A Nuclear Option for Climate Change: Historical lessons for the future of advanced fission energy in the United States

Abstract

As the largest source of emissions-free electricity in the United States, nuclear energy plays a pivotal role in efforts to combat climate change by decarbonizing our energy system. However, as the climate-energy challenge intensifies over the next half-century, the entire U.S. nuclear fleet will likely retire due to a combination of age and economic pressures — and as of now, there are no new reactors capable of taking their place. At the moment, the future of nuclear energy in the United States appears rather grim.

A new generation of advanced nuclear reactors is poised to take up the mantle of clean baseload generation, with technology that hopes to be cheaper, cleaner, safer, and more secure. However, they remain in the early stages of the research, development, demonstration, and deployment (R&D(DD)) process. Given nuclear energy's expected importance in deep decarbonization, the thirty-four advanced reactor development projects currently underway across the United States merit substantial support, even in the face of relatively immature technology and the adverse economic conditions.

This thesis seeks to identify a set of broad principles that could prove useful in enabling and accelerating the deployment of advanced nuclear reactors on a climate-relevant timescale. To do so, we consider five historical examples of U.S. federal government efforts to take immature technologies from the drawing board to deployment, driven not merely by economics, but by a broader definition of American national interests. Drawing lessons from these examples, we consider their applications to the current state of advanced nuclear energy in the U.S.

We find that a more active federal role in shaping advanced nuclear energy research is warranted, in order to streamline the R&D(DD) process, keep promising ideas alive, support long-lead development, and ensure the viability of a nuclear option for climate change.

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1 Introduction: A nuclear option for climate change?

Today, the future of nuclear energy in the United States seems murky at best. The combination of economic headwinds, aging reactors, a changing grid, safety and security concerns, and long-term waste challenges seems decidedly stacked against a large future role for nuclear energy in the U.S. generation mix. However, these analyses leave out a crucial driver of modern energy policy: the need to decarbonize in the face of climate change.

In 2013, the Intergovernmental Panel on Climate Change (IPCC) projected that if global greenhouse gas emissions continue on their current trajectory, the increase in global average surface temperature will very likely exceed 2ºC by the end of the century. This increase would have a dramatic impact on the climate system, with profound implications for society. Sea level rise could displace tens of millions within the century, while subjecting millions more to increased risks from temperature extremes, infectious diseases, food insecurity, and on.[1] The impacts of climate change are innumerable — from increased wildfires, to stronger hurricanes, to escalated risks of political conflict — yet uncertain, and quantifying their true costs (in not only economic, but also environmental and social terms) is an active area of research. However, even with the estimates of climate change's societal impact available to us today, it is quite evident that tackling the climate problem is a matter of vital global interest, and national interest.

This is especially true of the United States. In a wide-ranging study in 2015, the U.S. Environmental Protection Agency illustrated the substantial impacts that climate change could have on the U.S. alone, absent global efforts to tackle it: $5 trillion in damage to coastline, $180

[1] Intergovernmental Panel on Climate Change, "Fifth Assessment Report: Summary for Policymakers," December 17, 2013, 1–28; Susmita Dasgupta et al., "The Impact of Sea Level Rise on Developing Countries: a Comparative Analysis," *Climatic Change* 93, no. 3 (October 10, 2008): 379–88, doi:10.1007/s10584-008-9499-5; Anthony J McMichael, Rosalie E Woodruff, and Simon Hales, "Climate Change and Human Health: Present and Future Risks," *The Lancet* 367, no. 9513 (March 2006): 859–69, doi:10.1016/S0140-6736(06)68079-3.

billion lost to water shortages, 1.8 billion hours of lost productivity due to extreme temperatures, 7.9 million acres of land lost to wildfire — the list goes on and on.[2] In 2015, President Barack Obama asserted that "no challenge poses a greater threat to future generations than climate change," a statement that was echoed by both his scientific and military advisors.[3] Clearly, the climate problem is very much an American problem.

So, what role can the United States play in tackling this challenge? The most powerful is in leading efforts to cut global emissions of greenhouse gases, by switching from fossil fuels to alternative energy sources. As of 2015, the U.S. is responsible for roughly 15% of global CO_2 emissions, placing it second only to China. Electricity generation is the largest source of U.S. CO_2 emissions, accounting for around 35%, followed by transportation (32%), and industry (15%).

Globally, the U.S. was — until recently — one of the leading voices for emissions reductions and the energy transition, working through the IPCC to implement the Paris Agreement, and through bi- and multi-lateral partnerships to promote the deployment of alternative energy through technology transfer and financial support. Domestically, the federal Climate Action Plan sought to encourage the decarbonization of electricity generation. And while many elements of the Obama-era Plan have been withdrawn under the Trump Administration, a number of states have continued to push for lower emissions, through market-based schemes like the Regional Greenhouse Gas Initiative, and through direct financial support for renewables, storage, and nuclear energy.

[2] U.S. Environmental Protection Agency, "Climate Change in the United States: Benefits of Global Action," April 2, 2015, https://www.epa.gov/cira.
[3] Barack H Obama, "State of the Union Address as Delivered," January 13, 2016, https://obamawhitehouse.archives.gov/the-press-office/2016/01/12/remarks-president-barack-obama-%E2%80%93-prepared-delivery-state-union-address.

It is in this context that we must consider the future of nuclear energy in the United States. As the single largest source of emissions-free electricity generation in the country, as well as globally, nuclear power currently serves as our only source of emissions-free baseload electricity — and the bulwark of any effort to fight climate change through deep decarbonization of our energy system.

In order to continue aggressively cutting emissions in response to the climate challenge, the loss of the existing 99 GWe of generation capacity over the coming half-century will have to be replaced by zero-emissions sources of electricity. Instead, in the wake of the closing of plants like New England's Vermont Yankee in 2014 and California's San Onofre in 2012, emissions actually increased, as natural gas generation took up the load previously borne by nuclear generation.[4]

Moreover, numerous analyses of deep decarbonization — the process of entirely eliminating greenhouse gas emissions from energy use — demonstrate that even under scenarios with the most optimistic projections for the deployment of renewable generation, energy storage technologies, and demand response/energy efficiency measures, nuclear power will likely still be needed to meet at least its current load of roughly 100 GWe.[5] This is compounded by expected increases in overall electricity demand, as a result of the trend towards transportation electrification. Going beyond electricity generation, nuclear power also offers a potential source

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[4] Robert Walton, "With Clean Energy Standard, New York Looks to Save Nukes, Skirt Legal Challenges," *UtilityDive*, August 4, 2016, https://www.utilitydive.com/news/with-clean-energy-standard-new-york-looks-to-save-nukes-skirt-legal-chall/423673/; California Air Resources Board, "Newest Greenhouse Gas Emissions Inventory Shows California on Course to Lower Carbon Growth Economy," May 14, 2014, https://www.arb.ca.gov/newsrel/newsrelease.php?id=612.

[5] Alexander E MacDonald et al., "Future Cost-Competitive Electricity Systems and Their Impact on US CO2 Emissions," *Nature Climate Change* 6, no. 5 (January 25, 2016): 526–31, doi:10.1038/nclimate2921; J H Williams et al., "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: the Pivotal Role of Electricity," *Science* 335, no. 6064 (January 5, 2012): 53–59, doi:10.1126/science.1208365.

of process heat generation — which could be used for industrial purposes or even conceivably for district heating.

The pathway that the U.S. energy transition will follow is, at the end of the day, uncertain. While it is possible that renewables, storage, and demand response might steal the day all on their own, it seems more likely that there will be a hole for nuclear power. Given this, it's important to ensure that when the time comes for a new generation of nuclear energy to take the stage, an appropriate slate of developed, commercializeable nuclear fission systems are ready to be deployed.

The current climate — political, economic, and social — has led to a stagnation of research, development, demonstration and deployment (R&D(DD)) of new nuclear reactor technologies. However, if we are to be properly prepared for deep decarbonization, it's critical that these efforts are supported and accelerated, so they can be ready when needed.

Currently, the vast majority of existing, utility scale light water reactor designs are uneconomical. One need look no further than the cancellation of the V.C. Summer reactor projects, the subsequent bankruptcy of Westinghouse Electric, and the controversy surrounding cost overruns at Vogtle, to see that.

Many have argued, with merit, that nuclear power's economic plight is a result of a failure to value the climate and environmental benefits it produces by generating electricity without greenhouse gas or criteria pollutant emissions. A growing body of research has investigated mechanisms for valuing these benefits, ranging from carbon taxes to zero-emissions credits, with indications that a subsidy of roughly $3.5-5.5/MWh would make today's nuclear plants competitive with the cheapest generation sources, whether natural gas, wind, or solar.[6] However,

[6] Geoffrey Haratyk, "Early Nuclear Retirements in Deregulated U.S. Markets_ Causes, Implications and Policy Options," *Energy Policy* 110 (November 1, 2017): 150–66, doi:10.1016/j.enpol.2017.08.023.

as our examination of historical analogues will reveal, technology development and deployment efforts which are fundamentally dependent on government financial support for their continued operation have a decidedly mixed track record. Moreover, the current uncertainty in the nuclear sector makes it plausible for us to step back from second-best market mechanisms and consider how we might reshape nuclear development itself.

The relative lack of activity in the nuclear sector at the moment — compared to the wind, solar, or storage worlds, for example — presents a unique opportunity. The current lack of a market for new nuclear construction seems poised to persist for the foreseeable future, barring external influences such as a sudden spike in natural gas prices. In the same vein, the average construction time of nuclear reactors, even at the height of construction in the 1970s and 1980s was 14.1 years.[7] That number has ballooned in recent years, as numerous reactor projects are put on indefinite hold or are finally cancelled after languishing for decades. While that appears to be a rather dismal statistic, it can also be viewed as an opportunity — a metric of an inherent "lead time" for nuclear energy. It would appear to suggest that by laying groundwork today, we can potentially influence the course of nuclear reactor development for years to come, enabling its next move. Of course, one argument would be that the nuclear sector's next move is to fade away. However, the climate-mitigation motivation that we have explored suggests that — economics aside — there is a strong case to be made for ensuring that a nuclear option is available over the coming half-century, prepared to be deployed as part of a diversified response to climate change. As such, we now have the opportunity to consider nuclear energy not as it currently is, but as it might optimally exist.

[7] Lucas W Davis, "Prospects for Nuclear Power," *Journal of Economic Perspectives* 26, no. 1 (February 2012): 49–66, doi:10.1257/jep.26.1.49.

Succinctly, this boils down to a single question: given this opportunity to begin laying the groundwork today, what broad steps can we take to enable the development of a cheaper, safer, more secure, more efficient generation of nuclear reactors, over a timeframe that would allow them to be part of a robust response to the climate problem? This thesis seeks to answer that question about the future of nuclear energy, by looking back in time.

We will first take an overview of the current state of nuclear energy in the U.S., and the challenges faced by existing nuclear reactors and reactor designs.

We will then examine five cases where the United States government took action to bring feasible, but not yet demonstrated technologies from the drawing board to deployment — driven not merely by economics, but by a broader definition of American national interests. In doing so, we will extract a series of core organizing principles, best practices, and common pitfalls.

Then, we consider the current state of advanced nuclear reactor development, through the lens of those lessons.

Finally, we will draw a series of broad policy and strategic implications — a set of guiding concepts that could prove useful in enabling and accelerating the deployment of advanced nuclear reactors on a climate-relevant timescale.

2 Nuclear Energy in the United States

In 1957, the world's first civilian nuclear power reactor blinked on outside of Pittsburgh, PA, in a tiny town along the banks of the Ohio River. More than six decades later, nuclear energy remains a crucial component of U.S. electrical generation. However, as we will examine, the U.S. nuclear energy industry is in the midst of a period of profound turmoil, as powerful economic forces clash with a desire for a baseload source of emissions-free electricity. This has given rise to legitimate questions about what the future of U.S. nuclear energy will be — or whether one even exists. It is against this tumultuous backdrop that we will consider the prospects for a future generation of advanced nuclear reactors. But in order to consider the future of advanced nuclear energy, we must first step back and get a sense of the current state of nuclear energy in the United States.

2.1 Nuclear in today's U.S. electricity generation mix

As the source of 19.7% of all electricity generated in the United States, nuclear energy is a key component of today's generation mix. It also accounts for just under 57% of all electricity generated from zero-emissions sources annually, as of 2016.[8] As such, it is the largest source of emissions-free electricity generation in the U.S., a fact that makes it an integral component of any discussion about decarbonizing the U.S. electrical grid in order to reduce greenhouse gas emissions in view of the climate challenge. In addition to the climate benefits offered by nuclear energy, it also serves an important role as a reliable source of baseload electricity generation for the grid. As of 2017, the U.S. nuclear fleet as a whole had a capacity factor of 92.2% — in other

[8] EIA, "What Is U.S. Electricity Generation by Source?," accessed March 29, 2018, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

words, the average nuclear reactor was producing 92.2% of its maximum rated power output at any given time.[9]

There are currently 99 operational power reactors in the U.S — ranging in size from 550 MWe to 1.44 GWe.[10] The U.S. nuclear fleet consists exclusively of light water reactors (LWRs), with 65 pressurized water reactors (PWRs) and 34 boiling water reactors (BWRs).[11] Geographically, the nation's nuclear fleet is spread across 59 sites, located in 30 states. Six states[12] currently draw more than 40% of their electric power from nuclear reactors, with Illinois, South Carolina, and New Hampshire relying on nuclear energy a majority of their electricity generation.[13]

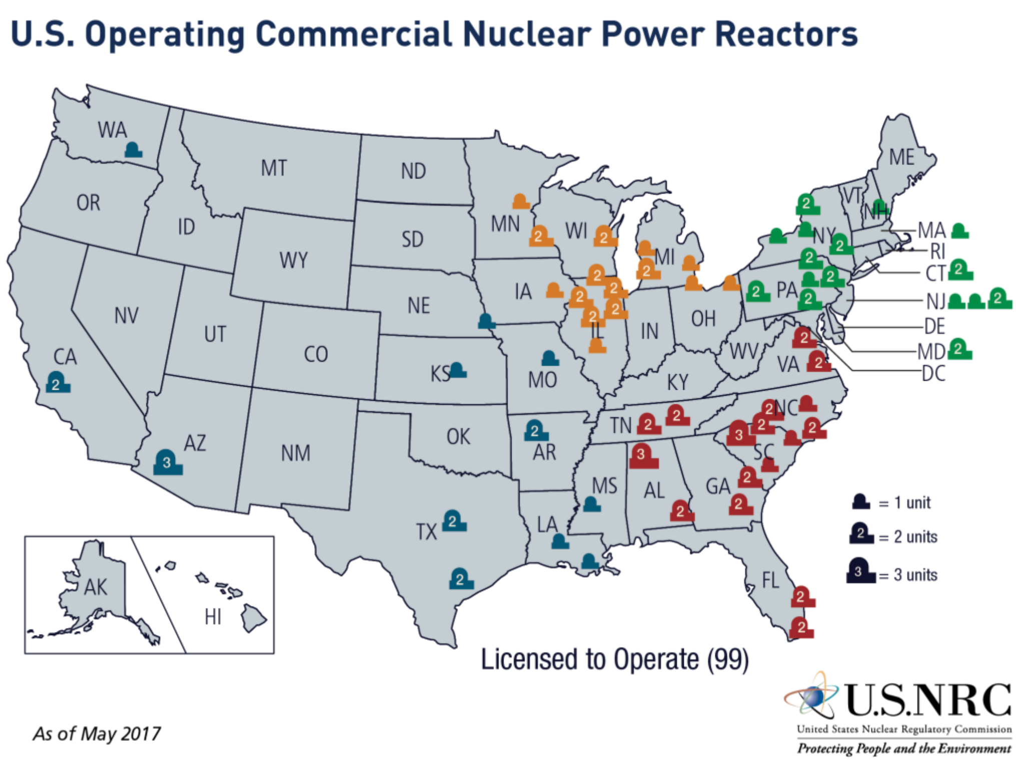

Figure 1: Currently operating U.S. nuclear reactors[14]

[9] EIA, "Electric Power Monthly, Table 6.7.B," September 2017, eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.
[10] EIA, "Monthly Nuclear Utility Generation (MWh) by State and Reactor.," September 2017.
[11] U.S. NRC, "2017-2018 Information Digest,"
[12] Illinois, South Carolina, New Jersey, Connecticut, Maryland, and New Hampshire
[13] EIA, "State Profiles and Energy Estimates," accessed March 29, 2018, https://www.eia.gov/state/?sid=NH.
[14] U.S. NRC, "Operating Reactors," May 2017.

