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Is Nuclear Fusion Losing the Race with Global Warming?

Vladimir Knapp, Nikola Dragić

Summary — **According to plans for development of fusion energy, the first stage is construction of device tokamak ITER [1] with main task of establishing burning gas plasma with required stability and duration. This stage should be accomplished by 2035, starting in 2005. The next stage should be the construction of complex DEMO [2] with the task of producing all the equipment for energy production and finally producing large amounts of carbon free energy. We do not want to make predictions on the outcome of fusion program, wishing the final success to the thousands of scientists and engineers who are contributing to this heroic effort. However, there are reasons to think (Seife [18], Stork [7]) that the time is too short. Starting with a planned date of end of work with ITER by 2035, we estimate that one needs to add 25 years for development of DEMO. We cannot see production of fusion energy before 2060. However more reliable energy sources are recommended when our existence is in question. We have problems with remarks by Stork and Seife. If solar, wind and hydro energy, and nuclear fission with high safety reactors can be deployed earlier than fusion, it must have a preference.**

Keywords— **nuclear fusion, DEMO, ITER, tokamak, nuclear fission, PWR, molten salt reactors, solar energy, OTEC, global warming, climate change**

I. Introduction

Planning a concise observation, it is firstly to mention on information that ITER project with tokamak-type devices and the realization of the fusion reaction is planned to be achieved in 2035. Here, it will not be widely commented on this time projection, convinced that it is in the nature of scientific work that the outcome cannot be precisely determined. This article and our considerations are limited to tokamak systems and do not consider inertial systems due to unsolved problems of required high repetition laser.

Tokamak is the way of stabilizing plasma by combination of two magnetic fields, one along the axis of symmetry of the torus and the other field perpendicular to it, Figure 1. Tokamak is the Russian name for a type of fusion device that became dominant in the 70s when the stability of the plasma in a closed toroid was improved by several orders of magnitude. In tokamak device plasma is confined using helical magnetic field being sum of poloidal magnetic field component (toroidal plasma electrical current and poloidal external coils) and toroidal magnetic field component produced by external toroidal field coils, Figure 2. Injected neutral particles and ions and radio-frequency excitation are used for plasma heating.

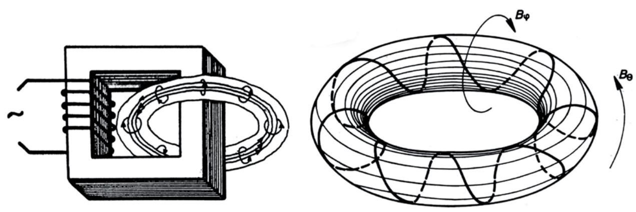

Fig. 1. Schematic diagram shows a transformer in which the secondary coil represents the burner heater. The main coil produces a toroidal field Bθ, the smaller one produces a perpendicular Bϕ to the main field.

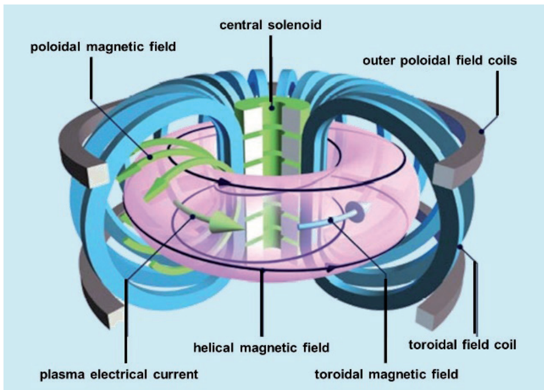

Fig. 2. ITER Tokamak magnetic field lines for plasma confinement, plasma major radius 6.2 m [28] (Figure source: https://www.iter.org/)

Based on the scientific knowledge on the ITER project, the way will be to bring the project to the end, that is, to prove that is possible to achieve stable plasma with ITER at sufficient temperature and plasma density, or, alternatively, to give a convincing denial. Therefore, it is likely that there still will be work on the fusion project with a lot of research even after the work on ITER is finished. That is why it is good that the dates in the DEMO project resulting from the Fast track strategy, the rapid development of fusion to energy production, were omitted. After the mastery and successful control of the fusion reaction in ITER, the development of the DEMO device aiming achieve energy production follows. In this phase, there is a lack of definiteness in the final phase for the same reason, requiring progress in several independent directions. It is about the introduction of many components in the chain from nuclear heat exchange to the con-

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version into kinetic energy of rotation with extreme and simultaneous demands on superconductors as well as on the physics of high-temperature plasma. The problems to be faced in DEMO phase relate primarily to material properties and changes under long-term radiation with high doses of radiation.

