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Review of the Deployment of and Research into Generation III & IV Nuclear Fission Reactors for Power Generation

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Abstract:

Nuclear fission is one of the more popular and efficient sources of energy that has been used in the last few decades. In the setting of the ongoing worldwide debate of the energy problem, this paper will review the different types and generations of nuclear reactors, and do comparisons with other notable energy sources (biofuel and fusion). The current generations III, III+, IV of reactor (mostly pressurized water reactors), their thermal efficiency, technical (structure and configuration), lifetime, energy output and how the systems contrast are discussed. The paper was written by gathering information from UTS library online database, as well as online articles related to fission power, all sources dating from 2000s onwards. Nuclear fission power is a very dense energy source as it provides

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higher amount of free energy than other energy sources from the same amount of fuel. The drawback, which is the high amount of radioactive waste that accumulates over time, along with thermal efficiency are improved upon by the current and next generations of reactors.

Keywords: Nuclear; Fission; Reactor; Power; Meta-study; Review;

1. Introduction

Nuclear Fission for commercial power generation has been in operation since 1957[5]. Over this time many different reactor designs have been researched and implemented. Today most commercial nuclear power plants are Light Water Reactors of the Boiling Water Reactor or Pressurized Water Reactor Design. Other common reactor types currently used are Heavy Water Reactors and Gas Cooled Reactors.

Many of the reactors that are currently in operation were commissioned decades ago and are reaching the end of their operating lives. The need for new reactors as well as safety concerns over older designs brought on by the 2011 Fukushima Daiichi Nuclear Disaster has fostered renewed research and development into new reactor designs. This research has not just been into upgrading and improving existing designs of Light Water Reactors it is also looking at some technologies that have lain relatively dormant since mid-last century as well as completely new reactor designs.

This report will look at the current state of research into and implementation of Generation III+ nuclear fission reactors as well as the emerging research being done into Generation IV reactor technologies. It will review existing research literature dealing with these reactor designs and their thermodynamic properties, and evaluate whether the thermal efficiency delivered or promised is competitive with existing designs of nuclear fission reactors as well as other systems of electricity generation.

2. Methods

A wide net was cast to obtain information into both the background and fundamental principles of nuclear fission for power generation. This information was checked against multiple sources to ensure that it was accurate.

When selecting papers and articles providing information about current research into, and development of modern fission reactors a more selective approach was used. Articles had to be discussing a current or planned generation III, III+, or IV reactor design, unless the source was being used to obtain a comparative statistic for an older generation reactor. Articles dealing with the thermodynamic properties of reactor designs were used, whereas articles that only dealt with other properties (i.e. safety or cost) were generally not used, unless these properties stemmed from thermodynamic properties.

3. Results and Discussion

Thermal Efficiency is an important property of any commercial power production system. It is defined as the ratio of the work we get out of the system and the energy we put into the system.

$$\eta \equiv \frac{W_{out}}{Q_{in}} \tag{1}$$

There are two main ways of increasing the thermal efficiency of fission reactors that are being focused on in the development of modern reactors. One is increasing the percentage of fissile fuel that is burnt by reactor before being removed and the other is decreasing the energy lost in steam generators when heat is transferred from the primary coolant loop to the secondary.

3.1.1 Percentage of Fuel Burnt

All generations of Light Water Reactors that use Solid Fuels have the problem that the solid fuel assemblies are, over time, damaged by the heat and radiation products produced by the nuclear reaction. Radioactive impurities that hinder the ongoing reaction build up inside the fuel rods. These solid fuel assemblies have to be regularly rotated within the core, and are eventually taken out of the core when only 3-5% of the available energy has been burnt (Hargraves, et al). This early removal of the fuel rods also means that dangerously radioactive trans-uranic elements are present in the spent fuel. These problems are not present in liquid fueled reactors such as liquid Fluorine Thorium reactors, as the fissile fuel in a solution of molten salt is not easily damaged by heat and radiation. This means the fuel can stay in the reactor much longer allowing almost all of the fissile fuel (including the trans-uranic byproducts) to be burnt. As the fuel is a liquid solution it remains homogenous throughout the core, it can be easily pumped through a processing loop in order to remove impurities without having to shut down the reactor.

