Tampere University of Applied Sciences

A nuclear energy – the energy of the future.

Hybrid Fusion Reactor.

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ABSTRACT

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The given research reveals global energy challenges, their relationship to environmental health, ecological safety, and human growth in general, and attempts to reconsider the current policy. The study poses the question of whether any alternative methods of receiving energy could be created, thus establishing a whole new energy supply structure. The subject of this study represents the alternative way for a nuclear energy system that can be implemented now and become the primary energy source in the nearest future.

The thesis was conducted as a literature study. After analysis of energy policy agenda, that calls to change the path from exhaustible-based energy system to the alternatives. The research and estimation of all currently used energy options have been driven, with nuclear and thermonuclear realms emerging as the most promising. Nuclear fission has been investigated as a viable energy source of the 21st century, compared with the existing ones. Due to technical challenges, an investigation of thermonuclear reactions was performed and determined to be the most optimal, but only in the long term. As a result of the study and comparison of the current energy scenario, the nuclear-thermonuclear reactors combination – Hybrid Fusion Reactor – was chosen. Hybrid Fusion Reactor possesses the advantages of fission and fusion reactors while getting rid of the disadvantages of each one. Thereby, it is the most efficient alternative way for energy production.

Key words: Energy crisis, nuclear fission, thermonuclear fusion, plasma, ITER, TOKAMAK, hybrid fusion reactor

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GLOSSARY

TAMK	Tampere University of Applied Sciences
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Nuclear fusion reactor - NFR

Controlled Thermonuclear Synthesis - CTS

TOKAMAK - a toroidal chamber with magnetic coils

Hybrid Fusion Reactor - HFR

Plasma – ionized gas, fourth state of aggregation

Thermal Power Plant - TPP

Nuclear Power Plant - NPP

1 INTRODUCTION

“Let the Sun warm and shine not in vain,
let not in vain water flow and waves beat against the shore,
one must bereave the squandered aimlessly natural blessings,
and bend them, having tied of one's own volition.”
Dante

This work outlines the essence of the principles of energy processes, evaluates the role and influence of energy on the life of mankind and the state of the environment. It touches upon modern energy problems and show their influence on the development of the world. Possible trends for the energy and economy development in the future are considered.

The purpose of the work is to rethink the problems of existing energy resources as well as which are currently under the work and by analysing and estimation of their features such as efficiency, safety, availability, and abundance, make an inference about the most promising one. This study raises the question of whether the potential of different nuclear energy sources in the future, which may substitute the traditional ones as a basic source. The objective of the thesis is to evaluate the potential of various nuclear power technologies and throughout the comparison study whether the most promising solution is Hybrid Fusion Reactor. The research was made by investigation of sufficient books, scientific articles and reports, international principles and agreements, recent scientific video materials, by parsing certain data about energy sources, its classification, distribution, and supply.

The relevance of the thesis topic justified by the fact that nowadays energy demands are permanently growing (BP Statistical Review… 2019, 2) The current circumstances of globalisation progress are enhancing the energy provision issue. Due to the lack of traditional energy resources and the insufficient number of alternative resources in the nearest future when the mining will equalize the consuming there is a huge likelihood in the shortage, which can lead to the conflicts within society (Velikhov et. al. 2014, 6). Oil has a huge impact on the global economy today. Besides, water deficiency in several regions is becoming essential. (Comby 2009, 145).

In the age of scientific and technological progress, issues related to the rational use of the Earth's energy resources, the interaction of nature and man are becoming increasingly important. Now the construction of the largest thermonuclear reactor (ITER) system is undergone in France. It is so-called Sun on Earth, which is claimed to become the main energy resource as the most efficient and safe appliance in the long run. The first attempt of launching it is planned for 2025. The best specialists from 35 countries all over the world participating in “the construction of the century”. This project is a huge step in the energy area. However, it has its technical difficulties that are not coped (Smirnov 2003, 302).

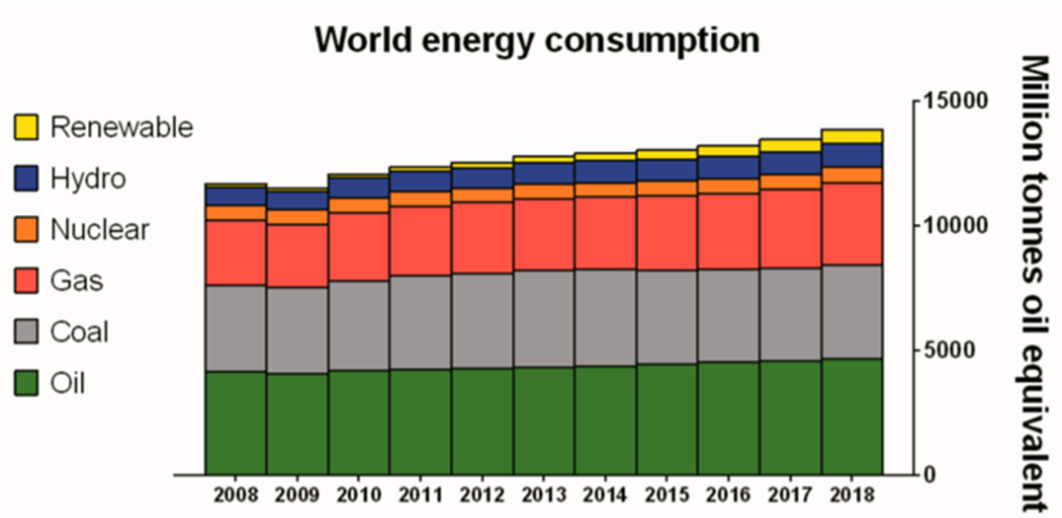
According to the global environmental issues the new way of receiving and supplying energy must be created that can replace the current techniques.
Thereby, as fossil fuels are not endless, renewable sources could be used only partially, nuclear energetics has safety issues and thermonuclear energetics is currently under the development, the promising alternative can be a Hybrid Fusion Reactor (HFR). HFR is the combination of both nuclear and thermonuclear reactors that can conquer current anergy supplies in all aspects of the energy agenda and become the main source of energy. At the same time in Moscow, Russia scientists are working under its creation. The significant supremacy of the hybrid machine is in its relative simplicity of implementation for at the present time (Azizov et. al. 2013, 95).

The practical significance of this study involves in the fact that the necessity to radically change the situation when the words “environmentally hazardous” are synonyms with the definition of “economically beneficial” has to be done. The cheapness of today's energy production may result not only in the lack of raw materials for energy, but also in the closure of industries that threaten the health and safety of mankind and nature. Energy, ecology and economics are three concepts based on the current and future technological and social progress. All these components are interconnected and can work efficiently only by mutually supporting each other.

2 ENERGY CRISIS. GLOBAL ENERGY AGENDA XXI

2.1 Energy issue

The energy demands are constantly growing which one may see on the Picture 1. It is predicted that by the end of the 21st century, energy consumption on Earth will grow 6 times compared to this moment (World Energy Model Documentation 2020, 12). The most discussed issue of the present is climate change and energy to be one of the key reasons for this change. By energy is understood any area of human activity associated with the production and consumption of energy. A significant part of the energy sector is provided by the consumption of energy released from the combustion of organic fossil fuels, which leads to the emission of a huge number of pollutants into the atmosphere. (Joint Research Centre 2021, 39). Such an approach causes real harm to the global economy and can deal a fatal blow to the economies of countries that have not yet reached the level of energy consumption required to complete the industrial stage of the development (Ekkert et. al. 2018, 38).



PICTURE 1. Energy consumption worldwide from 2008 to 2018. Aiseadha et. al. 2020. Energy and Climate Policy - An Evaluation of Global Climate Change Expenditure 2011-2018. [png].

2.2 Sources of Energy in XXI Century

2.2.1 Fossil fuel energy

”Status and role in the long-term perspective” report stayted that the main source of energy for humanity nowadays originates from the combustion of organic fuels. At present time more than 85% of energy, produced by human represented by coal, oil and natural gas. It is calculated that the production of energy will increase by 2050 in 3 times in comparison with current level. Though, their reserves are limited, and the combustion products pollute the environment. There are no doubts that in the nearest future the prior energy source – organic fuels – must be replaced with another kind of energy production. This will inevitably happen due to the depletion of natural resources (Velikhov & Putvinsky 1999).

Referensing to International Energy Agency (2019) in most countries of the world the share of electricity generated by Thermal Power Plants (TPP) is more than 50%. Coal, fuel oil, gas, shale is usually used as fuel at Thermal Power Plants, which are non-renewable resources. According to estimates given by Grainger & Gibson in ”Coal Utilisation Technology, Economics and Policy” it is enough coal on the planet for 100-300 years, oil for 40-80 years, natural gas for 50-120 years (Belyaev et. al. 2004, 239).

Referring to the International Renewable Energy Agency (IRENA), coal is the most promising fossil fuel source compared to oil and gas. The main world coal reserves are concentrated in Russia, China, and the United States. At the same time, the main amount of energy is currently generated at TPPs by petroleum products. (Ekkert et. al. 2018, 8). Thus, the structure of fossil fuel reserves does not correspond to the structure of its current consumption in energy production. In future, the transition to a new structure of fossil fuel consumption will cause significant environmental problems, material costs and changes in the entire industry (Ekkert et. al. 2018, 42).

The efficiency of TPP is on average 37 percent, according to IRENA's calculations. A typical TPP with a capacity of 2 million kW consumes 18,000 tons of coal, 2,500 tons of fuel oil, and 150,000 m3 of water daily. To cool the waste steam at TPPs, 7 million m3 of water are utilized every day, which leads to thermal pollution of the cooling reservoir. Daily 17 million tons of CO_2 and other gases emitted to the atmosphere. Transition from organic fuels to large-scale alternative energy is expected in the middle of 21 century. Coal power plant produces more radioactive emissions than nuclear power plant with similar capacity (Treshcheva, Treshchev, Anikina, Skulkin 2019, 4).

Furthermore, the work “Global Energy Perspectives: A Summary of the Joint Study by IIASA and World Energy Council” reveals data by the International Institute for Applied Systems Analysis (IIASA), made for the World Energy Council, estimations of the probable fuel costs dynamics in the period between 1990-2050. Based on the measured scenarios for the development of the world energy, these costs in 2020-2050 increase: for oil by 1.1-2 times, for gas by 1.05-1.7 times, for coal by 1.2-1.3 times respectively (Griibler, Jefferson & Nakicenovic 1996, 238).

2.2.2 Renewable energy

The progress in the field of renewable energy is impressive, however its capacity will not be enough in the foreseeable future. It is assumed that future energy will use a wider variety of energy sources, including renewable sources of energy, such as solar energy, wind energy, hydropower, growing and burning biomass, more widely than the current energy system. The share of each energy source in total energy production will be de-ermined by the structure of energy consumption and the economic efficiency of each of these energy sources. (Velikhov & Putvinsky 1999).

The most significant challenge facing alternative energy sources is to reduce carbon dioxide emissions. And according to statistics, that Mamedov describes in the article “Green Turn: How Europe is Shifting to Renewable Energy” (2020) this task seems to be coped with. However, unpleasant consequences have recently begun to manifest themselves, which were previously ignored due to the low prevalence of wind and solar energy.

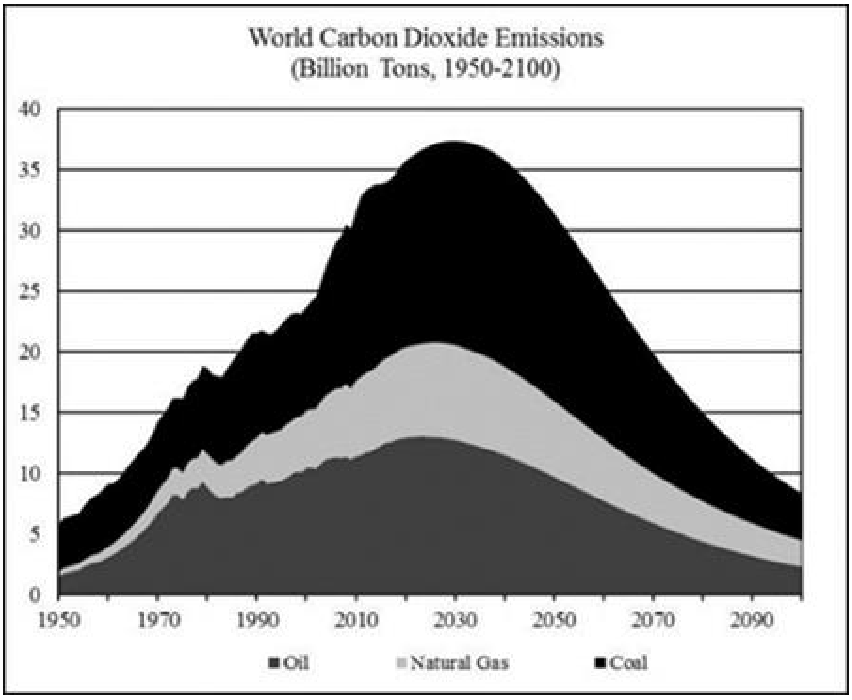
Scientific studies began to appear, in which data were placed in doubt the ecological cleanliness of renewable energy. One of the first scientific studies, carried out in 2014 “Satellite Observations of Wind Farm Impacts on Nocturnal Land Surface Temperature in Iowa” showed the formation of certain microclimate with predominantly elevated temperatures over modern wind farms. This raised the question of the possibility of a huge impact of use of wind energy on the global climate (Harris, Xia, Zhou 2014, 7).

