Advanced isn’t always better, but that’s no reason to burn down the library

Review of the Union of Concerned Scientists (UCS) publication: ‘Advanced Isn’t Always Better, Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Nuclear Reactors’. Reviewed by Kurt Smithpeters 07 June 2022

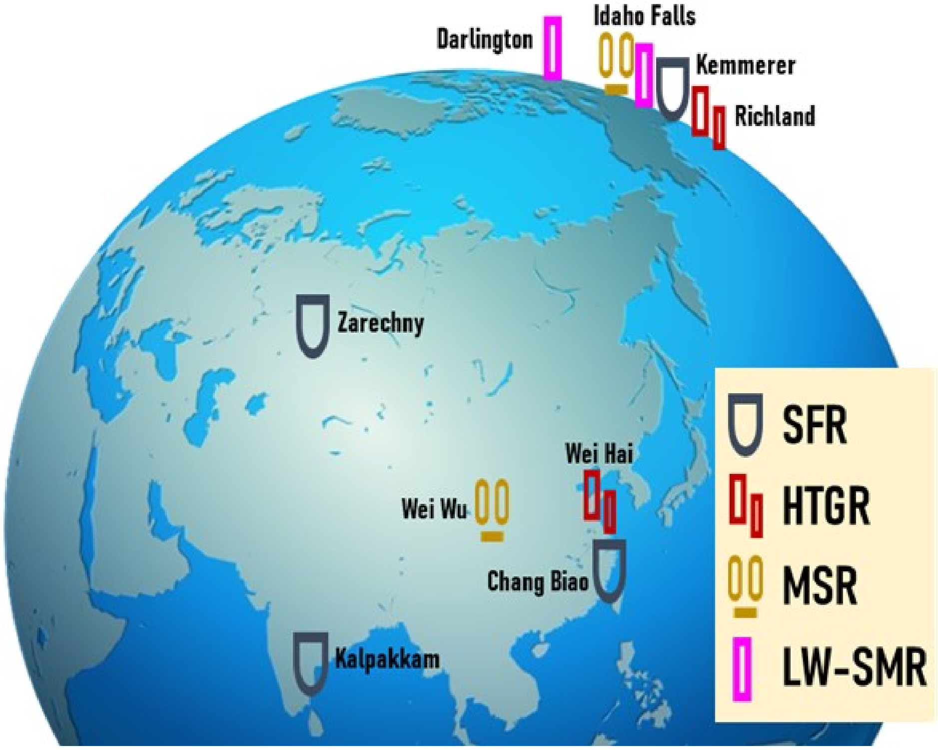


Figure 1 Advanced Nuclear Reactors operating or being constructed. Sodium Fast Reactor (SFR), High Temperature Gas Reactor (HTGR), Molten Salt Reactor (MSR), Light Water Small Modular Reactor (LW-SMR).

In March 2021 Edwin Lyman and the UCS published an assessment of new types of nuclear energy technology which are also known as ‘Generation IV’ (Gen 4) or ‘Advanced Nuclear Reactors’ (ANR).

Most existing nuclear power plants are the type ‘Light Water Reactor’ (LWR) that use water for coolant, while most advanced reactors use other coolants such as sodium, helium, or salt. The result of different coolants is that the heat-producing atomic chain reaction or ‘fission’ behaves differently, with potential benefits of producing more energy cheaper with fewer hazards. Smaller reactor vessels using water or non water coolant will allow nuclear power plants to be built in automated factories and installed with drilling machines, hence lowering construction cost and reducing defects. (1)

The UCS paper surveys the literature of past and present developers of ANR technology – the foremost advocates and experts – and describes ANR concepts and the technical research underway.

Neither the nuclear engineers nor UCS have found a technical impasse with any of the ANR design concepts. Yet the paper concludes the cost and hazard is so high and benefit so little that all development must be stopped. According to the UCS paper ‘The DOE should suspend the advanced reactor demonstration program…Congress should require that an independent, transparent, peer-review panel direct all DOE R&D on new nuclear concepts…immediately assess…nuclear terrorism implications…address…the security and safeguards needed…The United States should make all new reactors and associated fuel facilities eligible for IAEA [international] safeguards and…verification activities.’ (2)

‘***Torch the library to stop dangerous ideas from spreading!***’

It’s a strange time to clamp down on energy *research* – amidst a climate emergency, decaying electricity grids, and 20% of the world gridless, subsisting on brush, charcoal, and dung. How could the community of nuclear engineers and the UCS engineers review the same practice and literature and come to opposite conclusions?

The UCS paper is right that not all technical visions come true. But the nuclear community is also right that continued technical experimentation will separate the wheat from the chaff, the kilowatts from the PowerPoint. This poses an important question: Are the benefits from ANR large enough and the technical feasibility near enough to warrant investment? This is a vital determination for every decarbonization technology.

The UCS paper examines ANR safety, fuel consumption (sustainability), and weapon proliferation control. Lots of math applied in some offbeat excursions. The number of arguments evokes a feeling that there are just too many obstacles, even though the paper does not flatly rule out any of the ANR benefits. These UCS facts and interpretations are reviewed below. We will see that the fission process is being reengineered to remove several hazards inherent to LWR, reduce uranium mining and disposal, and create new inherent barriers to weapon proliferation. These and other advances indicate a high potential for ANR to expand nuclear deployment more widely and decarbonize sectors using fossil fuels today.

The factual descriptions in the UCS paper indicate normal engineering to mature technology proceeding through stages of demonstration. These facts should give every confidence in this technical activity. The civil public should engage ANR engineering reports with critical examination, learning, and dialogue. The UCS paper presents no plausible reason to stop research and development of the decarbonization potential of Advanced Nuclear Reactors.

Recent disruptions of electricity grids and energy trade have prompted India, Poland, and France to initiate serial build of nuclear power plants. Good start but the energy challenge will not be met without technology bringing down nuclear construction cost. Higher output temperature from reactors is required to competitively manufacture materials such as steel, cement, hydrogen, and desalinated water. (The UCS article does not address these two drivers of ANR: construction cost and industrial heat.) Placing reactors in industrial parks and additional countries will also require new technology with fewer inherent safety risks and more inherent obstacles to weapon proliferation.

The BN-800 commercial scale Advanced Nuclear Reactor power plant in Zarechny Russia reached full power in 2016 and a dozen countries are operating or committed to construct ANR. Interesting in their technical explorations today, the potential for these reactors to widely distribute nuclear energy will become more important if energy demand increases. New needs could emerge simultaneously: Electrify and provide direct heat to new sectors (material manufacturing, heating, transportation, desalination), power more cloud servers, and build electricity grids in gridless regions. Hydroelectric and natural gas can forego coal and cut global Green House Gas (GHG) emission by a quarter or half, but the compact density of nuclear infrastructure is needed to continue scaling up energy capacity without degrading habitat and climate.