3.1.2 Efficiency of Steam Generators

Table 1. The projected Thermal Efficiency of Various Gen III+ & IV Fission Reactors.[1 2 3 6]

Reactor Design	Projected Thermal Efficiency(%)
European Pressurized Water Reactor	37
Advanced Pressurized Water Reactor	37
Economic Simplified Boiling Water Reactor	35
High Temperature Reactor-Pebbled Modules	40
Gas Turbine - Modular Helium Reactor	48
Liquid Fluorine Thorium Reactor	45

3.2 Generations of fission reactor

Among many ways to classify nuclear reactors, classification by generations is one of the most common and will be used in this paper in order to analyze different types of reactors. Table 2 below summaries the features of generations of reactors for the last over half decade.

Table 2. Generations of nuclear power (Generation IV International Forum)

	Generation I	Generation II	Generation III	Generation III+	Generation IV
Period of deployment	1950-1960	1970-1990	1990-2000	After 2000	After 2030
Examples	Shippingport, Dresden, Magnox	PWR and VVER, BWR, CANDU	ABWR, AES-92 AP1000, EPR		
Comments	Early prototype reactors	Large commercial power plants that are still operating today	Advanced LWR	Evolutionary designs offering improved economic and safety features	- Life-cycle economic advantage - Enhanced safety - Minimal waste - Proliferation resistant
			One indication of being part of Generation III/III+ is certification by EUR (in Europe) or EPRI/URD (in the United States) utilities requirements[3]		

3.2.1 Generation III reactors

Generation III reactors, developed in the nineties, are replacing generation II reactors, which were built in the seventies and eighties (generation I reactors were early prototypes, built in the 50's and 60's). They have better economics, use natural resources more efficiently, produce less radioactive waste, have increased resistance to proliferation and have greater passive safety features, compared to previous generation reactors (Marques J.G.). Also generation III reactors' standardized designs mean licensing and inspection process is easier and more reliable (NRC's Section 3, Nuclear Reactors 2011-2012 Information Digest, pp 35-38). This section will discuss two leading generation III systems of reactors, their properties and features.

Table 3. Generation III reactors under construction or undergoing a licensing procedure. (Marques, J.G.)

Reactor	Developer(s)	Power (GWe)	Type	First deployment
ABWR	General Electric, Hitachi	1.37	BWR	Japan, 1996
AES-92	Gidropress	1.00	PWR	India, 2009[a]
EPR	Areva	1.60	PWR	Finland, 2012[a]
AP600, AP1000	Westinghouse	0.65, 1.12	PWR	China, 2013[a]
APR-1400	KHNP, Westinghouse	1.30	PWR	South Korea, 2013[a]
APWR	Mitsubishi	1.50–1.70	PWR	Japan, 2016[a]
ESBWR	General Electric	1.55	BWR	Awaiting license
ACR-1000	Atomic Energy of Canada	1.20	PHWR	Awaiting license

