Dr Charles W. Forsberg

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EDUCATION

1974 Sc.D. Nuclear Engineering, Massachusetts Institute of Technology (Thesis: Uranium Enrichment)
1971 M.S. Nuclear Engineering, Massachusetts Institute of Technology
1969 B.S. Chemical Engineering, University of Minnesota

RESEARCH AND PROFESSIONAL ACTIVITIES and EXPERIENCE

Dr. Charles Forsberg is a principal research scientist at MIT and the principle investigator for the DOE Integrated Research Project *Molten Salt Reactor Test Bed with Neutron Irradiation* with the goal to install a molten salt flow loop in the MIT reactor. The project includes MIT, University of California-Berkeley, North Carolina State University and Oak Ridge National Laboratory. He was the U.S. principle investigator for the MIT-Japan Future of Nuclear Power study that is examined how to integrate nuclear power and renewables into a cost-effective low-carbon energy system. Dr. Forsberg directed the *MIT Future of the Nuclear Fuel Cycle* study [Ref 40]. He has written many papers on implications of waste forms and fuel cycles on repository design choices. He (1) teaches the nuclear chemical engineering, nuclear fuel cycle systems and energy classes and (2) supervises graduate students. Before joining MIT in 2008, Dr. Forsberg was a Corporate Fellow at Oak Ridge National Laboratory where he led the FHR and MSR programs—and several fuel cycle activities.

He is a Fellow of the American Nuclear Society (ANS) and the American Association for the Advancement of Science. He is a recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding contributions to nuclear energy, the ANS 2002 special award for innovative nuclear reactor design and the ANS 2014 Seaborg Award for outstanding scientific or engineering research contributions to the development of peaceful uses of nuclear energy. He is a former director of the ANS. Dr. Forsberg has been awarded 12 patents and has published over 300 papers.

His research over several decades has primarily been in three areas: (1) advanced reactors with an emphasis on salt-cooled and high-temperature gas-cooled reactors, (2) interactions between fuel cycles, waste forms and repositories, (3) integration of nuclear and renewable energy resources. He is one of the three inventors [Ref 22, 44] of the Fluoride-salt-cooled High-Temperature Reactor (FHR) that lead to the formation of Kairos Power [https://kairospower.com] to commercialize the FHR and the co-inventor of electrically-conductive firebrick [Ref 16, 17], useable as an electric resistance heater, to replace natural gas in high-temperature industrial processes that lead to the formation of Electrified Thermal Solutions [https://www.electrifiedthermal.com].

Dr. Forsberg is working on two longer-term challenges. One is to replace all crude oil with cellulosic hydrocarbon liquids [Ref 1, 5] by addition of massive quantities of hydrogen and heat to cellulosic feedstocks at the refinery. Cellulosic biomass is the most abundant form of biomass on earth and includes corn stover, wood debris and kelp. With traditional biofuels processes, the biomass is the carbon source in the final product (gasoline, diesel and jet fuel) and the energy source for the conversion process. External heat and hydrogen reduces the quantities of feedstock required so liquid hydrocarbon fuels not limited by availability of cellulosic biomass. Hydrogen becomes the largest single cost component in the hydrocarbon product.

The other project is developing very low-cost crushed rock heat storage [Ref 3, 4] at the 100-GWh scale coupled to nuclear, wind and solar to replace natural gas for variable electricity production on an hourly to seasonal basis. Crushed rock is the lowest cost heat storage material. Very large heat storage systems enable seasonal storage because large systems have smaller heat losses—the primary requirement for economic seasonal heat storage.