The technologies required for an efficient transition to solar and wind energy require 10 times more mineral resources per 1 kW of installed capacity compared to traditional energy. This is a giant contribution to environmental pollution. The huge areas occupied by green appliances are a hundred times higher than the similar (per 1 kW) capacities of traditional energy - all this have a negative effect on the biodiversity, which could be seen in the form of a sharp decrease in biomass in the places where solar and wind power plants are located (Gasparatos et. al. 2017, 164).

Farid Mamedov (2020) adduces that annually more and more capacities are required for processing green waste, and the energy profitability of energy sources is falling, which will gradually lead not only to a halt in energy programs, but also to a regression of the whole world. Thus, one expects that renewable energy sources will be used generally as additional component of energy consumption. The main and the only candidate for basic energy is nuclear energy (Velikhov & Putvinsky 1999).

2.3 Climate Change

Since the Industrial Revolution great quantities of greenhouse gas have been released and its amount has skyrocketed in the past century. Daniela Burghila et. al. marked in “Climate Change Effects - Where to Next?”, the emissions of carbon dioxide rose by around 80%. This amount of carbon dioxide in the atmosphere goes beyond natural range. Most of the carbon dioxide in the atmosphere generates by burning fossil fuels. Many electric power plants utilize them (World Energy Model Documentation 2020, 62). Climate change rapidly became the determinant environmental, economic, and political challenge of the time. An ”IPCC Special Report on the impacts of global warming of 1.5°C” stated as concern about anthropogenic greenhouse warming and climate change grow, the need to reduce carbon dioxide emissions from coal-fired power plants will increase drastically. Referring to Intergovernmental Panel on Climate Change summary ”Climate change 2013 The Physical Science Basis”, this creates one of the key challenges in global energy policy: what energy supply infrastructures will provide the estimated additional 3,312 gigawatts of new electricity generation capacity that it is calculated the world will need by 2030? (Stocker & Qin 2013, 57).



PICTURE 2. The world carbon dioxide emissions from fossil fuels burning from 1950 to 2100. Li. 2017. World Energy 2017-2050: Annual Report. [png].

World carbon dioxide emissions are forecasted to peak in 2030 (Picture 2) at 37.1 billion tons. By comparison, in "World Energy 2016-2050" (Patterson 2016, 2), world carbon dioxide emissions were projected to peak in 2029 at 36.0 billion tons. In accordance with Intergovernmental Panel on Climate Change's Fifth Assessment Report, total carbon dioxide emissions will largely determine the global average surface warming by the late 21st century and beyond (Stocker & Qin 2013, 118).

Referring to Hansen et al. (2016), the global warming by more than two degrees might lead to the melting of West Antarctica ice sheets, with sea level rise by 5-9 meters over the next 50-200 years. Bangladesh, European lowlands, the US eastern coast, North China plains, and many coastal cities will be flooded. It will lead to the end of civilization as we know it. With the significant rise in global energy demand, new energy supply technology would need to show the capacity to scale to multi-terawatt levels (Gielen et. al. 2021, 18). Furthermore, in order to satisfy the demands of long-term supply security and development, the root of energy supplies, abundance, and carbon footprint should be considered.

2.4 Energy policy

Based on International Energy Agency (2019) technology report “The Future of Hydrogen” data, environmental and security concerns are stimulating global interest in hydrogen power, renewable energy, and advanced technologies. Key challenges will face the world's energy industry over the next few decades to ensure a smooth transition - challenges which will require government and industry solutions beginning as early as today (International Energy Agency 2019, 30).

European Environment Agency report “Climate change, impacts and vulnerability in Europe 2016” says energy-related issues are among the most pressing and critical issues confronting the world today. In “Toward a Sustainable Global Energy Supply Infrastructure: Net Energy Balance and Density Considerations” it is stated, the availability of adequate resources to satisfy the needs of an increasing population with rising living standards necessitates advancements in energy supply and production. Achieving this when mitigating the effects of climate change is a far more difficult challenge. It would necessitate a substantial change in the historical trajectory of fossil-fuel usage, as well as a significant transition of the global energy system. (Kessides & Wade 2013, 2). Especially in the developing countries, the choice of technology, policy, and economic levers that will be utilized to convert and expand their energy systems will have profound implications for their growth, international competitiveness, economic security and prosperity (Climate Change, impacts… 2015, 51).

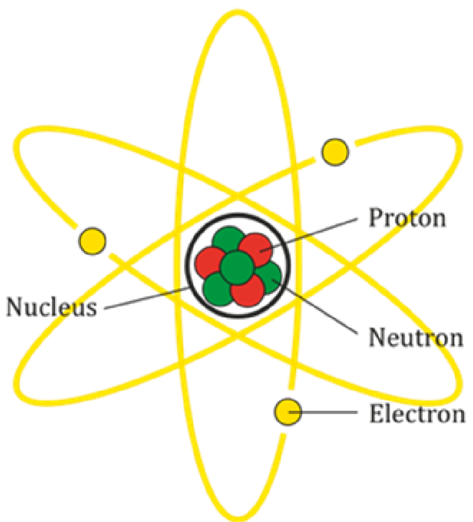
The 21st century is likely to witness a transition to a new infrastructure of energy supply supporting the principles of sustainable development. Key requirements of the new energy supply chain include scalability ability to expand to the multi-terawatt level, environmentally friendly minimal carbon footprint, capacity to deliver net excess energy, longevity abundance of energy source (Kessides & Wade 2013, 4).

Pursuant to the International Energy Agency (IEA), if current government policies continue, global primary energy demand is expected to increase from 12,013 to 16,790 million tons of oil equivalent (Mtoe) between 2007 and 2030. Over the same time frame, electricity demand is expected to rise from 16,249 to about 29,000 terawatt-hours (TWh). To satisfy these demands, the world's power generation capacity would expand by approximately 3,312 by 2030. As a result, the size of the energy challenge is massive (Kessides & Wade 2013, 4).

3 NUCLEAR ENERGY

3.1 Atom and atomic nucleus

The **atom** is a complex combination of other particles. Atom represents small planetary system. In the centre the small heavy particle is located, which is positively charged and called **nucleus**. The nucleus consists of protons and neutrons (nucleons). The nucleus possesses almost whole mass of the atom. Light particles with negative charge – electrons – are moving around the nucleus. The atom is neutral, it does not have electric charge. Thus, the number of electrons in atoms is equal to protons in the nucleus (Balabanov 1963, 7). The structure of the simple atom is shown on the Picture 3.



PICTURE 3. Structure of atom. Khillar, Difference Between.net. 2019. Difference Between Atom and Mole [png]. Updated on 24.06.2019. Read on 25.04.2021. http://www.differencebetween.net/science/difference-between-atom-and-mole/

3.2 Nuclear forces

Protons are taken together to extremely close distances in nuclei. The remainder of the protons in the nucleus repel each proton with great energy. Electrical repulsive forces acting between protons appear to disrupt the nucleus, throwing protons out of it. Nuclear energies, which are special forces of attraction, also operate in the nucleus.They make the particles attract each other, entering the nucleus. This attraction is extremely strong. As a result, radioactive matter has a strong intensity and density, which is demonstrated by **nuclear forces** that bring nucleons together to form a high density small particle known as the nucleus (Balabanov 1963, 11).

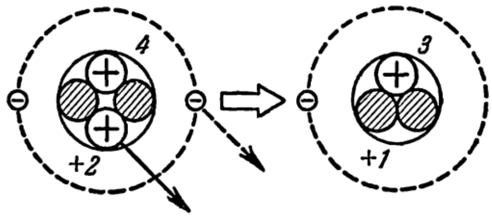
3.3 Nuclear reaction

The capability to alter the properties of matter, to turn one atom into another, is related to **nuclear reaction**. They are the source of nuclear energy. A rearrangement of atoms happens during chemical reactions, although this is not caused by a modification in their nature. A carbon atom, for instance, does not cease to be a carbon atom when it joins with two oxygen atoms to form carbon dioxide molecules CO2. In nuclear reactions, a profound change in the nature of the atom takes place, a radical breakdown of its basic properties. As a result of such reactions, carbon atoms can be converted into a nitrogen or oxygen atom (Leshkovtzev 1954, 16).

3.4 Example of nuclear reaction

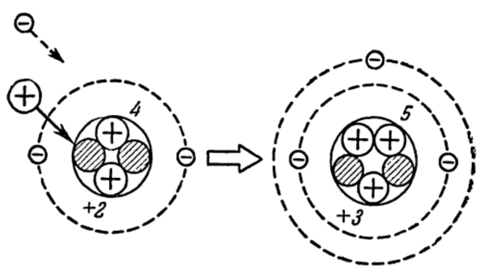
The weight of the nucleus does not determine the chemical properties of the atom. These properties depend only on the size of the nuclear charge and the number of electrons in the shell of the atom. Therefore, changes in chemical properties require a change in the charge of atomic nuclei (Leshkovtzev 1954, 17).

Leshkovtzev (1954) suggests to examine this by using the example of the helium atom. First, one to remove one proton from its nucleus. In this case, not only the mass, but also the charge of the nucleus decreases by one and a new nucleus with a charge of 1 and a mass of 3 is obtained, such a nucleus turns out to be a nucleus of tritium, which is superheavy hydrogen (Picture 3). Since the charge of the new nucleus is equal to one, it can hold only one electron. Therefore, as soon as the proton is removed from the nucleus, one of the electrons will leave the atom and only one electron will remain in the shell of the new atom. Tritium atom also contains one electron Leshkovtzev 1954, 17).



PICTURE 3. Transformation of helium into tritium. Source: V. A. Leshkovtzev. 1954. Nuclear energy.

Therefore, when a proton is removed from the helium nucleus, the helium atom turns into a hydrogen atom. Hence, if one proton is added to helium atom nucleus, the charge and the mass of the nucleus will increase by one and a new nucleus with a charge of 3 and a mass of 5 will turn out (Picture 4). Such a nucleus can hold already 3 electrons in the atom (Leshkovtzev 1954, 18).



PICTURE 4. Transformation of helium into lithium. Source: V. A. Leshkovtzev. 1954. Nuclear energy.

Therefore, one of the free electrons not associated with any atom that are always present in the substance will be captured by a new atom; the number of electrons in its shell will become equal to three. Since the electrons in the atom are arranged in layers and no more than 2 electrons can enter the layer closest to the nucleus, third electron is located in a new layer farther from the nucleus (Leshkovtzev 1954, 19). The atom with 3 charges in the nucleus and 3 electrons in the shell should occupy third place in the periodic table. Lithium is situated there. Thus, when a proton is added to helium nucleus, the helium atom turns into a lithium atom. Reactions accompanied by a change in the number of protons or neutrons in the nucleus are called **nuclear reactions** (Balabanov 1963, 18).

To convert helium into lithium one proton must be added to the nucleus of each helium atom but for this, the proton must move at a velocity of around 15,000 km/s. The proton, like a helium nucleus, is positively charged, and repulsive forces act on particles charged similarly. These forces are the greater the smaller the distance between the particles. The proton spends a lot of energy to overcome this repulsion. Therefore, only fast protons can destroy an atom nucleus. Thus, fast, positively charged nuclear projectiles are needed to carry out **nuclear reactions** (Leshkovtzev 1954, 18).

3.5 Radioactivity

Some natural elements themselves continuously produce positively charged particles, which carry away part of the energy of the atomic nuclei of these elements. The atomic nuclei of heavy elements are unstable. Without any external influence, they decay and change their nature. Atoms capable of such transformations are called radioactive, and the transformations taking place in them are called **radioactive transformations** (Ishkhanov 2011, 37).