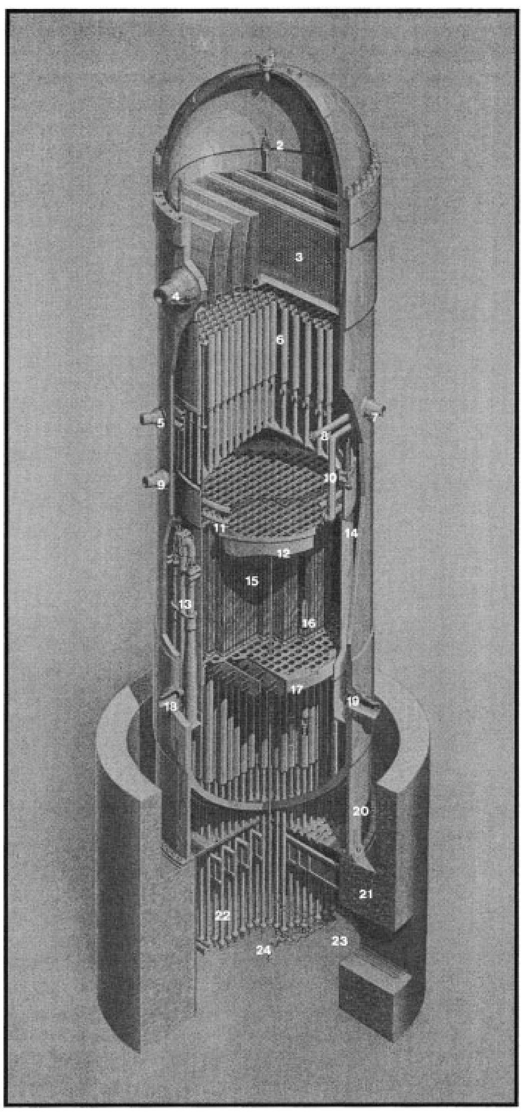
3.2.1.1 ACPR1000 Reactors

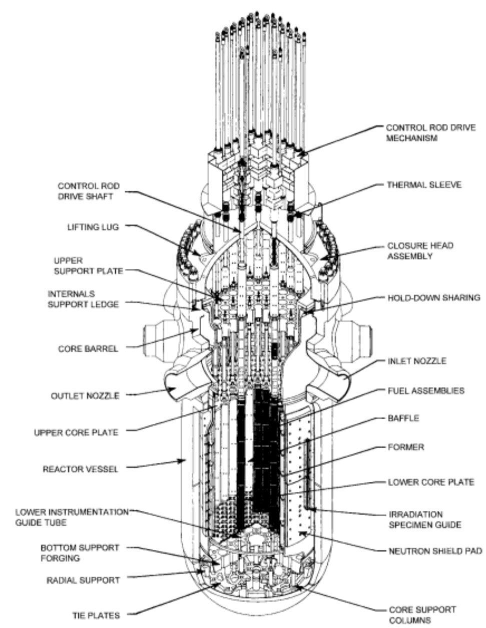
Advanced CPR - ACPR1000 reactor is the improved version of generation II+ reactor CPR – 1000 to generation III. They are both pressurized water reactors (PWR) that originate from China and use design based on the 900 MWe-class French M310 three-loop technology (Nuclear Power in China). Figure 1 below shows the design of a PWR. The ACPR1000 has 14-inch fuel reactor core, digitalized instrument control system, three safety systems, large and double layer containment, in-built refueling water tank, safety shutdown earthquake (Dynabond). All in all the reactor meets all the technical and economical measures required by generation III standards, China's latest safety regulation, American standard URD as well as European standard EUR (Dynabond). The construction cost of ACPR1000 reactor power plant is expected to be $2500/kw (Nuclear Power in China).

ACPR1000+ is the improved version of ACPR1000 that takes into account Fukushima nuclear disaster and fulfil post-Fukushima as well as international safety requirements (China General Nuclear Power Group). Some of the main technical features of the reactor include (China General Nuclear Power Group). ACPR1000+ is predicted to be exported from 2014 (Nuclear Power in China):

- Reactor: 157 fuel assemblies, in-core instrumentation is inserted from the top, metal reflector that extends the RPV design lifetime to 60 years.
- Nuclear Steam Supply System: large capacity pressure relief valve implemented to quick relief coolant in sever conditions, LBB technology is adopted to simplify design.
- Double Containments: outer containment can withstand large impact, the double containment reduces radioactive release during accident compared to CPR1000.

Figure 1. Pressurized water reactor (Courtesy of Westinghouse Electric Corporation)





3.2.1.2 Advanced Boiling Water Reactor

Figure 2. Boiling Water Reactor
(Courtesy of General Electric Company)

1, vent and head spray; 2, steam dryer lifting lug; 3, steam dryer assembly; 4, steam outlet; 5, core spray inlet; 6, steam separator assembly; 7, feedwater inlet; 8, feedwater sparger; 9, low-pressure coolant injection inlet; 10, core spray line; 11, core spray sparger; 12, top guide; 13, jet pump assembly; 14, core shroud; 15, fuel assemblies; 16, core blade; 17, core plate; 18, jet pump/recirculation water inlet; 19, recirculation water outlet; 20, vessel support skirt; 21, shield wall; 22, control rod drives; 23, control rod drive hydraulic lines; and 24, in-core flux monitor.

Advanced Boiling Water Reactor (ABWR) is the first generation III boiling water reactor to enter the market in 1996 (Marques, J.G.). Older boiling water reactor designs have their external pumps replaced by ABWR's internal recirculation pumps inside of the reactor pressure vessel (Marques, J.G.). The system, with power output is around 3926 Mega Watt Thermal, also include control rod drives that can be controlled by a screw mechanism, microprocessor-based digital control and logic systems, as well as digital safety systems. Other features compared to older generations of boiling water reactors are protection against over pressurizing the containment, passive core debris flooding capability, independent water makeup system, three emergency diesels and combustion turbine as alternative power source. Seven ABWR units are in operation or under construction in Taiwan and Japan, with two more planned to start operation in 2016-2017 in the US (Marques, J.G.). Figure 2 below shows the design of a boiling water reactor.