Massachusetts Institute of Technology; Cambridge, Massachusetts; January 2008-Present

Principle Investigator: Molten Salt Reactor Test Bed with Neutron Irradiation (Third salt project)
Director, MIT Future of the Nuclear Fuel Cycle (2008-2012, study complete)
Classes: Nuclear Chemical Engineering, Energy classes
Advisor: Graduate student thesis: salt reactors, hybrid energy systems and heat storage

Oak Ridge National Laboratory; Oak Ridge, Tennessee; May 1975 – January 2008

At time of departure
- Corporate Fellow
- Senior Reactor Technical Advisor
- DOE Molten Salt Systems Integration Manager (FHR and MSR)

Earlier activities (partial list)
- Salt-cooled reactors
- Thermochemical hydrogen production from water
- Nuclear biofuels production
- Technical lead: DOE ^{233}U Disposition Program, definition of weapons-useable ^{233}U
- Manager for ORNL Developmental LWR Program
- Group Leader Waste Systems Data and Development Group
- Reprocessing plant R&D (High-temperature reactor fuel, experimental and analysis)

Bechtel Corporation; San Francisco, California; November 1973 - May 1975

Centrifuge and gaseous diffusion plant design optimization studies

Partial List of Publications

1. C. W. Forsberg, "What is the Long-Term Demand for Liquid Hydrocarbon Fuels and Feedstocks?" *Applied Energy*, 341, 121104 (1 July 2023). https://doi.org/10.1016/j.apenergy.2023.121104

2. C. W. Forsberg, D. M. Carpenter, R. O. Scarlat, R. Kevin and A. I. Hawari, "Lessons Learned In How to Conduct Irradiated Salt Experiments", *Transactions of the American Nuclear Society Annual Meeting,* Indianapolis, June 11-14, 2023.

3. D. Bandyopadhyay and C. Forsberg, "Selecting Rock Types for Very-low-cost Crushed Rock Heat Storage Systems with Nitrate Salt Heat Transfer", *Journal of Energy Storage,* Vol. 61, 106664, *Journal of Energy Storage,* May 2023. https://doi.org/10.1016/j.est.2023.106664

4. C. W. Forsberg, "Low-cost Crushed Rock Heat Storage with Oil or Salt Heat Transfer", *Applied Energy* 335. 120753, March 2023. https://doi.org/10.1016/j.apenergy.2023.120753

5. C. W. Forsberg and B. Dale, "Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels?", *Hydrocarbon Processing,* January 2023. Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels? (hydrocarbonprocessing.com)

6. C. Forsberg and A. Foss, Fission Battery Markets and Economic Requirements, *Applied Energy,* 329, 2023, 120266. https://doi.org/10.1016/j.apenergy.2022.120266

7. C. W. Forsberg and G. Preston, "Long Duration Heat Storage Using Crushed Rock and Nuclear Heat: Impact on Grid Design", *Transactions American Nuclear Society*, 127 (1), 820-823, November 13-17, 2022. doi.org/10.13182/T127-3951

8. C. W. Forsberg, J. Buongiorno and E. Ingersoll, "Nuclear Tech Hub: Co-siting Cutting Edge Nuclear Facilities with Waste Management Sites" *Radwaste Solutions*, Spring 2022. https://www.ans.org/news/article-3726/nuclear-tech-hub-cositing-cuttingedge-nuclear-facilities-with-waste-management-sites/

9. C. W. Forsberg and C., B. Dale, *Can a Nuclear-Assisted Biofuels System Enable Liquid Biofuels as the Economic Low-carbon Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks and Enable Negative Carbon Emissions?,* Massachusetts Institute of Technology, MIT-NES-TR-023. April 2022. https://canes.mit.edu/download-a-report

10. C. Forsberg, "Public Health is a Job for Engineers", *Mechanical Engineering*, 36-41, February-March 2022. Pandemic Shows Public Health is a Job for Engineers - ASME

11. C. Forsberg, "Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge", *The Electricity Journal,* December 2021. https://doi.org/10.1016/j.tej.2021.107042.

12. C. W. Forsberg, "1000-MW CSP with 100-Gigawatt-Hour Crushed-Rock Heat Storage to Replace Dispatchable Fossil-Fuel Electricity", SolarPaces2021; Paper 7281, September 27-October 1, 2021

13. C W. Forsberg, "Separating Nuclear Reactors from the Power Block with Heat Storage to Improve Economics with Dispatchable Heat and Electricity", *Nuclear Technology*, 2021.

https://doi.org/10.1080/00295450.2021.1947121

14. C. W. Forsberg, C. W, B. E. Dale, D. S. Jones, T. Hossain, A.R.C. Morais and L. M. Wendt, "Replacing Liquid Fossil Fuels and Hydrocarbon Chemical Feedstocks with Liquid Biofuels from Large-Scale Nuclear Biorefineries", *Applied Energy*, 298, 117525, 15 September 2021. Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries - ScienceDirect