From a technical perspective, the fundamental science and engineering behind nuclear energy generation in each of the nation's 99 LWRs is the largely the same. Raw uranium (which consists mostly of the ^{238}U isotope) is enriched until it contains roughly 3% ^{235}U — the fissile isotope of uranium, capable of sustaining a nuclear chain reaction. Now considered low-enriched uranium (LEU), it is converted into uranium dioxide pellets, and loaded into a fuel rod. Hundreds of these fuel rods are then loaded into the core of a nuclear reactor, where they are immersed in light water (ordinary H_2O) which serves as a coolant. Some of the LEU undergoes radioactive decay, causing it to fission and release roughly three high-energy fast neutrons, for every fissioned atom of uranium. The emitted neutrons then pass through the light water, which also serves as a "moderator" by slowing them down to increase the probability that they will collide with another uranium atom. When a collision occurs, the impacted uranium atom fissions and releases three fast neutrons of its own, which can then collide with more atoms — continuing on and on, in a chain reaction.[15] The rate of this chain reaction can be controlled by inserting and removing control rods, which can absorb the emitted neutrons, within the core. Importantly, with each fission, a huge amount of energy is released as heat — this is what makes nuclear power generation possible.

Up to this point, PWRs and BWRs are the same. However, the process by which each generates power from the heat produced by nuclear fission is substantially different. In BWRs, the fission reactions heat the light water, causing it to boil off into steam. This steam then drives a turbine, generating electricity. In PWRs, the water is pressurized, which prevents it from boiling, and instead heats to more than triple its 100ºC boiling point at atmospheric pressure. This heated water is then circulated through a primary coolant loop, where it exchanges heat with

[15] Uranium fission is governed by the following equation: ${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3{}_{0}^{1}n + heat$

atmospheric pressure water in a secondary coolant loop, which boils off into steam and drives a turbine generator. This is how all electricity from nuclear fission over the past six decades has been produced. However, as we will now examine, the nation's fleet of BWRs and PWRs are beginning to show their age, which poses a unique set of challenges.

2.2 Lifespans and Licensing

The U.S. nuclear fleet is beginning to show its age: the median age of a currently operating power reactor is 36.6 years. For context, the U.S. Nuclear Regulatory Commission (NRC) licenses commercial reactors for an initial operating term of 40 years, with the option of a 20-year license renewal (contingent on successful completion of an NRC review). Thus, at the median, U.S. nuclear reactors have nearly reached their initial lifespans. As of 2017, 86 of the 99 currently operating reactors have been granted license renewals, with seven applications either currently under review by the NRC or in preparation for submission. (The two reactors at the Watts Bar Nuclear Plant in Tennessee came online in 1996 and 2016, respectively, and are thus substantially further from their license expiration dates than the rest of the fleet.)[16]

However, even with the license extensions, total nuclear generation capacity is expected to continue to decline over the course of the next several decades, given the lack of new reactor construction and a number of early retirements.[17] As seen in Figure 2, even after taking the license renewals into account, only Watts Bar Unit 2 is expected to remain operational after 2050. This would represent a reduction of 103 GWe of nuclear electrical generation capacity over the next 33 years.[18] Given this, the NRC has taken steps to provide for an *additional* license renewal for reactors that can continue to demonstrate that they are meeting adequate safety

[16] U.S. NRC, "Status of License Renewal Applications and Industry Activities," accessed March 29, 2018, https://www.nrc.gov/reactors/operating/licensing/renewal/applications.html.
[17] EIA, "U.S. Nuclear Capacity and Generation Expected to Decline as Existing Generators Retire," May 12, 2017, https://www.eia.gov/todayinenergy/detail.php?id=31192.
[18] EIA, "U.S. Nuclear Generation and Generating Capacity," September 2017.

standards. The subsequent license renewal process, introduced in 2017, would add another 20 years to selected reactor licenses, bringing their total operational lifespans to 80 years.[19] As of the end of 2017, operators at seven reactors have announced their intent to file for subsequent license renewals by FY2021. If approved, this would extend the reactors' lifespans into the late 2050s/early 2060s.

[19] U.S. NRC, "Subsequent License Renewal," accessed March 29, 2018, https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html.

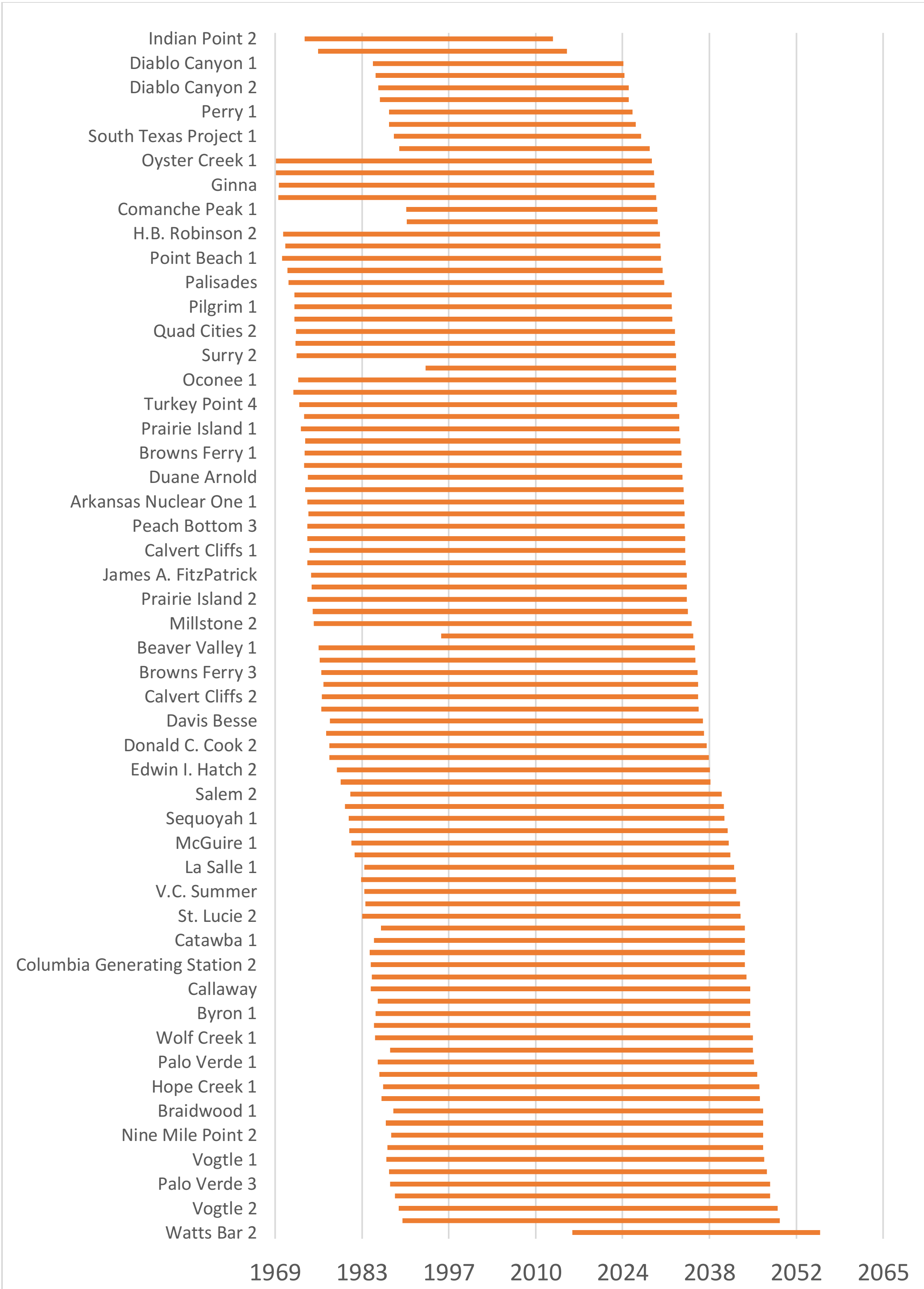

Figure 2: Lifespans of U.S. nuclear reactor fleet, based on approved licenses & renewals (NRC data)

2.3 Economic challenges

While nuclear energy remains a key component of the U.S. generation mix, the industry has faced economic headwinds over the past several years. Economic challenges have driven a number of reactors to shut down well before the expiration of their initial operating licenses — let alone the end of the 20-year license renewal extension. Per Haratyk (2017), the premature retirement of nuclear reactors is being driven by primarily by the continuous decline in wholesale electricity prices across the U.S., since 2007-2008. The drivers of this decline have been falling natural gas prices and decreasing electricity demand (due to increased efficiency and the rise of demand response/capacity markets). The rapid deployment of wind energy across the country has also been a significant driver of the decrease in electricity prices, but Haratyk notes that it has been largely cancelled out on a regional basis by the retirement of coal-fired generation.[20] The competition Haratyk describes is quite stiff: the price of natural gas for electricity generation has declined threefold, due to a boom in supply, from $9.26/tcf in 2008, to $2.99/tcf in 2018.[21] In a similar vein, the rapid growth of renewables poses yet another challenge to the economic viability of existing nuclear generation. For example, the price of solar PV has declined precipitously in recent years, evidently driven by a seven-fold decrease in solar panel prices over the past decade — from $3.50/watt in 2008, to $0.52/watt in mid-2017.[22]

2.4 Policy battles over existing plants

The deteriorating economic viability of existing nuclear reactors has led to significant turmoil in the electricity sector over the course of the past two years, with utilities pushing state governments to step in to support nuclear plants. Their arguments often focus on two key points: the value the plants generate by providing a consistent source of baseload generation, and the

[20] Haratyk, “Early Nuclear Retirements in Deregulated U.S. Markets_ Causes, Implications and Policy Options.”
[21] EIA, “Natural Gas Prices,” accessed March 29, 2018, https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm.
[22] EIA, “Electricity Monthly Update,” September 2017, https://www.eia.gov/electricity/monthly/update/.

climate and pollution avoidance value of the emissions they replace. In August 2016, faced with the potential closure of four upstate New York reactors owned by Exelon Corp. and Entergy Inc. (a combined 3.4 GWe of nameplate capacity) due to falling electricity prices, the state approved a Zero Emission Credit subsidy for the affected plants, as part of an effort to keep the state on track to meet aggressive greenhouse gas emissions targets by keeping nuclear generation online.[23] A similar situation played out a few months later in Illinois, where Exelon once again argued that it would have to shutter three reactors with a nameplate capacity of 3.2 GWe — 12% of the state's total electricity generation capacity. Relying on a similar line of reasoning as New York, Illinois also passed legislation providing a capped annual subsidy to the plants, in an effort to price in the value of their zero-emissions generation.[24]

These efforts have not been without controversy — both states' actions have faced legal challenges, and New York is currently scheduled to go before a federal appeals court early in 2018. Nevertheless, they have spawned similar efforts in Ohio and Connecticut, where subsidy bills are currently pending in the legislatures, as well as in New Jersey, where PSE&G (the state's largest utility) told lawmakers it would be forced to close two reactors by the end of 2019, without state subsidies.[25]

Meanwhile, as more and more plants fail to clear their supply in competitive market auctions, utilities are increasingly moving towards shuttering them on economic grounds. Exelon has already announced plans to close its Oyster Creek, NJ reactor— the oldest in operation — while Entergy has announced it will close the last nuclear plant in Massachusetts, both in 2019.[26]

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[23] Walton, "With Clean Energy Standard, New York Looks to Save Nukes, Skirt Legal Challenges."
[24] Rod Walton, "Illinois Passes Subsidy Bill to Save State's Nuclear Power Plants," *Electric Light and Power*, December 2, 2016, http://www.elp.com/articles/2016/12/illinois-pass-subsidy-bill-to-save-state-s-nuclear-power-plants.html.
[25] Peter Maloney, "Feud of the Year: Nuclear and Coal vs. Competitive Markets ," *UtilityDive*, December 4, 2017, https://www.utilitydive.com/news/feud-of-the-year-nuclear-and-coal-vs-competitive-markets/508266/.
[26] EIA, "Fort Calhoun Becomes Fifth U.S. Nuclear Plant to Retire in Past Five Years," October 31, 2016, https://www.eia.gov/todayinenergy/detail.php?id=28572.

Diablo Canyon, home of the only two currently operational nuclear reactors in California, and Pennsylvania's (in)famous Three Mile Island plant are both also said to be at risk, with utilities there appealing to regulators for assistance, as well.[27]

2.5 Security concerns

Historically, the major security concern for nuclear energy globally was nonproliferation. Civilian energy programs were often used as covers for nuclear weapons programs, as in Iraq, Libya, Iran, Syria, India, and more. Around the fall of the USSR, nuclear terrorism became a concern, as worries rose that rogue actors could get their hands on radiological materials from the nuclear energy fuel cycle and use them to construct crude "dirty bombs," or even as the feedstock for nuclear weapons. In the wake of 9/11, concern over terrorist attacks on reactor facilities grew. Over the past few years, concerns have been growing over a rising wave of cyberattacks on nuclear infrastructure and nuclear power plants themselves.

