Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

Advanced Plant Technologies

Biopower

Carbon Dioxide Capture and Storage Value-Added Options

Carbon Dioxide Capture for Natural Gas and Industrial Applications

Carbon Dioxide Capture Technologies

Carbon Dioxide Storage Technologies

Crosscutting Technologies in Carbon Dioxide Capture and Storage

Fast-spectrum Reactors

Geothermal Power

High Temperature Reactors

Hybrid Nuclear-Renewable Energy Systems

Hydropower

Light Water Reactors

Marine and Hydrokinetic Power

Nuclear Fuel Cycles

Solar Power

Stationary Fuel Cells

Supercritical Carbon Dioxide Brayton Cycle

Wind Power

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

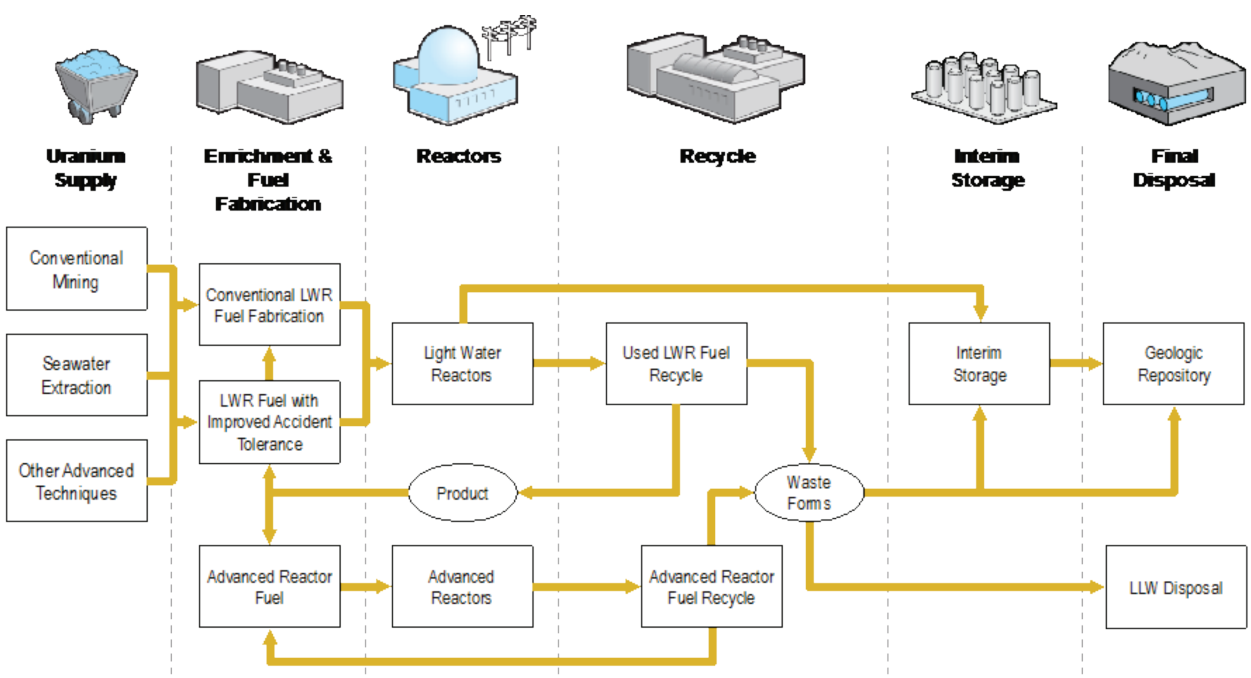
Nuclear Fuel Cycles

Chapter 4: Technology Assessments

Introduction and Background

The Nuclear Fuel Cycle (NFC) is defined as the total set of operations required to produce fission energy and manage the associated nuclear materials. It can have different attributes, including the extension of natural resources, or the minimization of waste disposal requirements. The NFC, as depicted in Figure 4.O.1, is comprised of a set of operations that include the extraction of uranium (U) resources from the earth (and possibly from seawater), uranium enrichment and fuel fabrication, use of the fuel in reactors, interim storage of used nuclear fuel, the optional recycle of the used fuel, and the final disposition of used fuel and waste forms from the recycling processes. Thorium (Th) fuel cycles have been proposed also, but have not been commercially implemented).

