

## NUCLEAR POWER AS A BASIS FOR FUTURE ELECTRICITY GENERATION

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It is well known that the electrical-power generation is the key factor for advances in any other industries, agriculture and level of living. In general, electrical energy can be generated by: 1) non-renewable-energy sources such as coal, natural gas, oil, and nuclear; and 2) renewable-energy sources such as hydro, wind, solar, biomass, geothermal and marine. However, the main sources for electrical-energy generation are: 1) thermal – primary coal and secondary natural gas; 2) «large» hydro and 3) nuclear. The rest of the energy sources might have visible impact just in some countries. The paper presents the current status of nuclear-power industry in the world and a comparison of nuclear-energy systems to other energy systems.

**Key words:** nuclear power industry, electricity generation, current status, thermal power plants, modern nuclear power plants, 4-th generation nuclear reactors.

### INTRODUCTION

It is well known that the electrical-power generation is the key factor for advances in any other industries, agriculture and level of living. In Table 1, the comparison of the electrical energy consumption (EEC) per capita for different countries is given including also the human development index (HDI) by United Nations [1 – 5]. It can be seen that the lower EEC per capita, the lower is the HDI value.

In general, electrical energy (see Fig. 1a – 1h) can be generated by: 1) non-renewable-energy sources such as coal, natural gas, oil, and nuclear; 2) renewable-energy sources such as hydro, wind, solar, biomass, geothermal and marine. However, the main sources for electrical-energy generation are: 1) thermal – primary coal (41%) and secondary natural gas (21%); 2) «large» hydro (16%) and 3) nuclear (14%). The largest power plants of the world by energy source based on installed capacity are listed in Table 2. The rest of the energy sources might have visible impact just in some countries. In addition, the renewable-energy sources, for example, such as wind and solar and some others, are not really reliable energy sources for industrial-power generation due to high relative cost of electrical energy produced by them and their dependence on various nature factors.

The following two parameters are important characteristics of any power plant. The

first of them is the overall (gross) or net efficiency of a plant during a given period of time. It is the ratio of the gross electrical energy generated by a plant to the energy consumed during the same period by the same plant. The difference between gross and net efficiencies is internal needs for electrical energy of a power plant, which might be not so small (5% or even more).

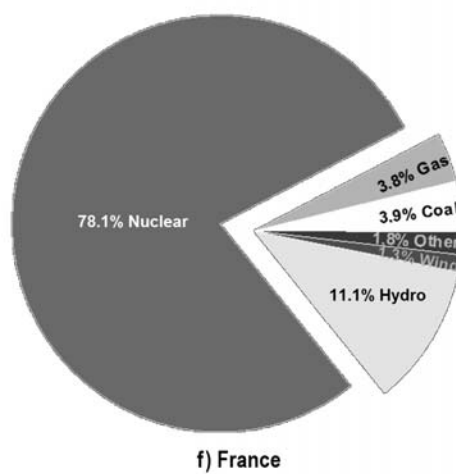
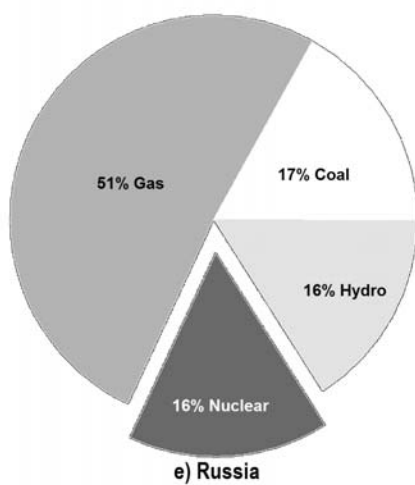
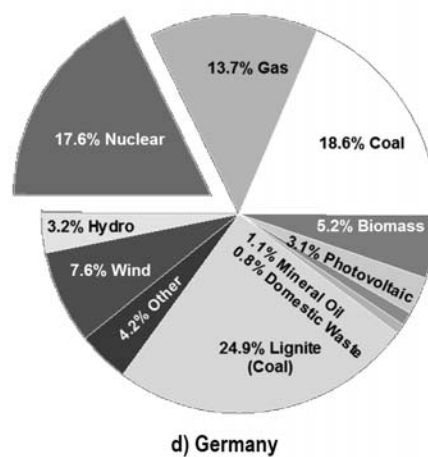
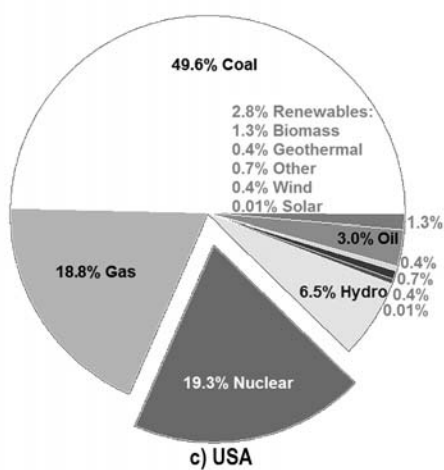
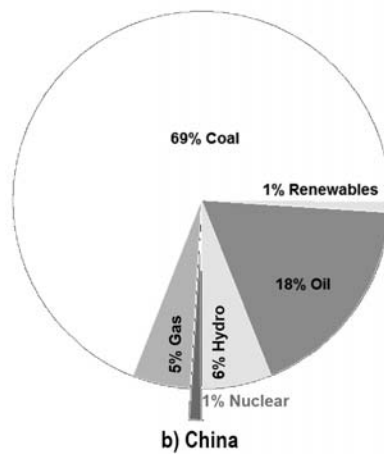
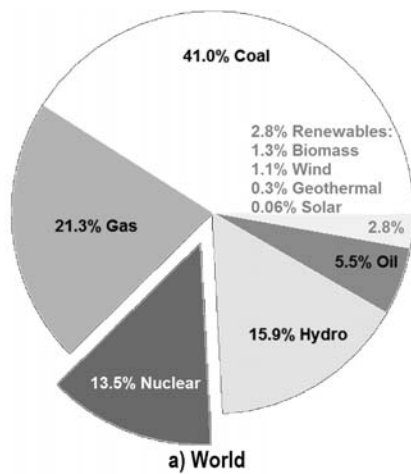
Table 1

**Electrical Energy Consumption per Capita  
in Different Countries**

| No | Country     | Population,<br>Millions | Energy Consumption |          | Year      | HDI  |       |
|----|-------------|-------------------------|--------------------|----------|-----------|------|-------|
|    |             |                         | TW h/year          | W/Capita |           | Rank | Value |
| 1  | Norway      | 5                       | 116                | 2603     | 2013      | 1    | 0.955 |
| 2  | Australia   | 23                      | 225                | 1114     | 2013      | 2    | 0.938 |
| 3  | USA         | 316                     | 3,886              | 1402     | 2012      | 3    | 0.937 |
| 4  | Germany     | 80                      | 607                | 822      | 2009      | 5    | 0.920 |
| 5  | Japan       | 127                     | 860                | 774      | 2012      | 10   | 0.912 |
| 6  | Canada      | 33                      | 550                | 1871     | 2011      | 11   | 0.911 |
| 7  | South Korea | 50                      | 455                | 1038     | 2012      | 12   | 0.909 |
| 8  | France      | 65                      | 461                | 804      | 2012      | 20   | 0.893 |
| 9  | UK          | 63                      | 345                | 622      | 2011      | 26   | 0.875 |
| 10 | Russia      | 143                     | 1,017              | 808      | 2013      | 55   | 0.788 |
| 11 | Ukraine     | 45                      | 182                | 461      | 2012      | 78   | 0.740 |
| 12 | Brazil      | 194                     | 456                | 268      | 2012      | 85   | 0.730 |
| 13 | China       | 1,354                   | 4,693              | 395      | 2012      | 101  | 0.699 |
| 14 | World       | 7,035                   | 19,320             | 313      | 2005–2012 | 103  | 0.694 |
| 15 | India       | 1,210                   | 959                | 90       | 2011      | 136  | 0.554 |
| 16 | Afghanistan | 30                      | 0.23               | 1        | 2012      | 175  | 0.374 |
| 17 | Chad        | 10                      | 0.93               | 1        | 2009      | 184  | 0.340 |
| 18 | Niger       | 17                      | 0.63               | 4        | 2012      | 187  | 0.304 |