The reactor technical features (General Electric Company):

- Output power 1350 to 1460 MW net
- Emission: Nearly zero C02 greenhouse gas emissions
- Lifetime: 60 years
- Core Damage Frequency: 1E-7
- Availability and Capacitor Factor: >90%

Overall, the reactor provides an economical, dependable energy solution. It is a great power source when environmental and safety concerns are a high priority.

3.2.2 Generation III+ reactors

Generation III+ reactors designs are evolutionary development of generation III reactors, providing improvements in safety. The development started in the 1990s by building on the experience of light water reactor fleets of the time (amacad.org). The most significant improvement over previous designs is believed to be the inclusion of passive safety features (amacad.org). Generation III+ reactors are expected to get higher fuel burn up than their predecessors (hence reducing fuel consumption and waste consumption. More than two dozen generation III+ reactors are planned for the US (amacad.org). This section will continue with two examples of generation III+ reactor. Table 4 shows a comparison for several generation III and III+ reactors.

3.2.2.1. Advanced CANDU Reactor (ACR-1000)

The Advanced CANDU Reactor (ACR) is a generation III+ heavy water reactor that has a 1200 MWe output. The reactor uses light water reactor coolant and higher burn up low-enriched-uranium fuel, while keeping operating CANDU 6 plant design's heavy water moderator and on-load refueling (candu.com). The Preliminary Safety Analysis Report demonstrates that ACR-1000 is safe, in compliance with international regulatory requirements and expectations.

To attain better operational savings than previous CANDUs, the ACR uses slightly enriched uranium fuel (0.9% ^{235}U) instead of natural uranium (Marques J.G.). The coolant of ACR is light water, while heavy water is used as moderator (Marques J.G.). The expected lifetime is 60 years and the planned lifetime capacitor factor is greater than 90%. The first ACR-1000 is planned to be operational by 2016 (Marques J.G.).

Technical features other than included above (iaea.org):
- Reactor thermal output: 3200 MW thermal
- Power plant efficiency, net: 36.5%
- Two fueling machines
- Safety measures including two shutdown systems, emergency core cooling, emergency heat removal system, and containment system.
- Steam flow rate at nominal conditions: 1728 kg/s

Table 4. Comparisons between generation III and III+ reactors:

ITEM	ACPR1000+	CPR1000+	AP1000	EPR	URD/EUR
Core Damage Frequency , /(pile·year)	$< 1\times10^{-5}$	$\sim 1\times10^{-5}$	$\leq 5.1\times10^{-7}$	7.75×10^{-7}	$< 1\times10^{-5}$
Large Release Frequency , /(pile·year)	$< 1\times10^{-6}$	$\sim 1\times10^{-6}$	$\leq 5.9\times10^{-8}$	8.1×10^{-8}	$< 1\times10^{-6}$
Electrical Output, MWe	1150	1085	1250	1700	Improved PWR upper limit 1350
Core Thermal Margin	>15%	10%	>15%	>15%	>15%
Fuel Cycle , month	18-24	18	18	18	24
Capacity Factor, %	92	≥90	93	≥92	87
SSE, g	0.3	0.2	0.3	0.25	EUR 0.25 URD 0.3
Period without operator actions	30min	10min	72hour	30min	At least 30min
Solid waste generation, $m^3/(a\cdot Unit)$	<50	<50	<50	>50	
Design lifetime, Year	60	60	60	60	60

