2.小型模組化反應器(SMR)的核廢料
(Nuclear waste from small modular reactors)

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小型模塊化反應堆（SMR；即每個產生 <300 MWelec 的核反應堆）因其固有的安全特性和降低的成本而受到關注。

然而，很少有研究分析其核廢料流的管理和處置。 在這裡，我們將三種不同的 SMR 設計與 1,100 MWe 壓水反應堆在能量當量體積、(無線電）化學、衰變熱和(名義上的)高、中和低水平的裂變同位素組成方面進行了比較 廢物流。結果表明，水冷、熔鹽冷卻和鈉冷 SMR 設計將增加需要管理和處置的核廢料的數量為 2 到 30 的因數。多餘的廢物體積歸因於在 SMR 設計中使用中子反射器和/或化學反應燃料和冷卻劑。

也就是說，數量不是最重要的評估指標； 相反，地質處置庫的性能是由衰變熱功率和乏核燃料的放射化學驅動的，SMR 對此沒有任何好處。 SMR 不會減少地球化學移動 129I、99Tc 和 79Se 裂變產物(FP)的產生，這些產物是大多數處置庫設計的重要劑量貢獻者。 此外，SMR 乏燃料將含有相對較高的濃度裂變核素(fissile nuclides)，這將需要新的方法來評估儲存和處置過程中的臨界性(criticality)。 由於廢物流特性受到中子洩漏的影響，中子洩漏是小型反應堆堆芯中增強的基本物理過程，SMR 將會加大核廢物管理和處置的挑戰。

Small modular reactors (SMRs; i.e., nuclear reactors that produce <300 MWelec each) have garnered attention because of claims of inherent safety features and reduced cost.

However, remarkably few studies have analyzed the management and disposal of their nuclear waste streams. Here, we compare three distinct SMR designs to an 1,100-MWelec pressurized water reactor in terms of the energy-equivalent volume, (radio-)chemistry, decay heat, and fissile isotope composition of (notional) high-, intermediate-, and low level waste streams. Results reveal that water-, molten salt–, and sodium-cooled SMR designs will increase the volume of nuclear waste in need of management and disposal by factors of 2 to 30. The excess waste volume is attributed to the use of neutron reflectors and/or of chemically reactive fuels and coolants in SMR designs.

That said, volume is not the most important evaluation metric; rather, geologic repository performance is driven by the decay heat power and the radiochemistry of spent nuclear fuel, for which SMRs provide no benefit. SMRs will not reduce the generation of geochemically mobile 129I, 99Tc, and 79Se fission products, which are important dose contributors for most repository designs. In addition, SMR spent fuel will contain relatively high concentrations of fissile nuclides, which will demand novel approaches to evaluating criticality during storage and disposal. Since waste stream properties are influenced by neutron leakage, a basic physical process that is enhanced in small reactor cores, SMRs will exacerbate the challenges of nuclear waste management and disposal.

意義

小型模塊化反應堆（SMR）被提議作為核能的未來，據稱與現有的千兆瓦級輕水反應堆（LWR）相比具有成本和安全優勢。 然而，很少有研究評估 SMR 對核燃料循環後端的影響。 低級、中級、此處介紹的高放廢物流特徵表明，與輕水堆相比，SMR 將產生更多的化學/物理反應性廢物，這將影響管理和處置的選擇這種浪費。

儘管分析僅關注數十種提議的 SMR 設計中的三種，但與 SMR 相關的本質上較高的中子洩漏表明大多數設計在核廢料中關鍵放射性核素的產生、管理和最終處置方面不如 LWR。

Significance

Small modular reactors (SMRs), proposed as the future of nuclear energy, have purported cost and safety advantages over existing gigawatt-scale light water reactors (LWRs). However, few studies have assessed the implications of SMRs for the back end of the nuclear fuel cycle. The low-, intermediate-, and high-level waste stream characterization presented here reveals that SMRs will produce more voluminous and chemically/physically reactive waste than LWRs, which will impact options for themanagement and disposal of this waste.