This view of research priorities in nuclear fusion is based on years of monitoring the development of research due to the importance of fusion energy. Completion of the first phase and conditions for the realization of the fusion reaction implies a sufficient duration of stable plasma with the necessary gas plasma density. This should be achieved by 2035 according to the latest report of the general director of the ITER project [3], Bernard Bigot who recently passed away, replaced as Director general by Pietro Barabaschi.

This report is the official and authoritative document on the progress of work on the international ITER fusion development program. It is a major project that continues the development of the concept of the most successful magnetic plasma confinement in toroidal geometry to date. In this paper we do not consider alternatives to tokamak configuration before 2035.

We must give a good try to the most promising concept which was developing over several decades. After such studies promising good results, it would not be difficult to put the blame on a too early decision to start with a big project rather than with more science of plasma burning. However, the time for producing the results was short and limited. The choice was between the assumed initial successful operation of ITER as could have been achieved by 2035, and some promising but untried new geometry.

Our understanding is that alternative devices after 2035 should be oriented to use of developments applying the maximum use of DEMO technology. An entirely different approach would prolong the road to fusion and be deleted for this reason. We are about to see one of the most expensive but understandable mistakes in science, due to the pressure of date.

The authority and the science behind one of the largest international projects cannot be underestimated. But also, the question of a great new source of energy without the emission of greenhouse gases remains unanswered. Global warming threatens to seriously endanger humans within 20-30 years [4], which is shorter than the time in which we can make a decisive contribution to combating global warming if society does not mobilize without delay. When it comes to other, faster ways, we think it is interesting to look at the development of the usage of sea heat based on new estimates of the economics of OTEC [5]. OTEC could be used with double benefits of cooling the hot southern shores of the Mediterranean while producing hydrogen from sea heat. A number of solar heat conversion installations exist in tropical seas, and the economics change with rising temperatures. Mediterranean regions with warmer sea can be interesting. When it comes to endangering survival, it should be emphasized that the degree of endangerment depends on the immediate situation; large areas of Africa and Asia will be most exposed due to climate extremes and under development and poverty. Those regions require priority. But even rich countries such as the USA and Canada cannot resist a rise in global temperature above three degrees for a long time when the action and activation of feedback positive links such as the melting of the Antarctic ice, the melting of the Greenland ice, the melting of permafrost and the release of methane, large fires, conditions for the creation of hurricanes, for which the sea is warmer than 27°C.

II. Recent work on magnetic confinement fusion

The recent report on fusion work is in the publication SOFT 32nd Symposium on fusion technology was held September 18-23, 2022, in Dubrovnik, Croatia [6]. The symposium provides fresh information on the development and construction work of new equipment for tokamak. Before the last SOFT F4E conference, eight large superconducting toroidal and three poloidal coils for ITER were manufactured, among others. These are the valuable contributions of hundreds of papers from which one can have information about progress on the broad front of efforts to step by step approach the stage goal of mastering the fusion reaction. Of course, this is not the place or space for a more detailed comment on present the development of fusion, but it can be concluded that it is taking place in accordance with the plan of completion of ITER in the planned period by 2035. A long-term comprehensive program for the development of fusion energy, including the estimate of helium reserves, prepared by Derek Stork [7] allows these necessary systematic contributions to be placed in the group of necessary research.

Unfortunately, the short-term influence of nuclear magnetic fusion is unlikely, but in the long-term it is possible. The fusion device is necessarily large, like ITER, or slightly larger, due to the principled impossibility of achieving a stable plasma on small devices. In addition, we demand the simultaneous development of both low temperatures and the physics of high plasma temperatures. In addition to the well-known problem of plasma stability, we have one major problem, in inadequate resistance of materials to large doses of radiation. A problem which DEMO has to solve is the development of radiation and heat resistant materials. A critical spot for fusion with tokamak magnetic plasma confinement is radiation damage to the first wall of the chamber where the plasma burns. The key question is whether the first wall will be sufficiently resistant to ionizing radiation to withstand a huge neutron flux of energy 14.3 MeV, of the order of several times MW/m2. The fusion power plant would necessarily be large, if we do not want to lose the advantage of a smaller radial change of the magnetic field. But the dimensions of ITER are probably a balanced upper limit for a project financed from the funds of quite a number of influential participating countries [8].

