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CONFERENCE REPORT

The IAEA's international fusion and plasma physics activities—report on the 49th regular session of the IAEA General Conference and the 8th Scientific Forum

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1. Introduction

Research in controlled nuclear fusion has self-sustainable burning plasma as its goal, and good progress has been made in recent years towards this objective by both inertial and magnetic confinement. Large new facilities are currently under construction, and detailed information on their progress can be found in a recent publication by the International Fusion Research Council [1]. A special issue of *Nuclear Fusion* also presents technical progress, as reported during the International Atomic Energy Agency (IAEA) Fusion Energy Conference 2004 in Vilamoura, Portugal [2].

The decision to construct ITER at Cadarache, France, was made on 28 June 2005. Soon after this decision, India joined the ITER partnership of China, the European Union, Japan, the Republic of Korea, the Russian Federation and the USA, showing the increasing worldwide interest in this endeavour. ITER is expected to gather much academic and public attention, and thus attract an increasing number of young scientists and researchers towards fusion and plasma physics and nuclear sciences in general.

The technological and organizational challenges were discussed during the 49th IAEA General Conference in September 2005 by countries involved in the joint ITER undertaking. Round table discussions during the Scientific Forum showed the increasing interest of developing Member States to join the fusion community, with improved access to new nuclear developments.

This report gives a brief overview of fusion discussions at the Scientific Forum of the IAEA General Conference, especially focusing on ITER. The different topics of the Scientific Forum will be briefly introduced and emerging trends presented. The Abdus Salam International Centre of Theoretical Physics (ICTP) also outlined aspects of relevant international research involving developing countries.

2. The 49th General Conference of the IAEA

The General Conference of the International Atomic Energy Agency is the highest policymaking body and is comprised of all Member States of the Agency. This body considers and approves the Agency's programme and budget and decides on other matters brought before it by the Board of Governors, Member States and the Director General. Events such as the Scientific Forum, exhibitions and satellite meetings inform the Member States about the latest scientific developments.

The Director General of the IAEA, Mr Mohamad ElBaradei, referred to recent events regarding fusion in his opening speech, 'Last November, more than 600 scientists covering all major research fields attended the biennial Fusion Energy Conference organized by the Agency in Portugal', and reported that 'a decision was announced this summer that the six-nation, $12-billion project to construct the International Thermonuclear Experimental Reactor (ITER) would be sited in Cadarache, France'.

Statements by several delegates also made reference to the ITER project, commended the role of the IAEA in its development and the valuable support the Agency has provided to this international enterprise. H.E. Mr R. Schaller, Ambassador of Switzerland (which will host the 22nd Fusion Energy Conference 2008 at which the 50th anniversary of Controlled Nuclear Fusion Research will be celebrated), stated that 'the decision to establish the ITER reactor in France opens a new period of research and development for the nuclear fusion field.' Mr A. Shichijo, Senior Vice-Minister for Science and Technology Policy of Japan, emphasized the close cooperation between the ITER partners and the progress towards making the utilization of nuclear fusion energy possible that ITER represents. Mr C. Cleutinx, Director of Nuclear Safeguards of the European Commission, expressed 'the Commission's sincere gratitude to the IAEA for the support that the Agency has provided to the ITER programme' and, 'for the instrumental role played by the Agency staff in facilitating a resolution of the ITER site issue'. Mr A. Bugat, Chairman of the French Atomic Energy Commission, thanked the IAEA for its role during different implementation phases of ITER, supporting the discussions and frequently hosting meetings between the parties, thus contributing 'to getting this vast and ambitious project off the ground.'

Further, in General Conference Resolution No 12 (Strengthening the Agency's Activities Related to Nuclear Science, Technology and Applications[1]), the General Conference expressed its awareness that 'the six-party International Thermonuclear Experimental Reactor (ITER) project achieved an important milestone, with the transition of the project to the engineering demonstration phase on 28 June 2005, by the announcement of the agreement on Cadarache as the site for the ITER facility'. The General Conference further acknowledged that the peaceful use of fusion energy can be advanced through increased international efforts and with the active collaboration of interested Member States and organizations in fusion-related projects, and welcomed the 21st IAEA Fusion Energy Conference to be held at Chengdu, People's Republic of China, 16–21 October 2006 and the 22nd IAEA Fusion Energy Conference 'Fifty Years of Fusion' to be held in October 2008 in Geneva, Switzerland, by encouraging the Member States to participate in these significant events.

