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# Adapting SMRs for the Arctic Conditions: Addressing Multi-Physics Permafrost and Seismic Interactions in a Changing Climate

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**ABSTRACT:**

The Arctic is undergoing a dynamic transformation, with emerging economic opportunities such as the opening of trans-Arctic trade routes and increased regional development anticipated to drive energy demands to unprecedented levels. These shifts, coupled with the United States' growing strategic interest in the Arctic, underscore the urgent need for reliable, sustainable, affordable, and decentralized energy systems to support dispersed and evolving infrastructure. Small Modular Reactors (SMRs) and microreactors, with capacities below 300 MWe and 20 MWe respectively, offer an effective solution to meet these energy demands.

However, the deployment of SMRs in permafrost regions presents significant technical challenges. Current Arctic infrastructure is already experiencing widespread damage, with 60–80% of structures experiencing failures due to thawing permafrost. These challenges are expected to worsen as climate change accelerates permafrost degradation, rendering many facilities operationally unsustainable. These challenges for SMRs are more significant as the evolving conditions in permafrost environments introduce multi-physics complexities, including thermal, structural, and seismic interactions between reactor systems and the permafrost. High-temperature reactors impose additional thermal loads on underlying permafrost, increasing risks of deformation and foundation instability. Seismic activity in frozen and semi-frozen ground adds dynamic stresses to reactor foundations, necessitating robust analysis of nonlinear system responses. Compounding these challenges are uncertainties in climate projections, which result in uncertain rates of permafrost thaw and long-term ground settlement, threatening the safety and operational viability of SMRs over their expected 60–80-year lifespan.

This project aims to address these challenges through an interdisciplinary approach that advances the scientific understanding of permafrost-reactor interactions under climate change and seismic effects and develops innovative design methodologies. Key research objectives include: (i) characterizing the multi-physics interactions within the Permafrost–Foundation–Reactor structure (PFR) system, focusing on thermal stresses, structural deformation, and changes in bearing capacity; (ii) probabilistically analyzing the emergence of local to global failures in PFR systems under seismic activities and varying ground thermal states; (iii) analyzing the medium- to long-term impacts of climate-induced permafrost degradation on SMR performance and safety; (iv) quantifying uncertainties in climate-induced permafrost degradation and propagating the effects through the coupled PFR system models to assess the long-term performance and safety of SMR facilities; and (v) exploring and developing design strategies, including active permafrost freezing, seismic isolation techniques, and adaptive foundation systems, for diverse reactor configurations and site conditions.

By addressing these critical scientific and technical challenges, this research will deliver comprehensive insights into SMR-permafrost interactions, establish design guidelines, and formulate siting strategies. These outcomes will directly inform the United States' strategic approach to Arctic development, enabling the establishment of resilient, clean energy systems that foster sustainable growth while aligning with indigenous community priorities.