Present choices for the construction of large system elements should be supported in general but the justified warning by Seife [18] should be given due attention. The design power of ITER is 500 MW, with a major plasma radius of torus of over 6 m, a large construction, and a costly investment. Considering the dimensions of ITER, the starting point of design could be the upper limit for the load on the first wall of the radiation chamber. Design value determined by many considerations, is energy flux around 10 MW/m2. If the first wall is to have a durability of 4 to 10 years, a comprehensive analytical study by 2009. Derek Stork [7] assumes a replacement time of five years and a replacement operation taking two years[1]. As can be seen, the essential characteristics of magnetic fusion device are closely related. A detailed consideration of the complex relationships of the main characteristics of the fusion power plant with tokamak magnetic limitation resulted in balanced, desirable, and physically acceptable design values of the dimensions and power of the power plant. Values are the result of numerous compromises dependent on future technological development. Long-term guidelines for this development and key dependencies are provided so that this study has lasting value.

We must consider the increasing possibility that fusion development cannot be done in time for global warming intervention, which means that we cannot use it before 2065 (2035+25+5, +required time to bring the plant to efficient operation, our estimate based on years of work with fission), based on the assumption that the DEMO device can be effective for operation in 2065. This commissioning date was obtained by adding 25 years to the information on the completion of work on ITER by 2035.

[1] It is too early to predict developments in solid states as far as 30 years in future.

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We will be able to determine the reality of this assumption only sometime after 2040. Considering the planned serial construction of fusion power plants, we must be prepared for delays. There could be various reasons for the delays. The first is in plasma combustion control. The DEMO device could be delayed, for several possible reasons, such as the unsatisfactory behavior of structural and other materials. As in fission many defects will show only in long use. Radiation would cause the change in mechanical properties, in fragility and strength and other material characteristics. For DEMO, the planned power per unit area of the active exposed electrode is about ten MW/m2, which is a huge intensity of radiation, dominantly produced by neutrons of energy 14.3 MeV. The second category of changes are changes in physical and chemical properties due to the activation of materials under massive radiation with 14.3 MeV neutrons. This again results in enormous, induced radioactivity, both in constructive materials and in most other materials. Considering a series of related project sizes, a projected surface load of 0.1 to 0.3 MW/m2 was chosen, which corresponds to the total projected maximum power flow of 500 MW from ITER.

To build a complex development as DEMO in 10 years is an impossible task. If we add 10 years, probably yes, but what do we have? It is difficult to imagine a more complex device, which is essentially dependent on the operation of all components, than the fusion power plant. The operational problems can be solved too, but that could take a much longer time. The operation of a fusion power plant would require special protective measures due to the super-intense neutron radiation. In the initial phase of operation of superconducting magnets, it would be necessary to have a number of low-temperature laboratories, equipped for quick interventions. Materials resistant to mega doses of neutron radiation, which have yet to be developed, are a much bigger problem. Assuming series of about 50 fusion power plants in operation, it would not essentially contribute to the solution of global warming, as it would be accompanied by frequent stoppages. Such a situation is expected based on the experience from the early days of fission power.

The construction of fusion power plants DEMO can be expected in the years around 2060, by being technically complete. But from the "utility use" point of view, users should see which of the utilities requirements for security and economy are acceptable or enforceable. This could cause indefinite delays. In Derek Stork's analytical study [7], the problems encountered during the construction of devices that belong to the DEMO circuit are systematically and thoroughly discussed, in as much it could be done without final dimensions of DEMO. The DEMO device is generically closely related to the development of ITER in the sense that there are many related developments when the main goal is to achieve the fusion reaction. The current perspective is that fusion will be expensive, relative to fission, at least because of the additional systems for heating the plasma and cooling the magnets. The operation of cooling devices must be reliable for long periods in an intense neutron flux. Operation at nominal fusion power should be demonstrated and verified over an extended period. An important parameter, beta [7], closely related to the strength of magnetic field, must be within the design limits according to DEMO design. Resistance to mega doses of radiation will be possible to check with a specially developed high-current neutron generator to be completed before 2035. DEMO should monitor production of tritium, the change in beta value during the operation of the power plant, and all other complex manipulations with the divertor[2]. It would serve to react to unexpected changes in the beta value. One has the impression that too many development problems were transferred to DEMO phase. Important results are expected from the Japanese tokamak JT60-SA, smaller device of tokamak type, for supporting ITER research. The development of tungsten divertors is expected. A significant contribution to development is expected from the introduction of new high-temperature superconductors.