3. IAEA Scientific Forum

Parallel to the proceedings of the IAEA General Conference, the Agency held its 8th Scientific Forum on the theme of 'Nuclear Science: Physics Helping the World' on 27 and 28 September. This theme had been chosen, as 2005 was celebrated as the International Year of Physics.

There were four sessions, namely Meeting Energy Needs, Developing Advanced Materials and Technologies, Advancing Radiation Medicine and Supporting Nuclear Safety. The first session covered promises, issues, challenges and possible solutions in respect of nuclear science meeting energy needs. The second session examined the development of advanced materials and technologies for nuclear energy. The third session focused on the use of ionizing radiation for the diagnosis and treatment of diseases such as cancer, and discussed the increasing need for well-trained medical physicists in developing countries. The fourth session focused on the global safety regime.

[1] IAEA General Conference, GC(49)/RES/12, September 2005

The scientific forum was opened with a speech by the Director General Dr ElBaradei, who remarked that the safety of nuclear fission power is now much greater than with earlier designs because of the reliance on 'passive' systems that work without the intervention of the operator. He referred to fusion power, saying that 'while some of us may be sceptics when it comes to any science that takes such a long time to develop, there is no denying that—looking further into the future—nuclear fusion promises some welcome characteristics: an inexhaustible source of energy in light nucleus atoms; the inherent safety of a nuclear reaction that cannot be sustained in a non-controlled reaction; and few negative environmental implications. With the construction of the International Thermonuclear Experimental Reactor now slated to go ahead, the international scientific community can begin devoting serious attention to this long term objective.'[2]

The Scientific Forum was chaired by Professor Burton Richter, who had received the Nobel Prize in Physics together with Samuel Chao Chung Ting in 1976 'for their pioneering work in the discovery of a heavy elementary particle of a new kind [the J-Ψ particle]'.[3] Professor Richter was director of the Stanford Linear Accelerator Center until 1999 and is now involved in energy, environment and sustainability issues that involve new energy sources free from greenhouse gases. In his presentation, as well as in the written synopsis, he stated, 'Nuclear energy is having a renaissance driven by both old fashioned supply and demand, and environmental concerns. Oil and gas prices have exploded and show no signs of returning to the levels of only a few years ago. Coal is not in short supply, but the pollution it generates has severe economic and health consequences. Concern about greenhouse gases and global warming has caused the environmental movement to begin a reassessment of the role of nuclear generated power in the world's energy portfolio'. His keynote speech outlined the increasing energy demand, which may lead to an increased worldwide nuclear power capacity of between 418 and 640 GW(e) in 2030 compared to 367.5 GW(e) in 2004.[4] The use of nuclear energy will increase the amount of spent reactor fuel, thus resulting in the need for new nuclear concepts, including new fuel, new advanced reactors and possibly the use of transmutation.

The keynote presentation on fusion was given by Academician E.P. Velikhov, the scientific leader of the realization of the Russian President's initiative on development of new generation nuclear energy since 2001, besides his many other duties.

3.1. Industrial production of fusion energy will be the next step

Academician E.P. Velikhov gave a presentation on ITER under the title 'Industrial Production of Fusion Energy will be the

[2] Introductory Statement to the Scientific Forum, www.iaea.org

[3] www.nobel.se

[4] 2004 *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030* Reference Data Series No 1 (Vienna: IAEA).

Next Step', focusing on the following subjects.

- Where are we in fusion?
- ITER – Study of the fastest way to burning plasmas
- ITER objectives
- ITER engineering
- Future of world fusion research and power development.