Contents

Five Arguments Made Against Research 3

Design for Safety 4

Long Term Development of Fuel Breeding 8

Containing Weapon Material Source within the Energy Facility 12

Disrupting the Nuclear Commercial-Regulatory Complex with Super Competition 12

Distributing Frontier Jobs 14

Notes 15

Five Arguments Made Against Research

The UCS paper goes sideways from common engineering practice and common sense when it sets up logical frameworks to interpret the ongoing ANR technical development:

1. The paper gauges the hazards and obstacles of ANR by comparing whether each ANR type will perform better or worse than existing LWR. Tables with RED cells state ‘Significantly Worse than LWR’. (3) There is a small problem here that we know everything about how LWR perform and but have no comparable data for ANR since they haven’t completed commercial demonstration. The RED tells nothing more than that ANR technical demonstration is underway.
2. The paper says ‘Nuclear reactors and their associated facilities for fuel production and waste handling are vulnerable to catastrophic accidents…The nuclear industry, policymakers, and regulators must address these shortcomings fully if the global use of nuclear power is to increase without posing unacceptable risks…’ (4) The discovery and removal of hazards occurs at each step of demonstration. It is contrary to engineering precedence to suggest that all hazards can be determined prior to full scale commercial demonstration. It is contrary to observed physics to imply ‘full’ removal of hazards is possible. Systems always have some uncertainty. The goal of ANR development is to demonstrate safe operation in all plausible scenarios.
3. The paper states that if ANR deployment does proceed it will require the same safety measures that are applied to LWR, such as containment domes and evacuation zones. There is no basis to make this determination prior to finalizing each ANR design, and the UCS paper provides none. Domes are expensive and evacuation zones intimidate the public, and neither is required for other industries that project more deadly hazards much more frequently. The ANR concepts with small vessels propose to demonstrate safe operation without domes and zones.
4. More than a quarter of the paper is spent arguing that improved fuel efficiency of ANR will take too long. ‘To significantly increase sustainability, most fast reactors…would need to operate continuously at extremely high levels of performance for many hundreds or even thousands of years’. (5) Today’s LWR burn about 1% of the mined fuel. If ANR can burn a higher percentage, then the continued generation of electricity without additional mining is a good thing from every practical angle: less mining, less transport, less ecosystem impact, more electricity, lower waste disposal volume, and lower total life cycle cost per unit of electricity.
5. Finally the paper says we can’t wait for the technical development of ANR, ‘Given the urgency of the climate crisis, rigorous evaluation is needed to avoid wasting time or resources in the pursuit of high-risk energy concepts. …If the world must wait several decades for less mature NLWRs [ANR] to become commercially available, it is hard to see how such reactors could be deployed quickly enough to play a significant role in limiting the worst impacts of climate change—even if they eventually turned out to be faster to build’. (6) What is urgent to avoid wasting time or resources is to steer development toward techniques that emit less GHG per investment level over the medium term. Using objective emission metrics and technology neutral policies will increase investment in both LWR and ANR as well as natural gas and hydroelectric. No one suggests ‘waiting’, i.e. not deploying available technology while enhancements are being developed.

Engineering combines and refines disparate techniques. Broad potential benefits can be surmised at early concept and simulation. As the design becomes more physical and more realistic to commercial operation, previously unknown characteristics will be discovered that reduce some of the giddy projections. This is technical maturation, the process of engineering and learning, not impasse. Similarly, not just ANR but technical progress in general introduces new hazards that must be learned and mitigated, yet the overall change significantly lowers total hazard impact. Without technical change the previously higher hazard impact would continue.

Design for Safety

The safety level of a nuclear design is a pretty straightforward question: Does the design reduce the potential for overheating? One approach to safety is to design the nuclear chain reaction process itself to remove or reduce behavior that can cause overheating. The other approach is to design protection measures in case the reaction does overheat.

ANR that don't use water coolant eliminate a series of hazards caused by interaction of water with the nuclear reaction, including the high pressure system needed to keep water functioning as a coolant when hot – most ANR operate at atmospheric pressure. We'll review other safety innovations opened up by specific ANR types below.

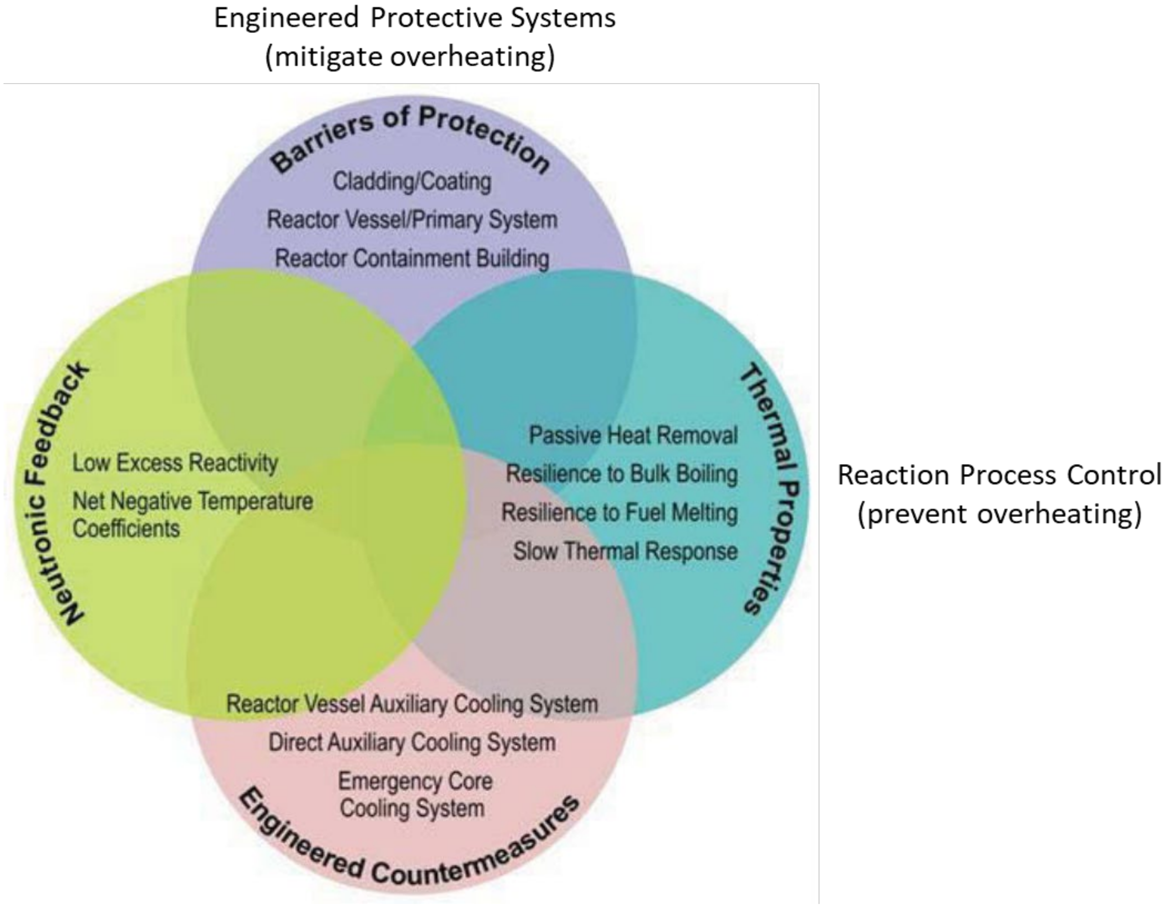


Figure 2 Inherent Process and Engineered Protection safety in nuclear design (7)

Ironically US nuclear regulations have limited safety innovations by imposing high fees for new nuclear designs. The developer must pay for the entire engineering and testing used to evaluate and approve a new design, which effectively blocked commercializing ANR until recently. The result was restricting safety improvement to what is possible with LWR.

In the mid-2010s Russian, Chinese, and US government agencies established partnerships with nuclear firms to share the cost of ANR development. The UCS paper calls for reestablishing the prohibitive evaluation fees and schedule delay. 'The DOE has selected two NLWR [ANR] designs…for demonstration of full scale commercial operation by 2027. However, the NRC has yet to evaluate whether these designs are mature enough that it can license them without first obtaining data from full-scale prototype plants...The DOE should suspend the Advanced Reactor Demonstration Program until the NRC…has determined whether prototypes will be needed first.' (8)

This is a request to stop ANR development without a reason – there is no 'data' a prototype reactor can provide that can't be provided from the commercial scale reactors under construction.