2.6 Future trends

While utilities grapple with the economic forces threatening the viability of existing nuclear plants, these trends are projected to hold for new construction as well. Construction of new reactors based on existing designs is expected to be quite costly, resulting in higher overall costs per MWh, as seen through the proxy of levelized costs of electricity (LCOE) for new generators coming online from 2018-2022. While the LCOE for new nuclear reactors based on current designs is projected to be roughly $99.70/MWh, new combined cycle natural gas generation is projected to come in at $56.40/MWh. While not weighted to account for intermittency/capacity factors, it's also instructive to note the projected LCOE for solar PV

[27] EIA, "Exelon Notifies NRC of Plans to Close the Three Mile Island Nuclear Facility ," July 5, 2017, https://www.utilitydive.com/news/exelon-notifies-nrc-of-plans-to-close-the-three-mile-island-nuclear-facilit/446324/; Jeff St John, " Critics Demand Clean Energy Guarantees for Diablo Canyon Closure," *Greentech Media*, November 30, 2017, https://www.greentechmedia.com/articles/read/critics-demand-clean-energy-guarantees-for-diablo-canyon-closure#gs.f7i=yKI.

($56.20/MWh) and for onshore wind energy ($50.90/MWh).[28] While LCOE is a decidedly imperfect measure for cross-source comparison, in this case it still serves to illustrate the substantial financial disadvantage that current nuclear reactor designs find themselves confronting.

This stark financial outlook has led to the withdrawal of nearly all planned construction of new nuclear reactors based on existing designs, across the U.S. In March 2017, billions of dollars in cost overruns on the construction of two reactors at the V.C. Summer plant in South Carolina drove Westinghouse, an industry giant owned by multinational conglomerate Toshiba, into bankruptcy. That July, South Carolina's major utility and its public service authority announced they would be cancelling the completion of the two reactors.[29] As a result, the only nuclear reactors under active construction in the country are Units 3 and 4 of the Vogtle plant in Georgia — and even those are at risk of cancellation, following the bankruptcy of Westinghouse, which served as lead contractor.[30]

Given the current trend, it seems quite possible that by the end of 2018, there will be no active nuclear construction in the United States.

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[28] EIA, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016," August 2016, https://www.eia.gov/outlooks/archive/aeo16/pdf/electricity_generation_2016.pdf.
[29] EIA, "South Carolina Utilities Stop Construction of New Nuclear Reactors," August 14, 2017, https://www.eia.gov/todayinenergy/detail.php?id=32472.
[30] "Plant Vogtle Decision Nears as Calls to Cancel Grow," December 15, 2017, http://www.savannahnow.com/news/2017-12-15/plant-vogtle-decision-nears-calls-cancel-grow.

3 The changing face of American "big science"

In the face of pronounced generational challenges like climate change and complex technical problems like the development of advanced nuclear reactors, it seems natural to hearken back to an era when such challenges were taken on in the form of grand, government-led “big science” projects, like the Manhattan Project and the Apollo Program, which rose out of the ashes of World War II and the Cold War. However, as we will see, the effectiveness of federally-led “big science” efforts has waxed and waned over the decades since the term was first coined by physicist Alvin Weinberg in 1961, in reference to the Manhattan Project and the emerging space program.[31] Indeed, the nature of American “big science” has evolved substantially over the years. Rather than the centrally-led, government-controlled efforts that brought us nuclear weapons and put men on the Moon, recent decades have favored public-private partnerships, which seek to draw on the political direction and financial resources of government, while simultaneously harnessing the creative energies of the private sector. We will examine five cases that illustrate the changing face of American “big science” over the past seventy years, in an effort to identify historical lessons that might offer insights for the development of advanced nuclear reactors.

3.1 The Manhattan Project

On a chilly Monday evening in January 1939, the course of American history was indelibly altered with a few words spoken in the physics department of Princeton University. Those present at that evening’s journal club were the first on the continent to learn of *nuclear fission*: the discovery by Lise Meitner, Otto Frisch, Otto Hahn, and Niels Bohr that nuclei of the element uranium would split into pieces, after being bombarded by neutrons. The fundamental scientific

[31] Alvin M Weinberg, “Impact of Large-Scale Science on the United States,” *Science* 134, no. 3473 (1961): 161–64.

implications of this discovery were profound, and news of the discovery spread like wildfire across American physics, bouncing from journals to conferences to department lounges.

Ordinarily, this is the point where a narrator would step in, to intone: "Little did they know… this discovery would have far reaching repercussions." But in this case, nothing could be further from the truth. For as one of his students would later recall:

> "When fission was discovered, within perhaps a week, there was on the blackboard in Robert Oppenheimer's office a drawing — a very bad, and execrable drawing — of a bomb."[32]

Driven by the needs of a nation and a world at war, J. Robert Oppenheimer — up to that point, just a talented physicist at Caltech and Berkeley — would soon come to lead a crash effort that would turn this laboratory discovery into the one of the most devastating weapons ever created by humanity. Within less than seven years, the bombs first sketched on Oppenheimer's blackboard would fall on the Japanese cities of Hiroshima and Nagasaki — bringing an end to World War II and ushering in the dawn of the nuclear age, with a terrible flash of light.

Taking nuclear fission from the lab bench to the battlefield in such a short period of time would ultimately require the combined efforts of over 130,000 people spread out across the United States, backed by more than $2.2 billion ($23 billion in 2007 dollars) in federal spending.[33] As we will see, in the seventy years since, this effort has come to be regarded as a *ne plus ultra* of "big science." When today's leaders want to make the case for bringing a challenging new technology from research to reality in the face of strong headwinds, they call for another Manhattan Project.

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[32] Richard Rhodes, *The Making of the Atomic Bomb*, (New York, 1986), 263-275.
[33] CTBTO, "Manhattan Project," accessed March 29, 2018, https://www.ctbto.org/nuclear-testing/history-of-nuclear-testing/manhattan-project/.

The Manhattan Project represents the first major example of a "big science" project in U.S. history. Driven by a desire to develop a nuclear weapon before Nazi Germany, the U.S. government created a massive, unified effort to research, develop, demonstrate, and deploy the world's first atomic bombs at a breakneck pace. By examining the period from 1941, when the Manhattan Project was officially launched, to its successful completion with the bombings of Hiroshima and Nagasaki in 1945, we can draw insights into centralization, research prioritization, and long-lead planning that offer potentially valuable lessons for the advanced nuclear effort.

Of particular interest to us is the work that went on at Los Alamos, the laboratory-city in the New Mexico desert which was purpose-built to bring together all the elements of the Project's core "bomb-making" work, fast-neutron fission research.

First, we can draw important lessons about the centralization and consolidation of research. The Manhattan Project's structure evolved substantially over time, as it shifted from a series of widely-dispersed university research groups, to a decentralized but coordinated research effort, and finally to a centrally-organized program. Based on its formal name — the "Manhattan Engineering District" — one might easily be led to imagine that the Manhattan Project was centralized from the start, a single, monolithic complex packed with machinery, work buildings and warehouses, akin to one of today's high-tech industrial factories.[34] However, the Manhattan Project began as a highly decentralized affair, scattered across the nation's universities. At U.C. Berkeley, E.O. Lawrence's Radiation Laboratory used his newly-devised cyclotrons to test electromagnetic techniques for separating plutonium, while Robert Oppenheimer explored the theory of fast-neutron fission which would ultimately make it possible to understand the

[34] Lillian Hoddeson, Paul W Henriksen, Roger A Meade, and Catherine L Westfall, *Critical Assembly: a Technical History of Los Alamos During the Oppenheimer Years, 1943-1945*, (Cambridge University Press, 2004), 2.

behavior of a nuclear explosive. At Princeton, Eugene Wigener led the study of the fission chain reaction, while at Columbia University, Enrico Fermi began work on what would become the world's first nuclear reactor. At the University of Chicago and Iowa State University, a whole host of researchers investigated everything from the chemical and metallurgical properties of plutonium and uranium, to their potential effects on the health of those working with them.[35] While this wide network of scientific collaborators was quite effective for the research-oriented efforts of the late 1930s and early 1940s, as the Manhattan Project began to take shape, more defined structures began to emerge.

In the wake of the discovery of nuclear fission in 1939, Albert Einstein wrote a letter to President Franklin Delano Roosevelt, warning that Nazi Germany appeared poised to develop an atomic bomb.[36] In response, Roosevelt created the Advisory Committee on Uranium, to coordinate research between the various groups investigating nuclear fission. With the outbreak of World War II, and the subsequent U.S. entry following the Japanese attack on Pearl Harbor, Roosevelt was determined to ensure that the U.S. beat the Germans to the bomb. As a result, he created the Office of Scientific Research and Development, which would serve as the civilian oversight for the bomb project, and the Manhattan Engineering District, a military unit which would oversee the day-to-day work of the effort.

As a result of this high-level support, the Manhattan Project grew rapidly, drawing on a near-unlimited source of federal and military funding. A plutonium production facility was established in Hanford, WA, while a uranium separation facility began work in Oak Ridge, TN. Meanwhile, the research groups continued to grow, with the establishment of the Metallurgical

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[35] ibid., 25-26.
[36] Cynthia C Kelly, *Manhattan Project: the Birth of the Atomic Bomb in the Words of Its Creators, Eyewitnesses, and Historians*, (Black Dog & Leventhal, 2009), 42-44.

Laboratory (Met Lab) at the University of Chicago. But while the atomic bomb research efforts now had a single chain of command, they were far from centralized. The disadvantages of this lack of coordination became immediately clear to Robert Oppenheimer, when he was tapped to lead the Manhattan Project's fast-fission group in 1942. He quickly came to notice that a great deal of research was being duplicated between the various research groups. While duplication and replication are core elements of the scientific research process, in a wartime, deployment-driven environment like the Manhattan Project, Oppenheimer viewed these duplications as emblematic of a different, larger problem. Researchers in the various groups, Oppenheimer, believed, lacked a sufficient overview of the project as a whole — which was, in turn, "stifling" ideas.[37] This challenge was a key driver in his determination to centralize the core science & weapons elements of the project under a single roof: Los Alamos.

Right from the first days of Los Alamos, Oppenheimer (who had been appointed director of the entire Manhattan Project) was determined to more effectively harness the vast resources — both in terms of personnel and matériel — available to him. In this vein, he supported an "indoctrination course" given by physicist Robert Serber in 1943 to the newly arrived residents of Los Alamos. It was designed to bring members of the various research groups — which had, up to this point, been scattered across the U.S. and engaged in their own, fairly discrete fields of study — up to speed on each other's work and how they connected, as well as lay out the overall thrust of the Project. One of the first coordinated activities of the Project, the course spanned roughly two weeks in April 1943 and laid out a clear goal: to construct a "practical military weapon using nuclear fission." [38]

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[37] Hoddeson, Henriksen, Meade, and Westfall, *Critical Assembly: a Technical History of Los Alamos During the Oppenheimer Years, 1943-1945*, 56.
[38] ibid., 69.

From the outset, it was clear that this would be the Manhattan Project's animating purpose: to construct a working atomic weapon, preferably before scientists in Nazi Germany were able to do the same. This singular objective meant that no expense was to be spared — an advantage offered by the security of military funding, and the financial flexibility of wartime.

Thus was born the "shotgun" research & development approach that produced the first fission weapons in the summer of 1945.

The shotgun approach was a product of both circumstance and planning. As Einstein warned Roosevelt in 1939, the best scientific and military intelligence available at the time suggested that the Nazis were determined to develop an atomic weapon of their own. As a result, the Manhattan Project scientists were charged with speed — their job was to hammer away at the problem of building a fission bomb on all fronts, as expediently as possible.

This led to consideration of two fissile materials, plutonium and uranium, and two separate weapons designs. In the gun-type bomb, one chunk of uranium was fired by a small explosive into another, which triggered the nuclear chain reaction. By contrast, in an implosion bomb, shaped explosive charges that detonated at precisely the same time would compress two hemispheres of either plutonium or uranium into a critical mass, triggering the chain reaction in that manner.

Each bomb design came with its own physics and its own set of challenges. Few, however, loom larger in the history of the Manhattan Project than what has been dubbed the "spontaneous fission crisis."

In the summer of 1944, scientists discovered that plutonium emitted far too many fast neutrons to be stably used in a gun-type bomb. That is, if they'd tried to build a plutonium gun-type bomb, it was believed that the bomb could "fizzle" — prematurely exploding and dramatically reducing its power.[39]

With millions of dollars invested in a nationwide infrastructure for plutonium production, the Project turned its eyes to the second stream of research underway — the implosion bomb. In a terse order to the Project's administrative board, Oppenheimer declared that "essentially all work on the [plutonium] gun program…should be stopped immediately…all possible priority should be given to the implosion program."[40] Though it had been a secondary focus of the program up until to the point, it would quickly take primacy, with scientists rapidly ramping up to build it.

This incident illustrates the importance of the "shotgun" approach. Had the Manhattan Project scientists not maintained an active, and reasonably robust research stream into the implosion bomb — an entirely different vein of research than the one that seemed most promising — the spontaneous fission crisis might well have proven to be a crippling blow for the atomic bomb effort.

Another organizational decision by the Manhattan Project, while quite controversial, would prove valuable in the future, in ways that could not have been anticipated. From the earliest days of the project, Hungarian physicist Edward Teller was insistent that the development of a thermonuclear fusion weapon also ought to be pursued. Teller (correctly) believed that the "Super" would be a far more powerful device than the fission weapons under consideration. However, the theoretical physics necessary for a fusion bomb had yet to be solved by the time the Manhattan Project began in earnest, and so Oppenheimer and the project's

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[39] ibid., 228-243.
[40] ibid., 243.

leadership pushed for a focus on the fission bomb, while the Super took a backseat for the duration of the war.

And yet, while the Super was effectively sidelined, Teller and a few other scientists were still given a passive sanction to continue their conceptual work on the physics and design of such a weapon, in addition to his primary duties on the Project. Leadership at Los Alamos, led by Oppenheimer, supported early-stage (largely theoretical) research on the Super.[41] This seemingly small concession would provide an invaluable jump-start for the development of thermonuclear weapons, which today make up the entire U.S. nuclear arsenal.

The story of the Super illustrates the remarkable ways in which even small investments in the deployment of early-stage ideas can have an enormous impact on their progress. While these investments —whether in time, resources, critical material, vital personnel, or money — may not appear to have any immediate payoff, and indeed, might seem to be based on half-formed information, insufficient technical validation, and generally dim prospects, they can still yield valuable results if properly applied. Long-lead development efforts — ones that attempt not just evolutionary, but truly innovative approaches to a given problem — nearly always offer a much riskier payoff structure. And yet, as the Super shows, this doesn't mean they ought not to be considered.