The second parameter is the capacity factor of a plant, which is the ratio of the actual output of a power plant over a period of time (usually, during a year) and its potential output if it had operated at full nameplate capacity the entire time. To calculate the capacity factor, the total amount of energy a plant produced during a period of time should be divided by the amount of energy the plant would have produced at the full capacity. Capacity factors vary significantly depending on the type of a plant. The average (typical) capacity factors of various power plants are given in Table 3, which are partially based on [6].

An example of how various energy sources generate electricity in a grid can be illustrated based on the Province of Ontario (Canada). Figure 2 shows installed capacity (a) and electricity generation (b) by energy source in Ontario (Canada). Analysis of Fig. 2 shows that in Ontario major installed capacities are nuclear (34%), gas (26%), hydro (22%), coal (8%), and renewables (mainly wind) (8%). However, electricity (see Fig. 2b) is mainly generated by nuclear (56%), hydro (22%), natural gas (10%), renewables (mainly wind) (just 5%) and coal (2%).



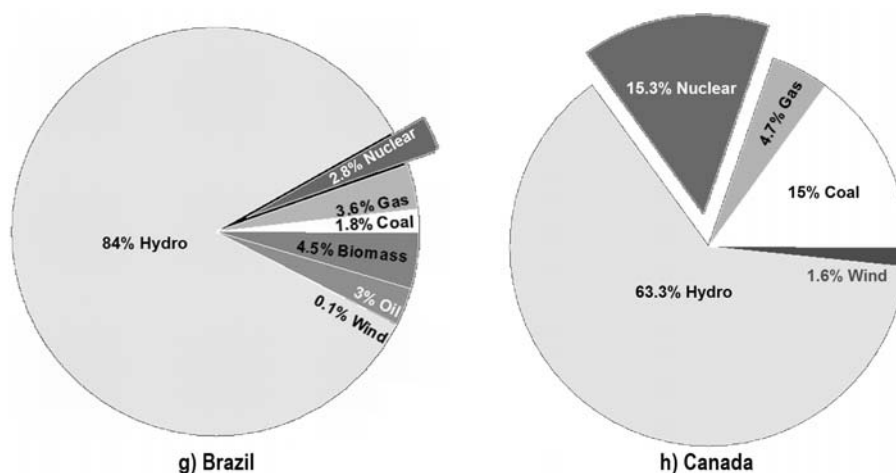


Fig. 1. Electricity generation by source in the World and selected countries given as electrical energy consumption (EEC) per Capita for each source

- a) – World: population – 7,035 millions, EEC – 313 W/Capita, HDI – 0.694, HDI Rank – 103;  
b) – China: population – 1,354 millions, EEC – 395 W/Capita, HDI – 0.699, HDI Rank – 101;  
c) – USA: population – 316 millions, EEC – 1,402 W/Capita, HDI – 0.937, HDI Rank – 3;  
d) – Germany: population – 80 millions, EEC – 822 W/Capita, HDI – 0.920, HDI Rank – 5;  
e) – Russia: population – 143 millions, EEC – 808 W/Capita, HDI – 0.881, HDI Rank – 25;  
f) – France: population – 65 millions, EEC – 804 W/Capita, HDI – 0.893, HDI Rank – 20;  
g) – Brazil: population – 194 millions, EEC – 268W/Capita, HDI – 0.730, HDI Rank – 85;  
h) – Canada: population – 33 millions, EEC – 1,871 W/Capita, HDI – 0.911 0, HDI Rank – 11.

Table 2

**Largest Power Plants of the World by Energy Source Based on Installed Capacity**

| Rank | Plant                                  | Country     | Capacity, MW <sub>el</sub> | Plant Type      |
|------|--|-------------|----------------------------|-----------------|
| 1    | Three Gorges Dam Power Plant           | China       | 21,000                     | Hydro           |
| 2    | Kashiwazaki-Kariwa NPP                 | Japan       | 8,210                      | Nuclear         |
| 3    | Taichung Power Plant                   | Taiwan      | 5,780                      | Coal            |
| 4    | Surgut-2 Power Plant                   | Russia      | 5,600                      | Fuel oil        |
| 5    | Futtsu Power Plant                     | Japan       | 5,040                      | Natural gas     |
| 6    | Eesti Power Plant                      | Estonia     | 1,615                      | Oil shale       |
| 7    | Shatura Power Plant                    | Russia      | 1,020                      | Peat            |
| 7    | Alta Wind Energy Center                | USA         | 1,020                      | Wind            |
| 8    | Ivanpah Solar Power Facility           | USA         | 392                        | Solar (thermal) |
| 9    | Hellisheiði Power Plant                | Iceland     | 303                        | Geothermal      |
| 10   | Alholmens Kraft Power Plant            | Finland     | 265                        | Biofuel         |
| 11   | Sihwa Lake Tidal Power Plant           | South Korea | 254                        | Tidal           |
| 12   | Charanka Solar Park                    | India       | 214                        | Solar           |
| 13   | Vasavi Basin Bridge Diesel Power Plant | India       | 200                        | Diesel          |
| 14   | Aguçadoura Wave Farm                   | Portugal    | 2                          | Marine (wave)   |

Table 3

**Average (Typical) Capacity Factors of Various Power Plants**

| No | Power Plant type           | Location          | Year              | Capacity Factor, % |
|----|----------------------------|-------------------|-------------------|--------------------|
| 1  | Nuclear                    | USA               | 2010              | 91                 |
|    |                            | UK                | 2011              | 66                 |
| 2  | Combined-cycle             | USA               | 2009              | 42                 |
|    |                            | UK                | 2011              | 48                 |
| 3  | Coal-fired                 | USA               | 2009              | 64                 |
|    |                            | UK                | 2011              | 42                 |
| 4  | Hydroelectric              | USA and UK        | 2011              | 40                 |
|    |                            | World (average)   | –                 | 44                 |
|    |                            | World (range)     | –                 | 10-99              |
| 5  | Wind                       | UK                | 2011              | 30                 |
|    |                            | World             | 2008              | 20–40              |
| 6  | Wave                       | Portugal          | –                 | 20                 |
| 7  | Concentrated-solar thermal | USA California    | –                 | 21                 |
| 8  | Photovoltaic (PV) solar    | USA Arizona       | 2008              | 19                 |
|    |                            | USA Massachusetts | –                 | 12–15              |
|    |                            | UK                | 2011<br>2007-2011 | 5.5<br>8.3         |
| 9  | Concentrated-solar PV      | Spain             | –                 | 12                 |