UCS also addresses safety by larding the paper with radiophobic and Hollywood sensational assertions without providing any factual basis, and none exists. For example 'It is even possible that an SFR core could explode like a small nuclear bomb under severe accident conditions'. (9) Possible except that it's not, SFR fuel is 10-15% fissile (reactive) material while a bomb requires 93.5% fissile material to reliably explode.

Safety of Sodium Fast Reactor (SFR)

The SFR uses liquid metal sodium to cool and transfer heat from the reactor. An inherent advantage is convection in the reactor vessel core, the liquid metal coolant rapidly conducts heat and naturally flows in a convection pattern allowing passive cool down of the reactor without mechanical or electrical or complex systems if overheating occurs.

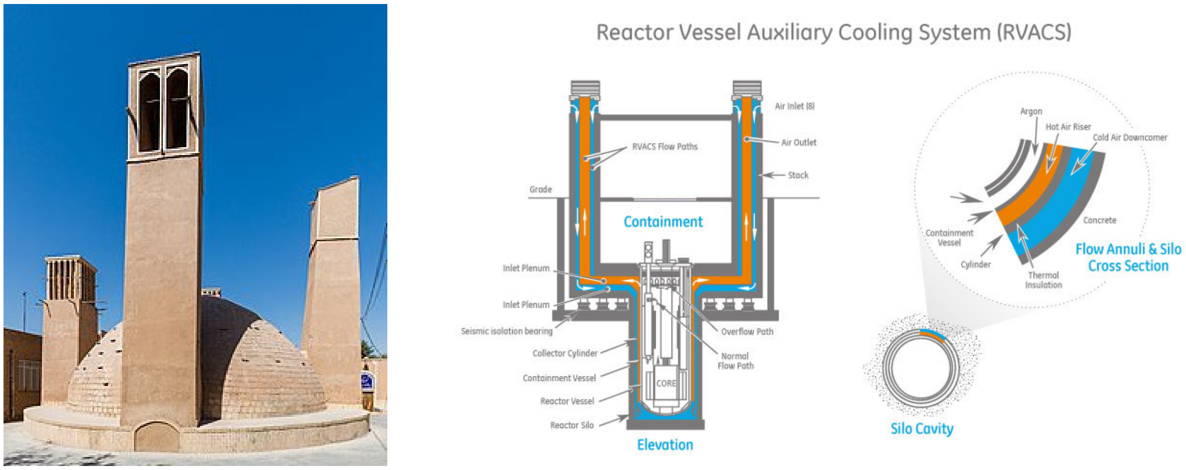


Figure 3 Left: Ancient cooling towers that capture wind in Yemen. Right: Sodium Fast Reactors use natural convection of liquid sodium in the reactor vessel 'bath' and ambient air surrounding the vessel and flowing freely to tower inlets and outlets, in order to cool down an overheating incident.

The UCS paper discusses the testing of the EBR-II SFR in 1986 which demonstrated that the reactor slowed and cooled itself down after the coolant pumps were turned off. UCS objects that these tests were not complete, did not reflect all real life factors, and are not sufficient to conclude that any SFR design is safe. This is a correct characterization by the UCS paper of the previous tests, however not remarkable in any way. Further testing is normal grist for safety engineering: Performing more comprehensive and more representative tests as design is matured.

The UCS paper discusses three aspects of safety for the SFR: sodium reactivity, nuclear reaction coefficients, and metal fuel durability.

The SFR must isolate or select materials inside the reactor vessel to prevent sodium reactions. SFRs have operated for decades without sodium reaction difficulty. It is not plausible that an SFR design won't control sodium reaction and corrosion.

All reactors must be designed for negative reaction coefficient – meaning that when the chain reaction power increases for any reason, it causes changes to the reacting material that reduce the reaction. In other words feedback inherent to the atomic reaction counteracts the generating of more and more power (positive coefficient) that leads to overheating. Specifically, if SFR fuel unexpectedly becomes packed more densely together than normal operation there is potential to increase reaction and overheat. The physical arrangement, fuel composition, and cladding material will be engineered to obtain negative coefficient. Initial experiments with Terrapower's SFR have indicated a negative reaction coefficient and this will be proven to certify the design. (10)

A more difficult technical challenge is durability of metal fuel. Many of the SFR concepts call for the metal fuel structure to remain in the reactor for a longer period of time than today's LWR, for advantages of breeding additional fuel and preventing weapon proliferation. The nuclear reaction builds up materials over time such as gases that raise the internal pressure on the fuel structure. This will be reviewed further below, but it is not a safety issue because testing will determine and set the time limit for fuel in the reactor. The metal fuel in all existing LWR is similarly restricted and is routinely replaced before degradation without incident.

These technical issues are simply a list of engineering tasks that are underway. To portray the sum of technical issues as a measure of safety risk is not valid. At most it is an indicator of the volume of development work pending and potential constraints on reactor operation for issues that cannot be resolved.

Safety of High Temperature Gas Reactor (HTGR)

Many HTGR (helium cooled) designs use fuel and graphite moderator completely sealed in ceramic (carbide) spheres or pebbles called TRISO. The fuel and products created by nuclear reaction never come in contact with the reactor or coolant thus removing a source of corrosion and providing resilience to the pressure of fission product buildup during reaction. The helium coolant is inert so it cannot transfer radioactivity outside the reactor when it provides industrial heat or heats steam for electricity generation.

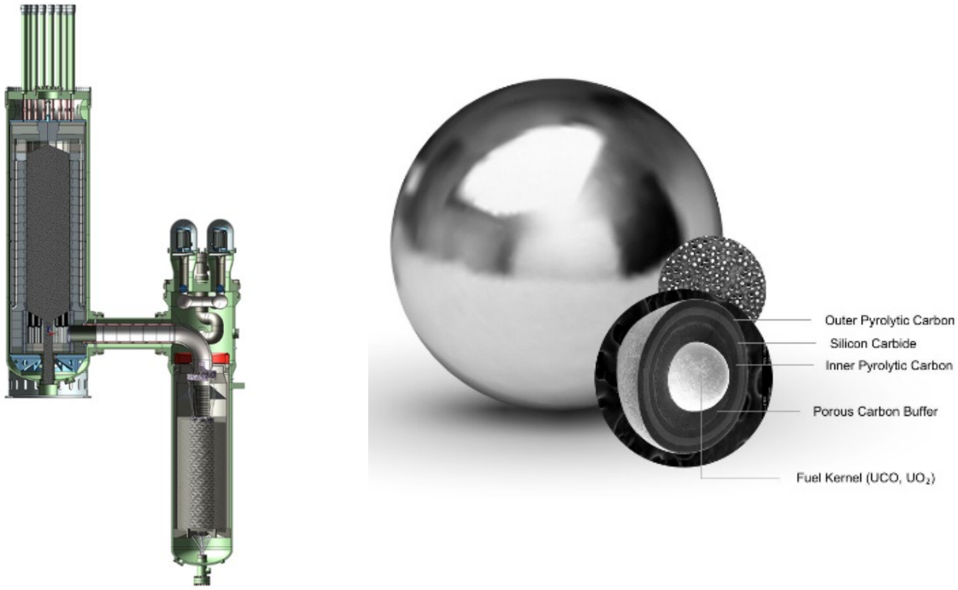


Figure 4 High Temperature Gas Reactor fuel is incased in ceramic pebbles through burn and disposal.

The safety of HTGR hinges on negative reaction coefficient inherent to the pebbles and the pebble ceramic shell remaining intact and preventing release of radioactive material.