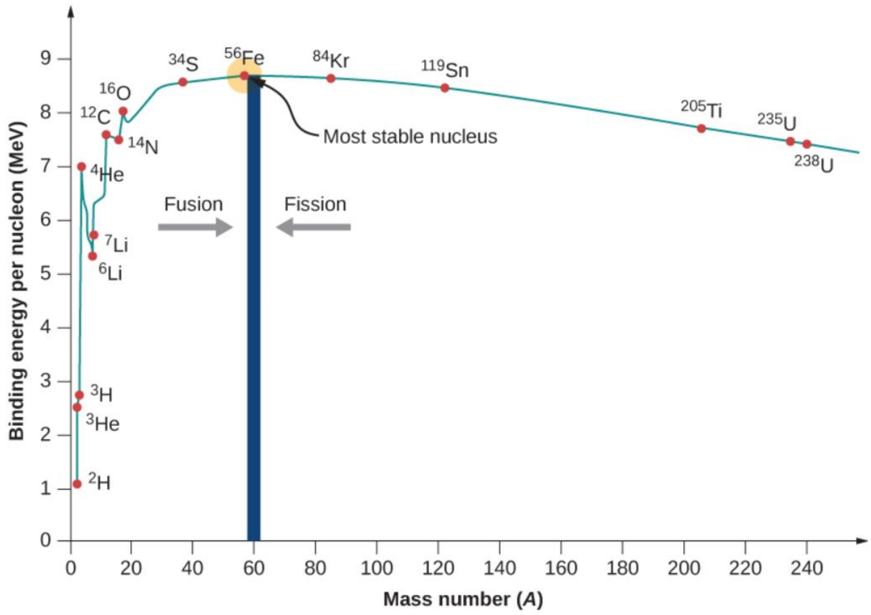
During **radioactive transformation**, a particle consisting of 2 protons and 2 neutrons is ejected from the nucleus. It is agreed to call it the alpha particle. Alpha particles can be used as nuclear projectiles. Radioactive fission releases a lot of energy. The energy released by radioactive atoms is **nuclear energy**. It is released because of processes that occur in the atomic nuclei of decaying elements. However, this energy is released extremely slowly and therefore it is difficult to use it for practical purposes (Ishkhanov 2011, 152).

The energy of **radioactive fission** is released as a result of the transformation of one chemical element into another, which can also be radioactive. Having experienced a series of consistent decays, nuclei with natural radioactivity turn into stable ones. The phenomenon of **artificial radioactivity** consists in the fact that when neutrons affect the nuclei of stable chemical elements, isotopes with artificial radioactivity appear. Isotopes of a chemical element are atoms that have nuclei with the same number of protons but differ in the number of neutrons (Leshkovtzev 1954, 20).

3.6 Binding energy of atomic nuclei

It is known that when a body moves under the action of a force, energy is always released. The conservation of energy law says that energy does not appear from nothing. Therefore, the work expended on removing the particle will be compensated by the energy that will be released when this or another particle joins the nucleus again. The value of this energy can be calculated by measuring the energy of the nucleus before and after the removal of the particle. This energy is called the **binding energy of the nucleon**. The **total binding energy of the nucleus** is the energy that is needed to separate the nucleus into all its composite particles (Balabanov 1963, 15).

The Picture 5 shows the curve of the dependence of the binding energy on the mass number of nuclei. The ordinate represents the average binding energy per nuclear particle, that is, E / A, where E is the nucleus binding energy, and the abscissa is the mass number A (the total number of protons and neutrons in the nucleus).



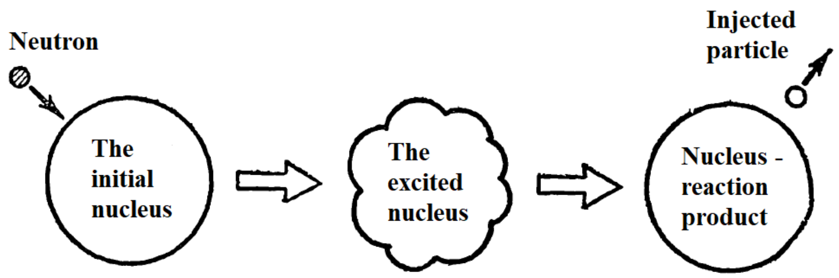
PICTURE 5. Binding energy curve of atomic nuclei. Openstax CNX. 2020. Nuclear Binding Energy. [png]. Updated on 20.10.2020. Read on 15.04.2020. https://legacy-content01.cnx.org/content/m10641/latest/

Since the binding energy is determined by the work expended to remove particles, it has a negative value, because an increase in the binding energy of the nucleus leads to a decrease in its internal energy, to a more stable state. The transition from a less stable state to a more stable one is always accompanied by the release of energy. The binding-energy curve indicates that we can expect the release of energy only in such nuclear transformations in a result of which will be formed the most stable nuclei - nuclei of average size, i.e., when combining the fission of heavy nuclei and during the fusion of light nuclei (Balabanov 1963, 16).

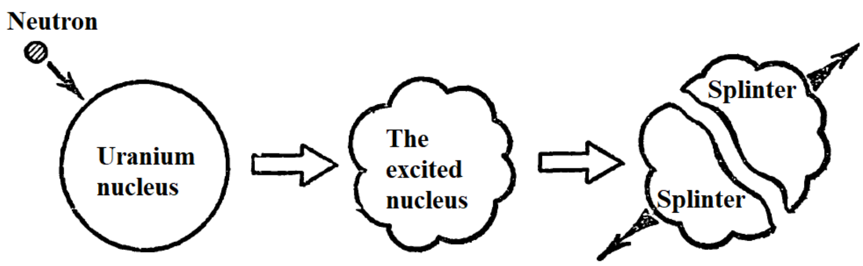
4 NUCLEAR FISSION (ENERGY OF HEAVY NUCLEI FISSION)

4.1 Nuclear fission

In a normal nuclear reaction (Picture 6), one particle enters the nucleus and knocks out another particle from the nucleus. In uranium, neutrons can cause completely different nuclear reactions. Penetrating the uranium nucleus and transferring its energy to it, the neutron brings the nucleus into an excited state. As a result, the nucleus formed after the absorption of a neutron is divided into 2 heavy splinters (Picture 7). (Leshkovtzev 1954, 36).



PICTURE 6. The scheme of normal nuclear reaction.

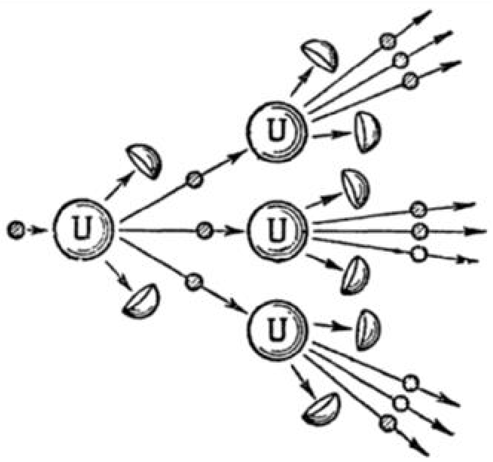


PICTURE 7. The scheme of uranium nucleus fission.

There are that many protons in the uranium nucleus that their mutual repulsion is hardly overcome by the attraction from the nuclear forces, so even a small neutron energy will be enough to destroy the entire nucleus. Fission of uranium nucleus releases in ten times more energy than radioactive fission and tens of millions of times more energy than chemical reactions (Leshkovtzev 1954, 37).
Nuclei-splinters emerging during the fission of uranium contain extra neutrons. Such nuclei are unstable. They get free from excess neutrons by converting them into protons. In this case, the emission of electrons occurs until the splinter turns into a stable nucleus of a new element. In addition to the electron, during such transformations, ɣ-rays are emitted. Hence, the nuclei-splinters are radioactive. (Leshkovtzev 1954, 39).

4.2 The chain process of nuclear fission

The energy released during fission in times greater than the energy released in conventional nuclear reactions. However, to obtain a significant amount of nuclear energy suitable for practical purposes, it is necessary to separate a huge number of nuclei. Due to this one should have the same number of nuclear projectiles-neutrons, the production of which is associated with even greater energy consumption. As mentioned earlier, extra neutrons are generated during the fission of uranium. Each neutron can split a new uranium nucleus and again, with each fission, new neutrons will be released that can split uranium nuclei. During uranium nuclei fission, the number of fissile nuclei increases not 2 but 3 times each time (Picture 4). This process of nuclear fission is called a **chain process**, since after the first fission caused by one neutron, a whole chain of subsequent fissions arises (Mukhin 1969, 138).



PICTURE 8. Nuclear fission chain reaction uranium. Leshkovtzev. 1954. Nuclear energy.

In such a chain process, a piece of uranium weighing around a kilogram can separate in a millionth of a second. The tremendous energy released by the fission of such many nuclei in such a short time leads to a powerful explosion. Thereby, in comparison to all previous cases of nuclear transformations, fission of uranium nuclei releases immeasurably more energy than is expended on creating a chain process (Mukhin 1969, 139).

4.3 Uranium

Uranium-235 is present in nature and decays with the emission of alpha-particles, turning into thorium-231 (Belyaev et. al. 2004, 177). Natural uranium consists mainly of uranium-238 and only 1/140 of it is uranium-235. The absorption of neutrons by uranium-238 nuclei does not lead to fission, therefore, only uranium-235 is a nuclear fuel suitable for creating a chain reaction. To separate the atomic nuclei enclosed in a piece of uranium, it is necessary to bombard this piece with one neutron. Since the neutrons appearing from the fission of uranium nuclei move at a high speed, they quickly produce new fissions (Leshkovtzev 1954, 42).

The uranium nuclei by themselves, without any bombardment by neutrons, are divided into splinters. With each fission, 2-3 free neutrons appear. This division is similar to the radioactive decay of natural elements. It is known that uranium is radioactive and decays by emitting alpha-particles. However, this process is very slow. The half-life of uranium-238 is 4,5 billion years. Besides the fission accompanied by the emission of alpha-particles, uranium nuclei can split. The process of spontaneous fission of uranium nuclei proceeds about a million times slower, the half-life is 10 million billion years. Nevertheless, due to the huge number of uranium nuclei enclosed in a piece weighing 1 kg, around 5 spontaneous fissions occur in it every second. As a result, 10-15 free neutrons appear capable of further fission of uranium nuclei (Leshkovtzev 1954, 39-41).

4.4 Nuclear reactor.

The apparatus in which the controlled chain fission process is carried out is called a **nuclear reactor**. The principle of operation of a nuclear reactor is simple. One can take, as an example, a piece of uranium in the form of a hollow short cylinder so that its weight is close to critical (minimum amount of fissile matter required to initiate a self-sustaining fission chain reaction) (Balabanov 1957, 52).

In this case, the fission factor will be close to one. If the uranium rod is gradually pushed into the cylinder cavity, then due to a decrease in neutron leakage through the cavity, the fission factor will increase and at a certain position of the rod it can become more than one. It is necessary to remember that the fission factor should not exceed 1.01, since at its large values the nuclear process will be determined by instantly emitted neutrons, the reactor can go out of control and an atomic explosion will occur (Balabanov 1957, 53).

With a fission factor of more than one, a chain reaction will start to develop, and the amount of released energy will increase. When the required power is reached, by changing the position of the uranium rod, it is possible to achieve a state in which the fission factor will be equal to one. Then in a nuclear reactor will be released atomic energy constant in time. The uranium cylinder will be heated, and the released heat can be used for various purposes (Balabanov 1957,53).

4.5 Ecology

According to Technical assessment of nuclear energy with respect to the ‘do no significant harm’ criteria of Regulation (EU) 2020/852 (‘Taxonomy Regulation’) taking into consideration the impacts on human health from all the different emissions, both radiological and non-radiological, from the whole lifecycle of the different technologies, the impact on human health of nuclear energy is seen to be low compared to the fossil fuel chains, and rather similar to the impact from offshore wind.

As approved by Nuclear Energy Agency (2015) in the work “The Environmental and Ethical Basis of Geological Disposal”. the utilization of uranium is associated with accumulation of long-life radioactive slag and the necessity of its constant increscent amount secure ground disposal. Nuclear waste was thought to offer nuclear power an edge in the early stages of production because of its high dosage, small scale, and the ability of tight monitoring, accounting, and separation, as well as slow radioactive decay, Thus, the inclusion of long-lived chemically active fragments of nuclear waste necessitates their careful disposal for hundreds of thousands or millions of years, which has no precedent in human experience. These issues are not solved yet (Belyaev, et. al. 2004, 108). Nevertheless, nuclear power is the only energy source that can replace hydrocarbon fuels for now. Recently, there has been renewed interest in nuclear power plants as the only option to date to reduce carbon emissions and achieve climate neutrality by 2050 (Velikhov & Putvinsky 1999).