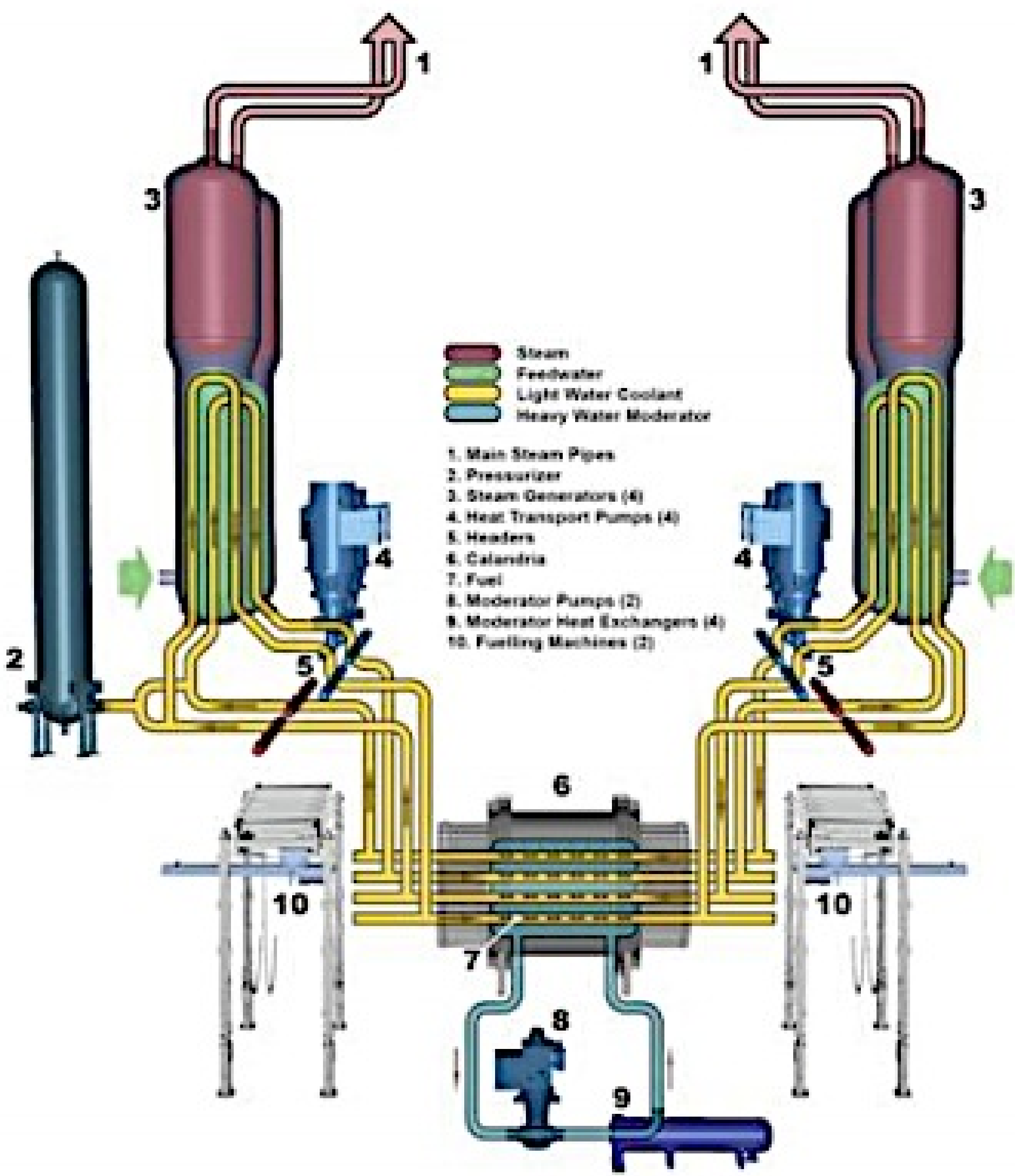
Overall compared to previous generation reactors, ACR has improved burn up, better safety margins, increased turbine cycle efficiency (thanks to higher pressure and temp in coolant and steam supply systems), improved performance thanks to new information systems.

3.2.2.2 AP1000 reactor

The AP1000 reactor is a generation III+ reactor developed by Westinghouse (USA). It is an advanced passive PWR that is a scaled up version of AP600, with expected output of 1000 MWe

(Marques J.G.). The system's passive protection means that emergency diesel generators are not needed in case of electricity loss, making the reactor more environmentally friendly.