The UCS paper acknowledges the negative coefficient and centers discussion on experience indicating that temperatures in the reactor could exceed what the pebble shells can handle, and that flaws in manufacturing the pebbles have been experienced that could also cause radioactive leakage. The paper says that material external to the pebbles such as graphite could cause damage.

These are valid concerns and will be engineered through development. Complete certainty that a given HTGR design will ‘never’ exceed safe pebble shell temperatures may not be provable, but the probability of exceeding temperature limits and the capacity of protections that operate if they are exceeded, can be learned through analysis and test, and provide confidence in safe reactor operation. Time limits on fuel usage can be determined and the circulation of pebbles may allow use of sensors to detect their condition and remove them when wear is indicated.

The UCS paper asserts that ‘…potential industrial users have demonstrated little interest in these applications to date, and will likely continue to be wary of co-locating nuclear power plants at their facilities until outstanding safety, security, and reliability issues are fully addressed’. (11) On the contrary the DOE is developing regulations for nuclear industrial heat. (12)

The paper describes the separate technical development needed to create production facilities for the HTGR pebble fuel. The HALEU fuel that will be used for both the SFR and HTGR and some MSR designs must be developed, and then the production of pebbles from the HALEU material must also be developed.

This and other supporting activities are complex and the UCS paper remarks that some steps cannot proceed until others are complete. The DOE is preventing this risk by coordinating concurrent development of fuel production, reactors, construction technique, and the community siting process for the front running ANR technologies. (13)

Safety of Molten Salt Reactor (MSR)

Molten Salt Reactors have many variations but typically dissolve nuclear fuel into liquid salt coolant and hence have liquid instead of solid fuel.

An inherent safety advantage of MSR is that the fuel and coolant are never separated – losing coolant means losing fuel at the same time, potentially counteracting overheating if leaks occur.

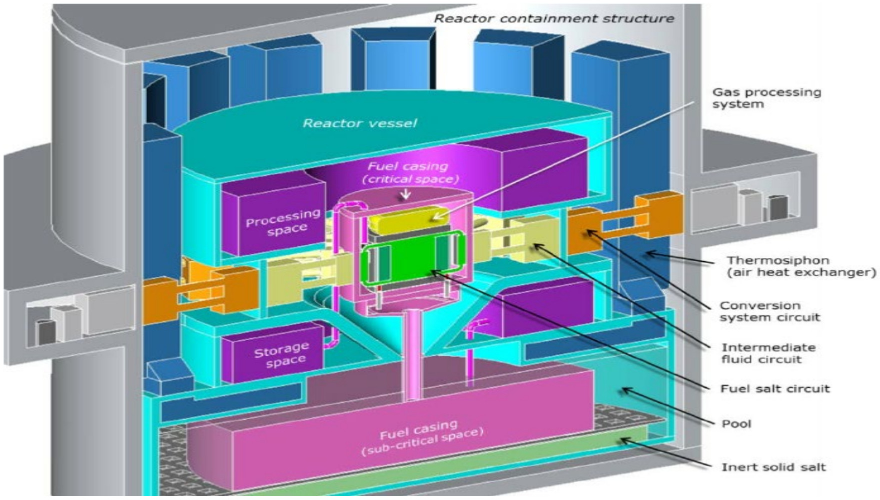


Figure 5 The Molten Salt Reactor concept proposes mixed liquid fuel and coolant with a drain that disperses fuel during an overheating incident.

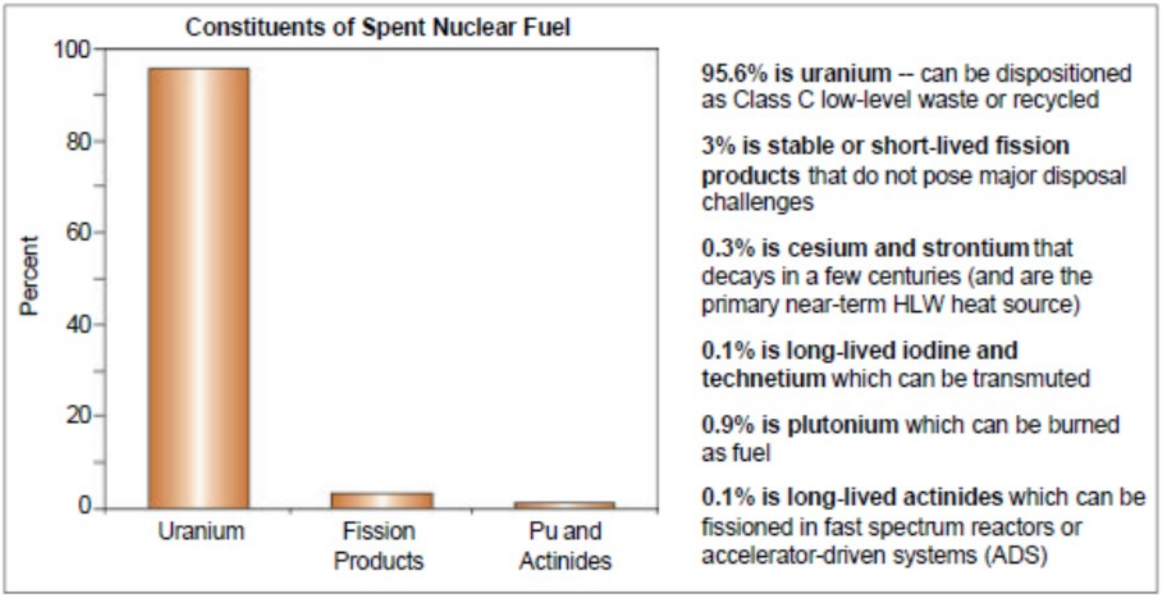
These MSR concepts of on-line reprocessing and passive draining of fuel-coolant have not been tested. (14) The potential for the liquid fuel and coolant in some conditions to heat up much faster than solid fuel is a characteristic of the reaction process requiring technical development.

These and other tests can now begin. The Shanghai Institute of Applied Physics (SINAP) is operating a small test MSR in Wei Wu, Gan Su, China and a partnership between Terrapower and Southern is preparing to construct an MSR at Idaho Falls, Idaho, USA.

Long Term Development of Fuel Breeding

A thumb size pellet of uranium generates the energy of one ton of coal. The replacement of worn out solar panels and wind turbines generates 10 times more waste than nuclear facilities/fuel per energy generated. And this nuclear energy output comes from the chain reaction burning only 1% of the mined fuel. 99% is not used, most of it being ‘fertile’ (radioactive but cannot support fission reaction) rather than ‘fissile’ (can support fission reaction i.e. generate heat and electricity). The ANR breeder reactor function converts or ‘breeds’ fuel from the 99%. A breeder reactor can also breed fuel from another material Thorium, which has at least as many reserves as uranium and probably more. For creatures used to filling a gas tank once a week, the longevity of breeder reactor fuel supply is in the Star Trek range.

SFR and MSR are breeder reactors and HTGR can be configured as a breeder. Most breeders are fast reactors, meaning the neutrons in the chain reaction travel at a higher rate of speed, which improves breeding of most fuel materials. A reactor becomes fast when it doesn’t have a moderator like water or graphite involved with the chain reaction. It is possible to breed fuel from thorium with moderated slower neutrons, this is called a ‘thermal’ reactor as opposed to a ‘fast’ reactor.