15. C. Forsberg, B. Dale and E. Ingersoll, "Nuclear Energy Drop-In Replacements for Gas Turbines, Natural Gas and Fossil Liquid Fuels", *Applied Energy Symposium: MIT A+B*, August 11-13, 2021 • Cambridge, USA. https://www.energy-proceedings.org/category/mitab2021/

16. D. Stack and C. Forsberg, "Combined Cycle Gas Turbines with Electrically-heated Thermal Energy Storage for Dispatchable Zero-Carbon Electricity," POWER2021-65529, *Power 21 Power Conference A Legacy to Power the Future*, American Society of Mechanical Engineers, Virtual Conference, July 20-22, 2021

17. D. Stack (C. Forsberg advisor), Development of high-temperature firebrick resistance-heated energy storage (FIRES) using doped ceramic heating system (PhD Thesis, MIT) 2021. https://dspace.mit.edu/handle/1721.1/130800

18. C. W. Forsberg, P. J. McDaniel, and B. Zohuri, "Nuclear Air-Brayton Power Cycles with Thermodynamic Topping Cycles, Assured Peaking Capacity and Heat Storage for Variable Electricity and Heat," *Nuclear Technology*, **207** (4), 543-557, April 2021. https://doi.org/10.1080/00295450.2020.1785793

19. C W. Forsberg, "Separating Nuclear Reactors from the Power Block with Heat Storage to Improve Economics with Dispatchable Heat and Electricity", *Nuclear Technology*, 2021. https://doi.org/10.1080/00295450.2021.1947121

20. C. Forsberg, E. M. Bucci and R. G. Ballinger, *Molten-Salt Fusion Liquid-Immersion-Blanket Integrated Validation Plan*. MIT-NES-TR-019, PSFC/RR-21-1, Massachusetts Institute of Technology. December 2020

21. C. Forsberg and S.M Bragg-Sitton, "Maximizing Clean Energy Utilization: Integrating Nuclear and Renewable Technologies to Support Variable Electricity, Heat and Hydrogen Demands, *The Bridge*, 50 (3) National Academy of Engineering, Fall 2020. https://www.nae.edu/239450/Maximizing-Clean-Energy-Use-Integrating-Nuclear-and-Renewable-Technologies-to-Support-Variable-Electricity-Heat-and-Hydrogen-Demand

22. C. W. Forsberg. Market Basis for Salt-Cooled Reactors: Dispatchable Heat, Hydrogen, and Electricity with Assured Peak Power Capacity, *Nuclear Technology*, 2020, https://doi.org/10.1080/00295450.2020.1743628

23. C. Forsberg, G. Zheng, R. Ballinger and S. T. Lam, "Fusion Blankets and Fluoride-salt-cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies between Fission, Fusion and Solar Salt Technologies", *Nuclear Technology*. https://doi.org/10.1080/00295450.2019.1691400

24. Charles Forsberg and Per Peterson, "FHR, HTGR, and MSR Pebble-Bed Reactors with Multiple Pebble Sizes for Fuel Management and Coolant Cleanup, *Nuclear Technology* 205:5, 748-754, https://doi.org/10.1080/00295450.2019.1573619

25. D. C. Stack, D. Curtis, and C. Forsberg, "Performance of Firebrick Resistance-Heated Energy Storage for Industrial Heat Applications and Round-Trip Electricity Storage", *Applied Energy*, 242, 782-796 (2019) https://doi.org/10.1016/j.apenergy.2019.03.100

26. B. J. Riley, J. McFarlane, G. D. DelCul, J. D. Vienna, C. I. Contescu and C. W. Forsberg. "Molten salt reactor waste and effluent management strategies: A Review", *Nuclear Engineering and Design,* **345**, 94-109 https://doi.org/10.1016/j.nucengdes.2019.02.002

27. C. W. Forsberg, "Variable and Assured Peak Electricity from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels", *Nuclear Technology;* **205**, 377-396, March 2019. https://doi.org/10.1080/00295450.2018.1518555