Another key challenge of the Manhattan Project was the gap between the science and the engineering. For the most part, the science was relatively well-understood. At the time the project was conceived, it was well-understood that the nuclei of certain heavy atoms would, over time, undergo radioactive decay — an understanding that dated back to the work of Marie Curie in the 1890s. Similarly, it was also well-understood that the fissioning of uranium and plutonium

[41] ibid., 47.

atoms could be induced by collision with neutrons, that these fissions could support a chain reaction, and that they released such massive energies (relative to their mass), that a sufficiently large mass could be converted into a fearsome weapon.

In fact, this information had become quite well-understood even in the few weeks between the discovery of fission and the letter from Einstein which convinced Roosevelt to set in motion the chain of events that lead to the creation of the Manhattan Project.

However, while the science of the bomb was relatively well-characterized, the engineering was quite a different matter. Engineering is — by its very nature — an empirical, iterative method. It refines through repeated attempts at implementation. This made building a bomb unlike any before it a daunting undertaking. The engineering challenges abounded, descending into hierarchical lists. Under the heading of "fissile material," we could list everything from the massive supply chain needed to enrich uranium, to the gaseous diffusion technologies that had to be built in order to do so, to the fine machinery needed to work the temperamental heavy metals.

As one historian later put it, this was a challenge for "Edison, not Einstein."[42] At its core, the Manhattan Project really was an *engineering* project, not a science project. The central challenge was turning lab-bench experimentation and theoretical calculations, into a working, deployable weapon.

Another key element to consider is the political role WWII and Nazi Germany played in driving the development of the atomic bomb. As discussed, defeating the Nazis by beating them to the bomb was a primary driver of the Manhattan Project, at its inception. Because this was considered a matter of the utmost national importance and the greatest national security, it meant

[42] ibid.

that the Project received all the funding it needed — plus, Oppenheimer was given broad latitude to run his scientific/engineering hybrid program within the usually regimented ranks of the military. Even when attention turned to Japan, and later the USSR, the single biggest thing that the Manhattan Project had going for it remained the same — its success was considered to be a matter of national success, and so it was given the highest priority, and all the resources it needed.

3.2 The Apollo Program

Moving beyond the Manhattan Project, we come to the Apollo Program. In popular culture, it's widely believed that President John F. Kennedy gave a speech declaring that "before the decade is out, we will put a man on the moon and return him to the Earth," and thus was born Apollo. Much as the Manhattan Project has become a cultural touchstone for government efforts to bring technology to maturity against the odds, the "moonshot" has also entered the American lexicon as an emblem of a crash effort to defy the odds. However, Project Apollo's roots stretch back far beyond Kennedy's declaration, through the tangled web of the early American space programs, well into the Eisenhower Administration.

In a 1970 analysis of what he called *The Decision to Go to the Moon*, noted space historian John Logsdon wrote that "by mid-1960, NASA had the manned space flight mission, the spacecraft and booster experts to carry it out, and plans for an ambitious second-generation program that would begin to send men towards a lunar landing."[43] Far from a spur-of-the-moment venture, the moonshot was the result of calculated, strategic planning by both the White House and the federal science apparatus, which in the late 1950s and early 1960s consisted of a scattered array of civilian and military bodies.

[43] John M Logsdon, *The Decision to Go to the Moon: Project Apollo and the National Interest*, Phoenix ed, (Chicago: The University of Chicago Press, 1976), 34.

On the military side, an Air Force advisory committee chaired by Edward Teller, the father of the thermonuclear bomb and no stranger to long-lead planning, sought as early as in 1957 to frame a lunar mission as part of a broader national security mission, recommending that the service "develop a second-generation ICBM that could also be used as a space booster and eventually could launch a manned lunar mission."[44] In stark contrast, the National Aeronautics and Space Administration (NASA) was formed from existing civilian space and aviation bodies in 1958 with expressly "peaceful and scientific purposes" in order to advance "the expansion of human knowledge."[45] In the early years of American space efforts, these seemingly contradictory motivations would lead to many a clash of the titans. It wasn't until President Eisenhower formally delineated the national space policy hierarchy, giving NASA clear responsibility for manned spaceflight in 1958, that planning for the moonshot could begin in earnest. But by that time, there was a new president on the way in — and he had his eyes on the skies.

Just two months after taking office as the 35th President of the United States, John F. Kennedy began to set the wheels of the Apollo Program into motion. Having campaigned in 1960 on a platform of ambitious rhetoric that presented space exploration not as a matter of scientific discovery, but as a question of "national prestige," Kennedy was determined to catch up to the Soviet Union, which seemed to have maintained a steady lead since the landmark launch of Sputnik I (the first manmade satellite) in 1957.[46] In March 1961, Kennedy approved the development of what would become the Saturn V rocket, the platform that would launch the Apollo missions, after being told by NASA Administrator James Webb that work on the Saturn V needed to begin immediately if the U.S. was to have any hope of beating the Soviet Union to

[44] ibid., 46.
[45] ibid., 56.
[46] ibid., 57.

the Moon. However, he had yet to make up his mind on whether or not to green-light the moonshot — a decision that was about to be effectively made for him.

On April 12, 1961, news broke that the Soviet Union had successfully launched a man into space, and Washington, D.C. immediately exploded into what Logsdon calls “an atmosphere of panic, almost hysteria.” Faced with yet another Soviet triumph in space, Kennedy “reluctantly came to the conclusion that, if he wanted to enter the duel for prestige with the Soviets, he would have to do so with the Russians’ own weapon: space achievement.” As Kennedy saw it, he had no other option: “the international and domestic political penalties" of not competing would be “unacceptable.”[47]

In an Oval Office meeting, he asked his advisers how the U.S. could beat the Soviets to the Moon, and was told that “the one hope… lay in this country's launching a crash program similar to the Manhattan Project.” After a moment’s silence, he made his decision: “There’s nothing more important.”[48] And with that invocation of Robert Oppenheimer’s feat of engineering organization, the Apollo Program was born.

Long-lead planning is at the heart of the Apollo story. The initial work done on heavy-lift rockets, the Saturn V’s predecessors, was green-lighted and begun under Eisenhower. As a result, so much work had been done on the underlying rocket development that by the time Kennedy took office, NASA was able to project that a manned landing would be technically feasible by 1967. In addition, he was able to give NASA administrator James Webb the green light to proceed with development of the Saturn V nearly a full year before he actually approved Project Apollo.

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[47] ibid., 105.
[48] ibid., 107.

As with the Super, long-lead planning — on projects that seemed outlandish, and even without practical or scientific purpose — paid off handsomely, giving the U.S. the first-mover advantage it needed to beat the USSR to the moon. And, of course, here again, the drivers were the compelling (military) interests of the Cold War — which meant that one of the greatest science and engineering efforts of the 20th century was primarily motivated not by any scientific or economic purpose, but by a broader sense of strategic national interest.

The research & development structure of the Apollo Program also leads us to interesting insights. For one, we can argue that Apollo was almost entirely an evolutionary program, from the technical perspective.

Now, this is not to naively minimize the challenges of building the most powerful rocket ever launched, sending it into space with three people and a lander strapped to the top, entering lunar orbit, landing and bouncing around on another celestial body, and then returning those three people back to Earth. But, if we break these into their constituent components, we realize that a surprisingly large amount of groundwork had actually already been laid.

Heavy-lift rocket technology had been worked on from the early Vanguard program, all the way through the mammoth Atlas and Redstone launch vehicles that sent the Mercury and Gemini astronauts into Earth orbit. Speaking of Mercury and Gemini, these pioneers of human spaceflight performed a huge amount of what was essentially validation testing for the human component of the moon landing — survival in the unforgiving void of space. Numerous lunar probes made it to the surface of the moon before humans did. And, of course, there's a reason it is the eleventh Apollo mission that is immortalized in our history — the preceding four manned flights served to test the Apollo spacecraft, and its ability to safely carry its crew to lunar orbit and back. To put this into perspective, as the chair of a high-level commission that laid out goals for the Apollo Program, NASA Administrator George Low wrote in 1961 that "no invention or breakthrough is believed to be required to insure the over-all feasibility of safe lunar flight."[49] While the actual spacecraft that would take men from the moon had yet to be designed, NASA was confident that it possessed a firm scientific and technical understanding of both the challenges of spaceflight, and the features these would necessitate in a lunar spacecraft. Per the Low Commission's analysis, there were no insurmountable technical barriers standing between NASA and a lunar landing.

It's also important to note the importance that federal organizational structure played in the effort. In the Eisenhower and Kennedy years, various factions of the military jostled for control of the nation's manned space program. When President Eisenhower centralized and codified the space program under the newly formed National Aeronautics and Space Administration in 1958, he laid the groundwork for the Apollo Program — a massive industrial effort that was fueled by federal dollars and driven by the massive resources of the NASA apparatus.

3.3 COMSAT

Moving beyond the Manhattan Project, the Apollo Program, and their systems of complete federal control over the R&D(DD) process, we examine a key example of federal efforts to deploy advanced technology for broad commercial and civilian use, by serving as an authoritative guide, rather than as a direct manager.

The Commercial Satellite Corporation (or COMSAT, as it is widely known), was formed in 1962 as a result of the federal Communications Satellite Act. It, too, was a child of the Cold War — driven in part by a desire to expand U.S. power by creating the first global satellite telecommunications network. Cognizant of the important political role of commercial satellite

[49] ibid., 62.

communications, the Kennedy White House became alarmed by how AT&T and its nationwide telephone monopoly appeared poised to immediately dominate the embryonic commercial satellite industry. In response, they pushed for the formation of a public corporation to oversee the development of the U.S.'s civilian satellite telecommunications infrastructure. Its key role was to facilitate the development of a single U.S. satellite network, by marshalling the resources of nine competing telecom companies and the U.S. government. It would also thread a needle that we will soon consider with regards to the development of advanced nuclear technology: how to decide if the primary aim of a given commercial R&D effort is purely financial, or a broader national goal of technology development. COMSAT left a powerful legacy, in the form of the INTELSAT and INMARSAT global communications constellations, and the infamous Iridium network.

Unlike the advanced nuclear industry today, the nascent commercial satellite industry of the early 1960s was one that everyone wanted a part of. From telecom giants like AT&T, to industry leaders like RCA, Hughes Aircraft, every player in the communications industry wanted a part of the incredible profits that the nation's first commercial satellite constellation was expected to bring. In fact, players in the market were willing to spend their own money on satellite constellations, even without government backing or funding, to a certain extent. Hughes Aircraft developed its prototype constellation fairly extensively, without NASA funding.[50] At the same time, however, government money was actively being sought by those hoping to develop commercial satellite technologies. For example, Lockheed Martin's Telsat proposal called on the government to subsidize its early stages.[51]

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[50] David Whalen, *The Rise and Fall of COMSAT: Technology, Business, and Government in Satellite Communications*, (London: Palgrave Macmillan UK, 2014), 14, doi:10.1057/9781137396938.
[51] ibid., 28.

However, the elephant in the room was undoubtedly AT&T. The nation's largest telecom company by far, “Ma Bell” made no secret of its desire to play a leading role in the nascent commercial satellite industry. It was AT&T's urging that first drove NASA to formally propose a commercial satellite constellation in 1960.[52] Given the scale of its operations, it seemed quite likely that AT&T would be able to handily establish a monopoly in commercial satellite communications, by gaining a sizable first-mover advantage and quickly cornering the market — as it had done with telephone communications.

Intriguingly, a common sentiment across the industry was that while the technical and engineering challenges of designing, constructing, and deploying a first-of-a-kind commercial satellite constellation would certainly be substantial, they wouldn't be the biggest hurdle. Early on, both COMSAT and Hughes expressed their belief that the economics of commercial satellites would be a greater impediment than the actual technology itself.[53] Similarly, in testimony before Congress, executives at Lockheed Martin noted that they greatest challenges they anticipated were legal, not technical, in nature.[54]

In 1960, the commercial satellite industry bore some resemblance to today's advanced reactor industry, from a technical perspective. The basic science behind commercial satellites was well-established, as is the basic science of many advanced nuclear reactor designs today. Engineering challenges were highly individualized: each company had its own set of designs, orbital parameters (in the early years), and thus its own unique set of technical roadblocks. And regulation and economics were large concerns. But that's about where the resemblance ends.

[52] ibid., 10.
[53] ibid., 11.
[54] ibid., 27.

The commercialization of satellite technology was heavily favored by market forces: everyone from AT&T to NASA to the Kennedy White House believed quite firmly that the deployment of the technology would lead to substantial profits for those involved. As a result, firms were jostling for position, each seeking federal approval to build the nation's first constellation.

In the face of this, NASA and the Kennedy Administration charted a course for commercial satellite technology that had broader aspirations. By legally designating COMSAT as the “chosen instrument” of the U.S. government for developing commercial satellite constellations, the federal government codified its desire to integrate the various private sector efforts, in order to streamline them and accelerate the ultimate deployment of commercial satellite technology. Concerns about an AT&T monopoly played a significant role here: COMSAT's primary goals were to enable (American) access to commercial satellite technology, prevent the emergence of a monopoly, and maximize efficiency of the sector.[55] However, COMSAT’s role would not be to develop, deploy, or operate the constellation — all that would be left to the private sector. Rather, it would serve as a convening authority, charged with unifying a number of players in an existing commercial effort, and shaping that effort in a manner that also optimized for the interests the government held to be important. All of this was keeping in line with its congressional mandate to “meet the nation's needs in the broadest sense.”[56]

That "broader sense" of national needs also included a strong political component. In testimony before Congress, AT&T executives lamented “what a shame it would be for the US to lose its leading role in space,” were it to fall behind in the development of commercial satellite

[55] ibid., 32-33.
[56] ibid., 31.

technology.[57] Lockheed executives chimed in as well, noting the "prestige" that would accrue to the U.S. by virtue of being first in commercializing space.[58] The politics of the Cold War loomed large in the minds of everyone from the business executives, to the Congress, to the White House.

These two drivers — economic demand, on the part of the satellite companies, and political incentives — would come into conflict over the years. While COMSAT was the U.S. government's "chosen instrument" by law, debates would emerge over whether it was meant primarily to promote a commercial enterprise (the deployment of commercial satellite constellations) or as a foreign policy instrument of the United States.[59] This would come to the fore with the development of INTELSAT, the COMSAT constellation. The Communications Satellite Act of 1960 empowered COMSAT to engage in negotiations on behalf of all of its member corporations with other nations and their telecommunications companies. As part of this process, numerous questions emerged as to whether COMSAT's priority ought to be commercial profit, or a broader set of goals driven by U.S. foreign policy — as in cases when negotiating with the USSR or accepting contracts with European allies that offered them a premium beyond what would ordinarily be considered market value.

3.4 Synthetic Fuels Corporation

For a more energy-centric example — as well as one with politics more akin to our own than to that of the WWII/Cold War era — we can turn to the U.S. Synthetic Fuels Corporation. In the spring of 1979, as the price of oil spiked following the Iranian Revolution, President Jimmy Carter went before the public to make a dire declaration: "The future of the country we

[57] ibid., 37.
[58] ibid., 28.
[59] ibid., 36.

love is at stake." Speaking from the White House, Carter told Americans that energy security was "the greatest challenge that our country will face during our lifetime."