95.6% is uranium -- can be dispositioned as Class C low-level waste or recycled

3% is stable or short-lived fission products that do not pose major disposal challenges

0.3% is cesium and strontium that decays in a few centuries (and are the primary near-term HLW heat source)

0.1% is long-lived iodine and technetium which can be transmuted

0.9% is plutonium which can be burned as fuel

0.1% is long-lived actinides which can be fissioned in fast spectrum reactors or accelerator-driven systems (ADS)

Figure 6 Fission Products, the lighter and low hazard material generated by burning nuclear fuel make up 3% of reactor output. Almost 97% of today's 'waste' is potential fuel for a fast reactor to generate heat and electricity. Another 10 times this amount of uranium is waste from fuel enrichment processing prior to reactor input, also potential fuel. Only about 0.3% of reactor output is high level waste. (15)

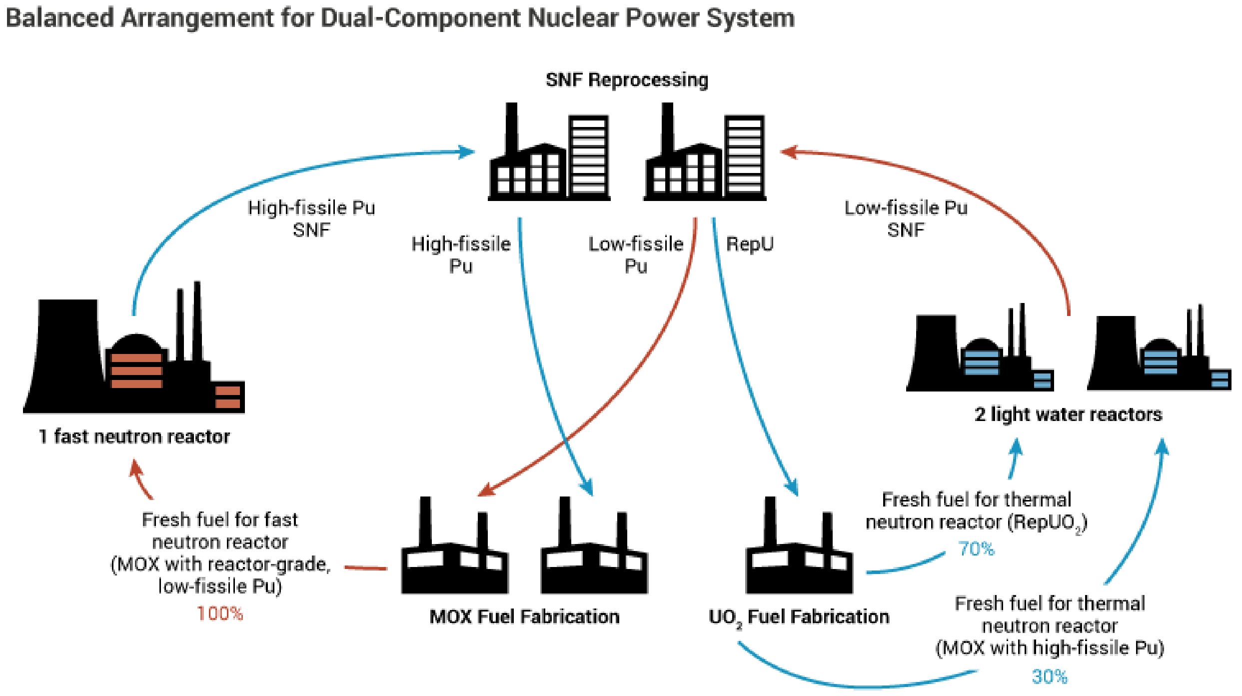
The catch with breeding fuel is both the technical development of the process and the cost of additional infrastructure for both the reactors and associated fuel processing systems. Fast reactors offer the largest potential improvement of nuclear energy but are the least known and proven of all ANR technical concepts.

Breeder test reactors have operated for decades but getting to commercial feasibility has a much more significant journey than other ANR concepts. The UCS paper obscures what is and isn’t known about the breeding process. Below we will lay out the current state of breeder reactors and then address the other UCS concerns.

Fast Breeder Reactor and Fuel Processing

Russia and India have continuously developed fast reactors for 60 years and other countries have had substantial if intermittent experience with test fast reactors. The Russian firm Rosatom is the largest provider of nuclear power plants globally and has developed the present state of the art commercial scale fast reactor fuel cycle and infrastructure, including the BN-800 SFR producing 880 Megawatt electricity. The larger BN-1200 SFR and the SVBR-100 lead cooled fast SMR are under development and construction.

The Rosatom fast reactors and associated fuel processing systems take output from existing LWR from around the world and convert, burn, and process the fuel repeatedly. The fuel is periodically removed from the reactor and sent to processing systems that separate usable fuel, potential fuel for additional breeding, medical and other materials used in other industries, Fission Products for simple disposal, and high level waste for isolated disposal. The intent is to keep burning all potential fuel until all that remains are Fission Products (low hazard material with atomic numbers 57-71) and high level waste for long term isolated disposal. Rosatom is experimenting with the four different solid fuel structures (oxide, nitride, carbide [ceramic], and metal) and alternative fuel mixtures (MOX) that affect the efficiency, safety, and longevity of fast reactor operation.



Source: Rosatom

Figure 7 Rosatom recycling system to process and breed new fuel from global LWR output.

Current breeding and processing activities have some percentage of losses, material that cannot be prepared and separated as intended for the reaction and disposal. These losses, the cost of breeding-processing infrastructure, and the time required to perform both breeding and processing, together set some limit on the uranium utilization (percent of potential fuel that fissions and generates energy) that is feasible. The operating efficiency is directly determined by the Conversion Ratio (how much new fuel is bred per input fuel) and Doubling Time (how long does it take to breed new fissile fuel equal to the quantity of original fissile fuel input to the reactor). Refining the reactor vessel and fuel design increases or decreases the performance of each of these key parameters.

The commercial operation and experimentation is now generating real understanding of the costs and efficiency gains of breeding-processing. Definitive reports are not yet available which means the upper ceiling of uranium utilization is not yet known.

Online Reprocessing

Some SFR developers including Terrapower's 'Natrium' reactor are seeking to improve the fuel shape and positioning and periodically move the fuel structures to different spots in the reactor in order to both breed new fuel and burn it, without removing it from the fuel structure or the reactor. Natrium reactors will test this theory of online reprocessing in stages. The pebbles of the HTGR are also candidates for this repositioning to breed and burn. This approach will require fuel preparation and final separation of products for disposal, but the interim generation of fuel would never be available outside of the reactor system. This is a significant barrier to proliferation of weapon material which will be addressed in the next section.

The other approach to online reprocessing is using liquid fuel such as in an MSR that can be continuously circulated through processing equipment while the reactor is operating. The potential benefits over SFR repositioned solid fuel are elimination of materials harmful for the nuclear reaction building up in the fuel, elimination of downtime for processing, elimination of separate processing facilities, more efficient and complete breeding, and more efficient and complete separation of materials for downstream industries (e.g. medicine) and disposal.