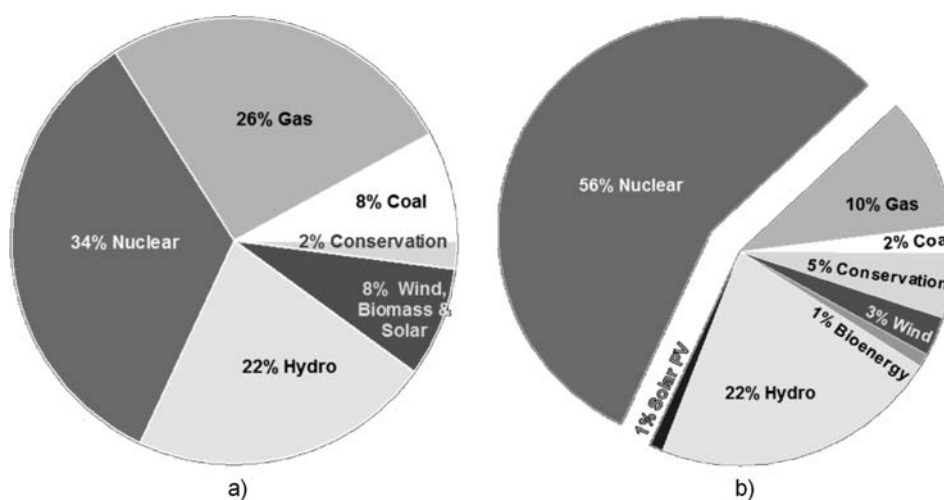


Fig. 2. Installed capacity (a) and electricity generation (b) by energy source in Ontario (Canada), during 2012 – 2013 years.

Figure 3 shows power generated by various energy sources and their capacity factors in Ontario (Canada) on June 19, 2012. It was a hot summer day taken as an example, when a lot of air-conditioning was required. Analysis of Fig. 3 has revealed that electricity that day from midnight till 3 o'clock in the morning was mainly generated by nuclear, hydro, gas, wind, «other» and coal. After 3 o'clock in the morning, wind power

started to be decreased by Mother Nature, but electricity consumption started to rise. Therefore, «fast-response» gas-fired power plants and later on, hydro and coal-fired power plants plus «other» power plants started to increase electricity generation to compensate both decreasing in wind power and increasing demand for electricity. After 6 o'clock in the evening, energy consumption slightly dropped in the province, and at the same time, wind power started to be increased by Mother Nature. Therefore, gas-fired, hydro and «other» power plants decreased energy generation accordingly («other» plants dropped power quite abruptly, but their role in the total energy generation is very small). After 10 o'clock in the evening, energy consumption started to drop even more, therefore, coal-fired power plants as the most «dirty» plants decreased abruptly electricity generation followed by gas-fired and hydro plants.

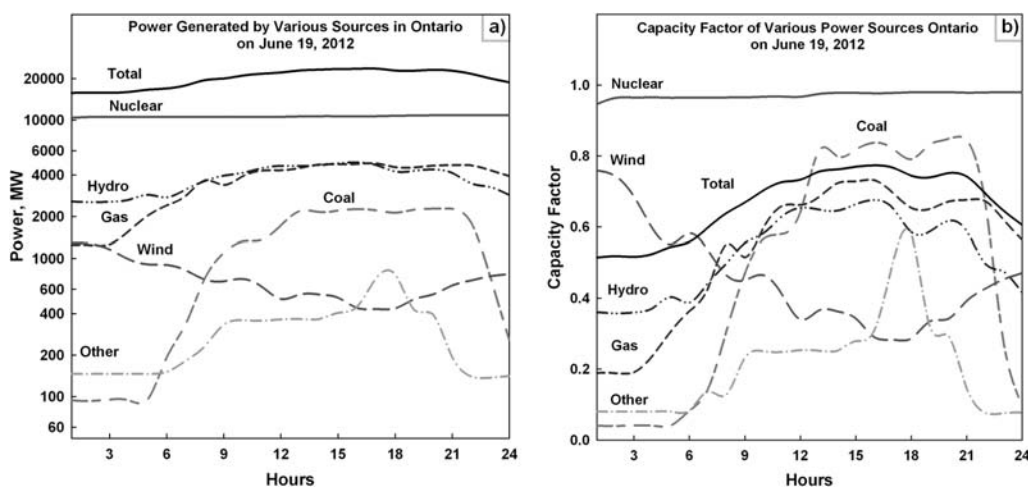


Fig. 3. Power generated (a) and capacity factors (b) of various energy sources in Ontario (Canada) on June 19, 2012

This example demonstrates that if a grid has Nuclear Power Plants (NPPs) and/or renewable-energy sources the grid must include «fast-response» power plants such as gas- and coal-fired and/or large hydro-power plants.

## THERMAL POWER PLANTS

In general, all thermal power plants [7] are based on the following thermodynamic cycles: 1) Rankine steam-turbine cycle (the mostly used in various power plants; usually, for solid and gaseous fuels, however, other energy sources can be also used, for example, solar, geothermal, etc.); 2) Brayton gas-turbine cycle (the second one after the Rankine cycle in terms of application in power industry; only for clean gaseous fuels); 3) combined cycle, i.e., combination of Brayton and Rankine cycles in one plant (only for clean gaseous fuels); 4) Diesel internal-combustion-engine cycle (only for Diesel fuel) used in Diesel generators; and 5) Otto internal-combustion-engine cycle (usually, for natural or liquefied gas, but also, gasoline can be used for power generation, however, it is more expensive fuel compared to gaseous fuels) also, used in internal-combustion-engine generators.

In general, the term «thermal power plants» can include: 1) solid-fuel-fired power plants based on Rankine steam-turbine cycle, fuels coal, lignite, peat, oil-shale, etc.; 2) gas-fired power plants – (a) Rankine steam-turbine cycle, (b) Brayton gas-turbine cycle and (c) combined cycle (combination of Brayton and Rankine cycles in one plant); 3) geothermal power plants (usually, Rankine steam-turbine cycle used); 4) biofuel thermal power plants (usually Rankine steam-turbine cycle used); 5) Diesel- and Otto-cycle-generators power plants; 5) concentrated-solar thermal power plants (Rankine steam-turbine cycle used) and 6) recovered-energy generation thermal power plants (electricity at these plants is generated from waste energy such as high-temperature flue gases, etc.; Rankine steam-turbine cycle used).



Table 4

**Gross Thermal Efficiency of Modern Thermal Power Plants**

| No | Power Plant   | Gross Thermal Efficiency, % |
|----|---|-----------------------------|
| 1  | Combined-cycle power plant (combination of Brayton gas-turbine cycle (fuel – natural or LNG; combustion-products parameters at the gas-turbine inlet: $T_{in} \approx 1650^{\circ}\text{C}$ ) and Rankine steam-turbine cycle (steam parameters at the turbine inlet: $T_{in} \approx 620^{\circ}\text{C}$ ( $T_{cr} = 374^{\circ}\text{C}$ ))) | Up to 62                    |
| 2  | Supercritical-pressure coal-fired power plant (Rankine-cycle steam inlet turbine parameters: $P_{in} \approx 25\text{--}38\text{ MPa}$ ( $P_{cr} = 22.064\text{ MPa}$ ), $T_{in} \approx 540\text{--}625^{\circ}\text{C}$ ( $T_{cr} = 374^{\circ}\text{C}$ ) and $T_{reheat} \approx 540\text{--}625^{\circ}\text{C}$ )                         | Up to 55                    |
| 3  | Internal-combustion-engine generators (Diesel cycle & Otto cycle with natural gas as a fuel).   | Up to 50                    |
| 4  | Subcritical-pressure coal-fired power plant (older plants) (Rankine-cycle steam: $P_{in} \approx 17\text{ MPa}$ , $T_{in} \approx 540^{\circ}\text{C}$ ( $T_{cr} = 374^{\circ}\text{C}$ and $T_{reheat} \approx 540^{\circ}\text{C}$ ))   | Up to 40                    |
| 5  | Concentrated-solar thermal power plants with heliostats, solar receiver (heat exchanger) on a tower and molten-salt heat-storage system<br>Molten salt maximum temperature is about $565^{\circ}\text{C}$ , Rankine steam-turbine power cycle used.   | Up to 20                    |