He outlined the following main points. Controlled fusion can provide mankind with an inexhaustible source of energy. The high safety level due to the impossibility of a non-controlled reaction and the low original and induced activities of the fuel, waste and construction materials are important safety features. There are two approaches to controlled fusion: one based on magnetic confinement and the other based on inertial confinement. At present, the magnetic confinement approach seems to be closer to energy production by fusion. The concept behind the tokamak device invented at the Kurchatov Institute, Russian Federation, fifty years ago turned out to be very productive and allowed us to realize the fusion of deuterium and tritium under conditions very close to breakeven. Other devices like lasers and Z-pinches may demonstrate their applicability for fusion energy production within the next few years. Although much is known about the tokamak plasma today, new advances are foreseen to occur in current and future experiments. Major research activity is shifting now to the problem of plasma-wall interaction, low activation materials and technologies activating resources for an industrial reactor that will be of commercial interest.

For more than fifty years, fusion research has been undertaken in many countries before the international fusion community decided in 2005 to build the first International Thermonuclear Experimental Reactor in Cadarache, France. The main reason for such a long period of development is the very complicated behaviour of high-temperature plasmas—a special state of matter that allows nuclei of hydrogen to react, setting free an enormous amount of energy due to mass loss. Basic and applied research in high-temperature plasmas has influenced a significant number of areas of science and technology.

Intensive work in this field is foreseen, and the fast track programme formulated by the European Union emphasizes the necessity of promptly solving basic problems of fusion energy production. After the construction of ITER over the next 10 years, it is expected that DEMO will start to operate in about 25 years time as a demonstration reactor, and in the middle of the 21st century the first industrial thermonuclear power station will be built. Finally Academician E.P. Velikhov stated that international collaboration in fusion has a long-term history and positive achievements, and should continue in the future including safety issues of fusion technology.

The Scientific Forum included panel discussions. The first debate followed the two keynote lectures and involved four invited experts. Professor K.R. Sreenivasan, director of the International Centre for Theoretical Physics and Abdus Salam Honorary Professor, also co-author of the present report, outlined perspectives on energy needs and the impact on emerging economies. Lord Julian Hunt, former head of the British Meteorological office, spoke on nuclear science, specifically on alternative nuclear fusion systems and the environmental risks. Professor R. Galvão, director of the Brazilian Conselho Técnico Científico, initiated the discussion on nuclear energy for sustainable energy growth in developing countries. Professor Jiangang Li, director of the Institute of Plasma Physics, Hefei, China, presented energy needs in developing countries.

3.2. Nuclear science and energy needs in developing countries

Professor K.R. Sreenivasan pointed out that it is useful to have in mind a time horizon and considered the end of the twenty-first century as a useful target. He said that: 'We can be pretty sure of what is feasible in the first fifty years, and what happens in the next fifty will depend on how we deal with the first fifty'. His further points were the following.

The world's energy needs will grow much more steeply in this century than at any time before. There are two obvious contributing factors. A large fraction of the world's population that uses little energy today is likely to use more tomorrow, as has been happening in China and India. At present, about 4.5 billion people use less than the world's average, and 1.6 billion of them do not have access to electricity. If they all catch up to the present average, the new average use of energy will go up by something like 60%. And if the world's population increases by something like 50% by 2050, we will be using twice the energy of now. And additional energy needs are likely to be upon us, for example, in providing future water needs to mankind via desalination.

Better energy conservation practices will no doubt play an important role. The improvement in energy efficiency achieved over the past fifty years is impressive and will no doubt be pushed further. However, no one thinks that this will be the answer to all-increasing energy needs. Therefore, the crude estimates mentioned above are adequate to conclude that we need a significant increase in energy supply.

What are the options? The points noted below are quite pragmatic.

Oil wells will dry up. The recent doubling of oil prices has already hurt the economies of developing countries (and also those of industrialized countries but, fortunately, the fundamentals of their economies are in better shape), but it is only a harbinger of tougher times to come, both economically and politically. However, the world economy is so strongly conditioned by the use of oil that a rapid switch to an alternative is not possible. Thus, as long as the last well stays in operation, oil will be the preferred source of energy, and will have to remain in the mix of our energy portfolio for the foreseeable future.