Figure 3. ACR-1000 Nuclear Systems Schematic (iaea.org)



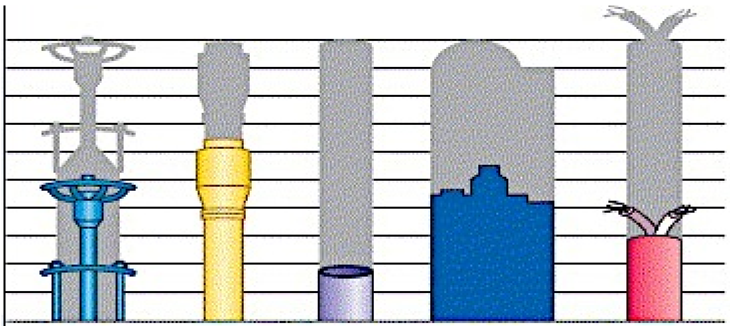
The reactor safety is further enhanced by the fact that in the case of core melt, flooding by operator prevents core debris from spilling into containment (Marques J.G.). Thanks to the lower amount of pipes, valves and associated components, AP1000 is cheaper than other PWRs. Two AP1000 reactors started operation in China in 2011 (Marques J.G.).

The AP1000 coolant system includes two heat transfer circuits, with each having a steam generator, two coolant pumps, one hot leg and tow cold legs for transferring coolant between reactor and steam generators (T.L.Schulz). Other than reactor coolant pump, all major components of AP1000 have been verified under similar flow, temperature and pressure conditions (T.L.Schulz).

AP1000 technical features improved compared to AP600:

Table 5. Selected AP1000 parameters (T.L.Schulz)

Parameter	AP600	AP1000
Net electric output, MWe	610	1117
Reactor power, MWt	1933	3400
Hot leg temperature, °C (°F)	316(600)	321 (610)
Number of fuel assemblies	145	157
Type of fuel assembly	17 × 17	17 × 17
Active fuel length, m (ft)	3.7(12)	4.3(14)
Linear hear rating, kw/ft	4.1	5.71
Control rods/gray rods	45/16	53/16
R/V I.D., cm (in.)	399 (157)	399 (157)
Vessel flow (thermal) 10^3 m3/h (10^3 gpm)	44.1 (194)	68.1 (300)
Steam generator surface area, m^2 (ft^2)	6970 (75000)	11600(125000)
Pressurizer volume, m^3 (ft^3)	45.3(1600)	59.5(2100)



Reduced Number of Components:

	1000 MW Reference	AP1000	Reduction
- Safety Valves	2844	1400	51%
- Pumps	280	184	34%
- Safety Piping	11.0×10^4 feet	1.9×10^4 feet	83%
- Cable	9.1 mil. feet	1.2 mil. feet	87%
- Seismic Building Volume	12.7 mil. ft^3	5.6 mil. ft^3	56%

Figure 4. AP1000 quantitative simplifications (T.L.Schulz)

From figure 4, it can be seen that from the use of more advanced technology, AP1000 gained many simplifications, bringing in many benefits over other current PWRs, such as less redundancy, operational cost and improved safety system. Overall, AP1000 design is much simpler, mature, proven to have benefits in construction and operation.

3.2.3 Generation IV reactor

Generation IV reactors are systems expected to reach maturity by 2030 (Frank Carre and Gian Luigi Fiorini), in other words they are in development and expected to be the future of nuclear energy. The designs take into consideration economic and safety progress, aim to support sustainable energy worldwide, and to open up the range of applications other than electricity production (Frank Carre and Gian Luigi Fiorini).

The general aims of generation IV reactors based on international agreement comprise of:

- Sustainability
- Economic viability
- Safety and reliability
- Resistance to proliferation risks and invulnerability from external attacks.

The range of applications can include hydrogen production, desalination of sea water, coal to diesel production, fertilizer production, and many more.

The Generation IV International Forum (GIF) outlined six reactor concepts for future generation IV reactor development, shown in Table 4.

Table 6. Generation IV systems under development (Marques J.G).

Reactor	Spectrum	Fuel cycle	Temp. (°C)
Sodium-cooled Fast Reactor (SFR)	Fast	Closed	~550
Lead Alloy Cooled Reactor (LFR)	Fast	Closed	550–800
Gas-cooled Fast Reactor (GFR)	Fast	Closed	~850
Very High Temperature Reactor (VHTR)	Thermal	Open	>900
Supercritical Water Cooled Reactor (SCWR)	Thermal and fast	Open and closed	350–620
Molten Salt Reactor (MSR)	Thermal	Closed	700–800

From table 4, it can be highlighted: that most designs use closed fuel cycles; half of the designs are fast reactors, and four designs are high temperature type. The high temperature designs can be used to produce hydrogen, synthetic fuels, or have application in transport (Generation IV International Forum). More technical features of generation IV systems are provided by table 5.