During a decade where millions of Americans experienced sticker shock at the pump and gas lines for the first time in their lives, the cost of oil and the nation's dependence on unstable/unfriendly nations to obtain it had become a major national threat for Carter — just as the USSR had been for Kennedy, and the Nazis for Roosevelt. For Carter, energy security was thrust to the forefront of the national interests that concerned him. As Kennedy had said in 1961, when it came to Carter's ranking of threats to American interests, "there [was] nothing more important" than securing a sizable domestic supply of oil.

As a result, Carter and the Congress turned to the production of synthetic fuels from the nation's abundant coal reserves, as a plausible solution. The challenge was dropped in the lap of the specially created Synthetic Fuels Corporation (SFC), which was formed as a separate agency independent of the Department of Energy.

Like COMSAT, the SFC was created in response to two truths. On one hand, the federal government recognized that it desired the deployment of a technology in a way that didn't quite align with the way firms in the marketplace were likely to implement it. Synthetic fuel technology hadn't received widespread support and wasn't a major area of interest for industry. However, at the same time, the government also recognized that its organs — in COMSAT's case, NASA; in the SFC's case, the newly-formed Department of Energy — weren't necessarily the best instruments for the task at hand.

From 1980 to its dissolution in 1986, the SFC supported the development of six synthetic fuels projects. If we consider the SFC's primary role to have been accelerating the development and deployment of industrial-scale synthetic fuel production facilities, then it was largely successful — all six of the projects it funded were brought online ahead of schedule, not to mention under budget.[60] As an incubator of technology, the SFC was reasonably effective. However, it failed to meet its congressional mandate, falling well short of the production goals set forth in Energy Security Act. While it was well-suited to serve as an enabler of technological development, it wasn't equipped to scale it to the substantial size demanded by the legislation.

The SFC fell victim to an expectations problem, due largely to the political circumstances that gave birth to its initial congressional mandate. The Energy Security Act of 1980, which created the SFC, mandated that it produce ½ million barrels of oil equivalent per day by 1987, and 1 million barrels per day by 1992 — enough to replace ¼ of US crude oil and petroleum imports. The combination of a failure to meet those goals and a crash in oil prices in 1985 led Congress to terminate the program in 1986.[61]

The political motivations that drove the SFC — the desire to correct a perceived weakness in U.S. energy security— may have been well-reasoned at the time of the program's initiation in the late 1970s and early 1980s. But by the time its projects came to fruition in the mid-1980s, the political drivers (and their legislative targets) were out of line with the economic realities: synthetic fuels were no longer a cost-effective competitor to traditional petroleum. Moreover, the security concerns that drove the initial push for the SFC had largely fallen away — prices had retreated to their pre-1979 levels, and the U.S. had enjoyed several years of largely un-interrupted oil supply. In their 2004 critique of the SFC, Deutch and Lester raise an important point about its purpose: namely, that it was intended first and foremost as an instrument of public policy — in this case, national security policy — during a time of global energy insecurity. As

[60] Arnulf Grübler and Charlie Wilson, *Energy Technology Innovation : Learning From Historical Success and Failures*, (New York, 2014), 263-266.
[61] ibid., 259.

such, they contend, it could have taken advantage of what they call the “national security premium”: the argument that since the SFC was creating alternatives to “less safe” foreign sources of petroleum, it ought to be afforded some extra financial leeway — which might have helped it weather the 1985 oil crash.[62] However, since its legislative authorization (and thus, its political support) was predicated on the Energy Security Act’s production mandate, it was difficult for the SFC to escape being tagged as a failure after missing the Act’s targets. Deutch and Lester also note that while the SFC can charitably be viewed as an “insurance policy” — an effort to be prepared in case a domestic source of oil suddenly became a critical necessity — it isn’t clear that it served as the cheapest form of insurance against that eventuality.[63]

3.5 FutureGen

FutureGen began in 2003 as a Bush Administration effort to develop “clean coal” — a pilot integrated gasification combined cycle (IGCC) power plant, which would be connected to a prototype carbon capture and sequestration (CCS) system. The result would be a coal plant with (in theory) near-zero emissions. However, substantial cost overruns led the Bush Administration to end funding for the project in early 2008. After a period of dormancy, the project was revived in 2010 by the Obama Administration, with its focus was narrowed to eliminate the IGCC effort in favor of a focus on CCS. Instead of building a brand-new IGCC plant, the project instead aimed to retrofit existing coal plants with oxy-combustion generation systems, connected to a 175-mile pipeline which would bring the captured CO_2 from the plant to an underground storage site. While it was initially announced to great fanfare, the project was ultimately scrapped in 2015, after twelve years. It serves as a cautionary tale for what can happen when there is a

[62] John M Deutch and Richard Keith Lester, *Making Technology Work: Applications in Energy and the Environment*, (Cambridge University Press, 2004).
[63] ibid., 203.

disconnect between federal support for a technology deployment effort, and private sector motivations to support it.

To consider the fate of FutureGen, we must first consider the political motivations at play — which, notably, shifted over time. Under the Bush Administration, the FutureGen program was motivated by an all-of-the-above approach, codified in the Energy Policy Act of 2005, which promoted the development of domestic fossil fuels. This was in line with the Administration's overall national security strategy post-9/11, which emphasized energy security as a paramount concern for the U.S. Clean coal was repeatedly described by the Administration as part of an effort to increase U.S. energy security while simultaneously minimizing the impact on the environment. Interestingly, in a vein similar to Carter, Bush also placed a great deal of importance on the broad need to develop domestic energy independence — although at the time, most of US electricity was produced from domestic coal reserves.

For the most part, Obama largely continued Bush's support for clean coal. An early advocate of the FutureGen project, which was located in his state of Illinois, he is reported to have called it "the future of coal in the United States." However**,** Obama's focus shifted markedly from his time as a senator to his presidency, as he lost the professional obligation to Illinois, and developed stronger political positions in support of aggressive action on climate change. It seems plausible that this shift in priorities would have eased his Administration's decision to cancel the FutureGen project, especially when combined with the economic challenges the project faced. While the economic factors seem to have been far and away the primary drivers of the decision to cancel FutureGen, it is interesting to consider the idea that the loss of high-level political support might have contributed to its ultimate downfall. As it had during the Bush years, economics and a legacy of failure trumped what little political clout the program had remaining.

Like COMSAT, FutureGen was instituted as a public-private partnership. However, in this case, the federal government was obligated to fund the first 74% of the estimated $1.65 billion in costs, while private developers would then fund the remaining 26%.[64]

However, economics dealt a blow to FutureGen. Costs on the project nearly doubled, per the Bush Administration's projections, driven by delays and increasing materials and construction costs. Later on, the Obama years coincided with a massive surge in fracking and natural gas production, that sent the price of natural gas — which has substantially lower emissions than coal — plummeting. Faced with a deluge of cheaper, cleaner electricity from natural gas, coal plants — much less a first of its kind coal plant with an expensive new CCS system strapped to it — could hardly compete. As a result, the economic incentives for the private sector developers was greatly reduced.[65] They were unable to justify the projected costs to ratepayers, which would require substantial price hikes. Due to the private sector's unwillingness to commit further money to the project, the Department of Energy pulled the plug on FutureGen in early 2015.

FutureGen also offers another interesting parallel to the fate of nuclear energy thus far, in the role played by the diminished prospects of the so-called "hydrogen economy." An idea that was widely-touted in the early 2000s, it centers on an energy system — both for electricity and transportation — that is driven by the production and use of hydrogen fuel. This made the initial FutureGen concept, which would have produced hydrogen as a byproduct, more attractive —

[64] Peter Folger, "The FutureGen Carbon Capture and Sequestration Project: a Brief History and Issues for Congress," (Congressional Research Service, February 10, 2014).
[65] ibid., 9.

similar to many early 2000s nuclear reactor proposals, which were comparably buoyed by their ability to produce hydrogen in large quantities. However, the decreased prospects for a hydrogen economy likely contributed to a similar deflation of the nuclear and FutureGen ambitions.

Another difficulty highlighted by the FutureGen case is the disconnect between the multi-year timescales on which legislative priorities are developed, implemented, and phased out — as opposed to the decadal timescales upon which deployment projects of this scale are often working. The 2015 cancellation of FutureGen was driven in large part by the expiration of the funding appropriated to it by the 2009 American Recovery and Reinvestment Act — the post-financial crisis stimulus legislation which prioritized "shovel-ready" projects, and consequently imposed time limits on spending.[66] While the ARRA may have offered a timely source of funding for FutureGen, it operated on a timescale that was far too short for a complex demonstration effort like FutureGen.

At face value, FutureGen was a promising, government-driven energy technology deployment project: a public-private partnership with clear goals and reasonably viable technology. However, due to unfavorable economic forces in the broader electricity markets, combined with a lack of buy-in from industry, the project lumbered along and was quickly surpassed by the prospects for natural gas — a development that significantly undercut its long-term viability. While it seems likely that CCS technologies will play a significant role in climate mitigation over the long run, it is clear that they were poorly served by the FutureGen effort, which placed them at risk of falling victim to the "shadow of failure" described with respect to the SFC. That said, FutureGen has some positive elements to its legacy. Extensive preparation went into obtaining EPA certification to construct and operate CO_2 sequestration wells as part of

[66] ibid., 6.

FutureGen, which in turn created a wealth of data on both the reservoir characterization work that went into characterizing the injection site and the regulatory process itself — both of which remain valuable references for ongoing CCS efforts.

FutureGen serves as a cautionary tale for what happens when industry lacks the proper incentives to follow through on a government-led deployment effort.[67] Moreover, in contrast to the financial juggernauts that were the Manhattan Project and the Apollo Program, FutureGen actually failed to utilize the money available to it — expending less than a tenth of the $1.2 billion appropriated by Congress over the entirety of its lifespan.[68] It demonstrated that simply throwing money at a technology development and deployment effort isn't sufficient to ensure its success. The private sector must have sufficient incentives to want to carry on with the project, otherwise adverse market forces can overwhelm the underlying intentions of the project when federal support begins to flag, leading to its ultimate demise.

[67] ibid.
[68] ibid., 5-7.

4 The advanced nuclear ecosystem

Having explored the state of nuclear energy in the U.S. today, and considered some interesting historical analogues, we now turn our attention to the technology at hand: advanced nuclear reactors. To begin, we will consider in depth what exactly it is that qualifies a nuclear reactor as “advanced,” and examine the basic characteristics of the main advanced reactor types under development today. We will then step back and consider the broader ecosystem of advanced nuclear R&D(DD), with an eye towards understanding the relevant players, policies, and programs. While substantive technological progress will be necessary for the success of any advanced nuclear development effort, it is not sufficient in and of itself. By surveying the regulatory, legislative, and financial environments for advanced nuclear development, we will contextualize our discussion of the current progress and challenges in the sector, as well as lay the groundwork for a forthcoming discussion of how the lessons drawn from our historical analogues can potentially be applied to modern advanced nuclear development in the U.S.

4.1 What is an advanced nuclear reactor?

Over the past decade, the phrase “advanced nuclear” has been used to describe a wide variety of nuclear reactor and plant designs. While definitions abound, they are often couched in imprecise language — leaving room for a broad range of interpretations.

Internationally, the International Atomic Energy Agency (IAEA) defines an “advanced plant design” for new nuclear reactors as “a design of current interest for which improvement over its predecessors and/or existing designs is expected.” Within this broad category, the IAEA draws further distinctions between “evolutionary” and “innovative” designs. Evolutionary designs are described as those which achieved their signature improvements through “small to moderate modifications” requiring “at most engineering and confirmatory testing.” Meanwhile, innovative designs are those which “incorporate[e] radical conceptual changes in design approaches or system configuration in comparison with existing practice." The likely need for "substantial R&D, feasibility tests, and a prototype or demonstration plant" is described as a defining characteristic of innovative designs.[69] While such broad definitions can be useful for general discussion, in a space as fluid as the advanced nuclear world we find that they can quickly come to muddy the waters, when it comes to operationalizing the definitions in service of an analysis of advanced reactor designs.

The limitations of the IAEA's broad, imprecise definitions are evident from a glance at its Advanced Reactor Information System (ARIS), a database populated with technical characteristics and detailed design information about each of 69 "advanced" reactor designs currently under development worldwide. However, while the ARIS database does cover many of the emerging, non-light water reactor designs and advanced PWR designs we will consider here, it also lists numerous BWR and PWR designs which have been in development for upwards of two decades, including several which have been placed on indefinite hold or cancelled by their developers.[70]

Here in the United States, the NRC has a similarly muddled, but slightly clearer approach to the definition issue.

The NRC currently uses the term "advanced reactors" primarily to refer to non-light water reactors (non-LWRs), while specifically referring to new LWRs below 300MWe in size as "small modular reactors" (SMRs).[71] In draft guidance for non-LWR designs released in 2017, the NRC specifically addressed the challenge of the ambiguity surrounding definitions for new

[69] International Atomic Energy Agency, "TECDOC 936: Terms for Describing New, Advanced Nuclear Plants," April 1997, https://www-pub.iaea.org/MTCD/Publications/PDF/te_936_web.pdf.
[70] International Atomic Energy Agency, "Advanced Reactors Information System," accessed March 31, 2018, https://aris.iaea.org/sites/overview.html.
[71] U.S. NRC, "New Reactors," September 29, 2017.

reactors, noting that "the characteristics of an 'advanced reactor' have evolved over time, and this evolution is expected to continue." As illustration, it noted that the Westinghouse AP1000 PWR, with its passive safety features, was considered a prime example of "advanced reactor" technology when it was first introduced in 2002.[72] However, as we will discuss shortly, we do not consider the AP1000 (and similar large LWRs) to be advanced designs for the purpose of our discussion here.

For simplicity's sake, in this thesis, we use the term "advanced reactors" as a catch-all for both new non-LWR designs, and new LWR designs in the SMR size range (≤ 300 MWe).

It's important to note that this definition does exclude new large LWRs — those exceeding 300 MWe in size. However, this exclusion can be justified on a number of grounds, given the U.S.-centric focus of this thesis. First, the prospects for new large LWR designs in the U.S. appear quite dim. There are currently three applications for new large (> 300 MWe) LWR designs pending before the NRC. However, of these designs, two — AREVA's European Power Reactor (EPR) and Mitsubishi's Advanced Pressurized Water Reactor (APWR) — have been put on indefinite hold by their parent companies. The remaining design, KEPCO's APR 1400 is currently undergoing NRC's design certification process, with completion expected in late 2018.[73] However, there are currently no active proposals for APR 1400 construction in the U.S., nor do any appear to be forthcoming. Second, the prospects for further construction of existing large LWR designs in the U.S. appears similarly dim. The NRC has currently issued combined licenses (COLs) for the construction and operation of 12 new reactor units in the U.S. However, ten of these licensed reactor projects have either been placed on indefinite hold or cancelled

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72 U.S. NRC, "DG-1330: Draft Guidance for Developing Principal Design Criteria for Non-Light Water Reactors ," February 2017, https://www.nrc.gov/docs/ML1630/ML16301A307.pdf.