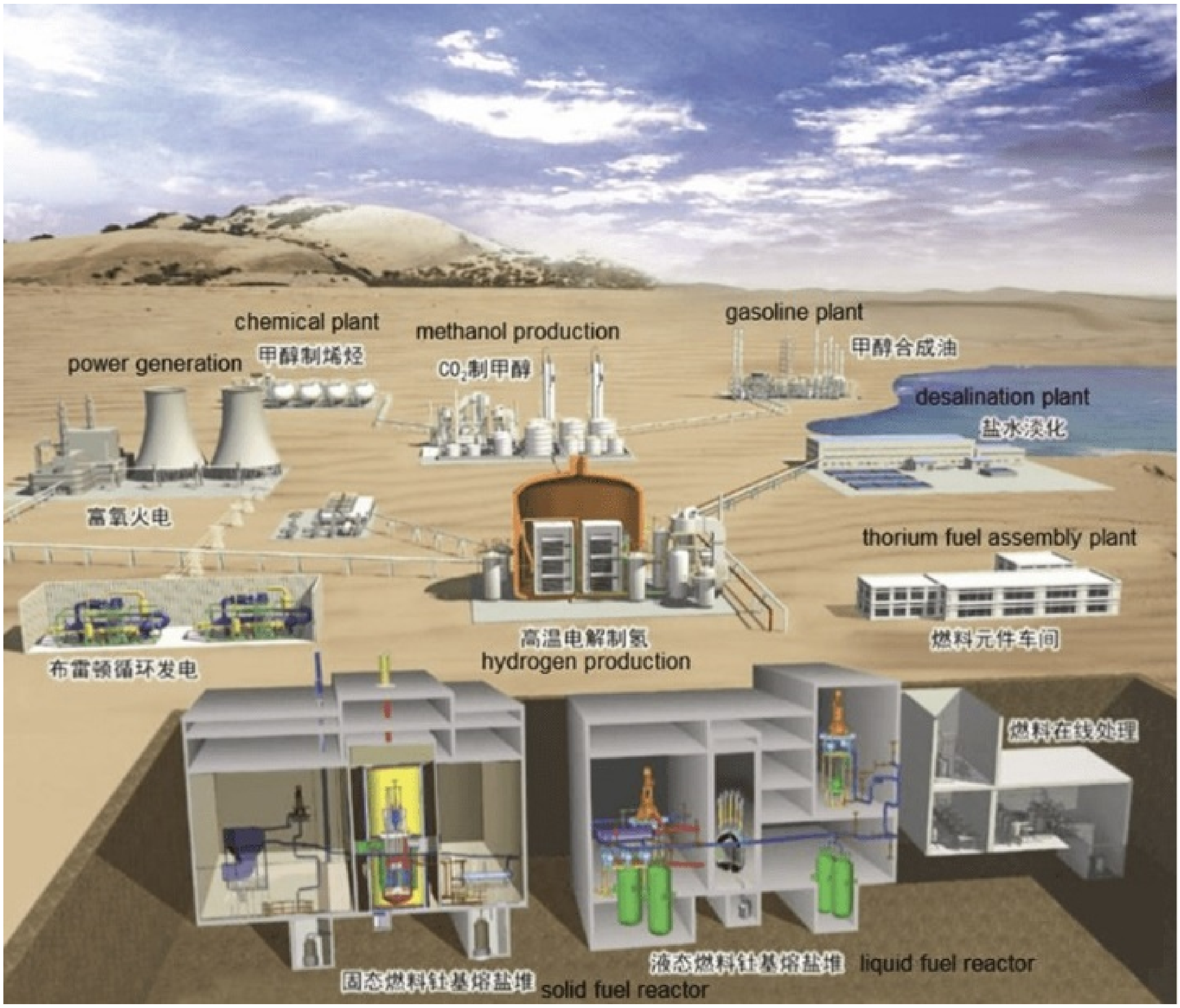


Figure 8 SINAP plan to build an industrial park using MSR heat and electricity in the North West desert. A test MSR is currently operating at this site in Wei Wu. The high temperature output of Advanced Nuclear Reactors allows use of ambient air instead of a water source to condense steam in the electricity generation steam cycle.

What is and isn’t possible with currently proven fuel technology

The UCS paper obscures what fuel usage improvements are known and feasible today vs longer term development.

Post processing spent fuel from nuclear power plants separates 98% of the low hazard material from high level waste. This is mature technology and for the price of processing plants would eliminate approximately 98% of existing waste destined for isolated disposal. No improvement of fuel utilization would be obtained by this.

The Rosatom breeding-processing system is commercially mature and achieving some higher fuel utilization. If their operation is approaching 10% fuel utilization vs the 1% of LWR, it would provide an order of magnitude reduction of mining and disposal per energy output. [16]

Today we don’t know how far fuel utilization can be improved. There is not yet an environmental urgency for breeding reactor deployment as existing LWR already have the smallest GHG emission and habitat impact of all energy sources. Half a dozen ANR firms are step by step developing breeder technology, which appears aimed at regional and provider self-sufficiency. The UCS paper correctly points out that in the best of scenarios these concepts involve gradual accumulation of bred fuel and capacity limits that drive how long it takes. However the UCS paper’s assertion that fuel utilization will take ‘thousands of years’ is misleading. Let’s examine the timeframe.

The basic capacity indicator of breeder reactors is Doubling Time (DT), the time a reactor needs to breed new fissile fuel equal to the quantity of original fissile fuel input to the reactor. Various analyses have estimated a wide range of potential DT, let’s assume a mid-range estimate of DT 12 years. (17) If we assume a breeder starts with 10% fissile fuel (double the current LWR 5%) then it would generate another 10% in 12 years and so on. Breeding 50% of the total load put in the reactor (fertile and fissile) would take 60 years at this rate, and losses and processing time would lengthen this further. If successful, online reprocessing would avoid some portion of processing downtime, but the basic limit is in the reaction capacity. Increasing power and conversion ratio (breeding) in a given size of reactor vessel tends to increase the wear upon the reactor structure. It’s safe to say guesstimated DT predicts an individual reactor would need hundreds but not thousands of years to convert a high proportion of one reactor load.

What is missed in this UCS math excursion is that during fuel conversion the electricity and heat output (from both the breeder reactor and any reactor downstream consuming the bred fuel) is increasing without mining new fuel. Extending the energy output from fuel is always beneficial. ANR breeder technology is discovering the tradeoff point between the cost and environmental impact of mining/handling infrastructure vs breeding infrastructure, i.e. the cost point between mining and breeding. We don’t know how far the fuel utilization will go, but the fact that there is a significant opportunity above the current 1% utilization cannot reasonably be doubted.

The UCS paper has a number of similarly irrelevant math applications. A mystery is supposed about whether to configure reactors to burn waste or breed new fuel. ‘…these two aspects of sustainability—significantly reducing the quantity of…nuclear waste and significantly increasing uranium utilization efficiency—cannot be simultaneously achieved with the same reactor and fuel cycle system. …This is because a nuclear reactor can only extract energy from a fixed amount of fissionable material per year…If the energy is produced by the fission…from nuclear waste, it cannot be produced by the fission of new [bred] fissionable materials..’ (18) It doesn’t take nuclear science to figure out that with 95% of the unused potential fuel being fertile and thus requiring breeding, the need for breeding capacity is large. And with only 1% of the unused potential fuel being fissile and thus requiring processing, the need for this specific processing capacity is small.

Nor should it be difficult to realize that reactor design aims to maximize breeding capacity. UCS states that the conversion ratio must be lowered in order to burn fissile fuel. Why? This makes no sense. Decreasing the breeding conversion ratio doesn’t increase burning, it just makes breeding less efficient – less fuel is bred per amount of fuel burned.

Containing Weapon Material Source within the Energy Facility

UCS says that processing 15-20% fissile fuel for some ANR is a proliferation hazard because it is higher than the current LWR 5% fissile fuel. This is more badly applied math. Reliable bombs need 93.5% and whether the material source is 5% or 20%, a similar skill and infrastructure is needed to enrich it to 93.5%.

Spent fuel from LWR is not considered at risk for deriving bomb material, but an increasing proliferation danger is the creation and separation of relatively pure fissile materials in a breeder reactor and processor system. The UCS paper points to this risk in the addition of breeder reactors and processing facilities. The International Atomic Energy Association (IAEA) has been 100% successful in preventing weapon proliferation so far, but the general rise of technical aptitude and the progress of breeding-processing suggests that enhanced controls are prudent.