Figure 4.0.1 Schematic of the uranium based Nuclear Fuel Cycle



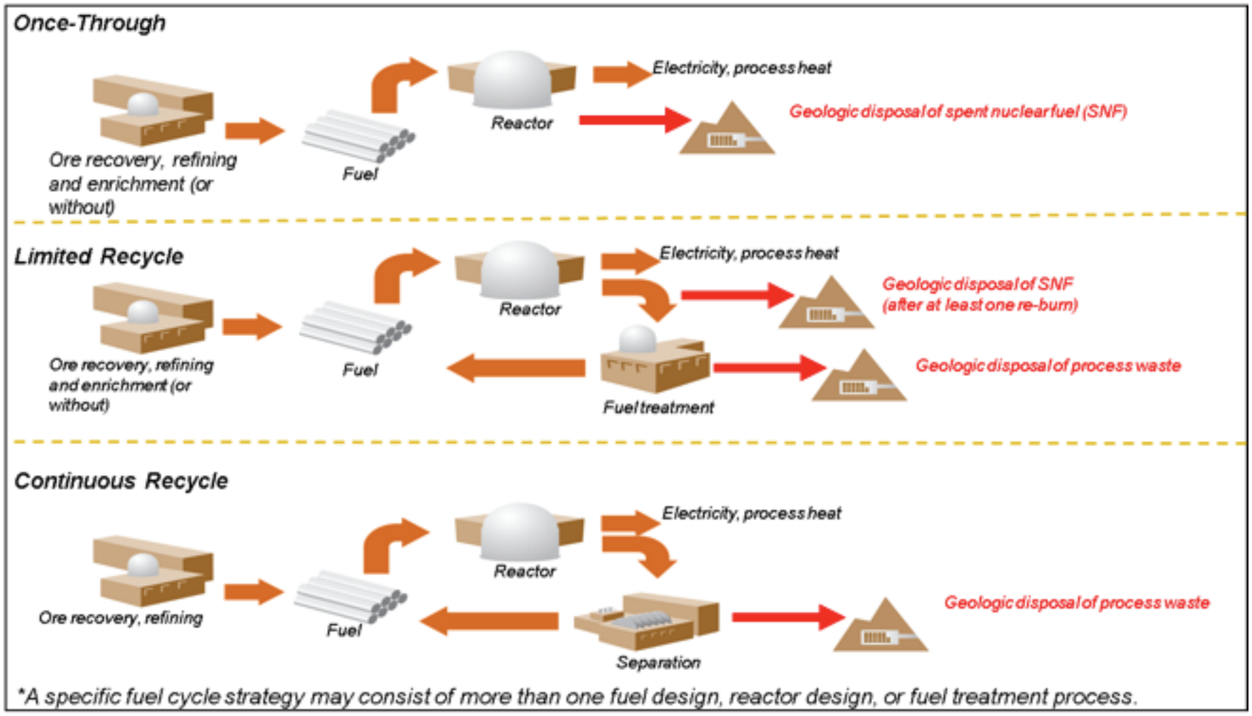
The nuclear fuel cycle is often grouped into three classical components (front-end, reactor, and back-end):