Table 5

**Gross Thermal Efficiency of Modern Nuclear Power Plants**

| No | Nuclear Power Plant  | Gross Thermal Efficiency, % |
|----|--|-----------------------------|
| 1  | Carbon-dioxide-cooled reactor NPP (Generation-III) (reactor coolant: $P = 4\text{ MPa}$ & $T = 290\text{--}650^{\circ}\text{C}$ ; steam: $P = 17\text{ MPa}$ ( $T_{sat} = 352^{\circ}\text{C}$ ) & $T_{in} = 560^{\circ}\text{C}$ )  | Up to 42                    |
| 2  | Sodium-cooled fast reactor NPP (Generation-IV) (steam: $P = 14\text{ MPa}$ ( $T_{sat} = 337^{\circ}\text{C}$ ) & $T_{in} = 505^{\circ}\text{C}$ )  | Up to 40                    |
| 3  | Pressurized Water Reactor NPP (Generation-III+, to be implemented within next 1–10 years) (reactor coolant: $P = 15.5\text{ MPa}$ & $T_{out} = 327^{\circ}\text{C}$ ; steam: $P = 7.8\text{ MPa}$ & $T_{in} = 293^{\circ}\text{C}$ ) | Up to 38                    |
| 4  | Pressurized Water Reactor NPP (Generation-III, current fleet) (reactor coolant: $P = 15.5\text{ MPa}$ & $T_{out} = 292\text{--}329^{\circ}\text{C}$ ; steam: $P = 6.9\text{ MPa}$ & $T_{in} = 285^{\circ}\text{C}$ )                 | Up to 36                    |
| 5  | Boiling Water Reactor NPP (Generation-III, current fleet) ( $P_{in} = 7.2\text{ MPa}$ & $T_{in} = 288^{\circ}\text{C}$ )   | Up to 34                    |
| 6  | RBMK (boiling, pressure-channel) (Generation-III, current fleet) ( $P_{in} = 6.6\text{ MPa}$ & $T_{in} = 282^{\circ}\text{C}$ )  | Up to 32                    |
| 7  | Pressurized Heavy Water Reactor NPP (Generation-III, current fleet) (reactor coolant: $P = 11\text{ MPa}$ & $T = 260\text{--}310^{\circ}\text{C}$ ; steam: $P = 4.6\text{ MPa}$ & $T_{in} = 259^{\circ}\text{C}$ )                   | Up to 32                    |

The major driving force for all advances in thermal power plants is thermal efficiency. Ranges of gross thermal efficiencies of modern thermal power plants are listed in Table 4. The gross thermal

efficiency of a unit during a given period of time is the ratio of the gross electrical energy generated by a unit to the thermal energy of a fuel consumed during the same period by the same unit. The difference between gross and net thermal efficiencies includes internal needs for electrical energy of a power plant, which might be not so small (5% or even more) [1, 7]. In spite of advances in thermal power-plants design and operation worldwide they are still considered as not environmental friendly due to producing a lot of carbon-dioxide emissions as a result of combustion process. In addition, coal-fired power-plants produce also slag, ash, and even acid rains. For example, the largest in the world 5,780 MW(el) Taichung coal-fired power plant (Taiwan) is the world's largest emitter of carbon dioxide with over 40 million tons per year. Therefore, nuclear power plants have to be considered.

### MODERN NUCLEAR POWER PLANTS

In general, nuclear power is also a non-renewable-energy source as the fossil fuels, but nuclear resources can be used for significantly longer time than some fossil fuels, especially, if fast reactors on uranium or probable thorium-fuel resources will be used. Major advantages of nuclear power [1, 3, 8] are: 1) No emissions of carbon dioxide into atmosphere; 2) Relatively small amount of fuel required (for example, a 500-MW(el) coal-fired supercritical-pressure power plant requires 1.8 million ton of coal annually, but a fuel load into the pressure water reactor (PWR) of 1300-MW(el) is 115 t (3.2% enrichment) or into the boiling water reactor (BWR) of 1330-MW(el) – 170 t (1.9% enrichment)). Therefore, this source of energy is considered as the most probable and viable for electrical generation for the next 50 – 100 years.

In spite of all current advances into nuclear power, NPPs have the following deficiencies: 1) Generate radioactive wastes; 2) Have relatively low thermal efficiencies, especially, water-cooled NPPs (up to 1.6 times lower than that for modern advanced thermal power plants (see for comparison Tables 4 and 5); 3) Risk of radiation release during severe accidents; and 4) Production of nuclear fuel is not an environment-friendly process. Therefore, all these deficiencies should be addressed.

Table 6

**Number of Nuclear Power Reactors in the World in Operation under Construction and planned according to WNA Data at February 19, 2015 [9]**

| Year | Reactors in operation |       | Reactors under construction |       | Reactors Planned |       | Reactors Proposed |       |
|------|-----------------------|-------|-----------------------------|-------|------------------|-------|-------------------|-------|
|      | Number                | N, GW | Number                      | N, GW | Number           | N, GW | Number            | N, GW |
| 2008 | 439                   | 372   | 34                          | 278   | 93               | 100.6 | 222               | 193.1 |
| 2009 | 436                   | 372   | 43                          | 37.7  | 108              | 121.1 | 266               | 262   |
| 2010 | 436                   | 373   | 53                          | 51    | 142              | 156   | 327               | 342.9 |
| 2011 | 442                   | 377   | 63                          | 64.6  | 156              | 174.7 | 322               | 342.9 |
| 2012 | 434                   | 370   | 61                          | 61.6  | 156              | 178   | 343               | 392   |
| 2013 | 435                   | 374   | 65                          | 65.1  | 167              | 184.4 | 317               | 359   |
| 2014 | 435                   | 375   | 71                          | 75    | 172              | 186.7 | 312               | 351.5 |
| 2015 | 437                   | 378   | 70                          | 73    | 183              | 203   | 311               | 349.2 |

First success of using nuclear power for electricity generation [8] was achieved in several countries within 50-s, and currently. The number of nuclear power reactors in the world in operation, under construction and planned according to data of the World Nuclear Association (WNA) at February 19, 2015 is given in Table 6 [9]. Table 7 presents the number of nuclear-power reactors in operation and forthcoming as per March 2015



and before the Japan earthquake and tsunami disaster before March 2011. There are arrows in this table, which mean increase or decrease in a number of reactors. Besides the data include 48 reactors from Japan, which are currently not in operation. [10, 11].