Rosatom has a commercial method to prevent diversion of bred fuel to weapons. They offer a lifecycle nuclear energy service where they build plants, train operators, supply fuel, collect the reactor spent fuel and breed/process/burn it in their SFR processing system in Russia, and dispose the high level waste. Chinese firms have announced they will also offer this service.

The lifecycle nuclear service model could significantly tighten control of all fuel movement and reduce the avenues for nuclear weapon proliferation. All nuclear exports to countries without a nuclear engineering skill base should be brought under the lifecycle service model.

But just as safety and fuel efficiency can be engineered into an enhanced nuclear reaction process, so should proliferation prevention. The online processing research in both the SFR and MSR technologies is seeking to contain breeding and burning within the reactor system, including fuel arrangement and processing equipment, until the newly bred fissile material has been burned and rendered into material not usable for bombs. How feasible this is will be determined through experimentation and trials. To the extent that proliferation material cannot be contained in the reactor system, other types of controls would be needed.

Disrupting the Nuclear Commercial-Regulatory Complex with Super Competition

It's hard to believe today, but the LWR second generation nuclear power plants built in the 1960s and early 1970s cost roughly even with coal, oil or any other energy at the time. Between 1968 and 1978, well before the Three Mile Island overheating incident, nuclear construction costs soared 10 times to the point that safety retrofits cost three times more than the original reactor. (19) The US government regulatory agencies and the private sector nuclear energy providers evolved together, with important directional factors being invalid theories of radiation hazard, expansion of regulatory agency scope, and protection of the market for incumbent providers.

The Linear No Threshold (LNT) model is a groundless concept of radiation hazard based on the false premise that small amounts of radiation are harmful to organisms. From LNT derives the As Low As Reasonably Achievable (ALARA) prevention principle which was used to develop excessive and pointless nuclear engineering, construction, and operation activities. (20) The regulators established internal incentives – if they chose to expand the engineering required from providers then the work statement for their own departments would grow. (21) And the providers in turn implemented safety requirements in ways that disrupted construction, with crafts idle as much as 75% of work time, time that generates revenue for providers regardless of productivity. (22) US regulations set the pattern for global regulations and hence the worldwide nuclear construction cost level, though in the past decade Korean providers have increased construction efficiency with application of advanced design and construction technology. (23)

This Nuclear Commercial-Regulatory Complex is a classic case of regulatory capture, where government regulations evolve with industry input to impose insurmountable barriers to new entrants and protect the market for large incumbents and the regulatory agencies. (24) The Commercial-Regulatory Complex had already choked off utility demand in the US before the Hollywood sensationalist 'China Syndrome' was released and life shortly followed art with the disruptive, unnecessary, and dramatic evacuation of Three Mile Island in 1979.

With demand down, supply chains and skilled labor were no longer maintained and the costs were driven even higher. The protected nuclear providers eliminated research of nuclear technology, outside the proven channels they developed together with regulators for evermore unneeded but lucrative safety retrofits.

The soil for this parasitic industry feeding on itself is the complexity of the technology. Nuclear requires a scientific infrastructure and government coordination for early stages of commercialization. Governments 'took their feet off the gas pedal' through the 70s-80s as nuclear weapon material supply was saturated and technology made oil cheaper. Energy self-sufficiency and decarbonization imperatives have only recently revived government interest in nuclear energy. The crystallization of the Nuclear Commercial-Regulatory Complex was a tragedy for the climate. In the US Washington State for example, the 'WPPSS' nuclear plants shuttered by cost overruns would have provided capacity to electrify transport, the main GHG source in the state. (25) Globally, coal and its smog deaths were required for the main developing countries to build grids and achieve mid-level economy.

The nuclear energy public-private partnerships expanding in Russia, China, and the US are establishing a new ecosystem that fosters technical exploration, innovation, and experimentation, and coordination of site communities, education, regulations, fuel and component supply chains, finance, and global market expansion. The cultivation of nuclear expertise within the Department of Energy (DOE) Gateway to Advanced Innovation Nuclear (GAIN) and Nuclear Reactor Innovation Center (NRIC) is a model of decelerating climate change by accelerating technology: Improve public sector capacity to replace the fits and starts of venture research with organized, stepwise commercialization. This model is needed to develop all energy technologies, and arguably needed for most domains that involve complex technical progression. (26)

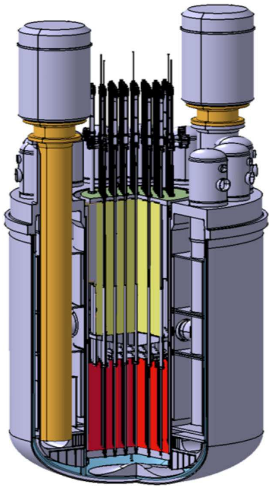


Figure 9 SVBR-100 lead cooled fast Small Modular Reactor being developed by a public-private partnership of Rosatom and EN+.

What's left of the nuclear providers are creating lean units and joining the ANR development, Rosatom and GE Hitachi in the forefront. French and Korean firms are launching ANR initiatives and several mid-level countries such as Poland are planning for ANR and likely to develop nuclear science infrastructure. This nuclear radiance with technical super competition is reviving Dwight Eisenhower's vision to electrify the world with Atoms for Peace. Trump bullied US firms and scientists to pull out of collaboration with Chinese ANR firms and Biden has bigger eyes seeking a global partition of science. Yet the genie is out of the reactor, there is too much scientific infrastructure and competition for the US or any set of powers to restrain or monopolize nuclear technology advance. The choice is develop technology or forfeit the market. Technology success in many domains is resulting from creating public-private systems with a rapid exploration and super competition superior to private sector only and non cloud environments. (27)

While the Nuclear Commercial-Regulatory Complex is a subtly evolved organic system among multiple key participants, the super competitive public-private ecosystems are entering a similar organic development among multiple key participants. Their goal is the opposite, to create and capture new global markets, rather than circling the wagons around an unaffordable and stagnant construction model.

The UCS paper argues that 'The DOE and Congress should do a more thorough evaluation of the benefits of focusing R&D funding on addressing the outstanding safety, security, and cost issues of LWRs rather than attempting to commercialize less mature reactor concepts. If the objective is to expand nuclear power to help deal with the climate crisis over the next few decades, improving LWRs could be a less risky bet.' (28) There are no outstanding safety or security issues with existing LWR. They were all reassessed after the Fukushima tsunami and where necessary retrofit with additional overheating protections. LWR fuel is not attractive for weapon proliferation. The answer to LWR cost issues is precisely ANR.

The depiction of LWR and ANR as distinct and contending zero sum categories in the UCS paper is a projection of regulations that restrict new reactor/fuel technology. The nuclear engineering community has breached this prohibition on innovation and is actively mixing and matching technical elements of ANR and LWR. The US regulatory support for ANR was increased after this breach progressed, when the Obama administration investigated and determined that a large amount of US private capital was *already* invested in ANR. (29)

The nuclear radiance of ANR experimentation is a healthy condition for new discovery. It is broadening the number of technology variants that will best fit different scenarios. Optimum reactor vessel size is independent of varied power plant capacity – vessels can be stacked as needed for local demand. Lower construction costs will enable widespread building of large power plants. At the same time material technology is evolving quickly and likely to speed up with use of emerging cloud-intelligent capability to design new materials. New materials could revolutionize longevity of reactor and fuel structure, but we'll only know if experiments are performed.