Although the analysis focuses on only three of dozens of proposed SMR designs, the intrinsically higher neutron leakage associated with SMRs suggests that most designs are inferior to LWRs with respect to the generation, management, and final disposal of key radionuclides in nuclear waste.

5。結論

對三種不同(水冷、熔鹽冷卻和鈉冷)SMR 設計的分析表明，相對於千兆瓦級 PWR，這些反應堆將增加 Spent nuclear fuel (SNF) 、長壽命 LILW(low- and intermediate-level waste (LILW)) 和短壽命 LILW 的體積(volume)分別高達 5.5、30 和 35。 這些發現與擁護者聲稱先進核技術可減少廢物的好處形成鮮明對比。

更重要的是，SMR 廢物流與現有反應堆的廢物流具有顯著的(放射)化學差異。熔鹽和鈉冷卻 SMR 將使用高腐蝕性自燃燃料和冷卻劑，在輻照後會變得具有高放射性。

低燃耗(low - burnup) SMR SNF 中相對高濃度的 239Pu 和 235U 將使再臨界成為這些化學不穩定廢物流的重大風險。

與水或其他處置庫材料接觸時易受放熱化學反應或核臨界影響的 SMR 廢物流不適合直接地質處置。 因此，在地質處置之前，需要對大量反應性 SMR 廢物進行處理、調節和適當包裝。

這些過程將給核燃料循環的後端帶來可觀的成本——可能還有輻射暴露和裂變材料擴散途徑——並且對長期安全沒有明顯的好處。

儘管我們只分析了數十種擬議的 SMR 設計中的三種，但這些發現是由基本物理現實驅動的，即相對於具有類似設計和燃料循環的大型反應堆，SMR 堆芯中的中子洩漏會增加。

因此，大多數 SMR 設計都對核廢料處理作業造成明顯的劣勢。 鑑於 SMR 與現有的核廢料處理技術和概念不相容，未來的研究應解決在美國地質處置庫開發持續延遲的情況下，反應 SMR 廢料流的安全臨時儲存是否可信。

5. Conclusions

This analysis of three distinct SMR designs shows that, relative to a gigawatt-scale PWR, these reactors will increase the energyequivalent volumes of SNF, long-lived LILW, and short-lived LILW by factors of up to 5.5, 30, and 35, respectively. These findings stand in contrast to the waste reduction benefits that advocates have claimed for advanced nuclear technologies.

More importantly, SMR waste streams will bear significant (radio-)chemical differences from those of existing reactors.

Molten salt– and sodium-cooled SMRs will use highly corrosive and pyrophoric fuels and coolants that, following irradiation, will become highly radioactive. Relatively high concentrations of 239Pu and 235U in low–burnup SMR SNF will render recriticality a significant risk for these chemically unstable waste streams.

SMR waste streams that are susceptible to exothermic chemical reactions or nuclear criticality when in contact with water or other repository materials are unsuitable for direct geologic disposal . Hence, the large volumes of reactive SMR waste will need to be treated, conditioned, and appropriately packaged prior to geological disposal.

These processes will introduce significant costs—and likely, radiation exposure and fissile material proliferation pathways—to the back end of the nuclear fuel cycle and entail no apparent benefit for long-term safety.

Although we have analyzed only three of the dozens of proposed SMR designs, these findings are driven by the basic physical reality that, relative to a larger reactor with a similar design and fuel cycle, neutron leakage will be enhanced in the SMR core.

Therefore, most SMR designs entail a significant net disadvantage for nuclear waste disposal activities. Given that SMRs are incompatible with existing nuclear waste disposal technologies and concepts, future studies should address whether safe interim storage of reactive SMR waste streams is credible in the context of a continued delay in the development of a geologic repository in the United States.

Data Availability. All study data are included in the article and/or *SI Appendix.*