The necessity in the nuclear energy development is conditioned not only by the factor of depletion of fossil fuels. Equally significant is the impact of the energy production method on public health and the environment. Under normal operating conditions nuclear energy is safer for the population and the environment than energy based on the combustion of fossil fuels. Referring to Gordienko et. al. the “Comparative analysis of radioactive pollution generated by nuclear power plants and the coal power thermal stations” by comparing the environmental impacts of nuclear and thermal power plants of the same electrical capacity, scientists have obtained that only the radiation emissions from coal plants are 10-20 times more dangerous than a modern nuclear power plant without considering the emission of other harmful products of coal combustion.

In accordance with International Atomic Energy Agency Annual Report 2006 nuclear energy can be utilized to solve the oncoming crisis of the growing shortage of fresh water both for domestic needs and for irrigation in agriculture. Due to the excess heat from nuclear reactors, it is possible by desalination to satisfy not only current needs, but even the constantly increasing needs for fresh water.

4.6 Efficiency

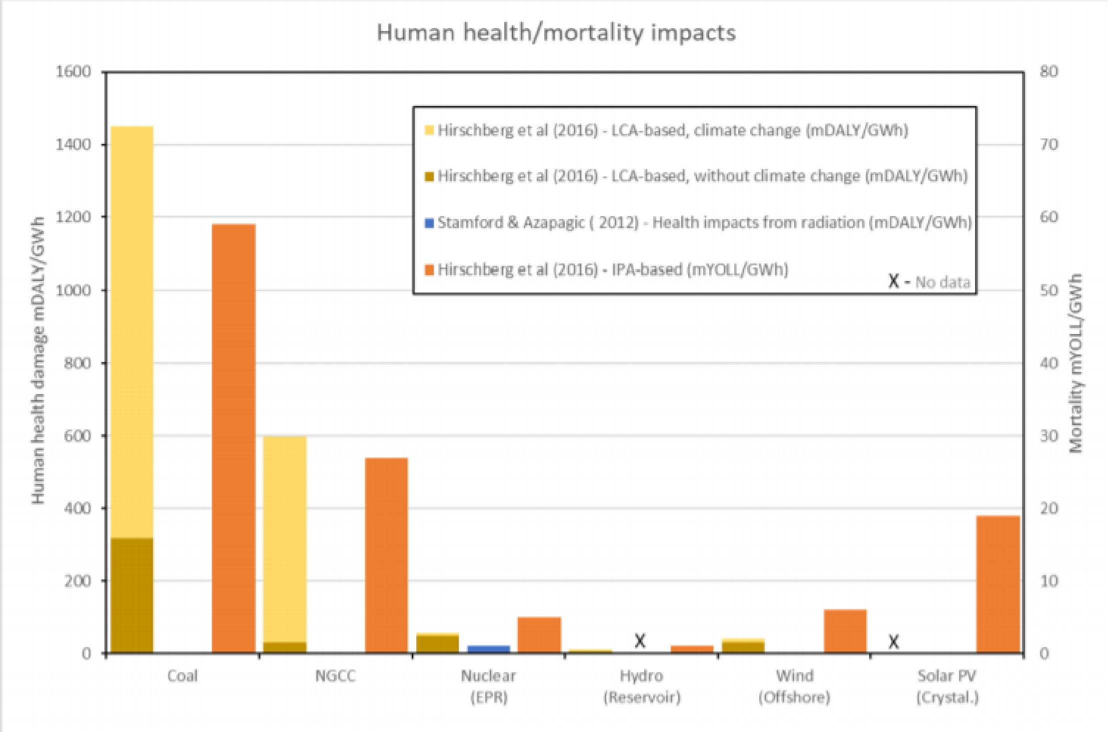
In contradistinction to the most power plants, nuclear power is characterized by the stable electricity prices over a long period, as nuclear power plants are independent of fuel sources due to their small volume of utilization. The structure of costs for electricity production in nuclear energy is dramatically differs from the structure of pricing in other energy types. Since the cost of nuclear electricity is based on the capital investments in the construction of nuclear power plants, unlike oil, gas, and coal, where costs on fuel prevail (Comby 2009, 143).

Recently, there has been a significant increase in oil prices. This causes an increase in prices for electricity generated by thermal power plants using fossil fuels. According to the International Energy Agency and Nuclear Energy Agency estimates, nuclear power is essentially cheaper than electricity based on oil, as well as from coal and gas, with high costs of their extraction and transportation. In comparison with nuclear fuel with coal and gas, with low costs for the extraction and transportation of fossil fuels, the price of electricity is approximately the same (Projected costs of generating…2015, 161).

The fuel component in the total cost of electricity produced by a nuclear power plant varies from 10 to 20%, and for thermal power plants operating on fossil fuel, at the level of 50-80%. This circumstance leads to raised stability of the atomic electricity price in relation to fluctuations in the price of fuel. It ought to be remarked the energy intensity of uranium in comparison with fossil fuel. One kilogram of uranium used in nuclear fuel releases energy equivalent to burn around 100 tons of high-quality coal or 60 tons of oil (Zhunisbekov, Dzhakiyaev & Zhashen 2019, 604).

4.7 Safety

Though, there are quite compelling arguments against the uranium usage as energy raw material and mainly they are related to the safety case. From the point of view of safety, the main disadvantage of a modern nuclear power reactor is a large excess of fissile material loaded into the reactor. Stable operation of the reactor in the critical mode is ensured by special rods that absorb neutrons, which are gradually removed from the reactor during the campaign (as the fissile material burns out). The danger of such a situation is that there is some probability of the development of an uncontrolled chain reaction, which can lead to a serious accident which may lead to a catastrophe (Belyaev 2004, 181).



PICTURE 9. Human health and mortality impacts from different electricity generation technologies. Technical assessment of nuclear… 2021. [png].

However, if one compares the frequency of accidents in various spheres of human labour activity (Picture 9), statistics says that the practical use of atomic energy ranks among the sewing, food, and weaving industries. Furthermore, the share of radiation accidents does not exceed 10% (including the Chernobyl and Fukushima accidents). Comparison of losses to society (in the form of the number of deaths and days of incapacity for work) for different types of electricity production speaks in favour of nuclear energy (Technical assessment of nuclear…2021).

4.8 Resource base

The main combustible raw material in nuclear reactors is uranium. In case of its usage as now, the uranium reserve will be expired in hundred years, according to the estimations by World Nuclear Association, published in the article “Supply of Uranium”. Another issue, there is little amount of uranium-235 in nature. Furthermore, referring to World Nuclear Organisation, the reserves of the original uranium are depleted. Therefore, nuclear physicists must enrich uranium, which means to change its isotopic composition. Besides, the reserves of the original uranium are depleted.

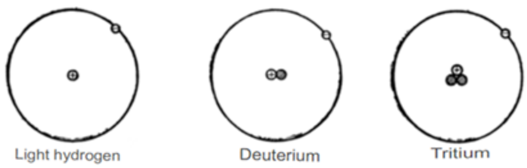
Today, nuclear power plants produce almost a fifth of all electricity, stated academician Aleksandrov in the report “On the energy of the future”, although, uranium itself is one of the most abundant metals on Earth (its crust contains about a thousand times more gold), almost all this amount is accounted for by uranium-238, which mostly goes to the dump, the resources of uranium ore suitable for nuclear fuel are nearing exhaustion. According to modern estimates, they will last for around 150 years, and after that humanity must look for new sources of energy (Belyaev et. al. 2004, 178).

5 THERMONUCLEAR FUSION (ENERGY OF THE LIGHT NUCLEI FUSION)

5.1 Thermonuclear fusion

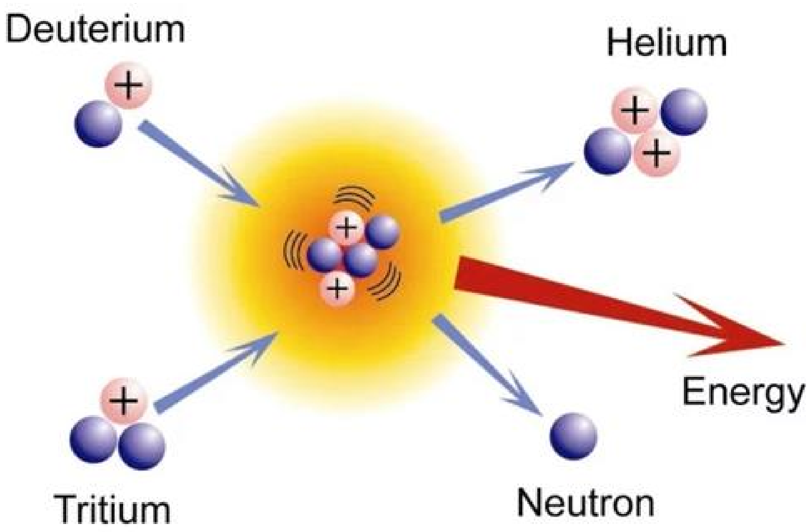
Appealing to modern physics conception there are several fundamental resources of energy that can be mastered and utilized by mankind. Nuclear synthesis reactions are one of them. In synthesis reactions the energy is generated due to nuclei's power work during merge of light element nuclei and formation heavier nuclei. These reactions are widely distributed in nature – it is considered that energy of stars and the Sun is generated because of chain of nuclear synthesis reactions that transform 4 nuclei of hydrogen to helium nucleus. One can say that the Sun is natural thermonuclear reactor (Balabanov 1957, 192). While nuclear fission occurs on Earth (all elements after lead in the periodic table are radioactive), thermonuclear fusion is possible only under extreme conditions, for instance, in stars. In order to originate a thermonuclear reaction technically, the initial atomic nuclei must overcome the Coulomb barrier - the force of electrostatic repulsion between them, similar to the force that repels any positive charges from each other (Balabanov 1957, 193).

Any nuclear reaction implies either an exchange of nucleons or a change in their number. If two nuclei merge into one heavier one, it is called ***thermonuclear fusion***. With bombardment light nuclei with fast charged particles the nuclear reactions occur, during which huge amount of energy is released. For instance, by bombing lithium with hydrogen nuclei – protons releasing energy about 2,5 times bigger than uranium division. Much more energy is released during helium's nuclei creation from various hydrogen isotopes (Picture 10). (Balabanov 1963, 35).



PICTURE 10. Isotopes of hydrogen. Balabanov. 1957. Nuclear reactors.

In order to receive the energy from connection light nuclei the self-supported process is needed. It is not necessary to apply accelerators for getting fast particles: atoms and molecules of any substance are always in continuous motion. Moreover, the velocity of atoms movement and consequently nuclei is increasing with the rising of the substance’s temperature. Thus, the mixture of light elements should be heated to connect nuclei of these elements with each other. Nuclear reactions happen and energy exudes. If there is enough amount of the resulting heat to retain the high temperature of substance than self-sustaining nuclear process will occur. This process is called ***thermonuclear reaction*** (Picture 11) (Balabanov 1957, 192).



PICTURE 11. Thermonuclear reaction. Krasilnikov, PostNauka. 2020. Thermonuclear reactor. [png]. 29.12.2020. Read on 21.04.2021. https://postnauka.ru/longreads/156011

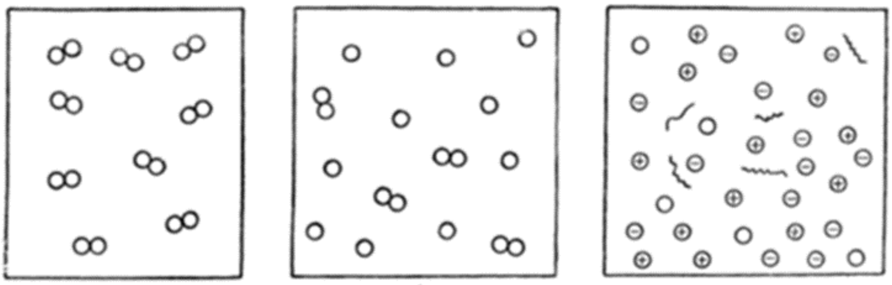
To implement the effective thermonuclear combustion several conditions have to be complied. The Coulomb repulsion prevents the nuclei's synthesis. To overcome the repulsion, the plasma has to be heated approximately to 100,000,000 degrees (10 keV). Wherein one needs to provide its sufficient concentration η and retain at temperature and density during time interval t, needed for "burnout" of the thermonuclear fuel substantial part. Estimations show that for this, at temperature of plasma $T \approx 10\, keV$ the product of multiplication of concentration of particles on time of retaining must meet the inequality

$$\eta\tau \geq 1014\, s/cm3,$$

known as Lawson Condition. Then the energy released as a result of thermonuclear reactions will exceed the energy spent (Ilkaev & Garanin 2006, 78).