It is to be aware of many problems and difficulties that have arisen, recently described in Charles Seife paper [18]. Even in a case that they are resolvable, they will require a lot of time for more demanding structural changes. The long-term perspective of the proposed changes is to be considered.

The general impression after reviewing the plans is that it leaves many important questions insufficiently determined, which is understandable given more than ten years since the publication of Stork's analytical text from 2009 on fusion with magnetic toroidal confinement. Considering that it will take from the concept of ITER to its final form in some thirty years, by 2035, our estimates that the work on DEMO will be completed and operational within 25 years, or up to 2060, seem optimistic. We believe that there are still too many open problems in the development of fusion on the way to an economical carbon free energy source, to be understood and accepted as a solution to global warming. We suggest that the burden of deadlines should be removed from the fusion project and that it would be free for new approaches that could have a chance to be successful in the battle against global warming. A combination with fission could be lifesaving for tokamak fusion by extending development time. We believe that the space for new ideas in energy production is decreasing, and the rich source of nuclear fission energy has been ruined by politics.

Nobel prize winner Noel-Baker conducted an early survey [9] of these unfortunate years. But for intervention by Stalin at Peace conference of 1946 the evil spirits of nuclear war would remain closed. The scientist's words of warning would not be listened to. We may recall the greatest blunder committed at the UN peace conference in 1946. Generous offer (Baruch plan) [13] by USA at UN conference in 1946, to place nuclear energy under UN control (IADA), International Atomic Development Agency. Refused by Soviet Union (already developing nuclear weapons with help of German scientist Claus Fuchs). This marked the beginning of the nuclear arms race. These are the most regrettable acts in the history of the last century. It resulted in the most dangerous nuclear arms race between the United States and the Soviet Union during the Cold War. By the 1970s the arms race was in full swing driven by military logic, almost leading to the destruction of our world.

The vast amount of physical energy, instead of being the basis of well-being for all, has become the threat of destruction for all. But despite the long-term problems with fission, especially with nuclear proliferation, nuclear fission benefices intervention is possible at least 20 years earlier than with fusion, which makes an essential difference in the fight against global warming. We must accept some long overdue decisions when using low enriched uranium. We are using low enriched uranium in many thousands of tons in peaceful use of nuclear energy. The US design of PWR reactors with containment building gives the annual probability for heavy damage to the reactor as low as 10^{-8} annually which is a high level of safety even by nuclear standards. Apart from the possibility of a person or group finding the way to doomsday cabinet, we are facing the certainty of horror and mass dying due to climate change. We should and must make the difference between uncontrollable forces of nature advancing and threatening to end the human race, and the risks that are small and controllable.

If there is a chance with the proposed intervention fission program, then any following and further development will be enabled.

[2] Electrode especially exposed to radiation, a structure from the combustion chamber, most exposed to radiation.

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III. the Construction of intervention fission power plants As a reliable and proven technology

The development of fusion power plants will experience similar problems as the development of fission power. It took many decades to develop safe fission power plants. At the same time, fission power plants are significantly simpler than fusion power plants because of the absence of complex devices for heating the plasma and cooling the magnets to low temperatures. Various defects with structural and other materials were discovered and largely resolved by monitoring the operation of fission power plants over many decades. It would be possible to build a series of about one hundred fission power plants as an international project in the next decades (2024+10+40, start of construction and operation), starting with 10 years of preparation and construction of the first power plant and ending by the completion of the construction of the last power plant during 2063-2065. At least half of these power plants could enter operation by 2050, and most by 2063-65.