Complete reversion to coal (leaving aside momentarily the issue of its abundance) will not be possible because of greenhouse effects and health issues. Carbon sequestration may be a solution but it is a long way over the horizon and the consequences are unclear.

As for fusion, a commercial power plant is at least fifty years away, even if everything concerning ITER works in accord with plans and further upscaling occurs as expected. ITER will take twenty or so years to work fully and at least one intermediate generation of fusion plants will be needed before commercial success becomes real. Thus, fusion will play no role in the next fifty years, although it may play an important role in fifty years' time. Hence, fusion research should be supported.

People disagree as to whether hydrogen is the future. According to many experts, there are basic problems at the thermodynamic, conceptual and practical levels. One should not forget the principal point that hydrogen, though an excellent carrier of energy, is not a source. Hydrogen will play some role, but not the same dominant one that fossil fuels now do.

Nuclear fission today supplies about 16% or so of the world's energy needs (but the distribution is geographically lopsided). One will have to increase the number of reactors five-fold in order to bring this value to about 80% (as in France now). Let us forget for a moment the lack of technological know-how in many countries (despite valiant efforts by IAEA), the unavailability of uranium, reprocessing and storage issues of spent fuel, and consider only what it will be like to populate the landscape of the world with five times as many reactors as now. In regions where the respect for technology is not adequately high (which is often where additional energy is needed), this step will increase the proneness to accidents, security issues will increase many fold, and the concern for proliferation of nuclear weapons will multiply. Thus, nuclear fission will play a moderately stronger role than now, but offers no final solution. Lately, the acceptability of nuclear power has increased because of the absence of greenhouse effects.

In summary, looking at the first fifty years, oil will become scarcer, the use of coal cannot increase many fold, fusion will play no role, hydrogen will be marginal and nuclear fission can be expected to increase only marginally. All these facts support the view that one will have to primarily add a significant fraction of renewable energies to the mix of oil and nuclear energy. Perhaps a roughly equal mix of the three is a viable option.

However, everyone knows the problems about renewable energies; but since some energy consumption is indeed retail, there is no reason why, especially in much of Asia, Australia, Africa and the Mediterranean region, some of the household energy cannot come from the sun, or why wind energy cannot be harnessed better. But, perhaps equally important, one needs to work with the same level of seriousness as with fusion on large-scale solar power plants. This involves high-tech and non-trivial engineering.

To repeat, it would seem that a reasonable goal for 2050 is a mix of fossil fuels, renewable energy and nuclear fission, roughly in equal proportions, with others thrown in as minor partners. We cannot go too far wrong with this combination. By 2050, we will surely know considerably more about fusion, hydrogen and the technology of renewable energy (in which category solar energy will have to figure dominantly), and we will have to re-adapt ourselves to a new equilibrium point by 2100.

Indeed, continual evaluation and adaptation is the essential key. Perhaps one statement must be explicitly made. If the developing countries of today follow the same technological path as has been followed by industrialized countries during their ascension, there will not be adequate resources to meet the energy needs of the world. Developing countries, some of which have the 'luxury' of taking a fresh look at energy demands, should look for new and alternative approaches. This requires a clear awareness of the issues involved, understanding the possible technologies, and therefore much research and knowledge of science. There cannot be a stronger argument in favour of science than stating that it is a matter of survival: an increasing number of problems will depend on science for their solutions.

3.3. Environmental risks and alternative fusion systems

Lord Julian Hunt emphasized the critical decisions facing society concerning future energy systems, and how they must be made to reduce dangers to the global environment. Physics and engineering can provide solutions, but the final decisions have to be made by the public and politicians in the light of practicalities, costs and risks. Displaying these options on a graph of time for implementation versus environmental risk, one sees that for fission and fossil fuel systems the time for implementation is short and the environmental risk is relatively large (but for quite different reasons), while for fusion power the trend is in the opposite direction, as some countries are now considering (and as an IAEA consultancy reported in 2005) the development of hybrid fusion–fission systems where both aspects might be reduced. The time frame for base-load reliance on renewable, non-nuclear energy would be comparable to that for hybrid systems, but the environmental risk would be lower, though not negligible. One concludes that all these options need to be developed before final decisions are made. Systems are needed that can operate in a passive way. Safety had been thought to be achieved with very complex control systems in the past, but a whole new philosophy of control is now emerging.