5.2 Plasma and magnetic bag

The key component of the controlled thermonuclear reaction is fuel, which is heated to a plasma state. For heating up hydrogen to million degrees little amount of energy is needed. (For one gram of deuterium - several kilowatt-hours.) The difficulty is that at this high temperature atoms and molecules of gases have enormous velocity and scatter in different ways. The gas pressure reaches million atmospheres. The heat transfers from deuterium to substance around, walls of the container in which the heating is occurring. In this case huge amount of energy will be spent on the container heating. One had to come up with thermo-insulation that gives walls the ability to stay cold while gas in the container is heated to millions of degrees temperature. Moreover, the pressure on the walls should not be very high (Lukyanov & Kovalskiy 1997, 18).



a b c

PICTURE 12. (a - gas at t > 100°C; b - gas at t > 1000°C; c - plasma, t > 10000°C). Balabanov. 1963. Thermonuclear reactions.

There are three aggregate states of matter in nature: gaseous, liquid and solid. However, there is a fourth - when it is as hot that the electrons in the atoms are detached from the nuclei. The result is a mixture that no longer consists of atoms and molecules, but of electrons and ions. This quasineutral formation (quasineutral means that the total charge of positive and negative particles is zero) and is called plasma (Picture 12) (Artzimovich & Sagdeev 1979, 6-7).

The challenge is to hold charged particles together, since when they fly apart the energy contained in volume of gas will go away. Provided that, not every plasma is suitable for fusion. As mentioned earlier, for the reaction to occur, the positively charged nuclei participating in it must overcome the Coulomb repulsion. This can be done by forcing the particles to come as close to each other that nuclear forces begin to act, which, are very short-range. In order to do this, the plasma must be heated to extremely high temperatures, from 150 to 300 million °C, so that the particles it consists of can accelerate and, as billiard balls, begin to collide with each other. Beyond that, the plasma must be dense enough, otherwise collisions of atomic nuclei will not occur often enough. Finally, the plasma formation must live long enough for the required amount of matter to react (Artzimovich & Sagdeev 1979, 20).

Academicians I. E. Tamm and A. D. Sakharov suggested to apply magnetic field for thermo-insulation of high temperature plasma. In the magnetic field charged particles cannot move straightforward and they roll up in a circular motion. The bigger magnetic field is the smaller circle, where ions and electrons move on. In a strong magnetic field, the plasma energy loss due to particles motion should decrease in hundred times. Charged particles of heated in millions of degrees plasma will be located in so called ***magnetic bag***. The walls of this bag, created by magnetic field are able to withstand super high temperature (Balabanov 1957, 195).

For the obtaining the temperature of million degrees, currents of million ampere are needed. One able to start up the current through plasma of discharge tube only at voltage of several tens of thousands volt. The solution is to pass the potent currents in form of pulses, lasting a millionth of a second. Thus, the average power, consumed for the facility power supply, has quite acceptable value while the instant power is colossal. Gas discharging tube with deuterium in experimental appliance received electric supply of 50 thousand volt (Lukyanov & Kovalskiy 1997, 19).

It was discovered that in the tube gas pulls into a narrow cord, torn from the container walls. Plasma undergone sharp fluctuations due to consistently compression and discharge. Shock waves are created in the container with huge propagation speed – several hundreds of kilometres per second. The temperature of plasma cord at the moment of the strongest compression reaches million degrees (Balabanov 1957, 197).

5.3 Tritium and deuterium

When deuterium and tritium merge, an alpha particle (helium-4 nucleus) and a neutron are formed. The total mass of the final products turns out to be less than the mass of the initial products - deuterium and tritium. The difference in the binding energy of the initial particles and products is converted into kinetic energy of the movement of alpha particles and neutrons. Thermonuclear energy exploits this conversion of mass into kinetic energy (Balabanov 1957, 195).

Thermonuclear synthesis is based on reactions of light elements' nuclei merge with formation of heavier with releasing of extra energy. The easiest way to implement synthesis of heavy isotopes of hydrogen – deuterium and tritium by reaction

$$D + T = 4He + n + 17{,}6\,MeV$$

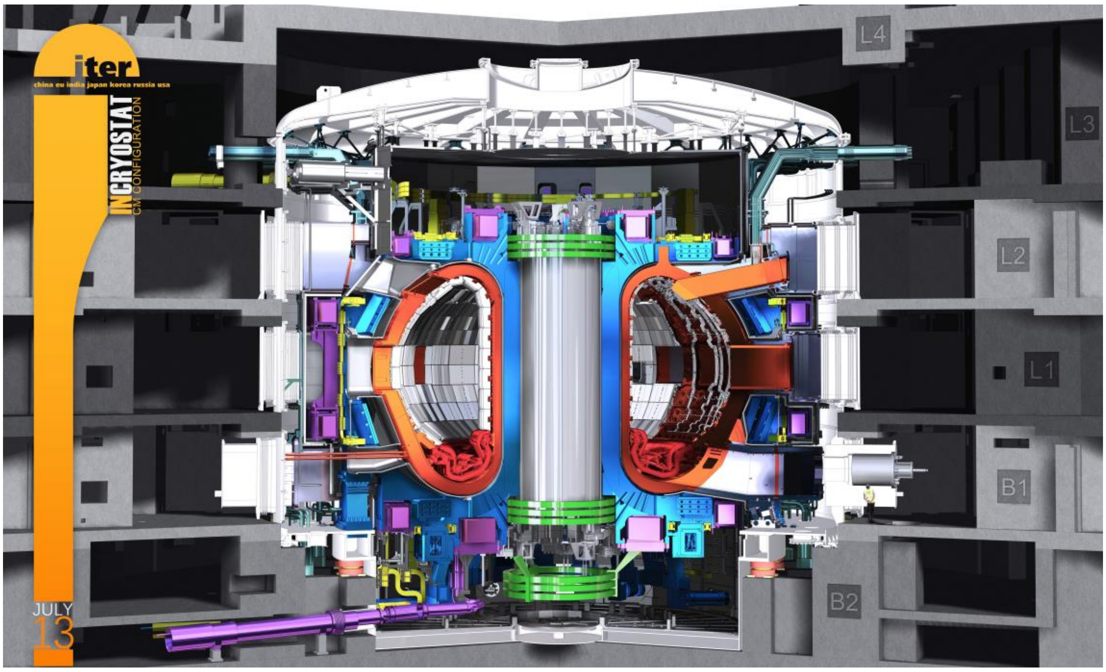
The reserves of deuterium in nature almost unlimited and radioactive tritium with half-life period 12,4 years can be derived as a result of reaction

$$n + 6Li = 4He + T + 4{,}8\,MeV.$$

The reserves of lithium are also huge, which allows to have the solution of humanity energy problem with help of controlled thermonuclear synthesis (CTS) (Ilkaev & Garanin 2006, 78).

5.4 Thermonuclear reactor ITER

International Thermonuclear Experimental Reactor (ITER) — the biggest in the world TOKAMAK (Picture 13), the most complex thermonuclear experimental machine, conscripted to demonstrate the feasibility of thermonuclear synthesis technology and proof that thermonuclear reaction can be controlled. The idea of ITER is to generate 10 times more energy at the output than at the input. ITER is based on the conception of TOKAMAK with magnetic retention of plasma (Smirnov 2003, 302).



PICTURE 13. ITER appliance. ITER Organization. 2013. ITER image galleries. [png]. Released on 23.07.2013. Read on 15.04.2021. https://www.iter.org/album/Media/7%20-%20Technical

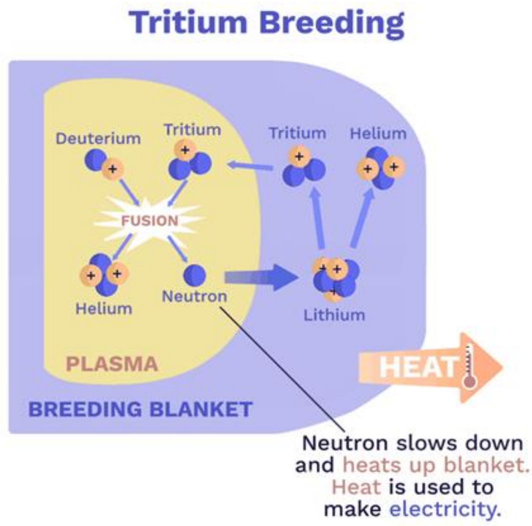
The operation of the ITER reactor is based on the fusion reaction of isotopes of hydrogen, deuterium, and tritium to form helium and a high-energy neutron. The construction works started in October 2007 after the ratification of the agreement about the project with all the participants. The construction is taking place in the South France. Seven partners (China, Korea, India, Russia, Japan, USA and the European Union) have agreed to invest their intelligent and financial assets.

The huge part of the investment consists of components and equipment for the reactor. The initial cost of ITER was estimated at €5 billion, however has increased in four times and it is not the final number (Smirnov 2003, 303).

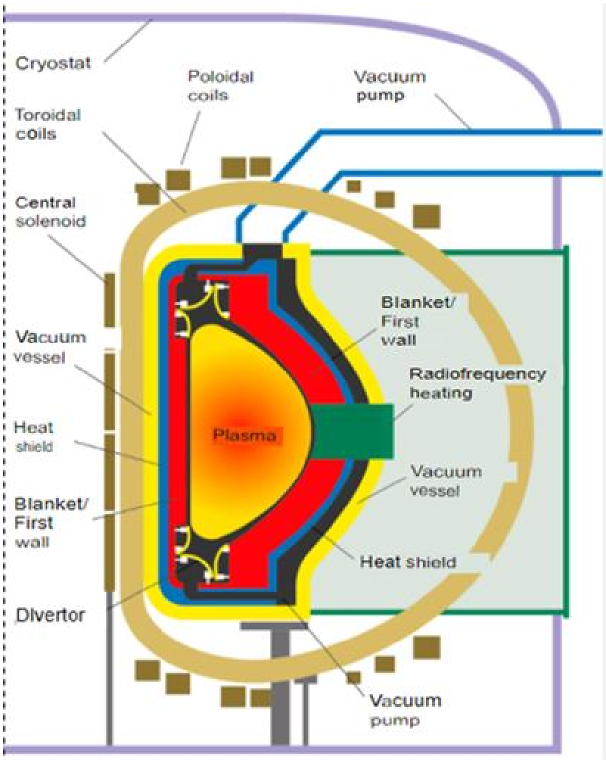
The basis for cryostat of 1250 tons is one of the heaviest single loads during the assembly of the machine of 23 thousand tons. European union is responsible for vacuum camera, however for the project optimisation and minimisation the delays, part of work was transferred to Korea, which demonstrated the high level of its technologies by launching TOKAMAK with superconducting magnetic system KSTAR (Korean Superconducting Tokamak Advanced Research). It has received first plasma in 2008 and showed the record 70-second highly productive plasma in 2016. China together with Russia work on superconductors creation, the first catering of which was carried out in June 2014 (Smirnov 2003, 302).

In Russia around 30 institutes and organisations are engaged in ITER project. Six ring-shaped poloidal magnets with field coil will surround ITER machine to form plasma and procuring its stability by separation from vacuum reactor walls. Japan engineers and scientists also work under magnetic system, especially, under design-project of coils toroidal field and obtaining superconducting niobium-tin strands. The receiving of the first plasma at ITER installation is planned for 2025 and reaching the full capacity – for 2035. Australia and Iran are recently announced their will to join the project (Smirnov 2003, 305).

Tritium is generated during the reactor operation phase (Picture 14). It is generated in TOKAMAK when neutrons from the leaving plasma interfere with the isotope ^{6}Li, which is held in the blanket. Furthermore, the blanket and divertor are the primary plasma components. It should be remembered that the first wall of the reactor, which is just three meters from the plasma, is an integral part of the blanket, which one can see on Picture 15 (Krasilnikov 2020).