With reliable technology and construction systems developed over decades, this endeavor can be accomplished and repeated using construction with established practices. There are numerous researched locations available for fast construction. The building of the fission power plant should not last longer than five years (the present situation is that many projects were experienced unjustified delays). This experience does not exist with new fusion power plants. The scientific and development capital invested in nuclear fission energy for 80 years is a unique example of development with different motives in different world regions, but which contributed to that magnificent undertaking started with the Manhattan Project in the forties of the last century in which leading American and world scientists participated. Unfortunately, politics turned that development into a nuclear arms race, but now there is an opportunity for nuclear fission energy to return with an essential contribution to the solution of the problem of global warming. Now that climate change is on the rampage, every year we gain, counts. Nuclear fission power plants could be in operation starting in 2034, which means at least some 20 years earlier than the operation of the first fusion power plant. Failure to act in a timely manner will result in an unavoidable climate catastrophe. We could gain at least 20 critical years before nuclear fusion could be ready. Who can accept responsibility for delaying feasible counter measures with proven construction of very safe fission power plants? The position of accepting the risks of fission energy instead of inevitable climate catastrophe has been discussed for many years in particularly eloquent words by James Lovelock [10] and Jim Hansen [11], leading world scientists concerned in survival.

We hope that a subjective risk assessment can change significantly now that we are already witnessing the rapid onset of disruptive climate chaos. We should understand that each year closer to 2070, we expect to see substantial changes in planned fusion energy production. Generally, we can have doubts about long energy projects starting in these years to be completed before next century. Such a planning in the next century is questionable for most long-term projects. Hope to be wrong in this pessimism but it takes some imagination to guess what is in the store for us.

Close to 440 nuclear power plants are in operation today. The last major accident involving PWR (Pressurized Water Reactor) [17] core meltdown happened in 1979[3] when a very small fraction of radioactivity escaped over border of the plant. Since then, safety of the PWR reactors has been vastly improved and the escape of radioactivity from massive containment is practically impossible. The advantage of PWR type reactors is that due to the relatively compact pressure vessel and the steam generators, they all could be placed inside very safe containment building. Radiation escape should satisfy the strictest regulations. There is only one of the possible sources of non-fossil energy, apart from abundant solar energy which needs much faster development. The next series of fission based power plants may be based on thorium reactors which are from this year in testing mode in China with a plan for more massive commercial use in following decades soon after the test phase [21]. The thorium or molten salt reactors which are promising to be more cost effective and less technical demanding with less impact on the environment providing additional safety [22].

We are entering a phase where more urgent measures are needed, but the available selection of sources is more limited.

Nuclear fission is ready and available to use while nuclear fusion is developing. Who could accept the responsibility of not supporting the construction of the first hundred safe and reliable nuclear fission PWR power plants that could be put into operation starting in 2034. That would be at least precious twenty years before the first fusion power plant could enter operation.

IV. Conclusion

Nuclear fission as a reliable and proven technology can help save the earth from climate change consequences before full-scale fusion energy is developed. We believe that this introductory text is correct in assessing the perspective of fusion. A positive outcome is possible with the ITER project and would be sufficient to support continued development of fusion. It is suggested to remove the deadlines for achieving the commercial production of fusion energy, and in the meantime to use sources without CO_2 emissions, including safe fission, under the control of the IAEA. The need to intensify the development of solar energy in all its forms exists, including ocean heat, independent from day-night cycle. As an example of what could be achieved by determined effort in years, we propose to put one hundred nuclear fission power plants into operation in the period 2034-2063/65. Highly developed intervention fission power plants of PWR type with pressure containments could enter operation at least twenty years earlier than fusion, which would be precious years in the battle against global warming. If fusion fails or is too late to use, no one can object to continued use of fission energy to counter the cause of global warming [19] [20]. Recent articles on global temperatures rise telling 2023 is the hottest year on record, with global temperatures close to the 1.5°C limit, Copernicus [25], do not give the optimism as well as the recent text on future of the fusion, P. Sutter [26]. If closing to date of decision when it must be clear that a chance of fusion source is seriously delayed beyond the chance to continue meaningful efforts to stop global warming, we have to acknowledge that clearly. The length of preparation period should be at least several years, but it cannot be shorter than five years (before 2055).

[3] Most serious accident on PWR plant occurred on the reactor from the Three Mile Island in 1979. Pressure vessel internals suffered heavy damage from partly molten reactor core, but only very small part of radioactivity escaped beyond the border of power station. In years later many improvements on containment building have additionally increased safety.

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