28. Charles Forsberg, Stephen Brick, and Geoffrey Haratyk, "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Base-Load Reactor Operation, *Electricity Journal*, **31**, 23-31, April 2018, https://doi.org/10.1016/j.tej.2018.03.008

29. C. W. Forsberg, R. Lester, N. Sepulveda, G. Haratyk, A. Omoto, T. Taniguchi, R. Kommlyama, Y. Fujii, K. Matsul, X. L. Yan, T. Shibata, and T. Murakami., *MIT-Japan Study: Future of Nuclear Power in a Low-Carbon World: The Need for Dispatchable Energy*, MIT-ANP-TR-171, Center for Advanced Nuclear Energy (CANES), Massachusetts Institute of Technology, September 2017, http://energy.mit.edu/wp-content/uploads/2017/12/MIT-Japan-Study-Future-of-Nuclear-Power-in-a-Low-Carbon-World-The-Need-for-Dispatchable-Energy.pdf

30. C. Forsberg, D. Stack, D. Curtis, G. Haratyk, N. A. Sepulveda, "Converting Excess Low-Price Electricity into High-Temperature Stored Heat for Industry and High-Value Electricity Production," 30, 42-52, *Electricity Journal*, July 2017, https://doi.org/10.1016/j.tej.2017.06.009

31. L. Dempsey, C. Forsberg, and T. J. Dolan, "Chapter 2: Electricity Production", *Book: Molten Salt Reactors and Thorium Energy*, T. J. Dolan Ed., Woodhead Publishing Series in Energy, Elsevier Ltd. 2017

32. C. Forsberg and P. F. Peterson, "Basis for Fluoride Salt-Cooled High-Temperature Reactors with Nuclear Air-Brayton Combined Cycles and Firebrick Resistance Heated Energy Storage, *Nuclear*

Technology, **196**, October 2016.

33. C. Forsberg and P. F. Peterson, "Spent Nuclear Fuel and Graphite Management for Salt-Cooled Reactors: Storage, Safeguards, and Repository Disposal", *Nuclear Technology*, **191**, August 2015.

34. C. Forsberg, "Implications of Plutonium Isotopic Separation on Closed Fuel Cycles and Repository Design," **189**, 63-70, *Nuclear Technology*, January 2015

35. Test Reactor Goals, Strategy, and Design: *Fluoride-salt-cooled High-temperature Test Reactor (FHTR): Goals, Options, Ownership, Requirements, Design, Licensing, and Support Facilities*, MIT-ANP-TR-154, Massachusetts Institute of Technology, Cambridge, MA, Dec. 2014.

36. C. W. Forsberg, "Hybrid Systems to Address Seasonal Mismatches Between Electricity Production and Demand in a Nuclear Renewable Electricity Grid," *Energy Policy*, **62**, 333-341, November 2013.

37. C. Forsberg and W. F. Miller, "Coupling Fuel Cycles with Repositories: How Repository Institutional Choices May Impact Fuel Cycle Design," Paper 7902, *Global 2013*, Salt Lake City, Utah, September 29-October 3, 2013.. https://www.osti.gov/biblio/22264142

38. C. W. Forsberg, "Continental-Shelf Seabed Disposal: Disposal of Non-Repository Radioactive Wastes for a World of 10-Billion People," Paper 6709, *International High-Level Radioactive Waste Management Conference, Albuquerque, New Mexico,* April 28-May 2, 2013.

39. C. W. Forsberg, "Coupling the Back End of Fuel Cycles with the Repository," *Nuclear Technology*, **180** (2), pp 191-204, November 2012.