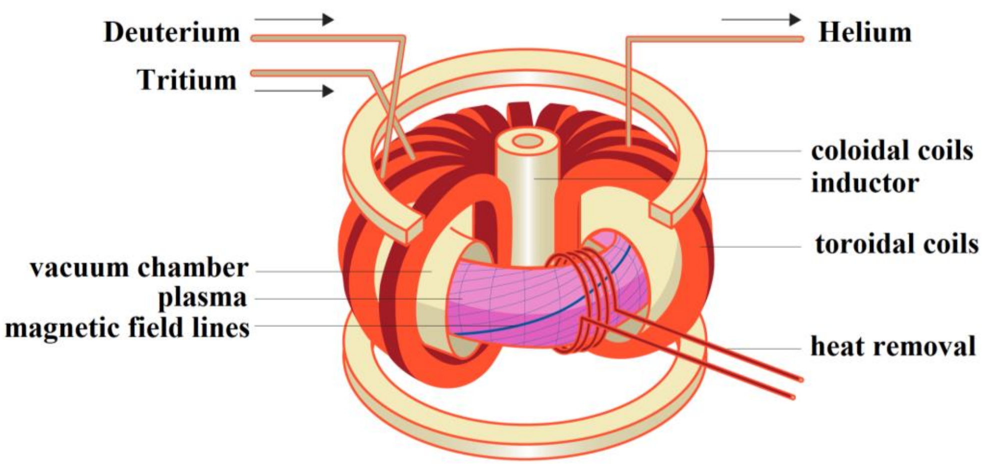
PICTURE 14. Tritium breeding. Climate Science. 2020. Can we make Fusion work? A Realistic Analysis Beyond Big Promises. [png]. Released on 14.12.2020. Read on 20.04.2021. https://climatescience.org/advanced-energy-make-fusion-work/



PICTURE 15. View of a vacuum vessel with the main positions of the components facing the plasma: the first wall, blanket, and divertor. Ipatova, Atomniy expert. 2019. The era of thermonuclear fusion. [png]. Released on 02.03.2019. Read on 20.04.2021. https://atomicexpert.com/era_of_thermonuclear_fusion

The fusion reactor runs on fuel consisting of a mixture of deuterium and tritium, which must be heated by temperature above 150 million °C. At such colossal temperature, the nuclei of hydrogen isotopes collide and, overcoming the Coulomb barrier, merge, forming the nuclei of helium atoms. As a result of each action of synthesis, 17.6 MeV of energy should be released. When heated, the fuel mixture becomes a fully ionized plasma. The superconducting toroidal and poloidal coils together with the central solenoid keep the plasma inside the vacuum container (reactor). These coils generate a magnetic field that forms the plasma into the torus. Today the international project ITER has come to this closer than ever (Gott & Kurnaev 2017, 84).

A TOKAMAK (Picture 17) is a superconducting electromagnet-encased torus or donut-shaped vacuum chamber. Since plasma reacts with a magnetic field, causing its ions to migrate along its lines of force, electromagnets direct it to pass inside the chamber without touching its walls. They actually evaporate at temperatures in the millions of degrees. the TOKAMAK has a central electromagnet - an inductor - that generates a powerful current while maintaining plasma stability (Krasilnikov 2020).



PICTURE 17. TOKAMAK scheme of work Krasilnikov, PostNauka. 2020. Thermonuclear reactor. 29.12.2020. [png]. Read on 21.04.2021. https://postnauka.ru/longreads/156011

To begin the reaction in the TOKAMAK, it is first important to expel air from it; this will eliminate residual gas that does not participate in thermal reactions but is capable of re-emitting radiation, resulting in an increase in its losses from the plasma. Following that, the thermonuclear fusion material - gaseous deuterium and tritium - is introduced into the chamber. As the inductor magnets are activated, a vortex electric field of sufficient amplitude is generated within the torus, causing a breakdown in the gas. Breakdown is analogous to lightning. The gas is ionized, that is, the electrons are detached from the atoms, as soon as it moves into the "donut," and the matter enters a plasma state (Krasilnikov 2020).

The resulting plasma takes on the shape that the external magnetic field gives it. It also holds it, not allowing it to touch the walls of the reactor. However, the plasma must not only be contained, but also heated to a temperature sufficient for the start of a thermonuclear reaction. For this, additional heating methods are used: either high-frequency heating methods at cyclotron frequencies for electrons and ions (ion cyclotron heating or electron-cyclotron heating), or neutral injection, when very energetic beams of deuterium and tritium atoms are injected into the plasma. If the plasma temperature is about 200 million degrees, then the energy of these atoms should be ten times higher. At such an energy, an atom flies into the plasma, quickly ionizes, and this ion begins to release energy due to Coulomb collisions with charged particles in the plasma and thus heats it up and starts a reaction (Gott & Kurnaev 2017, 109).

5.5 Ecology

As the President of the Kurchatov Institute Research Centre Mikhail Kovalchuk has repeatedly said, that thermonuclear fusion embodies the movement of technologies towards close-to-nature solutions. The photosynthesis has already been mastered in the form of solar cells. At the same time thermonuclear reactions in stellar interiors are going on permanently (Fishman 2019).

Controlled thermonuclear synthesis is theoretically to the uttermost secure and minimally affects environmental. Unlike a fission reactor, maintaining a positive energy balance in a fusion reactor requires constant and delicate plasma control and precisely synchronized operation of all major reactor systems. For example, in the TOKAMAK reactor, failure of almost any of its systems leads either to the loss of plasma stability, or to its contamination with impurities with its subsequent cooling, or to the loss of plasma equilibrium and its disruption. As a result, the energy balance in the plasma will be disturbed and thermonuclear combustion will stop (Smirnov 2003, 303).

The reactor ended its lifespan has to be preserved just for 30 years, after what these materials could be recycled and utilized in the new synthesis reactor. This situation fundamentally differs from fission reactors which produce radioactive waste, demanding recycling, and storage throughout 10 000 years (Belyaev et. al. 2004, 180). The key and principal difference is the absence of long-lived radioactive waste products which are distinctive for nuclear reactors. Fusion is considered cleaner and more powerful alternative to fission energy, as there is a fundamental possibility of creating low-activated structural materials that will "cool down" over a period of several decades and then can be recycled and used again. (Velikhov & Putvinsky 1999).

5.6 Efficiency

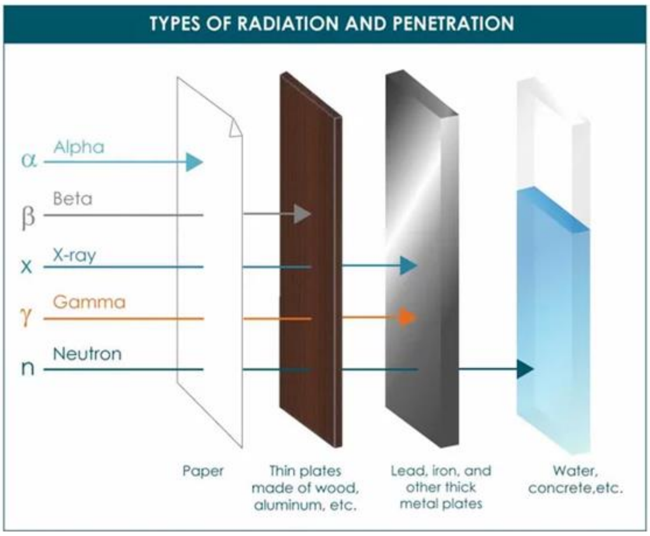
1 litre of water produces the same amount of energy as burning 8 tons of gasoline. The hydrogen isotopes deuterium and tritium, which will be used in thermonuclear reactors, are light. Their atomic masses are two and three, respectively, but the amount of energy emitted during the reaction is just 12 times that of a heavy uranium nucleus fission. As a result, the real energy release per nucleon in thermonuclear fusion is ultimately much greater than in fission reactions – about four times higher (Krasilnikov 2020).

The construction cost of thermonuclear reactor for today is much higher compared to conventional nuclear fission reactor. Furthermore, the expensive materials should be used that are more sensitive to radioactivity. By the middle of the next century, serious buyers of nuclear, including thermo-nuclear energy are expected to appear. And although preliminary estimates show that the price of electricity produced by a fusion reactor will be 1.5-2 times higher than the current price of electricity produced by modern power plants burning fossil fuels, one can agree that such a comparison is invalid for systems, which will compete only in a few decades (Velikhov & Putvinsky 1999).

5.7 Safety

The difficulty of feasibility of a controlled thermonuclear reaction plays a positive role in terms of reactor safety. In any of the known devices for controlled thermonuclear fusion, thermonuclear reactions cannot enter the mode of uncontrolled increase in power without subsequent disruption of the plasma and termination of the reactions. Thus, fusion reactors are intrinsically safe. Nevertheless, during the operation of the reactor, radioactive elements accumulate in it, which can present a known radiation hazard to personnel, the public and the environment (Artzimovich & Sagdeev 1979, 247).

Controlled thermonuclear fusion is much cleaner in comparison with nuclear power because its products are alpha particles and neutrons. Alpha-particles have very little penetrating power - even a sheet of paper can stop them (Picture 18), and although neutrons have an ionizing effect, they are unable to penetrate deeply into the stainless steel from which the vacuum chamber is made. And since the likelihood of an explosion in the case of thermonuclear energy is excluded, it is much secure. The safety of a fusion reactor is many orders of magnitude superior to that of a nuclear fission power plant (Velikhov & Putvinsky 1999).



PICTURE 18. Types of radiation and penetration. Mirion technologies. 2015. Types of ionizing radiation. [png]. Released on 03.04.2015. Read on 20.04.2021. https://www.mirion.com/learning-center/radiation-safety-basics/types-of-ionizing-radiation

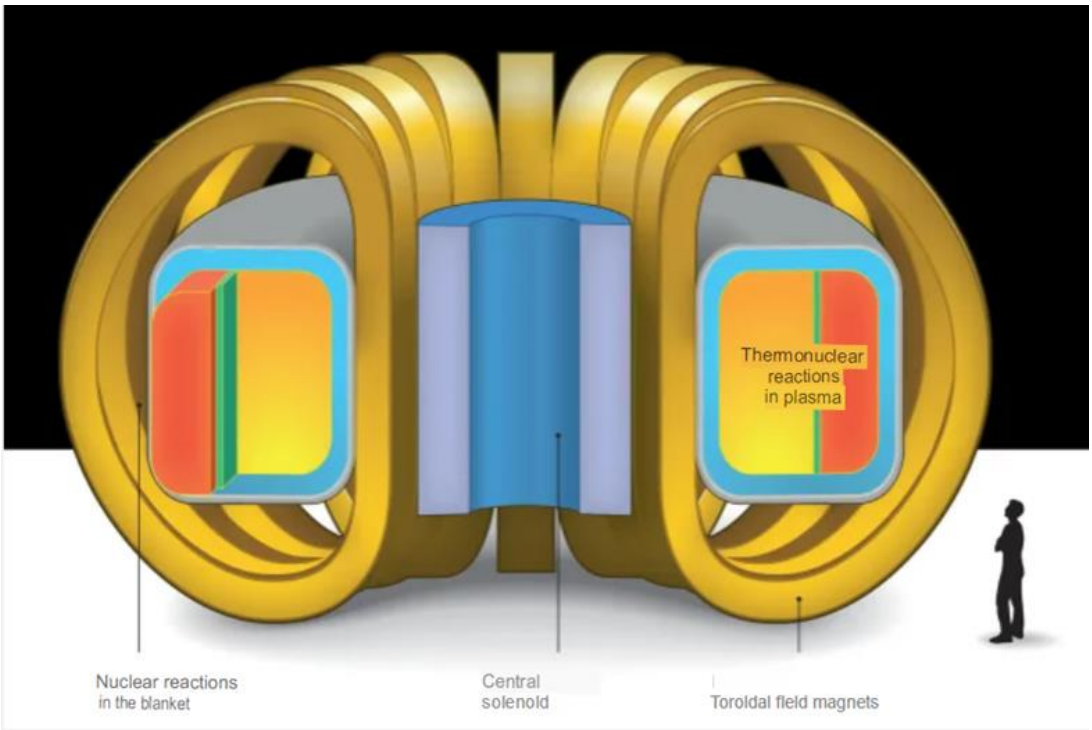
5.8 Resource base

The availability of fusion materials is huge advantage of thermonuclear reaction in comparison with other energy sources. Deuterium can be easily obtained from sea water. There is huge reserve of deuterium on Earth. It is contained in any water: approximately 0,015 percent of included hydrogen. And the water in Earth oceans is inexhaustible. Fast growing demands of humanity in energy would be provided for billions of years (Balabanov 1957, 185).

Tritium, another variable, is almost non-existent on Earth. However, there are technologies available today for processing tritium by irradiating lithium-6 with neutrons. Lithium is a naturally occurring mineral in the Earth's crust. It is possible to generate tritium in fusion reactors. Since lithium-6 deposits are plentiful and only a small amount is needed to turn it into tritium - hundreds of kilograms - it can also be called an almost limitless supply of power. Only the three substances mentioned above are needed to start and run a thermonuclear reactor during deuterium-tritium fusion. (Krasilnikov 2020).