73 U.S. NRC, "Design Certification Applications for New Reactors," September 13, 2017, https://www.nrc.gov/reactors/new-reactors/design-cert.html.

outright by their parent utilities, with the previously discussed Vogtle Units 3 & 4 as the sole exceptions.[74] Completing this grim picture, while there are technically COL applications pending before the NRC for the construction of two new reactors at the Turkey Point nuclear plant in Florida, Florida Power & Light announced in March 2018 that the reactors "will not be constructed in the foreseeable future."[75] Given this lack of new designs or new construction of large LWRs in the U.S., we are comfortable eliminating them from our discussion of U.S. advanced reactors.

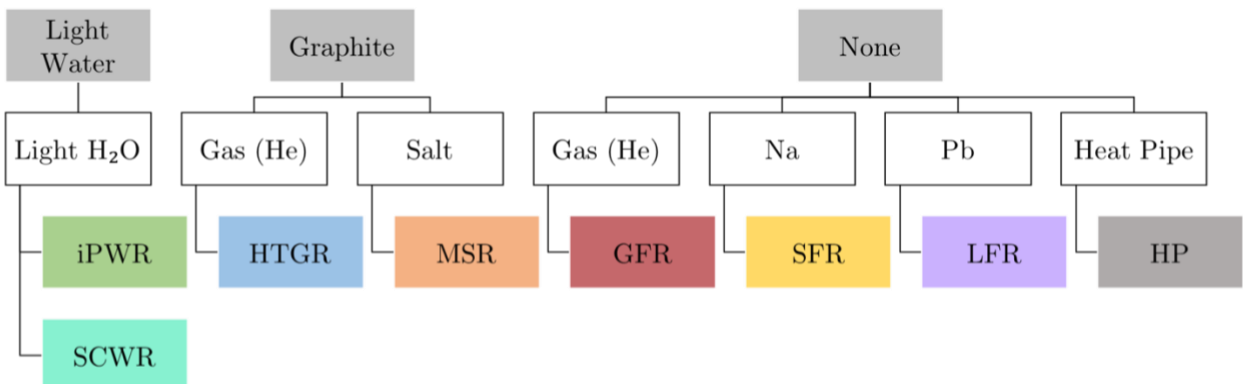

Figure 3: "Family tree" of advanced nuclear reactors

Nuclear reactors are most easily sorted by moderator, and then by coolant, as shown in the "family tree" of advanced reactors depicted in Figure 3. In the following sections, we will briefly survey the eight major categories of advanced reactors that we will consider here.

4.1.1 Advanced light-water reactors

As we discussed earlier, the prospects for new light water reactors in the United States seem rather dim at the moment, with only a single new LWR design currently proposed to the

[74] U.S. NRC, "Combined License Applications for New Reactors," September 15, 2017, https://www.nrc.gov/reactors/new-reactors/col.html.
[75] Gabi Maspons, "Economics Shelves FPL Nuclear Units at Turkey Point," *Miami Today*, March 13, 2018, http://www.miamitodaynews.com/2018/03/13/economics-shelves-fpl-nuclear-units-turkey-point/.

NRC for approval, and only two beleaguered reactors under construction. However, this does not necessarily mean that the era of LWR dominance in the nuclear sphere has come to an end. The development of advanced LWR designs today is largely focused on small modular reactors (SMRs), based on scaled-down, integral PWR designs (iPWR). For the most part, these reactors have the same basic operating properties as their large-scale PWR counterparts currently in operation across the country. What distinguishes them is their size and the prospect of modular/factory construction — both of which, proponents argue, make iPWR SMRs more economically viable and open to a broader variety of applications. They argue that the small size of iPWR SMRs makes them much more likely to be built, and that the expected volume of production will lead to significant learning and cost reductions.[76] However, critics of the SMR model argue that there is no evidence that the market for SMRs is substantial enough to support the kind of volume needed for significant reductions in cost — especially in the case of iPWRs, which are already able to draw on the considerable base of experience from conventional utility-scale PWRs.[77]

Another advanced LWR design is the supercritical water reactor (SCWR), which seeks to take a conventional PWR and pressurize the coolant water to above its critical point, allowing it to exist in a state close to saturated steam. This would allow it to operate on a single coolant loop, directly in series with a turbine like in BWRs, and at higher efficiency, which makes it an attractive iteration on the classic LWR design.[78]

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[76] William D Magwood IV and Henri Paillere, "Looking Ahead at Reactor Development," *Progress in Nuclear Energy* 102 (January 1, 2018): 58–67, doi:10.1016/j.pnucene.2017.07.001.

[77] M V Ramana and Zia Mian, "One Size Doesn't Fit All: Social Priorities and Technical Conflicts for Small Modular Reactors," *Energy Research & Social Science* 2 (2014): 115–24; M V Ramana and Ali Ahmad, "Wishful Thinking and Real Problems: Small Modular Reactors, Planning Constraints, and Nuclear Power in Jordan," *Energy Policy* 93 (2016): 236–45.

[78] Thomas Schulenberg, Laurence K H Leung, and Yoshiaki Oka, "Review of R&D for Supercritical Water Cooled Reactors," *Progress in Nuclear Energy* 77, no. C (November 1, 2014): 282–99, doi:10.1016/j.pnucene.2014.02.021.

4.1.2 Molten salt reactors

Molten salt reactors (MSRs) come in a variety of forms, but are primarily distinguished by the use of fluoride or chloride salts as their coolant. They have one of the more flexible core designs, with the option for fuel in traditional fuel rods, or dissolved directly into the cooling salts, yielding a fuel salt which is both fuel and coolant. Among the prospective advantages of MSRs are potentially higher fuel burnup (reducing waste and proliferation concerns), operation at atmospheric pressure (easing safety concerns), and passive cooling. This last element is a major selling point for MSRs — the idea that salt cooling systems lack the boil-off problems associated with water-cooled reactors and are thus much more robust to temperature excursions and indifferent to the loss of external power. Like most of the advanced reactors we consider here, MSRs have been the subject of much research over the years, including the Molten Salt Reactor Experiment, which ran during the 1960s at Oak Ridge National Laboratory, and demonstrated the viability of the MSR concept. That said, there remain major technical challenges in developing the chemistry of fuel and coolant salts, as well as concerns over the impact that direct contact with fuel/salt mixtures will have on the performance of various reactor materials and components. In addition, current NRC safety regulations are ill-equipped to deal with a molten fuel system, which has fundamentally different properties than pebble bed or traditional rod-encased fuel system.[79]

4.1.3 Liquid metal-cooled fast reactors

Liquid metal-cooled fast reactors generally rely on either lead coolant (LFRs) or sodium coolant (SFRs). In both cases, the high heat capacity and high boiling points of the coolant allows it to operate at atmospheric pressure, yielding considerable safety benefits. Research is

[79] Jérôme Serp et al., "The Molten Salt Reactor (MSR) in Generation IV: Overview and Perspectives," *Progress in Nuclear Energy* 77, no. C (November 1, 2014): 308–19, doi:10.1016/j.pnucene.2014.02.014.

currently ongoing into both designs, with rough expectations of 100MWth demonstration plants in the 2020s, with 1GWth operational reactors in the 2030s. In the interim, both LFRs and SFR have a number of challenges to overcome. For LFRs, the opacity of lead, its high melting point, and its corrosive effects on reactor structures remain persistent challenges. And for SFRs, sodium's chemical reactivity and propensity to leak makes it a difficult coolant to work with.[80] In addition to these conventional designs, a number of proposals for heat-pipe cooled fast "micro-reactors" (HP) have emerged over the past few years. These designs rely on natural convection to cool reactors of comparably small size — only around 1-10 MWe, usually. While they haven't been the subject of a great deal of active testing, they appear to have a variety of application for local-scale use.

4.1.4 High temperature gas-cooled reactors

High temperature gas-cooled reactors (HTGRs) have been the source of great excitement due to the breadth of their potential applications. Operating on a uranium, or potentially thorium/uranium fuel cycle, they are commonly cooled by helium gas, and produce output heat at temperatures of 700-1000ºC. This makes them prime candidates for use in industrial process heat generation, hydrogen production, as well as cogeneration systems for use in peak saving operations. In addition, as a breeder/burner of fissile isotopes, it creates and consumes plutonium, making it attractive both from a counter-proliferation and fuel cycle extension perspective. Based on the experience of previous experimental reactors in the U.S., it's commonly proposed with a "pebble bed" fuel system, in which fuel is encased in spherical "pebbles," which more effectively isolates it from its surroundings, preventing the outgassing

[80] Alessandro Alemberti et al., "Overview of Lead-Cooled Fast Reactor Activities," *Progress in Nuclear Energy* 77, no. C (November 1, 2014): 300–307, doi:10.1016/j.pnucene.2013.11.011; Magwood and Paillere, "Looking Ahead at Reactor Development."

and cross-contamination/leaching problems that are often experienced in conventional rod-based fuel systems. There are currently experimental plants operating in Japan (30MWth) and China (200 MWth), plus an operational plant under construction in China. Domestically, however, the HTGR has been largely languishing since the failure of the U.S. Next Generation Nuclear Plant effort. A nationwide research, development, and demonstration effort, the NGNP program was slated for completion by 2021, but is currently languishing in component R&D — casting a dark shadow across the future prospects of otherwise promising HTGR technology. A variant of the HTGR, the gas fast reactor (GFR) relies on a fast-neutron spectrum, but has not been the subject of as much active research.[81]

4.2 Key players in the advanced nuclear ecosystem

The major players in the U.S. advanced nuclear industry are:

- small reactor startups
- venture capital, backing those small startups
- large, conventional ("legacy") nuclear companies
- University-led research programs
- U.S. national labs
- Nuclear Regulatory Commission
- Department of Energy
- Advocacy, industry, and policy groups

Most of the technical work is going on in two large streams: basic research, and commercialization efforts. The research is largely centered on the national labs — Idaho, Oak Ridge, Los Alamos, Argonne, and Sandia, in particular — and university efforts. The commercialization work is further divided into two sectors: large corporations like GE Hitachi/AREVA/General Atomics, and small startups. However, this divide isn't quite as clean as it might appear. As the oft-quoted jibe goes, you can't build a nuclear reactor in your garage —

[81] Andrew C Kadak, "The Status of the US High-Temperature Gas Reactors," *Engineering* 2, no. 1 (April 25, 2016): 119–23, doi:10.1016/J.ENG.2016.01.026.

and these startups certainly aren't. Thus, they tend to have the backing of either large nuclear engineering firms (NuScale, with Fluor) or wealthy venture capital consortiums (Peter Thiel with Transatomic, Bill Gates with TerraPower).

The NRC has been thrust into a role it has not found itself in for years: contending with an entirely new breed of nuclear reactor designs. In response, it has begun an extensive rule making process, to set out a roadmap for how it's going to deal with this new generation of reactors. It has also begun to engage in pre-application activities, holding preliminary meetings with advanced nuclear firms to discuss their reactor designs and the regulatory pathway ahead for them. The NRC's engagement with the advanced nuclear industry has ramped up significantly in recent years. In 2016, it published its "Vision and Strategy" for non-LWR development, which is structured around some overarching goals and three Implementation Action Plans (IAPs), which lay out the NRC's advanced reactor regulatory goals through 2021, through 2031, and beyond 2031. However, there remains substantial concern that the U.S. is lagging on advanced nuclear licensing, as evidenced by the fact that many companies (TerraPower, Terrestrial Energy) are actively pursuing the demonstration and deployment of their initial demonstration reactors abroad — in countries like China and Canada, which have more permissive regulatory environments.

The advanced nuclear ecosystem draws on both private and public funding. Public money is largely geared towards the earlier stages of the commercialization cycle — basic research, engineering validation, and early translational efforts. Meanwhile, private money is largely headed towards companies looking to commercialize technology. Private money tends to come via investments from large corporations, venture capital, or angel investors. According to the think tank Third Way, $1.3 billion in private capital had been invested in advanced nuclear, as of 2015.[82]

The Department of Energy's role has largely been focused on providing research support, in the form of national lab resources and funding. Unlike the conventional nuclear sector, DOE funding in the advanced nuclear space has traditionally been in the form of research grants and other small grants, although it has begun to expand its loan guarantee and cost-sharing programs substantially over the past few years. A key element of this has come in the form of the GAIN initiative, which opened national lab resources to advanced nuclear firms in 2016, providing them with vouchers for the use of DOE research time, staff, and facilities.

Along with the various sources of technical research and work, the advanced nuclear industry also includes a growing cadre of advocacy and policy-focused organizations. Chief among these are industry-backed trade groups like the Nuclear Innovation Alliance, which was created in 2015 to focus on advanced nuclear, centrist think thanks like Third Way, which has emerged as a prominent voice in favor of advanced nuclear, and broadly energy-focused advocacy groups, like the Clean Air Task Force and the conservative ClearPath Foundation. In addition, there are broader nuclear industry groups, like the Nuclear Energy Institute and the World Nuclear Association.

In Congress, advanced nuclear energy has been the subject of a flurry of legislation in recent years. Over the past several sessions, the main points of focus have been on streamlining the regulatory process, opening up the capabilities of the national labs to reactor firms, and funding the creation of test reactors. Key efforts include the Nuclear Energy Innovation and Modernization Act (NEIMA), Nuclear Energy Innovation Capabilities Act (NEICA), and

[82] Samuel Brinton, "The Advanced Nuclear Industry," (Third Way, June 15, 2015), https://www.thirdway.org/report/the-advanced-nuclear-industry.

Advanced Nuclear Technology Development Act (ANTDA). NEICA focuses on developing an advanced test reactor to support new nuclear reactor designs, in addition to expanding R&D funding. NEIMA & ANTDA are the efforts by the Senate and House, respectively, to instruct the NRC to create a new licensing framework for advanced nuclear reactors. NEICA passed the Senate in March 2018, signaling growing legislative support for advanced nuclear.

5 Current state of advanced nuclear development

Now that we have an overview of the key technologies, players, and policies that are shaping advanced nuclear development, we can dive in and examine the current state of various active development efforts. Based on an analysis of the IAEA ARIS database and Third Way's Advanced Nuclear map, we have identified 34 efforts to develop advanced nuclear reactors in the U.S. These efforts are driven by a total of 29 organizations, which range from national laboratories and universities, to established nuclear companies and startups, and have a correspondingly broad array of proposed reactor designs and technologies. In this section, we will examine the current progress of each of these efforts and consider their common roadblocks and areas of research. In the process, we will also take a closer look at several advanced reactor development efforts, as representative examples of the current state of the sector.