3.4. Nuclear energy for sustainable energy growth in developing countries

Professor R. Galvão, from the Brazilian Centre for Research in Physics, outlined perspectives on nuclear fusion mainly with respect to the needs of developing and emerging economies. New resources are needed to replace fossil fuels, satisfy the demand of a growing world population and provide a better share of economic growth and quality of life. A strategy to improve the expertise and participation of developing countries, is needed, with due regard for effective safeguards. The next steps pose significant challenges, but also open new possibilities for international collaboration. The evolution of power technology, such as the new Generation IV reactors and fusion reactors will have to be based on strong international collaboration. As an example, Professor Galvão outlined the collaboration schemes that are effective in high energy physics. Possible actions that could improve the involvement of developing countries in fusion research may either include mechanisms for secondary participation, as exist at CERN, or even a common fusion experiment for developing countries. Direct action could further include an 'ITER GRID', which might be similar to existing grids like T2 – HEPGRID BRAZIL.

3.5. Fusion is urgently needed for the developing countries

With respect to the energy needs of emerging economies and developing countries, Professor Jiangang Li, from the

People's Republic of China, outlined the perspectives of energy production in these countries that have to include fusion as an urgent need. As an example, he provided the future energy demand in China, which will grow to be a moderately developed country by 2050. The coal-centred energy structure will remain in place until 2050. The annual energy consumption per person will increase from approximately 1 TCE (Tonne Coal Equivalent, 1 TCE = 2.929×10^{10} J, 8.136×10^{3} kWh) to more than 3 TCE (for comparison at present time: US 11.5 TCE; West Europe 5.6 TCE; Japan 5.1 TCE). The population will inevitably increase from the present 1.2 billion to about 1.6 billion in 2050. Thus the estimated energy demand will increase from about 1B TCE to over 4B TCE within the next 3–4 decades. Future direct options in China include developing hydro-power and using fission energy as a transit solution. Professor Li stated that fusion can be environmentally responsible and intrinsically safe, and the supplies of fuel are essentially limitless. For developing countries such as China and India, fusion is one of the very few options for large-scale sustainable energy generation and must be developed as quickly as possible together with international efforts.

4. Outlook

Professor Richter, as chairman of the Scientific Forum, presented a summary to the General Conference. Within the different topics of the scientific forum that had been covered, he stated that '... as far as fusion is concerned, the decision to build ITER at Cadarache is a very positive development. ITER must succeed in demonstrating the practicality of burning plasma for fusion energy generation. Even if this aim is achieved, the earliest commercial deployment of fusion is anticipated around 2040 to 2050, setting fusion development into the same time-frame as Generation IV reactors.'[5]

This long term perspective indicates that actions by the IAEA and its partners are needed to foster the exchange of scientific and technical information, which has been acquired during the years of research. Many Member States of the IAEA have small fusion devices, which contribute to the progress in fusion research [3]. Scientific exchange of the latest results is achieved in international conferences on plasma physics and fusion, and the IAEA has been organizing the IAEA Fusion Energy Conference since 1961. This conference receives high international scientific recognition, and is acclaimed by decision makers. Further, the IAEA has organized Technical Meetings with contributions often published in international journals. The IAEA is not a research institution, but encourages the exchange and training of scientists and experts in the field of peaceful uses of atomic energy. One specific example, where a close collaboration on fusion has existed since the mid 1960s, is the collaboration with the International Centre for Theoretical Physics at Trieste, Italy. The ICTP plays a major role in the forefront of science and has increased its contribution to plasma physics in recent years, so a few brief remarks are in order.