- *Front End:* The focus of the front end of the nuclear fuel cycle is to deliver fabricated fuel to the reactor. Nuclear material is initially collected from two main sources: nature (via mining or possibly extraction from sea water), or recycle of fissile isotopes from used nuclear fuel or other sources (e.g., surplus weapons material). The fuel material is then refined, potentially enriched in its fissile content, and fabricated into nuclear fuel elements with diverse geometries depending on the reactor technology. These fuel elements are then constituted into nuclear fuel assemblies. The geometry, material form, and isotopic content of the fuel are very specific to the reactor type in which the fuel is to be used. However, even within the same reactor type or design, variations are possible, due to various industry technologies. The fuel isotopic content may also vary significantly depending on the mission of the fuel cycle.
- *Reactor:* The mission of the reactor is to extract heat safely from the fuel in a self-sustained nuclear reaction. This heat can then either be used to drive turbines to generate electricity, or for industrial process heat applications. Various reactor types are described in other technical assessments, but two general types are relevant for discussion of the nuclear fuel cycle:
  - Thermal Reactors, including light water reactors (LWRs) – mainly used for commercial nuclear power production in the United States and also capable of recycling fractions of the plutonium from used nuclear fuel and possibly reprocessed and reenriched uranium; high temperature gas reactors (HTGRs) and molten salt reactors (MSRs) that have similar capabilities, but have not been commercially deployed in large numbers.
  - Fast Reactors – used for both power production and capable of breeding fissile isotopes and recycling of used nuclear fuel, including uranium/plutonium or the transuranic (TRU) elements. A number of coolant types have been assessed for Fast Reactors, leading to technologies such as the sodium-cooled fast reactor (SFR), the lead or lead-bismuth cooled fast reactor (LFR), and the gas fast reactor (GFR).
- *Back End:* The focus of the back end of the nuclear fuel cycle is to manage the used fuel produced by the reactor, and put it into a long-term safe and secure state. The back end of the fuel cycle also needs to dispose of processing wastes, including large amounts of low level waste (LLW). Two major options exist: (1) the once-through fuel cycle that ultimately transfers the used fuel into permanent geologic disposal and (2) recycle strategies, where the useful nuclear material is recovered and incorporated into fuel for re-use in thermal or fast reactors, improving ore utilization (when fast reactors are used) and reducing waste volumes sent to disposal, and the remaining radionuclides are converted into waste forms for stable, long-term disposal.

Fuel Cycle Options

When considering the various fuel cycle options, the emphasis is usually placed on the type of reactor and recycle option, if any. Figure 4.O.2 illustrates the fuel cycle options currently being considered in the United States. Typically, the function of the fuel cycle determines the architecture of the system.

Figure 4.0.2 Fuel Cycle Architectures



All fuel cycles require permanent waste disposal, with the once-through cycle producing used nuclear fuel (UNF) that is stored and eventually disposed of in a geologic repository. The other fuel cycles produce LLW, high level waste (HLW) and possibly UNF which also must be stored and eventually disposed of in a geologic repository. The continuous recycle fuel cycles are typically considered for their ability to provide more efficient use of fuel resources and to reduce the amount of waste requiring geologic disposal.

Historical Overview

Fuel cycle considerations have been at the center of nuclear energy development from the beginning. The electricity production complex followed the lead of the U.S. Navy, and developed LWRs with a once-through fuel cycle. The LWR open cycle is still the dominant approach in many nuclear-energy countries. However, a few countries in Europe and Japan have deployed a variant of that approach - limited recycle (originally developed in the United States). In the limited recycle approach, uranium and plutonium are extracted from UNF and recycled into new fuel either as enriched reprocessed uranium (ERU), or mixed oxide (MOX) fuel of plutonium and uranium. This approach provides potential (but limited) benefits in terms of resource extension, and waste management, depending on how the final fuel form is ultimately managed.

Other options for the once-through fuel cycle have also been investigated worldwide, including systems utilizing heavy water reactors (CANDU) deployed in Canada and South Korea. Options based on high temperature reactors (HTRs), that provide additional benefits in terms of thermodynamic efficiency and high temperature process heat applications, have been demonstrated historically (particularly in Germany), but not deployed commercially.

Furthermore, "breed and burn" or traveling wave reactor once through cycles based on fast reactors where fissile material is bred and burned in situ (without the need for recycling) have been proposed and are currently experiencing renewed interest.