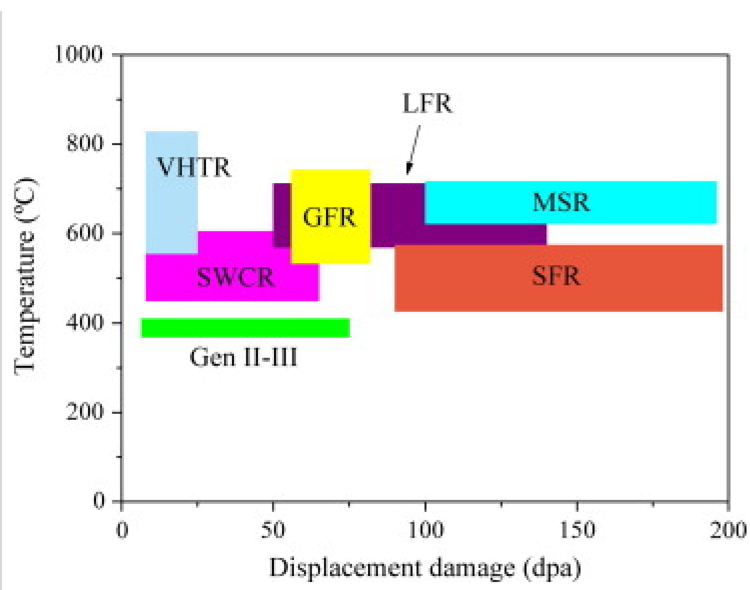
Overall, there are many perceived changes between generation IV and previous generations in parameters such as coolant medium, temperature, and fuel used as well as applications. From these changes generation IV reactors are expected to operate better than previous generations in many factors.

Generation IV reactors are however, not without problems. Two most significant problems are the fuel composition' impact on safety of reactor and the required materials for reactors (Marques J.G.). Figure 3 demonstrates that materials used presently are not suitable for GIF reactors. With higher operating temperatures and higher radiation (as shown by table 3, 4,5 and 6), GIF reactors are more demanding on coolant.

Table 7. Characteristics and Operating Parameters of the Eight Generation IV Reactor Systems under Development (amacad.org).

	Neutron Spectrum (fast/ thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel Cycle	Size(s) (MWe)	Uses
Gas-cooled fast reactors	Fast	Helium	850	High	U-238†	Closed, on site	1,200	Electricity & Hydrogen‡
Lead-cooled fast reactors	Fast	Lead or lead-bismuth	480–800	Low	U-238†	Closed, regional	20–180** 300–1,200 600–1,000	Electricity & Hydrogen‡
Molten salt fast reactors	Fast	Fluoride salts	700–800	Low	UF in salt	Closed	1,000	Electricity & Hydrogen‡
Molten salt reactor—Advanced high temperature reactors	Thermal	Fluoride salts	750–1,000		UO_2 particles in prism	Open	1,000–1,500 30–150	Hydrogen‡
Sodium-cooled fast reactors	Fast	Sodium	550	Low	U-238 & MOX	Closed	300–1,500 1,000–2,000 300–700	Electricity
Traveling wave reactors	Fast	Sodium	~510	Low	U-238 metal with U-235 igniter seed	Open	400–1,500	Electricity
Supercritical water-cooled reactors	Thermal or fast	Water	510–625	Very high	UO_2	Open (thermal) closed (fast)	1,000–1,500	Electricity
Very high temperature gas reactors	Thermal	Helium	900–1,000	High	UO_2 prism or pebbles	Open	250–300	Electricity & Hydrogen‡

Figure 5. Operating temperatures and expected displacement damage (in displacement per atom, dpa) of Generation IV designs compared with previous generations. (Marques J.G.)



In order to overcome the displacement damage, materials such as water in supercritical state, liquid metals, molten salts, high pressure helium gas (Marques J.G.). These materials can cause high corrosion, hence materials technology (possibly even nanomaterial) should be applied in order to maintain protective surface layers.

3.3 Other power generating systems

In 2012, nuclear power provided only about 5.7% of world's energy and 13% of world's electricity in 2012 (International Energy Agency). In the grand scheme of things, it is important to compare and contrast with other power sources in the discussion of nuclear power, to really know how efficient and viable nuclear power really is.

