# Chapter 5

# Conclusions and Future Work

To conclude this dissertation, we present a summary of the results and analysis delivered in the previous chapter followed by an outlook for future work based on the preliminary endeavors undertaken here. The ultimate research goal achieved in this work as well as the complementary objectives met along the way serve to contribute to the body of knowledge regarding hybrid methods for neutral particle radiation transport in shielding and deep penetration applications.

## 5.1 Summary and Conclusions

In this work, the LDO equations were implemented in the Exnihilo parallel neutral particle radiation transport framework for the purpose of using the equations' solutions in Monte Carlo variance reduction parameter generation via the ADVANTG software to improve the results of simulations run with MCNP5. A small variety of test case scenarios were examined in the CADIS and FW-CADIS contexts with biasing parameters generated from flux solutions of different quadrature types to ascertain the LDO solutions' performance relative to unbiased Monte Carlo calculations as well as those with biasing parameters from standard quadrature types.

Deterministically-calculated forward and adjoint scalar flux solutions from the LDO equations were found to be comparable to those of standard quadrature types. The LDO equations saw their best-performing Monte Carlo biasing parameters in the FW-CADIS context. For the DLVN experimental benchmark, LDO variance reduction parameters generated the highest Figures of Merit for two of the six detector locations in the assembly. Of those studied here, the only other quadrature type to achieve this was the QR quadrature set. In the case of the simplified portal monitor scenario studied in the FW-CADIS context, the LDO biasing parameters attained the highest FOM values for three out of four detector locations. Considering results from the test case scenarios in which neutrons were transported using the CADIS and FW-CADIS methods, we suggest a coarse angular mesh for Monte Carlo variance reduction parameter generation based on flux solutions resultant from solving the

LDO equations. For photon transport problems, a more refined LDO angular mesh is recommended for generating Monte Carlo biasing parameters and achieving detector responses with high Figures of Merit.

In general, the LDO formulation is most useful in the specific context of Monte Carlo variance parameter generation using the FW-CADIS method for photon transport problems. It is also effective in the FW-CADIS method for neutron transport problems, though somewhat less so. However, the LDO representation is currently limited in applicability by its current implementation in the Exnihilo framework and the ADVANTG software. The problem space available to explore is limited to those with vacuum boundary conditions and isotropic fixed particle sources with non-zero volume. Adopting the LDO formulation in another radiation transport and Monte Carlo variance reduction parameter generation framework would be of interest if the framework is flexible in allowing for asymmetric quadrature sets to be used and if the framework allows for relative ease in implementing the unique features of the LDO representation such as interpolation in angle.

To conclude, we note that the novel work towards this dissertation includes the implementation of the LDO equations in a radiation transport framework as well as the study of the resultant scalar flux solutions' efficacy in Monte Carlo variance parameter generation in both the CADIS and FW-CADIS methods. The results and analysis presented here are of interest to the community at large in that the LDO representation treats particle scattering differently than the traditional discrete ordinates formulation and incorporates angular information into scalar flux solutions in a new way. This improves the performance of hybrid methods in shielding problems with highly anisotropic particle movement and particle streaming pathways when using the FW-CADIS method, especially for photon transport problems.

## 5.2 Future Work

Various avenues of future work have become apparent over the course of this work. Some facets of investigation are more rudimentary and concern details regarding the implementation of the LDO equations in a radiation transport software framework, while others are more research-oriented questions.

We will first discuss suggested future work that concerns implementation details and studies that may follow. As reflective boundary conditions are commonly used in both deterministic and Monte Carlo transport methods to reduce problem space and compute time, one of the first next steps to take would be to enable the use of reflective boundary conditions with the LDO equations in Denovo. This is less straightforward than for standard quadrature types because of the LDO equations' asymmetry in angle, but it should be possible using the interpolation property of the LDO representation. In a similar vein, enabling the use of analytic approximations of uncollided flux sources in combination with solving the LDO equations in Denovo would be a next logical development. This would enable the direct use of point sources when solving the LDO equations through the Exnihilo framework and help to mitigate the ray effects from the point sources in the resultant flux solutions.

Modifying the ADVANTG software to support more variety in deterministic calculations and Monte Carlo variance parameter generation would open doors for more interesting studies with the LDO equations as well as standard quadrature types. Specifically, implementing the use of anisotropic particle sources would allow for studies involving commonly-used directional particle sources such as beams. Additionally, generalizing the FW/CADIS-$\Omega$ methods implemented in the ADVANTG software such that quadrature sets that are not rotationally symmetric could be directly used in concert with the methods would bring about an additional channel for capturing the LDO equations' unique scattering treatment in angle-informed scalar flux solutions used to generate Monte Carlo biasing parameters. Currently, the LDO equations' deterministic flux solutions could be used in combination with the FW/CADIS-$\Omega$ methods with the use of the interpolation property of the LDO equations. This interpolation functionality does not exist in either the Exnihilo framework or the ADVANTG software at the time of this writing.

Broader research questions involving solving the LDO equations are of interest as well. The test case scenarios in this work were limited to relatively small scales with respect to computational hardware usage; studies with finer LDO angular meshes across larger hardware configurations would be instructive to see at what subspace degree, if any, the LDO equations' flux solutions mitigate ray effects in relevant real-world scenarios. Additionally, we suggest testing rotated versions of the LDO quadrature sets to study the relationship between ordinate placement and problem geometry in detector response and FOM production. This would be a fairly straightforward next step; the point sets generated by Womersley used in this work are rotationally invariant and the Exnihilo framework imports the LDO quadrature sets from plain text files. So, rotation matrices or formulae could be applied to the already-existing LDO point sets with the new rotated quadratures directly input to Exnihilo (and ADVANTG) for study in deterministic calculations as well as in Monte Carlo variance reduction parameter generation. As an alternative to conducting studies with increased angular resolution, we suggest undertaking investigations that use the interpolatory nature of the LDO representation once this ability has been realized in the various software frameworks involved.