Alternatively, several national programs (including the United States, United Kingdom, France, and the former Soviet Union focused early on long term, fissile material resource availability due to the perceived scarcity of uranium at the time and developed fast reactor "breeder" technologies that can produce significant amounts of new fissile materials for re-use in reactors, and can increase resource utilization by a factor of 100, once deployed. The current U.S. fuel cycle requires about 190 MT of natural uranium per GWe-yr, which could be reduced to about 1.3 MT of uranium per GWe-yr if additional fissile material was bred in the reactor. A number of technologies have been tested and demonstrated throughout the world, but have never been deployed commercially. Starting in the 1980s, it became evident that resource issues were not going to be of concern for many years to come, and these efforts were redirected towards using the same technologies for burning excess plutonium and for managing minor actinides, in order to potentially reduce the environmental burden of geologic disposal. Depending on the geologic medium, improvements in the key environmental criteria (such as reduction in estimated dose rate, or overall size of the repository) are expected, as well as a reduction of over three orders of magnitude for the disposal of uranium (depleted uranium from the current U.S. fuel cycle, compared with only small amounts from processing losses when recycle with sufficient conversion of fertile materials to fissile fuel, "breeding," is used). For example, the current U.S. fuel cycle generates about 2000 MT/yr of spent fuel for disposal, and this could be reduced to about 120 MT of hazardous material per year using recycle.

Description of the Technology

Table 4.O.1 summarizes the key U.S. technology choices for the three types of fuel cycles, and provides their estimated technology readiness level (TRL).

Table 4.0.1 Different Types of Fuel Cycles and Their Technology Readiness Levels

Once-Through Technology Options				
Reactor	Fuel	TRL	Back End	TRL
LWR	Uranium dioxide (UO_2)	High	Storage & Disposal	Medium
HTGR	Particle fuels	Medium	Storage and Disposal	Medium
MSR	Particle fuels	Medium	Storage and Disposal	Medium
	Liquid fuels	Low	TBD	Low
Fast Reactor – Breed and Burn	Metal	Medium	TBD	Low

Limited Recycle Technology Options					
Reactor	Fuel	TRL	Recycle	TRL	Back End
LWR	UO_2 / MOX	High	Aqueous	High	Storage and Disposal

Table 4.0.1 Different Types of Fuel Cycles and Their Technology Readiness Levels, continued

Continuous Recycle Technology Options					
Reactor	TRL	Fuel	TRL	Separations	TRL
SFR, LFR	Medium	MOX, Metal	Medium	Aqueous or Electrochemical	Medium
		Nitride Carbide	Low	Aqueous or Electrochemical	
GFR	Low	Particle Fuel	Low	To Be Determined	Low
MSR	Low	Particle Fuel or Molten Salt Fuel	Low	To Be Determined	Low

Getting from the Present to the Future

A comprehensive evaluation of fuel cycle options was recently completed by DOE, identifying those options that have the potential for significant benefit compared to the current once-through U.S. fuel cycle. In the Evaluation and Screening Study, nine evaluation criteria were specified.[1] The first six criteria were related to the potential for benefit and the last three addressed the potential challenges:

1. *Nuclear Waste Management:* focused on the quantity and characteristics of the radioactive wastes generated by the different fuel cycles, but not on the details of waste disposal technologies such as geologic disposal environments.
2. *Proliferation Risk:* focused on the evaluation of technical differences between fuel cycle options at the physics-based functional level (no consideration for any specific implementing technologies).
3. *Nuclear Material Security Risk:* informed on the materials available from the fuel cycle and not on the impacts of specific facility designs and operations, including physical barriers and assumptions made about the protective force and adversary force capabilities.
4. *Safety:* considered whether a fuel cycle could be safely deployed and the relative challenges in addressing safety hazards for an alternative fuel cycle in comparison to the current U.S. fuel cycle.
5. *Environmental Impact:* considered the environmental impacts from the routine operations of a nuclear fuel cycle that are not covered by other criteria, and focused on impacts from fuel acquisition and nuclear power generation.
6. *Resource Utilization:* focused only on the natural resources required for nuclear fuel (i.e., uranium and thorium), not nuclear fuel cycle resources in general (e.g. not zirconium, graphite, steel, etc.).
7. *Development and Deployment Risk:* considered the technology development needs for fuel cycle options considering the status of these technologies today, and then including what would be necessary for maturing the technologies that would affect deployment of a first-of-a-kind facility and integration of all parts of the entire fuel cycle.
8. *Institutional Issues:* focused on the compatibility with the existing infrastructure, current regulations, and market conditions and any different supporting needs that alternative fuel cycles would have as potential challenges to the deployment of a fuel cycle.
9. *Financial Risk and Economics:* considered the relative differences in financial risk and economics among nuclear fuel cycle options as represented by the differences in the expected cost of electricity, but not on the overall economic viability of nuclear power in the United States.

