that over approximately 4 hours the Satartia rupture released 31,405 barrels of carbon dioxide, which PHMSA considers to be the minimum amount.

Depending on assumptions about the temperature of the carbon dioxide at the time of release and Denbury's stated pressure, I estimate that the Sartartia rupture released between 3,700 metric tons and 4,500 metric tons of carbon dioxide. This is between 27 and 33 times more carbon dioxide than the 2015 Spadeadam test rupture.

Researchers have also conducted test ruptures of 9, 24 and 36-inch diameter pipelines, but the volumes released by these tests were also relatively small.

While these tests provide "real world research data," the number of test ruptures is small, such that they do not provide data in a substantial number of topographies and weather conditions. Also, they do not release anywhere near the volume of carbon dioxide as do real-world high-volume ruptures, such as the Satartia rupture, which released at least 31,405 barrels of liquid or supercritical carbon dioxide. Even the largest test ruptures do not provide plume data that are comparable to full bore ruptures of major carbon dioxide pipelines. As such, PHAST validation efforts must be understood to be conducted based on limited experimental data.

In any case, the Satartia rupture provided the acid test for PHAST with regard to a high-volume real-world rupture. As PHMSA found, the PHAST dispersion analysis was "wrong." Attachment 1, page 5, para. 18.

**13. Does this conclude your testimony?**

Answer: Yes. I reserve the right to amend or modify these opinions upon presentation of any additional information that may justify such a change.

*/s/ Dr. John Abraham*

Dr. John Abraham