Table 7

**Number of Nuclear Power Reactors in Operation and Forthcoming as per March 2015 and before the Japan Earthquake and Tsunami Disaster at March 2011 [10, 11]**

| No              | Reactor type<br>(some details on reactors)   | Number of<br>units  |                      | Installed<br>Capacity,<br>GW(el) |                      | Forthcoming<br>Units |            |
|-----------------|--|---------------------|----------------------|----------------------------------|----------------------|----------------------|------------|
|                 |  | As of<br>March 2015 | Before<br>March 2011 | As of<br>March 2015              | Before<br>March 2011 | Number of<br>Units   | GW(el)     |
| 1               | <b>PRESSURIZED WATER REACTORS (PWRs)</b><br>(largest group of nuclear reactors in the World – 63%).  | 276 ↑               | 268                  | 257 ↑                            | 248                  | 88                   | 93         |
| 2               | <b>BOILING WATER REACTORS (BWRs)</b><br>OR <b>ADVANCED BWRs</b> (2-nd largest group of<br>reactors in the World – 18%; ABWRs –<br>the only ones Gen-III+ operating reactors).  | 80 ↓                | 92                   | 76 ↓                             | 85                   | 6                    | 8          |
| 3               | <b>PRESSURIZED HEAVY WATER REACTORS</b><br>(PHWRs) (3-rd largest group of reactors in the<br>World – 11%; mainly CANDU-reactor type).  | 48 ↓                | 50                   | 24 ↓                             | 25                   | 9                    | 5.8        |
| 4               | <b>GAS COOLED REACTORS (GCRs)</b> (UK, Magnox<br>reactor) or <b>ADVANCED GAS-COOLED REACTORS</b><br>(AGRs) (UK, 14 reactors);<br>(all these CO <sub>2</sub> -cooled reactors will be shut-<br>down in the nearest future and will not be built<br>again. Forthcoming GFR is a helium-cooled<br>reactor).   | 15 ↓                | 18                   | 8 ↓                              | 9                    | 1                    | 0.2        |
| 5               | <b>LIGHT-WATER, GRAPHITE-MODERATED REACTORS</b><br>(LGRs) (Russia – 11 RBMKs; 4 EGPs in<br>Bilibino – power heterogeneous loop reactor.<br>They are of channel-type, graphite-<br>moderated, light-water coolant, boiling<br>reactors with natural circulation. These<br>reactors will be shut down in the nearest<br>future and will not be built again). | 15                  | 15                   | 10                               | 10                   | 0                    | 0          |
| 6               | <b>LIQUID-METAL FAST-BREEDER REACTORS</b><br>(LMFBRs) (Russia, SFR – BN-600; the only<br>one Gen-IV operating reactor)   | 1                   | 1                    | 0.6                              | 0.6                  | 6                    | 2.2        |
| <b>IN TOTAL</b> |  | <b>435 ↓</b>        | <b>444</b>           | <b>375 ↓</b>                     | <b>378</b>           | <b>109</b>           | <b>109</b> |

As can be seen from Fig. 4, the largest number of nuclear power reactors in the world has installed capacities within the range of 900-999 MW(el). According to the base version of the forecast, the total capacity of the world nuclear power engineering will increase during the five years (up to 2020 year) from the today's level of 373 GW(el) at least up to 435 GW(el). The WNA prediction gives the number of nuclear reactors in the world up to 2030 year as about 500 units with installed capacity of 500 GW(el).

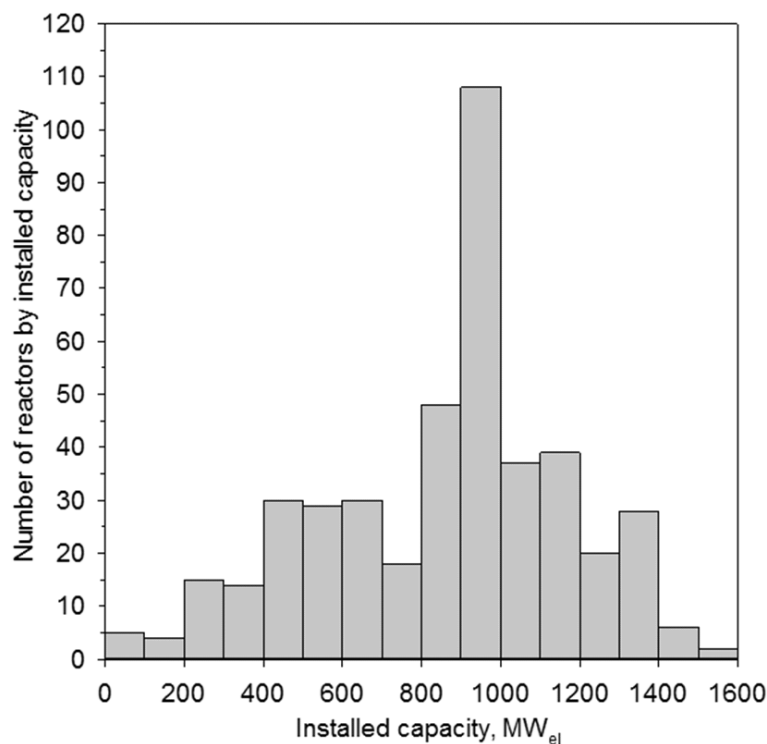


Fig. 4. Number of nuclear power reactors in the World by installed capacity

Table 8

**Deployment of Generation III+ Reactors in the Nearest 5–10 Years**

| No | Reactor Type  | Nuclear Vendor  |
|----|---|---|
| 1  | <b>ABWR</b>   | Toshiba, Mitsubishi Heavy Industries (MHI) and Hitachi-GE (Japan-USA) (the only one Generation III+ reactor design already implemented in power industry) |
| 2  | <b>ACR-1000</b><br>Advanced CANDU Reactor                     | CANDU Energy (former AECL), Canada  |
| 3  | <b>AP-1000</b><br>Advanced Plant                              | Toshiba-Westinghouse (Japan-USA) (6 under construction in China and 6 planned to be built in China and 6 – in USA)  |
| 4  | <b>APR-1400</b><br>Advanced PWR                               | South Korea (4 under construction in S. Korea and 4 planned to be built in UAE)   |
| 5  | <b>EPR</b><br>European Pressurized-water Reactor              | AREVA, France (1 should be put into operation in Finland, 1 under construction in France and 2 - in China and 2 planned to be built in USA)               |
| 6  | <b>ESBWR</b><br>Economic Simplified BWR                       | GE-Hitachi (USA-Japan)  |
| 7  | <b>WWER</b><br>Design AES-2006 or WWER-1200 with ~1200 MW(el) | GIDROPRESS, Russia (4 under construction in Russia and several more planned to be built in various countries: Belarus', Finland, Turkey, Vietnam, etc.)   |