Throughout our analysis, we will focus primarily on the development of integrated reactor designs as our central metric of progress. In some ways, this is an odd choice — given the long timescales upon which advanced reactor development occurs, it is quite plausible that many of the "game-changing" technologies which might ultimately shepherd viable advanced reactors to deployment are still in the component research and development stage. That is to say that at present, they could very well be nothing more than a fundamental materials science study in a laboratory, or a development effort for a new generation of reactor core models. However, given that our ultimate interest is in the deployment of advanced reactors, it seems appropriate to focus on how efforts to do so are faring today. It is reasonable to argue that the advanced reactor development efforts that could ultimately lead to widespread deployment do not exist yet, and thus will likely look quite different from the work currently being undertaken at various startups, companies, universities, and national laboratories. Yet even though they may seem anemic at the moment, especially in relation to the scale needed to tackle the climate problem, an examination of current efforts to develop and deploy advanced reactors offers valuable insights into the steps that might help accelerate and enable deployment on a broad scale.

5.1 Current progress

In order to easily discuss the progress of the 34 U.S. advanced reactor efforts at a high level, we offer a simplified four-level classification system, which defines each effort as having No Evident Design, having a Conceptual Design, being Under Design, or being under Active Development.

Organizations with No Evident Design have proposed broad concepts for the kinds of advanced reactors they intend to develop, and may have received funding to support their efforts, but fail to offer high-level technical details and characteristics of their proposed design.

Conceptual Designs are those which lay out, at minimum, high-level technical details and characteristics for their proposed designs. However, organizations with Conceptual Designs either have yet to conduct sustained work towards validating the technical details of their design, or have no express intent to do so, intending their Conceptual Design as a theoretical exercise.

Organizations which have reactors that are classified as Under Design have laid out a conceptual design and are taking steps towards validating the technical elements of that design. This can include everything from computer simulation work, to laboratory experimentation on materials and fuels.

Organizations engaged in Active Development of advanced reactors have achieved the milestones of reactors that are Under Design, at minimum. In addition, they are engaged in an ongoing development program, which is making tangible progress in refine their design to the standards needed for obtain regulatory approval to construct demonstration units.

Currently, there are ten reactor designs in Active Development, eleven Under Design, seven Conceptual Designs, and six organizations with No Evident Design. There are 12 MSRs, 5 SFRs, 4 HTGRs, 4 iPWRs, 4 LFRs, 2 HPs, 1 GFR, and 1 SCWR.

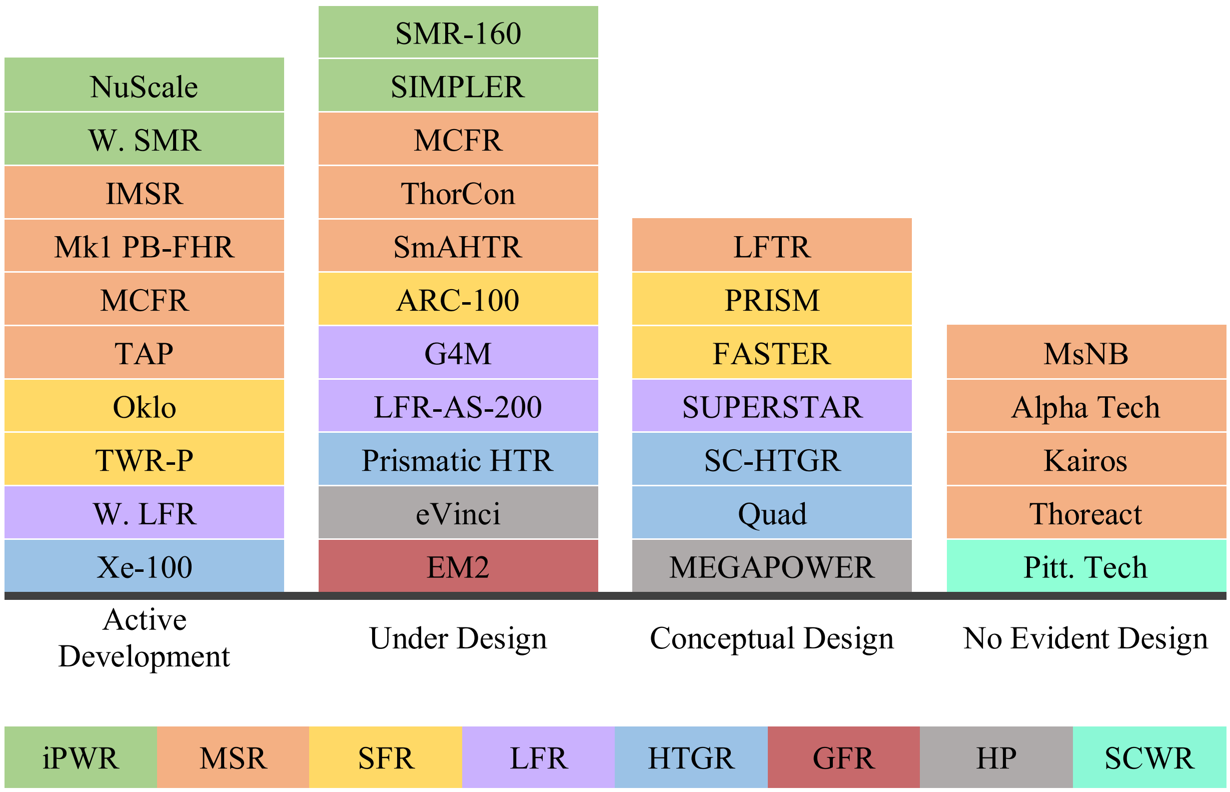

Figure 4: U.S. Advanced Reactor Projects by Status and Design

NuScale Power is currently the only advanced reactor firm to have submitted a complete design application to the NRC. Oklo, TerraPower, Terrestrial Energy, and X-Energy are all engaged in pre-application activities with the NRC — a catch-all description which indicates that they are working with the agency to begin the process of preparing their reactor designs for review.

5.2 Common areas of R&D

Our examination of the 34 ongoing advanced reactor development efforts in the U.S. reveals a number of areas of common research and development. These range from research into materials and fuel properties, to the validation of component designs and their robustness, to investigations of novel use cases for the proposed reactors.

Research into the economics and engineering of reactor sizing is a key focus for the vast majority of the development efforts we examined. Of the 26 proposed reactor designs for which power data is available, 21 fall under the ≤300 MWe SMR threshold. The average power of reactors under Active Development is 238 MWe, while the average power for reactors Under Design is 225 MWe. Developing reactors with the SMR scale in mind is evidently a major area of focus for a large swath of the advanced nuclear industry. NuScale Power is the industry leader, when it comes to development of small reactors: in addition to its completed design application to the NRC, the company constructed a fully-functional 1/3-scale version of its iPWR SMR design, and has conducted extensive tests with it using electric heating in the place of fission heating.[83]

In addition to the SMR size, there's also a fair amount of interest in what are commonly referred to as micro- or nano-reactors, or "nuclear batteries." These are reactors which only generate power on the order of a few MWe. Firms like Oklo, Holos, and Micronuclear are all building reactors in this range, with an eye towards applications in remote communities, places that need secure generation sources (like hospitals or military bases), and emergency response scenarios. At this scale, common research areas are the development of heat-pipe based cooling systems and so-called "walkaway-safe" control technologies which would allow the reactors to operate without continuous human management.[84]

[83] Robert Houser, Eric Young, and Adam Rasmussen, "Overview of NuScale Testing Programs," August 9, 2013, http://www.nuscalepower.com/images/our_technology/overview-nuscale-testing-ans-winter-2013.pdf.
[84] C Filippone and K A Jordan, "The Holos Reactor: a Distributable Power Generator with Transportable Subcritical Power Modules," August 31, 2017, doi:10.17605/OSF.IO/JZAC9; U.S. NRC, "Pre-Application Activities - Oklo," July 26, 2017, https://www.nrc.gov/reactors/new-reactors/advanced/oklo.html.

In both SMR and "micro-reactor" efforts, modularization is a central element of the reactor design strategy. Many of the development efforts we examined have placed the ability to construct reactor components, and even entire reactors, in a factory-style assembly line process at the core of their designs. Pittsburgh Technical, an engineering contracting firm, has actually gone ahead and constructed a factory-built prototype of the containment vessel for their proposed SIMPLER iPWR SMR, as a demonstrator.

From a technical perspective, the development and validation of both novel materials and novel use cases for various materials is a crucial component of many development efforts we considered. Among those under Active Development, we found that materials testing accounted for a substantial component of their activity at present. Key questions that need to be answered are how materials will perform under the extreme temperatures, corrosive environment, high levels of radiation, and mechanical stress that can be expected inside an advanced reactor. Understanding these characteristics will allow for a much better quantification of the expected longevity, limitations, and performance of various reactor components, and through them, the reactor itself.[85]

Given the rapidly changing composition of the U.S. electric grid, load following capacity and compatibility with intermittent renewables and energy storage are a major point of research for advanced reactor development efforts.

Many of the reactor development efforts have also placed a great deal of emphasis on developing a number of secondary use cases for their proposed designs. These range from hydrogen production, to process heat generation, to district heating, to marine applications, and more.

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[85] Pascal Yvon et al., "Structural Materials for Next Generation Nuclear Systems: Challenges and the Path Forward," *Nuclear Engineering and Design*, October 23, 2015, 1–9, doi:10.1016/j.nucengdes.2015.09.015.

In a less exotic vein, another fertile area of research focuses on the application of novel power cycles to nuclear reactors. These efforts include both LWR and non-LWR designs. For the LWR designs, the core organizing principle seems to be that by combining a more efficient power cycle with well-developed reactor technology, it might be possible to build more powerful reactors without having to deal with the complexities of designing a new core.

A major focus for HTGR design efforts is the development of particle or pebble fuels. The TRISO fuel particle is the current state of the art.

A number of advanced reactor designs rely on thorium fuel cycles, which are not currently employed in operational U.S. reactors, but appear to have a great deal of potential.

5.3 Common roadblocks

While we found much room for common research, we also noted several common roadblocks faced by advanced reactor development efforts. Much as the previous section revealed the substantial overlap between the development efforts, these results indicate the opportunity to accelerate reactor development across the board, by creating shared capacity on a few critical fronts.

One major issue was difficulty obtaining regulatory permission to construct and test demonstration reactors. While only NuScale is currently at a sufficiently mature stage to be having serious conversations about constructing a demonstration reactor, a wide variety of firms have either announced their intention to take their demonstration efforts abroad or have signed formal memoranda of understanding to construct demonstration reactors in foreign countries. TerraPower has signed an MoU to construct its demonstration SFR in China, and X-Energy has signed an MoU to explore demonstration and deployment of its HTGR in Jordan, just to name two. This is a result of the stringency of NRC safety regulations to some extent, but it also speaks to lack of a finalized system for the early-stage regulation, much less testing, of advanced reactor designs. While the NRC does offer pre-application support for advanced nuclear firms, this is an amorphous process that lacks standardization or formal regulatory weight. By contrast, the Canadian Nuclear Safety Commission (CNSC), has a formally-instituted phased system for the review of advanced nuclear reactor designs, and for early-stage permitting of proposed demonstration reactors.

In a similar vein, we found that reactor firms lack easy access to experimental testing capabilities, and thus must rely heavily on computer modeling for validation of their designs.

Table 1: U.S. Advanced Nuclear Reactor Projects

Designer	Acronym	Full Name	Design Status	Coolant	Moderator	Type	MW(e)	Spectrum
Oklo	Oklo	Oklo Reactor	Active Development	Sodium	No Moderator	SFR	1	Fast
NuScale Power Inc.	NuScale	NuScale Power Modular and Scalable Reactor	Active Development	Light Water	Light Water	iPWR	50	Thermal
X-Energy	Xe-100	Xe-100	Active Development	Helium	Graphite	HTGR	76	Thermal
UC Berkeley/MIT/UWisconsin	Mk1 PB-FHR	Mk 1Pebble-Bed Fluoride HTR	Active Development	Fluoride Salts	Graphite	MSR	100	Thermal
Terrestrial Energy	IMSR-400	Integral Molten Salt Reactor-400	Active Development	Fluoride Salts	Graphite	MSR	194	Thermal
Westinghouse	Westinghouse SMR	Westinghouse Small Modular Reactor	Active Development	Light Water	Light Water	iPWR	225	Thermal
Westinghouse	Westinghouse LFR	Westinghouse Lead Fast Reactor	Active Development	Lead	No Moderator	LFR	300	Fast
Transatomic Power	TAP	Transatomic Power Reactor	Active Development	Fluoride Salts	ZrHx	MSR	550	Thermal
TerraPower	TWR-P	Travelling Wave Reactor-Prototype	Active Development	Sodium	No Moderator	SFR	600	Fast
TerraPower	MCFR	Molten Chloride Fast Reactor	Active Development	Chloride Salts	No Moderator	MSR		Fast
Los Alamos National Laboratory	MEGAPOWER	MegaPower	Conceptual Design	Heat Pipe	Graphite	HP	2	
HolosGen	Quad	Holos Quad	Conceptual Design	Helium	Graphite	HTGR	10	Thermal
Argonne National Laboratory	SUPERSTAR	Simplified Lead-Cooled Fast SMR	Conceptual Design	Lead	No Moderator	LFR	120	Fast
Flibe Energy	LFTR	Liquid Fluoride Thorium Reactor	Conceptual Design	Fluoride Salts	Graphite	MSR	250	Thermal
GE-Hitachi	PRISM	Power Reactor Innovative Small Reactor	Conceptual Design	Sodium	No Moderator	SFR	311	Fast
Argonne National Laboratory	FASTER	Fast Test Reactor	Conceptual Design	Sodium	No Moderator	SFR		Fast
AREVA	SC-HTGR	Steam Cycle High-Temperature GCR	Conceptual Design	Helium	Graphite	HTGR		Thermal
Westinghouse	eVinci	eVinci Micro Reactor	Under Design	Heat Pipe	Graphite	HP	25	
Gen4 Energy Inc.	G4M	Gen4 Module	Under Design	Lead	No Moderator	LFR	25	Fast
Oak Ridge National Laboratory	SmAHTR	Small Modular Advanced HTR	Under Design	Fluoride Salts	Graphite	MSR	50	Thermal
Adv. Reactor Concepts	ARC-100	ARC-100	Under Design	Sodium	No Moderator	SFR	100	Thermal
General Atomics	Prismatic HTR	Prismatic Modular High Temperature GCR	Under Design	Helium	Graphite	HTGR	150	Thermal
Holtec	SMR-160	SMR-160	Under Design	Light Water	Light Water	iPWR	160	Thermal
Hydromine Nuclear Energy	LFR-AS-200	LFR-AS-200	Under Design	Lead	No Moderator	LFR	200	Fast
Martingale	ThorCon	ThorCon	Under Design	Fluoride Salts	Graphite	MSR	250	Thermal
General Atomics	EM2	Energy Multiplier Module	Under Design	Helium	No Moderator	GFR	540	Fast
Elysium Industries	MCFR	Molten Chloride Fast Reactor	Under Design	Chloride Salts	No Moderator	MSR	1000	Fast
Pittsburgh Technical	SIMPLER	Small Integral Modular PWR	Under Design	Light Water	Light Water	iPWR		Thermal
Micronuclear	MsNB	Micro-Scale Nuclear Battery	No Evident Design	Fluoride Salts	Graphite	MSR	5	Thermal
Pittsburgh Technical	SAFER	Secure Autonomous Feasible Economic Reactor	No Evident Design	Light Water	Light Water	SCWR	20	Thermal
Thoreact	TMSR	Thorium Molten Salt Reactor	No Evident Design	Fluoride Salts	Graphite	MSR		Thermal
Alpha Tech Research Corp			No Evident Design			MSR		Thermal
Kairos Power			No Evident Design	Fluoride Salts	No Moderator	MSR		Thermal
Yellowstone Energy			No Evident Design					

6 Historical lessons for advanced nuclear

Based on our analysis of the current state of nuclear energy in the U.S., we see that LWRs are headed towards the end of their lives — and not without good reason. In terms of economics, safety, and waste disposal, the current crop of American nuclear reactors leaves much to be desired. However, recalling our discussion of the climate problem, we note the likelihood that nuclear power will be called upon as part of any effort at deep decarbonization. Thus, at bare minimum, it makes sense to develop and maintain the capability to deploy a new generation of nuclear reactors, should the need arise. Given this, what's the best path forward for nuclear power in the U.S.?