6 HYBRID FUSION REACTOR (HFR)

A **Hybrid Fusion Reactor** (Picture 19) combines thermonuclear and nuclear energy. The concept is not new It was explored at the dawn of nuclear technology growth, but due to significant accidents, it was discarded in favour of the development of renewable energy from thermonuclear fusion without the production of fissile materials. Igor Kurchatov came up with the idea for such an installation. He pointed out that almost half of the energy deposited on Earth is found in three elements: uranium-238, thorium, and interchangeable deuterium and lithium, with the remaining two percent being crude, gas, and coal. A hybrid fusion reactor could run on thorium rather than uranium, which is not only cheaper but has five times the reserves. Furthermore, this reactor does not require very high temperatures or pressure. It is extremely effective in terms of energy recovery; its activity generates much less long-lived highly radioactive waste than needs dependable disposal for tens of thousands or hundreds of thousands of years (Ipatova 2019).



PICTURE 19. HTR model cutaway. Fishman, Popular mechanics. 2019. The third way of nuclear power: tokamak T-15. [png]. Released on 13.10.2019. Read on 23.04.2021. https://www.popmech.ru/science/501272-tretiy-put-atomnoy-energetiki-tokamaka-t-15/

The idea of hybrid fusion is intended to reconcile the advantages and disadvantages of two nuclear generation paradigms: a chain reaction produces a massive amount of energy in a single fission act, while thermonuclear fusion, which generates energy in a smaller volume, contributes to neutron formation without triggering a nuclear chain reaction (Ipatova 2019).

There are two main problems in modern TOKAMAK construction. The first is the interaction of the plasma with the first wall of the reactor. Physicists strive to ensure that deuterium and tritium used as fuel are free of impurities. And if the substance of the material from which the wall is made has a high charge number (Z), then as a result of its interaction with the wall, "pollutants" with a high Z will enter the plasma. Ions with a high Z value have many electrons, and therefore they are able to re-emit a large amount of energy from the plasma, which leads to its losses. Moreover, because of this process, the plasma may even be extinguished, so the material of the first wall must have a low Z (Mirnov 1999, 18).

Another big problem is the organization of long-term plasma burning. Today, the largest tokamaks, such as the JET in England, can hold plasma for ten seconds. It is planned to reach thousands of seconds on ITER. However, plasma needs to burn for hours, and for this it is necessary to overcome two obstacles. The first is to make an electric current flow over a long period of time. To create non-pulsed current generation, methods are needed that are currently only at the development stage. The second obstacle is impurities. As the plasma burns, their number increases and reaches a critical value, which makes it damp. And this is a huge difficulty, because today there is no method to purify plasma from these impurities (Mirnov 1999, 19).

However, a hybrid system does not need a full-fledged nuclear or thermonuclear reactor. The TOKAMAK in it serves only as a source of neutrons that trigger the nuclear decay of fuel in the outer blanket. There is no need for a stable fusion reaction, therefore, it is no longer necessary to comply with the Lawson criterion, and it is enough to heat the deuterium-tritium plasma to relatively moderate temperatures, 30-50 million degrees, and neutrons are formed due to the interaction of beams of deuterium atoms accelerated in injectors with this plasma (Velikhov et. al. 1978, 98).

The nuclear half of the hybrid is also simplified. The decay of the fuel in it should no longer be self-sustaining; it is stimulated by neutrons emitted from the deuterium-tritium plasma. The main function of the thermonuclear part of the reactor was initially to ensure the production of nuclear fuel (isotopes that are fissionable in the neutron spectrum of a nuclear reactor). Within the framework of the modern approach, which considers the nuclear part of the HFR as an amplifier of the neutron current of internal sources (delayed neutrons) and external sources of neutrons, the main role of the thermonuclear part is to ensure a stationary nuclear reaction in a subcritical nucleus with a fast neutron spectrum, that is, in fact, to perform the function control of a fast neutron reactor (Kuteev & Khripunov 2009).

The creation of the HFR TOKAMAK (PICTURE 15) is now becoming a practical area due to the reduction of the requirements for the thermonuclear part due to the elimination of the problem of new radiation-resistant structural materials, a significant reduction in plasma loads on the first wall and divertor of the TOKAMAK. The difference between the modern approach to a hybrid thermonuclear reactor from the traditional one consists in changing the function of a thermonuclear neutron source (Kuteev & Khripunov 2009).

A computer simulation of the fuel cycle of a thorium hybrid reactor, in which a high-temperature plasma contained in a long magnetic trap is used as a source of additional neutrons, was carried out by experts from three Russian institutes (Russian Federal Nuclear Centre - All-Russian Scientific Research Institlute of Technical Physics named after Academician E.I. Zababakhin; National Research Tomsk Polytechnic University; G.I. Budker Institute of Nuclear Physics).
The benefits of such a hybrid reactor over current nuclear reactors include moderate capacity, limited scale, high operating protection, and low level of radioactive waste. The isotopic composition, and thus the nuclear-physical properties of the fuel, change over the course of the installation's life - computer modelling aids in forecasting the evolution of nuclear fuel, considering the multitude of reactions that occur in the reactor (Ipatova 2019).

To date, the hybrid facility's evolution has been modelled, and the reactor's operating modes during the fuel cycle have been determined. The estimated installation's fuel cycle would be 3000 successful days (24 hours of service at 100 percent power level) - after this time, the burned fuel blocks are replaced with new ones, and the reactor is ready for a new fuel cycle. The fuel is selected in such a way that the reactor's multiplication characteristics cause it to meet all safety criteria for the duration of its operation (Ipatova 2019).

6.1 Ecology

In the contrary to nuclear and thermonuclear reactors the hybrid one has the minimum amount of radioactive waste. Furthermore, it is expected that such facilities, in addition to being used in the energy sector, will find application for the disposal of spent plutonium, the destruction of trans uranium elements and some fission products in order to reduce the amount of radioactive waste before its final disposal (Velikhov et. al. 2014, 9).

A hybrid reactor, in which the production of fissile isotopes occurs in a blanket and in which the salt composition is rapidly purified, including from a small amount of fission products, makes it possible to count on the minimum release of radioactivity during the reprocessing process. The released activity per 1 g of the produced fissile isotope will be the smallest in comparison with other methods of conversion of raw isotopes into fissile isotopes (Velikhov et. al. 2014, 9).

Using 232-Th as a raw material, the sequence for obtaining a fissile isotope is as follows:

$$232Th + n \rightarrow 233Th\ (22{,}3\ min) \rightarrow 233Pa\ (27\ d) \rightarrow 233U,$$

a new fissile isotope is produced after a short delay, which further reduces the likelihood of blanket fission and the formation of radioactive fission products. Unlike nuclear reactors, the spent nuclear fuel of a hybrid reactor (salt fuel composition) is processed continuously in such a way that the entire volume of the blanket is processed during the year (Velikhov et. al. 2014, 9).

6.2 Efficiency

One kilogram of Thorium can produce the same amount of energy that is received by burning 3,5 million tons of coal. The assignment of the role of replication of tritium, which burns in the thermonuclear portion, to it is a natural result of the strong increase (multiplication) of the number of neutrons in the nuclear part of the reactor, opening the possibility of using already mastered tritium technologies in the interests of the thermonuclear part of the reactor. As neutrons absorb thorium isotope 232-Th, it is converted into uranium isotope 233-U, which is well separated by thermal neutrons. In terms of energy produced, this reaction is equivalent to that found in nuclear reactors with a fuel cycle that uses only the natural isotopes of uranium 235-U and 238-U (Shmelev et. al. 2014, 8).

If the technological challenge of developing a hybrid thermonuclear reactor based on producing fuel for fission reactors is solved successfully, there will be no need for a fundamental transition in nuclear power structure combined with the substitution of thermal reactors with fast reactors. There will be no need for a deterioration or deep renovation of the nuclear industry's infrastructure, which has been built up over decades. At the same time, this definition should not preclude fast reactors from the scheme, which in certain cases might be more adaptable to the external system than thermal ones (Ipatova 2019).

6.3 Safety

The most promising installation from the standpoint of protection is thought to consist of a subcritical (unable to independently support a chain reaction) reactor and some system (booster) that provides an additional supply of neutrons required to carry the reactor into a critical mode. In the case of an emergency, the booster is deactivated, and the reactor comes to a halt. As a result, fusion reactors would be cleaner than traditional reactors. The peculiarity of using thorium fuel is that when the delivery of extra neutrons from an external source stops in such a hybrid power-generating plant, nuclear fission reactions rapidly decay. Thereby, fusion reactors would be cleaner than traditional ones. The peculiarity of using thorium fuel is that when the delivery of extra neutrons from an external source stops in such a hybrid power-generating plant, nuclear fission reactions rapidly decay. (Krasilnikov 2020)

6.4 Resource base

Thorium-232 is even more widespread than uranium-238. There is 10 grams of this isotope per ton of lithosphere, and it is distributed evenly, so that theoretically it is possible to start mining it in any suitable place. However, for normal nuclear reactors pure thorium is not suitable. To obtain energy from thorium fuel, it must be bombarded with neutrons. After that, it turns into uranium-233, which gives off heat, the amount of which is comparable to the energy from traditional nuclear fuel (Belyaev et. al. 2004, 178).

Monazite, which contains rare earths, is the only mineral containing thorium. As a result, when we discuss thorium as a potential energy fuel, as the next step in the production of nuclear energy, we will inevitably discuss the complicated processing of monazite raw materials and the removal of rare earths - this ultimately makes the industrial use of thorium more economical and appealing (Thorium is the future…2018).

DISCUSSION

Everything that human creates – machines for facilitating labour, new means of transport, rockets - everywhere energy is needed. However, mastered energy reserve on Earth is non-renewable. Moreover, these substances are valuable chemical raw materials and nowadays it is irrational to burn fuel in stream boiler furnace. It can be said that the world is interconnected ecologically and interdependent energetically and economically. Liquid fuel prices have changed - gas prices have fluctuated. The production of solid fuels has decreased - the prices for gas and fuel oil have risen.

People are creating giant industrial systems for obtaining, converting, and consuming energy from coal and oil, solar energy, wind energy, geothermal nuclear energy, and many other types of energy. The functioning of these power systems is associated with high costs of materials, with a high level of production and services, with the cost of energy to obtain useful energy. Therefore, it is often overlooked which systems consume more energy than they produce. Many ways of using energy are associated with environmental pollution, which from an energy point of view interferes with the functioning of energy flows of the life support system of this environment.

Overall, due to the global situation and estimations it has been concluded unambiguous decision to reject the usage exhaustible resources as soon as possible. Thereby, some countries have already set the course on the development of the alternative energy sources. However, in fact the likelihood of replacement the whole coal-oil-gas-based energy supply cannot be done with only one energy source of today, such as renewable, nuclear or thermonuclear energy. So-called green energy resources combat the carbon footprint issue. At the same time, the world is only at the very beginning of automotive electrification, not all countries are suitable for possessing renewable appliances as the main source of energy and climate conditions are of high importance.

Nuclear energy does not produce harmful emissions by itself, however it has other issues. The first one is radioactive waste from nuclear fission by-products, that nowadays is difficult to eliminate because of inappropriate waste storage and radiation disease can be one of the results of it. Another issue is the small but still likelihood of the explosion repeat, as at Chernobyl and Fukushima, caused by uncontrolled chain reaction of nuclei. Besides, nuclear power plants use the energy of nuclear fuel that the widespread use of it is limited by not large reserves of uranium on Earth. Thus, nuclear energy also is not a complete substitution for today considering constantly increment of energy consumption. Therefore, one needs to give the preference to the alternative ways of energy production.

The energy of controlled fusion of light nuclei - thermonuclear reactions - can be the potential for production of basic energy. Over the last years, continuous advancement in the field of thermonuclear fusion has resulted in a slow improvement in plasma parameters in thermonuclear instruments. However, the complexity of the controlled plasma is still not solved and necessitates the refinement. Thereby, it can replace the conventional energy sources but only in the long run. Throughout the study the analysis of the different nuclear power reactors have been led and the main items are put into the table (Table 2) below and comparison of three reactors has been done and classified by four factors as ecology, efficiency, safety and abundance.