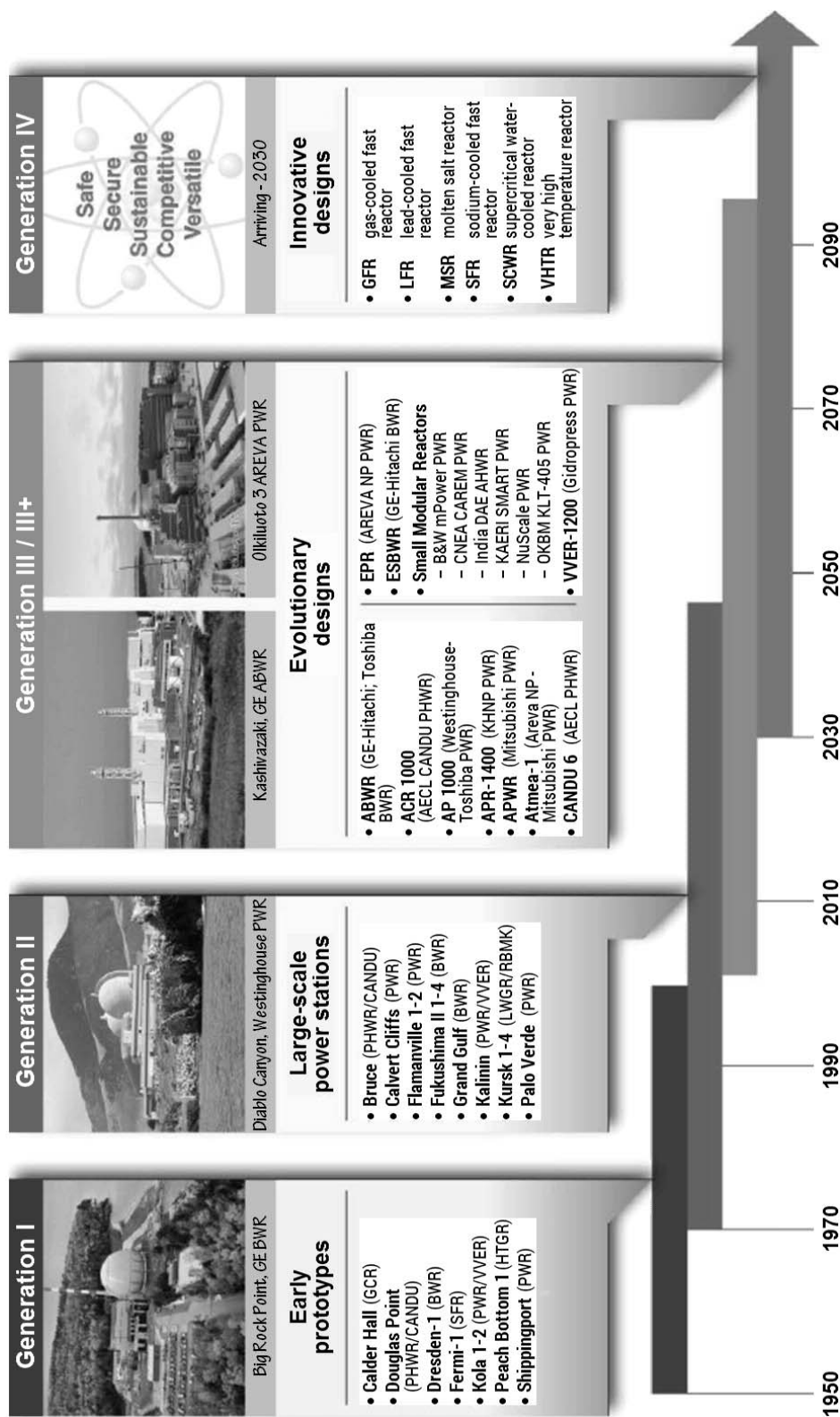


Fig. 5. Generations of nuclear reactors

In general, definitions of nuclear reactor generations are as the following: Generation I (1950 – 1965) – early prototypes of nuclear reactors, Generation II (1965 – 1995) – commercial power reactors and Generation III (1995 – 2010) – modern reactors, see Fig. 5. The Generation III reactors include water-cooled NPPs with thermal efficiency within 30 – 36%, carbon-dioxide-cooled NPPs with thermal efficiency up to 42% and liquid sodium-cooled NPPs with the thermal efficiency up to 40%. The reactors of Generation III+ (2010 – 2025) characterized by evolutionary design improvements are water-cooled NPPs with thermal efficiency up to 36 – 38%, see Table 8. The development of the last Generation IV reactors has begun in 2000 year in the frame of the «Generation IV International Forum» (GIF) program. These advanced reactors have in principle new operating parameters and thermal efficiency within 40 – 50% and even higher for some types of reactors [11].

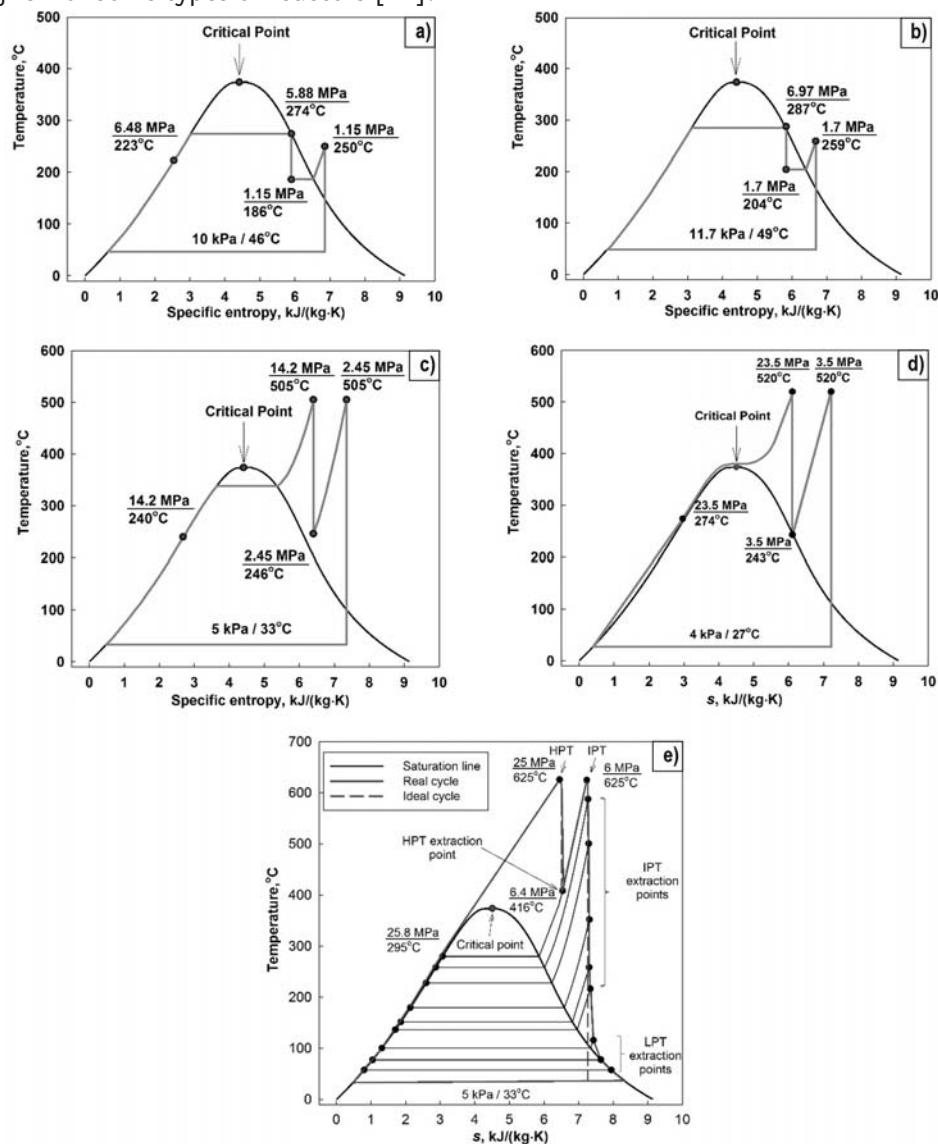


Fig. 6. Simplified  $T$ - $S$  diagrams of selected nuclear power plants: a) VVER-1000 (PWR), Generation III; b) ABWR, Generation III+; c) BN-600 (SFR), Generation III; d) LFR (based on data for Brest-1200 and corresponding Russian turbine K-1200-240), Generation IV; e) SCWR of 1200-MW(ell), Generation IV (HPT – High Pressure Turbine; IPT – Intermediate Pressure Turbine; LPT – Low Pressure Turbine).