3.3.1. Biofuels

Biofuels are energy derived from biomass, bio materials made of living and recently living organisms. Biofuels are classified as primary and secondary, primary biofuels being used for heating, cooking or infrequently electricity production. Primary biofuel is in fact inefficient and toxic to the environment (Biomass to biofuel). Secondary biofuels are produced from the processing of biomass that can be used for many applications. Secondary biofuel is further categorized into first, second and third generations (Biomass to biofuel). Table 7 indicates the varying efficiency through different biomass utilization ways. From the processing to the fuel used, biofuel attracts attention as a cleaner power sources. It provides a way to produce transportation fuel from renewable sources hence reducing net CO2, as CO2 from combustion of fuel is recaptured by the growth of feedstock (c2es.org).

3.3.2. Fusion power

Fusion power is generated from nuclear fusion processes, in which, two light atomic nuclei fuse to form a heavier nucleus, by the heating of nuclei plasma so they move at high speed and collide. The force which stick the two positive particles together is the Strong Force, which holds protons and neutrons together. From here the mass-energy equivalence equation comes in, dictating the energy released from the releasing of the smaller leftover particles (efda.org).

From the process of fusion it can be seen that it has many advantages:

- No carbon emissions, as the only by products are small amount of helium.
- Large amount of fuels. Deuterium can be extracted from water and tritium from lithium (abundant in Earth's crust)
- Energy efficiency: 10 million more efficient than fossil fuel (ccfe.ac.uk)

Once the technology can commercialize fusion, its efficiency means lower costs.
The problems with fusion includes (Magaud, P., G. Marbach, and I. Cook):
- Materials for withstanding the high energy release of fusion products
- The reaction chamber's walls and the blankets themselves will become radioactive due to the neutrons depositing energy
- Methods needed to contain radioactive dust and radioactivity induced by neutrons

Table 8. Biomass to fuel efficiency through different biomass utilization pathways (Wei-Dong Huang and Y-H Percival Zhang)

Biofuel	Technology	Feedstock	Efficiency	Original Data	Original Data unit
corn ethanol	fermentation	corn	46.4%	0.372	L/kg dry
	fermentation	corn	49.4%	0.396	L/kg dry
	fermentation	corn	50.1%	0.402	L/kg dry
cellulosic ethanol	fermentation	corn stover	48.4%	0.298	kg/kg
	fermentation	corn stover	55.6%	0.342	kg/kg
sugar	hydrolysis	corn stover	55.8%	0.652	kg/kg
	hydrolysis	corn stover	61.1%	0.714	kg/kg
hydrogen	gasification	wood	55.0%	55.00	%LHV
	gasification	almond shells	70.8%	74%	HHV
methanol	gasification	wood	50.9%	0.477	kg/kg
	gasification	lignocellulose	54.9%	59.0	%HHV
DME	gasification	energy crop	39.0%	39–56.8%	LHV
FT-diesel	gasification	lignocellulose	41.4%	42.0	%HHV
	gasification	lignocellulose	52.0%	52.0	%LHV
ester micro-diesel	fermentation	glucose	7.2%	14.0	% theoretical efficiency
	fermentation	glucose	36.5%	64	%LHV
butanol	fermentation	glucose	46.7%	0.350	g/g glucose
	fermentation	glucose	52.8%	92.6%	LHV
methane	fermentation	ley crops	62.2%	10.6	GJ/dry ton
	fermentation	energy maize	81.3%	0.374	m^3/kg dry maize
electricity	boiler	lignocellulose	25–43%	25–43%	LHV

4. Conclusions

Nuclear power is now a highly efficient source of power thanks to the development over the years of generations I, II, III, the current III+, and the future generation IV. The generations consistently improve in efficiency, safety, operation, cost and many others. The Fukushima disaster however still reminds us that the safety factor can never be underestimated, and the cost of nuclear fission power is still very high, not just in economy but also in risks. Developments must continue for nuclear to keep being viable, as there are still many other viable power sources out there with their own pros and cons. Nuclear fission power may not thrive for a very long time to the future, with technology getting us closer to fission, we still learned a lot from it, from the operation of big power plant projects, to knowing the risk proliferation, contributing to the future sustainable energy.

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