The study determined that the choice of fuel cycle only had the ability to provide potential benefits associated with reduced nuclear waste generation and improved resource utilization, and identified promising fuel cycle options that have the following characteristics in common.

- Continuous recycle of actinides (uranium/plutonium or uranium/TRU most promising; uranium-233/Th providing somewhat less benefit)
- Fast neutron-spectrum critical reactors
- High internal conversion (of fertile to fissile)
- No required uranium enrichment once steady-state conditions are established

Assessment of the challenge criteria showed that the promising fuel cycles all required additional R&D prior to demonstration and deployment. The DOE Fuel Cycle R&D Program, in conjunction with the Advanced Reactor Technologies program, is developing the technologies necessary for eventual demonstration and deployment of alternate fuel cycles. The program includes research in the following areas:

- Separations/Reprocessing Development
  - R&D on separation of uranium/plutonium or uranium/TRU from irradiated fuel to make them available for recycle, e.g., advanced aqueous or electrochemical processes or others based on different separations science and engineering approaches.
  - R&D on developing effective safeguards approaches and technologies for advanced reactors and reprocessing options, improving safeguards and material accountancy technologies, e.g., sensors, monitoring technologies, and isotopic predictive capabilities.
- Fuel Development
  - R&D on recycle fuel development to facilitate use of separated uranium/plutonium or uranium/TRU as fuel, with the fuel having irradiation capability (e.g., fuel burnup, cladding integrity) comparable to or greater than today's fuel.
- Waste Form Development
  - For any fuel cycle technology, managing the wastes from all parts of the fuel cycle should be included as an integral part of the R&D, including development of waste forms that have the potential to reduce the volume of HLW compared to current ceramic and glass based waste forms.

The criteria indicating the challenges associated with developing and deploying an alternative fuel cycle identified several commonalities among the promising fuel cycle options:

- The most promising fuel cycles that might use uranium/plutonium fuels have estimated total development costs in the range of $2 - $10 billion, while those that might use uranium/TRU fuels are in the range of $10 - $25 billion, and estimated development times in the range of 10 to 25 years to bring all enabling implementing technologies and facilities to successful demonstration at engineering scale. The government has historically been the major source of funding for such R&D activities.
- Following completion of the technology development, the promising options have an estimated initial total deployment cost in the range of either $10 - $25 billion (uranium/plutonium – fast reactor only) or $25 - $50 billion (uranium/TRU –fast reactor only, and uranium/plutonium and uranium/TRU with fast and thermal reactors) to continue development from engineering demonstration through the deployment of first-of-a-kind commercial facilities. Fully deploying an alternative fuel cycle to replace the current U.S. fuel cycle would likely require several hundred billion dollars or more, but this is comparable to the cost of continuing with the current fuel cycle replacing existing reactors as they are retired with new similar reactors.
- The market disincentives and barriers to commercial implementation of nearly all of the promising options are expected to be very significant, raising issues of public sector roles in the form of direct

investment, mandates, or changes in law in order to establish and sustain market drivers will likely be required for full-scale implementation of a new fuel cycle. The current waste disposal fee based on energy production provides a disincentive for waste reduction because for a given amount of energy production, the disposal fee is the same regardless of waste amount.

- Based on the Study results for the estimated levelized cost of electricity at equilibrium (LCAE), the promising options may be expected to have electricity production costs that are similar to, or close to, the estimated LCAE for the current U.S. fuel cycle (defined as being within 30%, but estimated as being more likely about 10% higher), and that the dominant fuel cycle cost contributor is for the reactors. It was observed that more complex fuel cycles could cost more to build and operate, but can have offsetting lower costs elsewhere in the fuel cycle. For example, a recycle fuel cycle adds costs for reprocessing and recycling, but will have lower fuel resource costs and may eliminate enrichment costs.