Table 9

**Nuclear Electricity Generation and Power Reactors by Nations [9, 12]**

| Country            | Nuclear Electricity Generation (2014) |             | Reactors Operable, June 2015 |                |
|--------------------|---------------------------------------|-------------|------------------------------|----------------|
|                    | Billion kWh                           | %           | Number                       | MW(el) net     |
| Argentina          | 5.3                                   | 4.0         | 3                            | 1627           |
| Armenia            | 2.3                                   | 30.7        | 1                            | 376            |
| Bangladesh         | 0                                     | 0           | 0                            | 0              |
| Belarus            | 0                                     | 0           | 0                            | 0              |
| Belgium            | 32.1                                  | 47.5        | 7                            | 5943           |
| Brazil             | 14.5                                  | 2.9         | 2                            | 1901           |
| Bulgaria           | 15.0                                  | 31.8        | 2                            | 1906           |
| Canada             | 98.6                                  | 16.8        | 19                           | 13553          |
| China              | 123.8                                 | 2.4         | 26                           | 23144          |
| Czech Republic     | 28.6                                  | 35.8        | 6                            | 3904           |
| Finland            | 22.6                                  | 34.6        | 4                            | 2741           |
| France             | 418.0                                 | 76.9        | 58                           | 63130          |
| Germany            | 91.8                                  | 15.8        | 9                            | 12003          |
| Hungary            | 14.8                                  | 53.6        | 4                            | 1889           |
| India              | 33.2                                  | 3.5         | 21                           | 5302           |
| Iran               | 3.7                                   | 1.5         | 1                            | 915            |
| Italy              | 0                                     | 0           | 0                            | 0              |
| Japan              | 0                                     | 0           | 43                           | 40480          |
| Mexico             | 9.3                                   | 5.6         | 2                            | 1600           |
| Netherlands        | 3.9                                   | 4.0         | 1                            | 485            |
| Pakistan           | 4.6                                   | 4.3         | 3                            | 725            |
| Romania            | 10.8                                  | 18.5        | 2                            | 1310           |
| Russia             | 169.1                                 | 18.6        | 34                           | 25264          |
| Slovakia           | 14.4                                  | 56.8        | 4                            | 1816           |
| Slovenia           | 6.1                                   | 37.2        | 1                            | 696            |
| South Africa       | 14.8                                  | 6.2         | 2                            | 1830           |
| South Korea        | 149.2                                 | 30.4        | 24                           | 21657          |
| Spain              | 54.9                                  | 20.4        | 7                            | 7002           |
| Sweden             | 62.3                                  | 41.5        | 10                           | 9487           |
| Switzerland        | 26.5                                  | 37.9        | 5                            | 3333           |
| Taiwan             | –                                     | –           | 6                            | 4884           |
| Turkey             | 0                                     | 0           | 0                            | 0              |
| Ukraine            | 83.1                                  | 49.4        | 15                           | 13107          |
| UAE                | 0                                     | 0           | 0                            | 0              |
| United Kingdom     | 57.9                                  | 17.2        | 16                           | 9373           |
| USA                | 798.6                                 | 19.5        | 99                           | 98792          |
| <b>TOTAL WORLD</b> | <b>2,411</b>                          | <b>11.5</b> | <b>437</b>                   | <b>380,250</b> |

In Fig. 6 (a – e), there are the simplified  $T$ - $S$  diagrams of thermodynamic cycles for the following NPPs, namely: a, b) PWR and BWR on saturated steam; c) sodium cooled fast reactor (SFR) on superheated steam at subcritical pressure; d) lead cooled fast reactor (LFR); e) supercritical water-cooled reactor (SCWR) on superheated steam at supercritical

pressure. The cycles (c, d, e) are with the single steam superheat. However, later the cycle (d) was rejected [12]. The superheated steam provides a more deep expansion in a turbine without achievement of the maximum permissible values of steam humidity in the turbine last steps. In the case of cycles on saturated steam, it needs to use specific installations for steam drying such as separators and reheaters. The greater is the steam pressure, the larger is the temperature required for steam superheat, see Fig. 6 (a, b). The gross thermal efficiency of turbine on superheated steam at pressures more than 7 – 8 MPa depends only slightly on the stem superheat temperature, see Table 5.

Currently, 31 countries in the world have operating nuclear power reactors, see Table 9. As shown in Table 9, the most part of electric energy generated by NPPs has such countries as France – 76.9%, Slovakia – 58.6%, Hungary – 53.6%, Belgium – 47.5%, Ukraine – 46.9%, Sweden – 41.5% [13]. Unfortunately, 15 countries have no plans to build new reactors at least for now. However, some non-nuclear countries including Bangladesh, Belarus', Turkey and United Arab Emirates (UAE) work towards introducing nuclear energy on their soils. Important question for a wide-spread of nuclear-based electrical-energy generation is how reactors are safe. Analysis of causes of death due to various accidents in different industries, transportation and from firearms clearly shows that the major cause of huge number of deaths in the world is car accidents. Nevertheless, the international community has to do everything possible and impossible to prevent any future severe accidents at NPPs with radiation release and other consequences.

### **NEXT GENERATION NPPS**

The demand for clean, non-fossil-based electricity is growing; therefore, the world needs to develop new nuclear reactors with inherent safety and higher thermal efficiencies in order to increase electricity generation per kg of fuel and decrease detrimental effects on the environment [1]. The current fleet of NPPs is classified as Generation II and III (just a limited number of Generation III+ reactors (mainly, Advanced Boiling Water Reactors (ABWRs) operate in some countries). However, all these designs (here we are talking about only water-cooled power reactors) are not as energy efficient as they should be, because their operating temperatures are relatively low, i.e., below 350°C for a reactor coolant and even lower for steam in the power-conversion cycle.

The GIF program devoted to development of the Generation IV reactors is based on an international collaboration of such countries as Canada, China, France, Japan, Euratom, Republic of South Africa, Russia, South Korea, Switzerland, USA. These reactors are characterized by high thermal efficiency up to 45 – 50% and even higher (see Table 10). This increase in thermal efficiency would result in a higher generation of electricity compared to current Light Water Reactor (LWR) technologies per 1 kg of uranium. As can be seen from Table 10, the GIF program has narrowed design options of nuclear reactors to six concepts: VHTR, GFR, SCWR, SFR, LFR and MSR [1, 3, 14].

The fourth generation is aimed for fast reactors due to their ability to convert a large amount of  $^{238}\text{U}$  into  $^{239}\text{Pu}$  while production electricity. Thus it will become possible to exploit more than 90% of natural uranium to generate electricity instead of only 0.5 to 1%. The large quantities of depleted and reprocessed uranium could be used to maintain the current electricity production for several thousand years. As result, the worldwide availability of primary fissile resources can be multiplied by approximately 100 times. Another attractive feature of the Gen IV reactors is that they can be effectively used for reducing of long-lived radioactive waste including minor actinides (americium, neptunium, curium etc.) [15].

Analysis of Gen IV nuclear-reactor concepts and corresponding power cycles [15] shows that such three concepts as VHTR, GFR and SCWR; will use supercritical fluids as reactor coolants, namely: helium in the first two concepts and water in the third one.



Also, the following three Supercritical pressure (SCP) power cycles can be used: 1) direct SCP-helium Brayton gas-turbine cycle as the primary choice in VHTR and GFR; 2) SCP Rankine «steam»-turbine cycle as the only option for SCWR (direct or indirect cycle); and as the current option for LFR (Brest-300, Russian design, indirect cycle); and 3) indirect SCP-carbon-dioxide Brayton gas-turbine cycle as primary or back-up option for SFR, MSR, LFR and even VHTR and GFR.