Any technical success will quickly spread and set the bar for all providers. It is unlikely that any providers without cloud-based design and global market reach will survive this expansion. Good news for climates and consumers.

Distributing Frontier Jobs

The ANR technology features of higher heat, smaller capacity, and lower safety and proliferation hazard have the geographic implication of spreading power plants to new types of locations. Smaller capacity power plants can be placed closer to consumers and thereby reduce transmission lines and their land use. Coal fired steam electricity plants can drop in replace ANR as the energy source. Urban office steam heating may become feasible again with nuclear. A nuclear centered high heat industrial park is likely to result from ANR development. Remote areas can enjoy clean electricity for decades without refueling.

Figure 10 Terrapower's SFR will drop in replace coal heat for this steam cycle electricity plant in Kemmerer, WY.

In addition to environmental benefits, distributing low footprint energy may also help overcome the hollowing out of heartland skills and regions caused by technology advance in the developed countries. 'Frontier jobs' are new skill types generated by new markets as technology advances through the historic economic pattern of creative destruction. (30) A limitation so far in information based economies is that frontier jobs cluster in metropolitan areas where a critical mass of the new work domains emerge. Distributed ANR power plants not only provide operator jobs, but may also increase the mobility of other industries by giving them cheap and reliable power anywhere. The combination of heat and electricity output from ANR supports high energy industries that today use fossil fuels such as material manufacturing, information and communication technology (ICT), and biotechnical manufacturing. Distributed fission based industrial parks could implant a diversified knowledge and skill base into a region.

Nuclear energy is a social attractor of opposite political wings, an antidote to social wedge issues like guns and abortion in the US. It began with Eisenhower's 1953 'Atoms for Peace' address to the United Nations. Despite the best engineering effort, Ike's world electrification goal, declared just 50 years after the *discovery* of radiation in 1905, proved too lofty on the first pass. Today the nuclear engineering community, small and big entrepreneurs, and civil advocates are building on the past to create new global energy markets and power the world.

Left: US Representative A.O.C. with nuclear energy advocates at climate conference COP26. Right: US Senator Joe Manchin champions coal-to-nuclear legislation on the Senate floor.

Notes

(1) For the types of Advanced Nuclear Reactors see Ahn, Alan, Allen, Todd. '2022 Advanced Nuclear Map'. Third Way, Jan 27 2022. https://www.thirdway.org/graphic/2022-advanced-nuclear-map-charting-a-breakout-year
(2) Lyman, Edwin. Union of Concerned Scientists, March 2021. 'Advanced Isn't Always Better, Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Nuclear Reactors' (AIAB) p 11.
(3) AIAB p 6.
(4) AIAB p 1.
(5) AIAB p 6.
(6) AIAB p 15, 22.
(7) Bays, Samuel, Piet, Steven, Soelberg, Nick, Lineberry, Michael, Dixon, Brent 'Technology Insights and Perspectives for Nuclear Fuel Cycle Concepts'. September 2010. Idaho National Laboratory p 35.
(8) AIAB p 11.
(9) AIAB p 5.
(10) Neider, Tara. Terrapower. 'Presentation to National Academy of Sciences Engineering and Medicine'. February 22, 2021. P 10
(11) AIAB p 5.

(12) ‘Gateway for Accelerated Innovation in Nuclear’. https://gain.inl.gov/SitePages/Home.aspx ‘Nuclear Reactor Innovation Center (NRIC)’. https://www.energy.gov/sites/prod/files/2019/08/f65/NRIC_Fact_Sheet.pdf

(13) King, Christine, Finan, Ashley. ‘The Role For Communities in Demonstrating Advanced Nuclear Technologies’. May 4 2021. Engaging Energy Communities in Advanced Nuclear

(14) ‘Molten Salt Reactors’. World Nuclear Association. https://world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx#References

(15) ‘Advanced Fuel Cycle Initiative’. US DOE Office of Nuclear Energy, Science, and Technology January 2003 p II-2

(16) Note that the frequently used term ‘fuel burn up’ is unrelated to fuel utilization. The percentage of burn up of fuel in a reactor can be increased by processing fuel before it is loaded to increase the fissile proportion. This means the fuel utilization has not increased – the unused waste is simply created before loading the reactor.

(17) He Liaoyuan, Xia Shaopen, Chen Jingen, Liu Guimin, Wu Jianhui, Zou Yang. ‘Th-U Breeding Performances in an Optimized Molten Chloride Salt Fast Reactor’. American Nuclear Society Nuclear Science and Engineering Volume 195 p185-202. February 2021. Kosaka, Nanami. ‘A Study on Breeding Performance of Commercial Liquid Metal Cooled Fast Breeder Reactor’. Doctoral Thesis Dept of Engineering University of Tokyo. February 1981. Vondy, D.R. ‘On Nuclear Fuel, Mass Balances, Conversion Ratio, Doubling Time and Uncertainty’. ORNL Neutron Physics Division. November 1976. Lake, J.A., Doncals, R.A., Rathbun, R.W., Robinson, H.C. ‘Breeding ration and doubling time characteristics of the Clinch River Breeder Reactor’. Westinghouse Advanced Reactors Division. 1975.

(18) AIAB p 34.

(19) ‘Bret Kugelmass The Heterodox Anthropologist of Nuclear’, Decouple Podcast. December 07, 2020. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjwqMDZ9Oz3AhWSJDQIHQBFAsoQFnoECAcQAQ&url=https%3A%2F%2Fanchor.fm%2Fchris15401%2Fepisodes%2FThe-Heterodox-Anthropologist-of-Nuclear-feat--Bret-Kugelmass-enajnj&usg=AOvVaw0FoO6GuhvhLr3XuFzqkU1J

(20) ‘Radiation: The Facts’. Climate Game Changers. https://climategamechangers.org/context/radiation-the-facts/

(21) Delaney, Jack. ‘Why Nuclear Energy is a Flop at Solving the Gordian Knot of Electricity Poverty and Global Warming’. CTX Press 2020.

(22) Eash-Gates, Philip, Klemun, Magdalena, Kavlak, Goksin, McNerney, James, Buongiorno, Jacopo, Trancik, Jessika. ‘Sources of Cost Overrun in Nuclear Power Plant Construction’. Joule 4 2348-2373, November 18, 2020.

(23) Lovering, Jessica, Yip Arthur, Nordhaus, Ted. ‘Historical construction costs of global nuclear power reactors. Elsevier Energy Policy’. February 02, 2016.

(24) Coyle, Diane. ‘Markets, States, and People’. Princeton University Press 2020. Chapter 2

(25) Davidson, F., Tuttle, Dave, Rhodes, Joshua, Nagasawa, Kazunori. ‘Switching to electric vehicles’. The Conversation. December 4, 2018. ‘List of cancelled nuclear reactors in the United States’ Wikipedia https://en.wikipedia.org/wiki/List_of_cancelled_nuclear_reactors_in_the_United_States The data linked to the ‘Switching to EV’ article estimates 25% increase of WA state electricity capacity to electrify transport, which is 7.85 Gigawatts. The four cancelled WWPPS reactors had a total capacity of 5 Gigawatts.

(26) Mazzucato, Mariana. ‘The Entrepreneurial State’. Public Affairs 2011.

(27) Lee, Kai Fu. ‘What China Can Teach the U.S. About Artificial Intelligence’. New York Times September 22, 2018.

(28) AIAB p 12.

(29) Toth, Jackie, Kempfer, Jackie. ‘How Advanced Nuclear Got on the Map’. Third Way Memo. April 08 2021

(30) Wells, Mark P. ‘The Cloud Revolution’. Encounter Books. November 02 2021.