Finally, as previously stated, all fuel cycles eventually require a geologic repository. In 2010, at the request of the President, the Secretary of Energy formed the Blue Ribbon Commission on America's Nuclear Future to recommend a strategy for managing the back end of the nuclear fuel cycle.[2] The strategy recommended eight key elements including consent-based siting of future nuclear waste management facilities, and prompt efforts to develop one or more consolidated storage facilities and geologic disposal facilities. In 2013, the Administration released its *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*.[3] In support of this Strategy, the DOE Used Nuclear Fuel Disposition Program is pursuing preliminary generic process development and associated activities related to storage, transportation and consent-based siting.

Endnotes

1 "*Nuclear Fuel Cycle Evaluation and Screening – Final Report*," R. Wigeland, T. Taiwo, H. Ludewig, M. Todosow, W. Halsey, J. Gehin, R. Jubin, J. Buelt, S. Stockinger, K. Jenni, B. Oakley, October 8, 2014, FCRD-FCO-2014-000106, INL/EXT-14-31465.

2 *Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy*, January 2012. http://energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf.

3 *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*, U.S. Department of Energy, January 2013. http://www.energy.gov/sites/prod/files/Strategy%20for%20the%20Management%20and%20Disposal%20of%20Used%20Nuclear%20Fuel%20and%20High%20Level%20Radioactive%20Waste.pdf

Acronyms

CANDU	Canada Deuterium Uranium reactor
ERU	Enriched reprocessed uranium
GFR	Gas fast reactor
HLW	High level waste
HTGR	High temperature gas reactor
HTR	High temperature reactor
LFR	Lead or lead-bismuth cooled fast reactor
LCAE	Levelized cost of electricity at equilibrium
LWR	Light water reactor
LLW	Low level waste
MSR	Molten salt reactor
MOX	Mixed oxide fuel
NFC	Nuclear fuel cycle
R&D	Research and development
SFR	Sodium-cooled fast reactor
TRL	Technical readiness level
TRU	Transuranic elements
UNF	Used nuclear fuel

Glossary

Breed and Breeder Reactor	Breeding is the process of producing fissile material, like plutonium-239. It occurs as a result of neutron capture in fertile material, like uranium-238. A breeder reactor is one that produces more fissile material than it consumes.
Burnup	Burnup is a measure of thermal energy released by nuclear fuel relative to its mass. It is typically expressed in Megawatt days per metric ton of fuel (MWd/MT).

CANDU	The Canada Deuterium Uranium or CANDU reactor is a Canadian-based reactor design. It is considered a Pressurized Heavy Water Reactor. Heavy water or deuterium oxide serves as the coolant and neutron moderator to lower the energy of the neutrons to thermal levels. The fuel is typically uranium dioxide. The system can operate with uranium that has not been enriched and with low-enriched uranium. The reactor is typically operated using a once-through fuel cycle.
Enrichment	Enrichment is the process by which the amount of the uranium-235 isotope is increased from its natural amount in uranium compared to the uranium-238 isotope.
Fast Neutrons	Fast neutrons are the neutrons released during fission that have high energy levels and are travelling at very high velocity.
GFR	The gas fast reactor or GFR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_42148/gas-cooled-fast-reactor-gfr). The proposed reactor design operates at high temperatures and uses helium as a coolant. The reactor uses fast or high-energy neutrons and would likely employ a continuous recycle fuel cycle. Because of the high-temperatures generated, the system is proposed for potential support of a wide range of industrial processes requiring large amounts of heat or steam.
Generation IV Reactor	Generation IV reactors are the next generation of reactors that are currently being researched for potential deployment in the future. Reactors operating today are primarily Generation II and III designs. New reactors under construction in the United States are considered Generation III+.
HLW	High level waste or HLW is the highly radioactive liquid and solid materials resulting from the reprocessing or recycling of used nuclear fuel. HLW contains the bulk of the fission products from used nuclear fuel and some uranium and transuranic elements. HLW would be disposed in a geological repository.
HTGR	High temperature gas reactor or HTGR is an advanced reactor design that operates at high-temperatures (above 700 °C) and uses helium as a coolant (http://www.ngnpalliance.org/index.php/htgr). The fuel is coated compounds of uranium (often uranium dioxide). The reactor is typically proposed for operation using a once-through fuel cycle. Because of the high-temperatures generated, the system is proposed for potential support of a wide range of industrial processes requiring large amounts of heat or steam.