Table 10

**Estimated Ranges of Thermal Efficiency (Gross) of Generation IV NPP Concepts**

| No | Power Plant   | Gross Efficiency |
|----|---|------------------|
| 1  | <b>VHTR</b> – Very High Temperature Reactor cooled by helium:<br>$P = 7$ MPa and $T_{in} / T_{out} = 640 / 1000^{\circ}\text{C}$ ;<br>primary power cycle – direct Brayton gas-turbine cycle;<br>possible back-up – indirect Rankine steam cycle  | $\geq 55\%$      |
| 2  | <b>GFR</b> – Gas-cooled Fast Reactor cooled by helium:<br>$P = 9$ MPa and $T_{in} / T_{out} = 490 / 850^{\circ}\text{C}$ ;<br>primary power cycle – direct Brayton gas-turbine cycle;<br>possible back-up – indirect Rankine steam cycle.   | $\geq 50\%$      |
| 3  | <b>SCWR</b> – SuperCritical Water-cooled Reactor.<br>One of Canadian concepts; reactor coolant – light water:<br>$P = 25$ MPa and $T_{in} / T_{out} = 350 / 625^{\circ}\text{C}$ ( $T_{cr} = 374^{\circ}\text{C}$ );<br>direct cycle; high-temperature steam superheat: $T_{out} = 625^{\circ}\text{C}$ ;<br>possible back-up – indirect supercritical-pressure Rankine steam cycle with high-temperature steam superheat.  | 45 - 50%         |
| 4  | <b>MSR</b> – Molten Salt Reactor with reactor coolant as– sodium-fluoride salt with dissolved uranium fuel: $T_{out} = 700 / 800^{\circ}\text{C}$ ;<br>primary power cycle – indirect supercritical-pressure carbon-dioxide Brayton gas-turbine cycle;<br>possible back-up – indirect Rankine steam cycle.  | $\sim 50\%$      |
| 5  | <b>LFR</b> – Lead-cooled Fast Reactor cooled by melt of Pb or Pb-Bi eutectic.<br>Russian design Brest-300:<br>reactor coolant – liquid lead: $P \approx 0.1$ MPa and $T_{in} / T_{out} = 420 / 540^{\circ}\text{C}$ ;<br>primary power cycle – indirect supercritical-pressure Rankine steam cycle:<br>$P_{in} \approx 24.5$ MPa ( $P_{cr} = 22.064$ MPa) and $T_{in} / T_{out} = 340 / 520^{\circ}\text{C}$ ( $T_{cr} = 374^{\circ}\text{C}$ );<br>high-temperature steam superheat;<br>possible back-up in some other countries – indirect supercritical-pressure carbon-dioxide Brayton gas-turbine cycle.   | $\sim 43$        |
| 6  | <b>SFR</b> – Sodium-cooled Fast Reactor cooled by liquid sodium.<br>Russian design BN-600:<br>reactor coolant – liquid sodium (primary circuit):<br>$P \approx 0.1$ MPa and $T_{in} / T_{out} = 380 / 550^{\circ}\text{C}$ ;<br>liquid sodium (secondary circuit): $T_{in} / T_{out} = 320 / 520^{\circ}\text{C}$ ;<br>primary power cycle – indirect Rankine steam cycle:<br>$P_{in} \approx 14.2$ MPa ( $T_{sat} \approx 337^{\circ}\text{C}$ ) and $T_{in, max} = 505^{\circ}\text{C}$ ( $T_{cr} = 374^{\circ}\text{C}$ );<br>steam superheat: $P \approx 2.45$ MPa and $T_{in} / T_{out} = 246 / 505^{\circ}\text{C}$ ;<br>possible back-up in some other countries – indirect supercritical-pressure carbon-dioxide Brayton gas-turbine cycle. | $\sim 40$        |

In the frame of the GIF program the SFR development is the main priority. The operating experience of fast neutron reactors cooled by liquid sodium is about 390 reactor-years. According to the IAEA data, the world costs on the SFR during the period 1950 – 1990 years were equal about 50 billion dollars. However at present time, from the known 31 SFRs only 6 reactors are under operation: 2 – India (FBTR and PFBR), 2 – Japan (JOYO and MONJU), 1 – Russia (BN-600) and 1 – China (CEFR). The Russian SFR reactor BN-800 was under construction beginning from 1983 year, and the achievement of its criticality was performed at June 2014 [16].

In general, we need to have bright future for the most «popular» reactors, i.e., water-cooled ones (96% of the total number of operating power reactors in the world). Therefore, an SCWR concept [17, 18, 19] looks quite attractive as the Generation IV water-cooled reactor with high thermal efficiency. However, more research is required, especially, in material science to define candidate materials for reactor-core elements, which will be subjected to very aggressive medium such as supercritical water, high pressures and temperatures, and high neutron flux.

Generation IV reactors as high-temperature reactors will require new nuclear fuels with high thermal conductivity. Therefore, a summary of thermal aspects of conventional and alternative fuels are presented in [19].

## CONCLUSIONS

In general, the major driving force for all advances in thermal and nuclear power plants is thermal efficiency. Ranges of gross thermal efficiency of modern power plants are as the following: 1) Combined-cycle thermal power plants – up to 62%; 2) Supercritical-pressure coal-fired thermal power plants – up to 55%; 3) Carbon-dioxide-cooled reactor NPPs – up to 42%; 4) Sodium-cooled fast reactor NPP – up to 40%; 5) Subcritical-pressure coal-fired thermal power plants – up to 40%; and 6) Modern water-cooled reactors – 30 – 36%.

In spite of advances in coal-fired thermal power-plants design and operation worldwide they are still considered as not environmental friendly due to producing a lot of carbon-dioxide emissions as a result of combustion process plus slag, ash, and even acid rains.

Combined-cycle thermal power plants with natural-gas fuel are considered as relatively clean fossil-fuel-fired plants compared to coal and oil power plants, but still emit a lot of carbon dioxide due to combustion process.

Nuclear power is, in general, a non-renewable source as the fossil fuels, but nuclear resources can be used significantly longer than some fossil fuels plus nuclear power does not emit carbon dioxide into atmosphere. Currently, this source of energy is considered as the most viable one for electrical generation for the next 50 – 100 years.

However, all current and oncoming Generation III+ NPPs are not very competitive with modern thermal power plants in terms of thermal efficiency, the difference in values of thermal efficiencies between thermal and nuclear power plants can be up to 20 – 25%.

Therefore, the new generation (Generation IV) NPPs with thermal efficiency close to those of modern thermal power plants, i.e., within a range of at least 45 – 50%, should be designed and built in the nearest future.

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## ЯДЕРНАЯ ЭНЕРГИЯ – ОСНОВА ПРОИЗВОДСТВА ЭЛЕКТРИЧЕСТВА В БУДУЩЕМ

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### РЕФЕРАТ

Производство электрической энергии обеспечивает деятельность промышленности, сельского хозяйства и быта. В общем случае электрическая энергия может быть получена с помощью

– невозобновляемых источников энергии, таких как уголь, газ, нефть и ядерное топливо;

– возобновляемых источников – энергии воды, солнца, биомассы, энергии морских волн и приливов, а также геотермических источников.

Однако основными источниками производства электрической энергии являются

– тепло при сжигании угля и газа;

– большие гидростанции;

– ядерное топливо.

Остальные источники используются только в некоторых отдельных странах.

В статье кратко излагается современное состояние атомной энергетики и дано ее сравнение с другими источниками энергии.

**Ключевые слова:** ядерная энергетика, производство электроэнергии, текущее состояние, тепловые электростанции, современные АЭС, четвертое поколение ядерных реакторов.

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