IAEA's perspective. Within its mandate, the IAEA supports Member States in nuclear fusion research, under the advice of the International Fusion Research Council, an advisory body. In a recent status report on controlled thermonuclear fusion [1], progress in fusion research over the last 15 years has been summarized. The technical progress in inertial and magnetic confinement, as well as in alternative concepts, which has been outlined in the status report on fusion, will result in a further increase in international collaborations. ITER will be the most visible achievement of such an international endeavour. ITER will help gaining the scientific and engineering knowledge before the first fusion power plant is built. The IAEA can play a pro-active role in catalysing innovation and enhance worldwide commitment to fusion by creating awareness of the different concepts of magnetic as well as inertial confinement. Engineering and materials challenges will influence the work of the fusion community. The results achieved by fusion research will, in many cases, enhance the use of plasma physics in industrial applications. Another greatly appreciated outcome of specific high level research on fusion will be the likely increase in the number of young fusion scientists, who in many cases will leave research to engage in the various aspects of work in the commercial sector.

ICTP's involvement and perspective in fusion research. The Abdus Salam International Centre for Theoretical Physics (ICTP), which was created under the umbrella of the IAEA, now operates under a tripartite agreement between the government of Italy and two UN agencies, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the IAEA. The ICTP has been concerned with energy from its very beginning. The first long-term programme of ICTP in 1964 was, in fact, on fusion, and has gone down in the history of ICTP as a watershed event. ICTP has sustained interest in renewable energies from the beginning, and organized some 30 courses on this topic, several in cooperation with IAEA, from the physics to the economics of renewable (or non-conventional) energies in all forms. About 2000 scientists from all Member States of IAEA and UNESCO have taken part in these courses, and many of the participants are, in fact, involved directly in projects on renewable energy in their own countries. Furthermore, through its TRIL Program, which stands for Training and Research in Italian Laboratories, the ICTP has supported approximately 400 post-doctoral scientists coming to Italy and working on projects involving renewable energy. This has been a substantial investment on ICTP's part, and is a strong indication that ICTP recognizes the seriousness of the scientific issues involved, and is committed to addressing them.

Professor Sreenivasan outlines as follows: 'Mention should be made of ICTP's interest in the ITER Programme. This facility is unique and will not be replicated anywhere in the world anytime soon. If our goal is to provide a viable source of energy to the world at large through fusion, it is important that people from needy countries be involved in the enterprise from the very beginning. It is unrealistic to think that the fusion programme will be perfected by a selected few countries, with others staying away from it until the technology is ready to be transferred to those who are in need. Obviously, only a few selected countries can be principal partners, but

[5] www.iaea.org/About/Policy/GC/GC49/ScientificForum/index.html

some minimal access must be available right from the start to capable scientists from all developing countries. We have to start identifying appropriate groups who can act, when needed, as the nuclei for fostering this new technology.

If we agree on this general principle, there is no better institution than ICTP to become involved in ITER. Because scientists from a large number of countries visit ICTP, often through programs organized in cooperation with IAEA, they can make connections to ITER through ICTP. As one measure, ICTP could run courses in cooperation with ITER and the IAEA on fusion-related issues (even if at a basic level) in which scientists from developing countries could participate. As a second measure, we would develop at ICTP a remote access and control facility for the ITER experiment, through which acknowledged scientists from developing countries could participate without physically being at Cadarache. One can similarly imagine developing, through ICTP, a network of scientists to work on the analysis of data coming from ITER. We are quite seriously involved in grid computing and think of it as one of the mechanisms by which participation by larger communities will become possible. Finally, ICTP can serve an even more important function. It is the one place where the international scientific community can discuss in a scholarly arena both the limitations of the present theoretical understanding of fusion physics and the opportunities in basic physics provided by the 'new' state of plasma to be created in ITER. The ICTP community looks forward to this extraordinary opportunity with some excitement. It is probably worth mentioning that the number of scientific programs that were held at ICTP last year reached about 60 (among which the College in Plasma Physics was one), and that they encompassed from the very fundamental to applied topics. Participants have numbered more than 6000, about half of whom were from developing countries. These statistics are typical for the last few years.'

References

[1] International Fusion Research Council 2005 *Nucl. Fusion* **45** A1–28

[2] *Nucl. Fusion* 2005 **45** S1–298

[3] Gryaznevich M.P. *et al* 2005 *Nucl. Fusion* **45** S245–254