40. M. Kazimi, E. Moniz, C. Forsberg, et. al., *The Future of the Nuclear Fuel Cycle, an Interdisciplinary Study*, Massachusetts Institute of Technology, April 2011. https://energy.mit.edu/wp-content/uploads/2011/04/MITEI-The-Future-of-the-Nuclear-Fuel-Cycle.pdf

41. A. H. Slocum, D. S. Codd, J. Buongiorno, C. Forsberg, T. McKrell, J. Nave, C. N. Papanicolas, A. Ghobeity, C. J. Noone, S. Passerini, F. Rojas, and "A. Mitsos "Concentrated Solar Power on Demand," *Solar Energ*y 85, 1519-1529 (2011)

42. C. W. Forsberg and D. L. Moses, *Safeguards Challenges for Pebble-Bed Reactors Designed by People's Republic of China*, ORNL/TM-2008/229 (November 2009)

43. C. W. Forsberg, E. D. Collins, C. W. Alexander, and J. P. Renier, "Can Thermal Reactor Recycle Eliminate the Need for Multiple Recycle?", *Actinide and Fission Product Partitioning and Transmutation: 8th Information Exchange Meeting, OECD Nuclear Energy Agency, November 9-*

11, 2004, Las Vegas, Nevada, NEA No. 6024, CD-ROM, pp 177-186, OECD Nuclear Energy Agency, Paris (2005).

44. C. W. Forsberg, P. S. Pickard, and P. F. Peterson, "Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity", *Nuclear Technology*, **144,** 289-302 (December 2003).

45. C. W. Forsberg, "Rethinking High-Level Waste Disposal: Separate Disposal of High-Heat Radionuclides (^{90}Sr and ^{137}Cs)," *Nuclear Technology*, **131** (2): 252-268 (August 2000).

46. C. W. Forsberg, "Recovery of Fissile Materials from Wastes and Conversion of the Wastes To Glass, "*Nuclear Technology*, **123**:341-349 (September 1998).

47. C. W. Forsberg, C. M. Hopper, J. L. Richter, and H.C. Vantine. *Definition of Weapons-usable Uranium-233*, ORNL/TM-13517, Oak Ridge National Laboratory, Oak Ridge, Tennessee (March 1998).

48. C. W. Forsberg, E. C. Beahm, G. W. Parker, and J. Rudolph, "Director Conversion of Spent Fuel to High-Level Waste (HLW) Glass", pp. 303-310 in *Proc. DOE Spent Nuclear Fuel: Challenges and Initiatives Conference, Salt Lake City, December 13-16, 1994,* American Nuclear Society, La Grange Park, Illinois, 1994.

49. C. W. Forsberg, "An Ocean Island Geological Repository—A Second-Generation Option for Disposal of Spent Fuel and High-Level Waste", *Nucl. Technol.* **101** (1), 40B53 (January 1993).

50. C. W. Forsberg and A. M. Weinberg, "Advanced Reactors, Passive Safety, and the Acceptance of Nuclear Energy", *Annual Reviews of Energy*, **15**: 133-152 (1990).

51. C. W. Forsberg, D. L. Moses, E. B. Lewis, R. Gibson, R. Pearson, W. J. Reich, G. A. Murphy, R. H. Staunton, and W. E. Kohn, *Proposed and Existing Passive and Inherent Safety-Related Structures, Systems, and Components (Building Blocks) for Advanced Light-Water Reactors,* ORNL-6554, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 1989. https://doi.org/10.2172/7023863

52. C. W. Forsberg, *Addendum to ORNL-6554: Proposed and Existing Passive and Inherent Safety-Related Structures, Systems, and Components (Building Blocks) for Advanced Light-Water Reactors*, ORNL/CF-89/313, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 1989.

53. C. W. Forsberg, "A Process Inherent Ultimate Safety Boiling Water Reactor", *Nucl. Technol.*, **72**: 121-134 (February 1986). https://www.tandfonline.com/doi/abs/10.13182/NT86-A33735

54. C. W. Forsberg, et al., *Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, DOE/RW-0006, U.S. Department of Energy, Washington D.C., September 1984.

55. C. W. Forsberg, "Regional Waste Treatment Facilities with Underground Monolith Disposal of all Low-Heat-Generating Nuclear Wastes", *Nucl, Tech.*, **59**, 119-135 (October 1982).

56. C. W. Forsberg and Manson Benedict, "An Evaluation of Uranium Enrichment by Mass Diffusion", pp. 24-30 in *Recent Developments in Uranium Enrichment, AIChE Symposium Series*, **78**, 221, American Institute of Chemical Engineers, New York, New York (1982).

57. C. W. Forsberg, et al., *Spent Fuel and Waste Inventories and Projection*, ORO-778, August 1980.

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