HTR	High temperature reactor or HTR is an advanced reactor design that operates at high-temperatures (above 700 °C) and uses either helium or molten salt as a coolant. The fuel is coated compounds of uranium (often uranium dioxide). The reactor is typically proposed for operation using a once-through fuel cycle. Because of the high-temperatures generated, the system is proposed for potential support of a wide range of industrial processes requiring large amounts of heat or steam.
LFR	Lead or lead-bismuth cooled fast reactor or LFR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_9358/lfr). The proposed reactor design operates with molten lead or lead-bismuth as a coolant. The reactor uses fast or high-energy neutrons and would likely employ a continuous recycle fuel cycle.
LWR	Light water reactors are the standard reactor design deployed today. They use normal water (H_2O) as the coolant and neutron moderator to lower the energy of the neutrons to thermal levels. The fuel is typically uranium dioxide pellets that are placed into cladding of a zirconium alloy. The system can operate with low-enriched uranium. In the United States and a number of other countries, LWRs are operated using a once-through fuel cycle, but some countries also deploy a limited recycle option.
LLW	Low level waste or LLW is a general term for a wide range of items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. A variety of industries, medical institutions, educational and research institutions, laboratories, and nuclear fuel cycle facilities generate LLW as part of their day-to-day use of radioactive materials. The radioactivity in these wastes can range from just above natural background levels to much higher levels.
Moderator (neutron)	Material used to lower the energy level of neutrons (from fast to thermal) that are generated from fission. Moderators are materials like natural water, heavy water, or graphite. The energy of the neutron is lowered due to collisions with the moderator atoms.
MSR	Molten salt reactor or MSR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_9359/msr). The MSR is distinguished by its core in which the fuel is dissolved in molten fluoride salt. The salt is both the fuel and coolant. The reactor can be designed to operate with either low or high-energy neutrons. The MSR has been proposed for operation as both a once-through fuel cycle and a continuous recycle fuel cycle.
MOX	Mixed oxide fuel or MOX is a type of nuclear reactor fuel that contains plutonium oxide mixed with either natural or depleted uranium oxide, in ceramic pellet form. This differs from conventional nuclear fuel, which is made of pure uranium oxide.

NFC	Nuclear fuel cycle or NFC is the series of industrial processes, which involve the production of electricity from uranium in nuclear power reactors (http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Nuclear-Fuel-Cycle-Overview/). The processes can vary depending on reactor type and on the disposition of used nuclear fuel.
Reprocessing or recycling	Reprocessing is the chemical treatment of used nuclear fuel to separate uranium and plutonium and possibly transuranic elements from the fission products. The recovered uranium, plutonium, and transuranic elements can be recycled to a reactor to be burned. The fission products can be converted to high-level waste for disposal. Example technologies include aqueous-based processes like PUREX and dry processes like electrochemical recycling.
SFR	Sodium-cooled fast reactor or SFR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_9361/sfr). The proposed reactor design operates with molten sodium as a coolant. The reactor uses fast or high-energy neutrons and would likely employ a continuous recycle fuel cycle.
Thermal Neutron	A neutron whose energy has been reduced by collisions with moderator materials such that the neutron is in thermal equilibrium with the medium in which it is interacting.
Traveling Wave Reactor	The traveling wave reactor is a fast reactor design that has also been termed the breed and burn concept. Most of the fissile material for this reactor design is bred from fertile material like uranium-238. A small amount of enriched fissile material is needed to start the reaction. In theory the zone in the reactor where the bulk of the fission occurs moves over time as material is bred in adjacent regions, hence the traveling wave. A reactor design of this type is currently being developed by TerraPower (http://terrapower.com/).
TRU	Transuranic elements or TRU are artificially made, radioactive elements that have an atomic number higher than uranium in the periodic table of elements such as neptunium, plutonium, americium, and others.
UNF	Used nuclear fuel or UNF are fuel assemblies that have been removed from a nuclear reactor after being used to power the reactor. UNF can be either recycled or disposed as a waste.