	Eco-friendliness	Efficiency	Safety	Resource base
Nuclear Reactor	European Commission puts the nuclear energy on a par with alternative renewable energy sources such as sun and wind. The inclusion of long-lived chemically active fragments of nuclear waste necessitates their careful disposal for hundreds of thousands or millions of years.	**1 kg of Uranium=100 tons of coal=60 tons of oil** The stable electricity prices over a long period and essentially cheaper than electricity based on fossil fuels.	An uncontrolled chain reaction may occur, which may lead to a catastrophe.	The resources of **Uranium** ore suitable for nuclear fuel are nearing exhaustion.
Thermo-nuclear Reactor	The absence of long-lived radioactive waste. The reactor ended its lifespan has to be preserved only for 30 years, after what these materials could be recycled and used in new reactor.	**1 litre of water=8 tons of oil** The electricity price will be 1.5-2 times higher than the price of electricity produced by thermal power plants. The construction cost of reactor for today is much higher compared to nuclear fission reactor.	Inability to enter the mode of uncontrolled increase in power. During the operation radioactive elements accumulate in it.	**Deuterium** is contained in any water. **Tritium** is almost non-existent on Earth. **Lithium-6** are can also be considered as almost inexhaustible source of fuel.
Hybrid Fusion Reactor	The spent nuclear fuel is processed constantly during the year. Minimum radioactive by-products. Recycles end-materials of other plants' waste.	**1 kg of Thorium=200 kg Uranium=3,5 million tons of coal** The ability to built the machine now. No radical change in the structure of nuclear power.	The chain reaction is not possible to occur.	**Thorium** reserves in the earth's crust are 4 times higher than uranium.

TABLE 2. The comparison of three types of nuclear reactors.

Thus, the main candidate for the settlement the whole new system of energy supply of the current time as well as the future is the combination of the most promising energy sources for now – nuclear and thermonuclear reactors- Hybrid Fusion Reactor. The key paradigm alteration in the progress of nuclear and thermonuclear systems consist in moving away from the period of separate existing and mutual competition in favour of the search of synergetic ways of the development with the ultimate utilization of the positive sides each of energy systems. It is vital that the new approach has smaller in scale tasks, expenses, what expands the field of application.

The main advantage of such an appliance as Hybrid Fusion Reactor is the possibility to build it now. Nowadays there is no barriers that do not allow from scientific and applied point of view to create the machine. The high efficiency consists in the reduced requirements from both nuclear and thermonuclear parts of the hybrid reactor. Furthermore, the chain reaction is not possible to occur in this type of the reactors because in case of the disturbance of the balance of energy in plasma the burning stops by default, which is the crucial safety factor. Another benefit is that not only hybrid reactor produces the minimum radioactive by-products by itself, but also has it the ability to recycle end materials of other plants' waste. The application is comparatively plain for setting if take into consideration nuclear or thermonuclear reactors separately.

To obtain energy, hybrid nuclear-thermonuclear reactors use simultaneously the reactions of fission of heavy nuclei and fusion of light nuclei, therefore, it can be expected that such installations will enhance the positive features and neutralize the disadvantages inherent in power engineering based on the separate use of these nuclear reactions. To effectively use the reaction of controlled thermonuclear fusion in energy production, it is necessary to first obtain and then constantly maintain a stable state of plasma with a very high temperature (above 100 million °C) at its high density.

The creation of a reactor operating according to a hybrid scheme seems to be an easier task, since in this case the plasma is not used to obtain energy, but only as a source of additional neutrons to maintain the necessary scheme for the course of nuclear reactions. Under conditions when neutrons are generated in the plasma, which additionally enter a nuclear reactor, it becomes possible to replace a large (up to 95%) part of the fissile uranium used as fuel with non-fissile-feedstock - thorium. In contrast to uranium, thorium is represented in nature by practically one isotopic state, and therefore it is easily and at low cost isolated from natural raw materials. Thereby there is no resource-shortage issue, every-one will be able to consume energy for low price and as oil will not yet be the main index for establishing world prices, hence the prices will start decreasing.

CONCLUSION

To sum it up, the response to the question about potential of different energy resources of the current time and future has been found. Throughout this work the materials were studied and the analysis were held that permits to evaluate the current situation in energy field. The conclusion involves the fact that the most potential candidate to produce basic energy is nuclear energy. As it has been studied nuclear energy the cleanest energy source for today. Besides, in comparison with other energy sources it put the environmental considerations at first place and operates without disturbing the balance of nature.

The research upon nuclear fission and thermonuclear fusion has been conducted, two ways of receiving energy has been analysed, relying on modern investigations, current worldwide projects, scientific articles, and other sufficient materials. The advantages and disadvantages have been considered. Thus, the assumption has been made, based on the explored data, that in the nearest future approximately by the middle of this century the Hybrid Fusion Reactor has huge probability to become if not the only, at least one of the main resources of energy supply in the contrary to separate systems of nuclear or thermonuclear energy systems. As the Hybrid Fusion Reactor combines all the modern necessary features, opens the ability of cheap energy source and responses to the current agenda, including high safety, ecological purity and economically efficiency.

REFERENCES

Aiseadha, C., Quinn, G., Connolly, R., Connolly, M., Soon, W. 2020. Energy and Climate Policy - An Evaluation of Global Climate Change Expenditure 2011-2018. 09.2020, 7-8.

Aleksandrov, A. 2015. On the energy of the future. Collection of scientific papers. Moscow: Nauka.

Artzimovich, L. A., Sagdeev, R.Z. 1979. Physics of plasma for physicists. Moscow: Atomizdat.

Azizov, E. A., Alekseev, P. N., Asmolov, V. G., Kukharkin, N. E., and others, 2013. I.V. Kurchatov and A.P. Aleksandrov on the strategy of nuclear energy development. Moscow: Scientific Research Centre Kurchatov Institute.

Balabanov, E.M. 1957. Nuclear reactors. 1st edition. Moscow: Military Publishing House of the Ministry of Defense of the USSR.

Balabanov, E.M. 1963. Thermonuclear reactions. 1st edition. Moscow: Military Publishing House of the USSR Ministry of Defense.

Belyaev, L.S., Lagerev, A.V., Posekalin, V.V., and others. 2004. Energy of the XXI Century Development conditions. Technologies. Forecasts. Novosibirsk: Nauka.

Burghila, D., Bordun, C., Doru, M., Sarbu, N., Badea, A., Cimpeanu, S. 2015. Climate Change Effects – Where To Next?

Comby, B. 2009. Environmentalists for nuclear energy. Paris: TNR Editions.

BP Statistical Review of World Energy 2019. 2019. 68th edition. London: S&P Global Platts.

Ekkert, M., Schöpe, M., Bazilian, M., Møller Porst, K., Barroso, L., and others. 2018. Global Energy Transformation. IRENA International Renewable Energy Agency. Abu Dhabi. 04.2018, 8-10.

Fishman, R. 13.10.2019. Popular mechanics. The third way of nuclear power: TOKAMAK T-15. Read on 23.04.2021. https://www.popmech.ru/science/501272-tretiy-put-atomnoy-energetiki-tokamaka-t-15/.

Gasparatos, A., Doll, C.N.H., Esteban, M., Ahmed, A., Olang, T.A. 2017. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. Renewable Sustainable Energy Review, 161–184.

Gielen, D., Gorini, R., Leme, R., Prakash, G. and others 2021. World Energy Transitions Outlook: 1.5OC Pathway. IRENA International Renewable Energy Agency. Abu Dhabi. 02.2021, 9-14.

Gordienko, V. A., Brykin, S. N., Kuzin, R. E., Serebryakov, I. S., Starkova, M. Ì., Tairov, T. N. 2011. Comparative analysis of radioactive pollution generated by nulear power plants and the coalpower thermal stations. Moscow: Moscow University Physics Bulletin 1.

Gott, Y. V., Kurnaev, V.A. 2017. Towards the energy of the future. Moscow: National Research Nuclear University MEPI.

Grainger, L., Gibson, J. 1982 Coal Utilisation Technology, Economics and Policy. Springer Netherlands.

Griibler A., Jefferson, M., Nakicenovic, N., 1996. Global Energy Perspectives: A Summary Of The Joint Study By Iiasa And World Energy Council.

Hansen, J., Sato, M., Hearty, P., Ruedy, R. and others. 2016. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. 04.2016, 39-41.

Harris, R., Xia, G., Zhou, L. 2014. Satellite Observations of Wind Farm Impacts on Nocturnal Land Surface Temperature in Iowa. 12.2014, 3-5.

Ilkaev, R. I., Garanin, S. G. 2006. Investigation into Thermonuclear Fusion at High-Power Laser Facilities. Moscow: Bulletin of the Academy of Sciences.

International Atomic Energy Agency Annual Report 2006. Vienna.

International Energy Agency and Nuclear Energy Agency. 2015. Projected costs of generating electricity. Paris.

International Energy Agency. 10.2020. World Energy Outlook 2020. Read on 06.04.2021 https://www.iea.org/reports/world-energy-outlook-2020.

Ipatova, U., Nuclear Expert. 02.03.2019. Era of thermonuclear fusion. Read on 06.04.2021 https://atomicexpert.com/era_of_thermonuclear_fusion.

Ishkhanov, B.S. 2011. Radioactivity. Moscow: Universitetskaya kniga.

Joint Research Centre (JRC), 2021. Technical assessment of nuclear energy with respect to the ‘do no significant harm’ criteria of Regulation (EU) 2020/852 (‘Taxonomy Regulation’).

Kessides, I. N., Wade, D. C. 2013. Toward a Sustainable Global Energy Supply Infrastructure. Net Energy Balance and Density Considerations. The World Bank Development Research Group Environment and Energy Team. 01.2013, 4-5.

Krasilnikov, A., 29.12.2020. Thermonuclear reactor. Read on 06.04.2021 https://postnauka.ru/longreads/156011.

Kuteev, B. V., & Khripunov, V. I. 2009. Modern look at a hybrid fusion reactor. Moscow: Kurchatov Institute.

Leshkovtzev, V. A. 1954. Nuclear energy. Moscow: State Publishing House of Technical and Theoretical Literature.

Lukyanov, S. U., & Kovalskiy, N. G. 1997. Hot plasma and controlled thermonuclear fusion. Moscow: Atomizdat.

Mamedov, F. 19.10.2020. Green Turn: How Europe is Shifting to Renewable Energy. Read on 06.04.2021 https://ecosphere.press/2020/10/19/perspektivy-i problemy-zelenoj-energetiki-v-evrope/.

Mirnov, S. V. 1999. TOKAMAKs: triumph or failure? E. 11. Moscow: Priroda.

Mukhin, K.N. 1969. Intertaining nuclear physics. Moscow: Atomizdat.

Nuclear Energy Agency, The Environmental and Ethical Basis of Geological Disposal, A Collective Opinion of the NEA Radioactive Waste Management Committee, OECD, Paris (1995).

Patterson, R. 2016. World Energy 2016-2050: Annual Report. 06.2016, 27-28. https://content.csbs.utah.edu/~mli/Economies%205430-6430/World%20Energy%202016-2050.pdf.

Shmelev, A. N., Kulikov, G. G., Kurnaev, V. A., Salakhutdinov, G. Kh., Kulikov, E. G., Apse, V. A. 2014. Hybrid Synthesis-Fission Reactor with Torium Blanket. About Its Potential in the Fuel Cycle of Nuclear Reactors. Moscow: National Research Nuclear University MEPI.

Smirnov, V. P. 2003. Bulletin of the Russian Academy of Sciences. Research about thermonuclear synthesis. 11.2003, 299-313.

Stocker, T. F., Qin, D. 2013. Climate change 2013 The Physical Science Basis. Intergovernmental Panel on Climate Change. 09.2013, 13-29. https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf.

The Rare Earth Magazine. 25.01.2018. Thorium is the future of nuclear power and the arctic. Read on 11.05.2021. http://rareearth.ru/ru/pub/20180125/03686.html

Treshcheva, M., Treshchev, D., Anikina, I., Skulkin, S. 2019. The potential for reducing TPP water consumption through the use of heat pumps. Peter the Great St. Petersburg Polytechnic University, St. Petersburg.

Velikhov, E.P., Davidenko, V.D., Tsibulskiy, V.F. 2019. Some thoughts on nuclear energy future. Moscow: Kurchatov Institute.

Velikhov, E.P., Glukhikh, V.A., Guriev, V.V., Kadomtsev, and others. 1978. Hybrid Thermonuclear Reactor TOKAMAK for Fisible Fuel and Electric Power Production. Nuclear Energy.

Velikhov, E.P., Kovalchuk, M.V., Azizov, E.A., Ignatiev, V.V., Subbotin, S.A., Tsibulsky, V.F. 2014. Hybrid Thermonuclear Reactor for Production of Nuclear

Fuel with Minimum Radioactive Pollution of The Fuel Cycle. National Research Center Kurchatov Institute, Moscow, Russia.

Velikhov, E.P., Putvinsky, S.V. 1999. Thermonuclear energy. Status and role in the long-term perspective. Report within the Energy Centre of The World Federation of Scientists.

Zhunisbekov, S., Dzhakiyaev, D.K., Zhashen, S.Zh. 2019. Environmental Problems of Radioactive Ore Mining in the Mining Industry of Kazakhstan. Philadelphia.