As our discussion of the current state of nuclear energy in the U.S. shows, the prospects for currently-available reactor designs are rather dim. Moreover, the uncertainty created by the current economic environment has virtually halted all new nuclear development in the country. While in general, this thesis argues for widening the slate of approaches to be considered, in this case, I strongly argue for a narrowing: the elimination of evolutionary designs, in favor of innovative, advanced reactor designs.

Though nuclear power's prospects appear grim at the moment, we find that the historical record offers strong support for the idea that with the proper strategy, a robust deployment of even immature technologies like the proposed advanced nuclear designs we have examined is certainly feasible.

We can now combine our exploration of historical U.S. government efforts to rapidly deploy immature technologies, with our analysis of the current state of advanced nuclear reactor development in the U.S., in an effort to identify key lessons and broad principles which might help guide efforts to accelerate the eventual deployment of advanced nuclear in the U.S. In doing so, we seek to take advantage of historical perspective in looking beyond the current stagnation in the nuclear industry, and considering how to fundamentally reshape advanced nuclear energy development in the United States.

6.1 A changing role for government

While massive government-run efforts like the Manhattan Project and Project Apollo were feasible given the economic and political climate of World War II and the Cold War era, the lessons of the SFC and FutureGen efforts indicate that the government-run model of technology development, demonstration, and deployment is not necessarily the best fit for the current environment. Instead, a form of public-private partnership which focuses on outcomes, rather than specific technologies, in the vein of COMSAT, seems likely to meet with greater success.

The experience of the SFC demonstrated that while the government can serve as a powerful catalyst for the development and demonstration of new technologies like synthetic fuel production, it isn't well-equipped to scale those technologies to industry-wide deployments. While the SFC served as an excellent technology incubator, it was ill-equipped to create a new synthetic fuels industry. Had there been a private sector appetite for synthetic fuels in 1986, it's certainly possible that the projects incubated by the SFC could have been at the vanguard of a boom in domestically produced synthetic fuels. However, without market demand for synthetic fuels, their deployment on the scale mandated by Congress would have necessitated the commitment of massive financial resources by the federal government, with the explicit goal of enhancing energy security and independence, without regard to market forces. Barring a willingness to commit that level of resources in the face of adverse market conditions, the SFC lacked the ability to serve as anything more than a well-run technology incubator.

Building off this, the experience of the FutureGen effort demonstrates that simply throwing money at a technology demonstration effort isn't enough to encourage broader adoption of the technology, if industry lacks an incentive to take up the cause. By the time FutureGen was cancelled in 2015, it had spent less than 10% of the total amount allocated to it by Congress over its decade-long lifespan — nearly $1 billion lay unallocated and was returned to the federal purse. FutureGen shows that without buy-in from the private sector, no technology can succeed.

In a strange twist, it is COMSAT — the oldest public-private partnership we examined — which seems to offer the most compelling model for today's advanced nuclear industry. COMSAT's role was primarily to offer an authoritative point of organization for a mix of aerospace and telecommunications firms eager to take advantage of the prospect of the commercial space industry. While, as an independent corporation, it did provide some financial support for the efforts, its key strength wasn't massive federal resources (like the Manhattan Project or Apollo Program) nor was it the ability to dole out federal funding (like the SFC or FutureGen). Rather, it was the authority it had to take charge of a defined technical effort — the development, demonstration, and deployment of a U.S. telecommunications satellite constellation — and guide the private sector towards an implementation of that effort which met a few defined U.S. national interests.

Obviously, the economic situations are a key distinction between COMSAT and today's advanced nuclear industry — commercial satellites were widely viewed as huge moneymakers in the 1960s, while the entire advanced nuclear industry accounts for a paltry $1.3 billion, by Third Way's estimate. And yet, the COMSAT example still applies. As in 1960, there are today at least 29 different private and public sector organizations with a pronounced interest in tackling the challenge of advanced reactor development and deployment. Given this, it is worth considering how the government might be able to step in to coordinate and guide that process.

6.2 Shotgun/Edison approach

The Manhattan Project introduced us to the “shotgun” or “Edison” approach to technological development under uncertainty: fire on all possible pathways, in order to maximize the probability that one of them will yield the desired result. This proved to be critical to the ultimate success of the Manhattan Project — without the small effort dedicated to the implosion bomb waiting in the wings, the spontaneous fission crisis could have dealt a crippling blow. This example serves as a poignant reminder of the dangers of prematurely narrowing one’s focus when dealing with a class of technologies all designed to achieve the same goal, through slightly, but significantly different pathways.

With regards to advanced nuclear, this serves as an indicator of the value of continuing to pursue all eight types of reactor design for the time being, even though they may appear far from mature and significantly less than promising, today. Thinking back to the lessons of the SFC, we note Deutch and Lester’s warning that while investing in technology development as an “insurance policy” in the event of a potential future need is a smart decision, it is best done in a way that minimizes cost. The cost of pursuing the development of a number of reactor designs at once is far less than the cost of going all-in on just a few, only to discover years down the line that the market or the private sector are less than receptive, or that the specific need which you had in mind (hydrogen production, for example) failed to materialize — as we learn from the case of FutureGen.

6.3 R&D(DD) consolidation

During the era of the Manhattan Project and the Apollo Program, how to best consolidate research efforts on the atomic bomb effort or the Moon program was a fairly simple matter: the government decided what the priorities were, and the timeframe in which the work needed to be completed. However, in today’s world, that sort of authority is hard to come by. Moreover, it is difficult to envision a scenario in which public sector resources alone would be enough to successfully accelerate the development and deployment of advanced nuclear reactors. While the national labs and major research universities do play a substantial role in driving and supporting several of the reactor design efforts we examined, it cannot be denied that in the realm of advanced nuclear development, the private sector is — at least for the moment — leading the way.

Even so, the Manhattan Project and COMSAT both demonstrate the value of being able to marshal all available research, development, demonstration, and deployment efforts in order to accelerate the deployment of an immature technology — especially when there is a particular manner, or time frame, in which we'd like for that to occur. As a result the challenge that faces the advanced nuclear effort is the same that faced COMSAT over half a century ago: how can we best streamline the R&D(DD) efforts of competing commercial firms? The COMSAT model once again seems appealing here — find a role for the government to guide the direction of the development, without tipping the scales in favor of one particular technology or approach.

However, another promising solution can be found in the GAIN initiative launched by the Department of Energy. By opening up the U.S.'s world-class national lab network to small startups and under-resourced advanced nuclear firms, it helps ensure that all worthy reactor designs can overcome the testing and validation roadblocks we identified, while also ensuring the free flow of knowledge across the advanced nuclear ecosystem.

6.4 Political motivations

This is the trillion-dollar question: Can climate change be as effective of a political driver as WWII, the Cold War, the Iran crisis, or the post-9/11 energy scare? In each of the five historical cases we examined — even the two that were ostensibly energy development projects — we found that national security concerns or concerns about the broader national interests of the United States served as powerful motivators. A recognition that the climate challenge is of the same magnitude as these historical threats will go a long way towards justifying the development of advanced reactors on climate-driven grounds. Additionally, it's important to note the significant role that executive priorities and high-level political support can play in ensuring the success of technology development efforts that fly in the face of economic trends. From Roosevelt, to Kennedy, to Carter, to Bush, to Obama, in each of our five cases, we noted distinct impacts based on the political priorities of the administration in power.

6.5 Long-lead planning

Both the Manhattan Project and Project Apollo made clear the importance of long-lead planning: whether in the groundwork laid by Oppenheimer for the implosion bomb, or by Teller for the thermonuclear one, or in the legacy of rocket development dating back to the Eisenhower administration that made it possible for Kennedy to set NASA loose towards the Moon. Even small, incremental investments in seemingly far-fetched efforts can yield outsized rewards when applied properly.

These examples are a vote in favor of the wisdom of broad and immediate support for advanced nuclear reactor development. Consider climate change as the analogue of the 1979 oil crisis, which sent President Carter and the Congress scrambling for a solution to their suddenly-critical energy security problem. Imagine if instead of being slapped together in the late 1970s as a response to a threat, the SFC had been created two decades earlier and given the mandate to lay the groundwork necessary to be able to spring into action should that threat materialize. In the same vein, by supporting the development of advanced reactors today, we are taking out a Deutch and Lester-eqsue "insurance policy" against the likelihood that we might come to a point in the future when we find ourselves in critical need of advanced nuclear generation, in order to take on the climate challenge.

6.6 Commercial Enterprise vs. Policy Instrument

Finally, we must examine a theme that persists throughout each of the last three historical cases. COMSAT, the SFC, and FutureGen all had to grapple with a fundamental question about why they sought to promote the development and deployment of their respective technologies. In each case, there was a middle ground between support based purely on commercial grounds, and the idea that technological development can be a powerful instrument of U.S. federal policy.

Yes, the INTELSAT constellation was (at least in the short run) a financial windfall for the members of COMSAT. But it also allowed the U.S. to establish a dominant role in commercial space operations, a legacy that persists from COMSAT straight to SpaceX. The SFC was, on its face, an effort to jumpstart a lucrative new energy in order to exploit an abundant reserve of domestic coal. But as we have seen, its true motivation was to ensure a secure energy supply for the United State in a world buffeted by turmoil. The FutureGen project did take substantial steps towards proving the commercial viability coupling an IGCC plant with a CCS system, but as a closer examination reveals, in both its Bush and Obama-era incarnations, it was propelled to a certain extent by political motivations.

Promoting the development of commercial technologies that also serve broader national interests has been a powerful instrument of the U.S. federal government for decades, and it is one that can have a potentially immense impact when it comes to advanced nuclear reactors. Tackling the climate challenge is a decidedly political problem, as well as an area of major national interest for the United States. Given this, it is worth considering the idea that even if advanced nuclear reactors don't immediately merit our support on purely commercial grounds, they have earned it as a potentially powerful instrument of our fight against climate change.

7 Conclusion

When I first set out to write this thesis, I fully expected to call it "The Case for a Nuclear Moonshot" — a forceful argument for an all-in, federally funded and managed effort to take on the climate-energy challenge by promoting the rapid development and deployment of advanced nuclear reactors. However, it quickly became evident to me that while a "nuclear moonshot" or a "Manhattan Project for clean energy" may sound like an inspiring, yet straightforward solution to the defining challenge of our time, the challenge at hand isn't quite that simple.

Having examined the current state of nuclear energy, it is clear that while nuclear power will likely play a critical role in deep decarbonization as a response to climate change, our current reactor technologies are not quite up to the job. As a solution, we turned to a new generation of nuclear reactors which promise to rectify some of the shortcomings of their predecessors, but which still have a long road ahead of them before they are ready to do so. Faced with a potential solution to the climate-energy challenge that is still far from mature, we looked back to history, and sought guidance from times when the United States sought to enable and accelerate the development of immature technologies, in service not of pure commercial gain, but of a broader national interest. Absorbing some key lessons from past efforts at technology development and deployment, we then turned our eyes to the current effort to develop and deploy advanced nuclear reactors. By evaluating their progress to date, and identifying common challenges and areas for research, we were able to get our bearings on the current state of advanced nuclear energy in the United States. Finally, we combined historical lessons with an understanding of the advanced nuclear industry as it stands today, in order to draw six broad conclusions about how the U.S. federal government can enable and accelerate the development and deployment of advanced nuclear reactors, as an instrument in the fight against climate change.

We find that the U.S. federal government would benefit from taking a more active role in promoting the development of technologies like advanced nuclear reactors which, while immature and not yet favored by the market, have great potential for enhancing our broader national interests. In doing so, the government ought to take on the role not of a controlling manager, but of an authoritative guide: marshalling the resources of both public sector research infrastructure and private sector agility to drive the development of a new generation of nuclear reactors. It should also resist the urge to go all-in on a narrow set of technological choices, and instead take advantage of the uncertainty inherent in advanced nuclear development by pursuing all paths that could lead to potentially useful answers. We find that political motivations, driven by national security, have played a key role in enabling and driving technological development in each of the cases we examine — leading us to argue that fighting climate change with clean energy ought to be considered a national security imperative and a matter of national interest of the same magnitude as conflicts past. Our examination of history makes a strong case for the need to take a long-lead gamble on the prospects of advanced nuclear energy, if only as an "insurance policy" against the increasing likelihood that the demands of the climate-energy challenge will call for it in the not-so-distant future. And finally, we recognize that the development and deployment of advanced nuclear reactors is not merely a question of economics, but a question of national interests — and raise the idea that even if they aren't profitable from a purely financial standpoint, their value in the broader climate context makes them worthy of support.

To close his investigation of the crash of the Space Shuttle *Challenger*, Richard Feynman issued a warning that rings especially true today: "For a successful technology, reality must take precedence over public relations — for nature cannot be fooled."

Through this thesis, I've endeavored to separate the technical and organizational realities of advanced nuclear energy from the public relations hype (both positive and negative) that so commonly surrounds it — all in the hope that we will neither be lured by false optimism, nor fooled by unreasonable pessimism, but will instead consider the nuclear option for climate change on its own merits.

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