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The Legacy of Artsimovich and the Lessons of ITER

Mr Chairman, Ladies and Gentlemen

I should like to thank the Director-General of the IAEA for extending to me the invitation to present this lecture at the Artsimovich Memorial Session of this, the 17th IAEA fusion energy conference. During his lifetime, Academician Artsimovich's presence enlivened the proceedings of these biennial conferences and his contributions epitomised their positive spirit. As he fluently projected his enthusiasm, scientific rigour, insight, vision and wit, he was an inspiration to a generation of fusion scientists and engineers.

I was lucky enough, as a young research physicist, to have attended seminars in Europe led by Artsimovich. I myself am one of that group - now diminishing in number and growing older by the day - to whom he imparted directly both the excitement of the scientific and engineering challenges and his sense of the nobility of the quest for fusion energy as a responsibility owed towards future generations of mankind. It is entirely appropriate that we continue to celebrate his momentous contributions to the world's development of fusion energy.

I feel especially honoured to have been given, this year, the opportunity to join the list of distinguished speakers who have graced previous such occasions, for 1998 marks the anniversary of two of Academician Artsimovich's particularly auspicious contributions.

It was forty years ago, at the second United Nations International Conference on the Peaceful Uses of Atomic Energy, in Geneva, that Artsimovich articulated the need, indeed the imperative, for continuous international collaboration to combine efforts "in the field of controlled fusion reactions investigation". If I may quote directly:

> "**A most important factor in ensuring success in these investigations is the continuation and further development of the international cooperation initiated by our conference. The solution of the problem of thermonuclear fusion will require a maximum concentration of intellectual effort and the mobilisation of very appreciable material facilities and complex apparatus.**
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> **This problem seems to have been created especially for the purpose of developing close co-operation between the scientists and engineers of various countries, working at this problem according to a common plan, and continuously exchanging the results of their calculations, experiments and engineering developments. (Geneva 1958)"**

Then, ten years later at the 1968 conference in Novosibirsk, it was Artsimovich's report on the emergence and promise of the Tokamak configuration — later to be confirmed by the Culham team in a celebrated early example of international collaboration — that reinvigorated the major programmes throughout the world, leading directly to the remarkable technical progress that we have been able to share at these regular meetings.

By chance, July 1998 also marked the end of the six year term originally set for the quadripartite ITER Engineering Design Activities which embody the two pillars of Artsimovich's legacy — the Tokamak configuration and international collaboration. It is therefore timely to review how the world's fusion programmes have responded, over these intervening decades, to the opportunities and challenges presented by Artsimovich and to consider the outlook.

What technical progress have we made?

There is much to report that would, I hope, be gratifying to Artsimovich.
In the technical domain one can readily point to the enormous advances in key fusion performance measures:

- the realisation of significant levels of fusion power — 10.7 MW over 0.4 s in TFTR (1996), followed by 16.1 MW over 0.85 s in JET (1997) — a technical achievement which has also allowed experimental observation of significant α-particle heating
- more than ten thousand fold increases in the fusion triple product - $n\tau T$ - to 1.5×10^{21} keVm^{-3}s (JT-60U,1996);
- achievement of energy multiplication factor - Q - close to unity in DT plasmas (JET, 1997) and of Q-equivalent ~1.25 in (JT-60U,1998)

Underlying the headline results from the leading tokamaks, a complementary range of small to medium size tokamaks have been built and operated, and have advanced our understanding across a broad front. Between them, these smaller machines have produced important new discoveries and developments in plasma behaviour and operation (H-mode, high β operations, X-point and Divertor operations) and have allowed to explore the widest domain of plasma parameters, so generating a broad database from which to analyse and extrapolate with confidence into domains beyond the capacities of today's machines.

One of the key challenges envisaged by Artsimovich, in view of the inefficiencies of ohmic heating at high temperature, — " **to devise new methods of plasma heating**" — has been successfully addressed and now places at our disposal a range of proven heating tools and an understanding of each one's specific characteristics.

At the theoretical level serious "first principles" models of Tokamak behaviour are now becoming available. It would be premature to claim that these are yet proven or dependable, although we have a healthy framework for their comparative evaluation and validation. On the other hand, the depth and breadth of databases at our disposal, including initial α-particle studies, have allowed significant advance in empirical phenomenology and hence provide confidence in extrapolations to as yet unexplored domains.

Whilst Artsimovich is associated mainly with the Tokamak configuration, he also advocated advancing on a broad front - or, in his words, **"peaceful co-existence between the various lines of controlled nuclear fusion research"**. Thus, in my view, Artsimovich would also have noted with approval the continuing lively efforts in alternative confinement concepts; unconventional tokamaks/spheromaks, and stellarators continue to receive attention and to serve as valuable comparators to the tokamak line. We look forward to hearing later of the first results from LHD and TJII. Referring to a "**system in which plasma blobs of very high density and very short lifetimes are produced**", Artsimovich also anticipated the inertial confinement line of approach which is well represented at this conference. (A valuable response to the rich diversity here present would be the development of a common frame of reference and vocabulary to allow meaningful comparison between the different lines.)

Has the Tokamak fulfilled its promise?

Our experience to date suggests that the tokamak concept has amply fulfilled the promise that was outlined in 1968. In his Artsimovich Memorial lecture in 1980, Donato Palumbo commented:

"It is difficult to say at this stage whether the tokamak is the best solution for a thermonuclear reactor, even if there are no reasons to say the contrary. What is undeniable is that the plasma parameters, density, temperature, purity and duration, produced simultaneously in the tokamak have provoked (and permitted) enormous progress in the study of stability and transport, the improvement of diagnostics and the development of powerful methods of plasma heating."

Since that comment, the tokamak has indeed brought our programmes to the threshold of reactor conditions. Whatever its ultimate future, the Tokamak remains the only established platform on which to base plans for a next step across the threshold into the exploration of burning plasmas in reactor-relevant conditions. Moreover recent reactor studies and economic assessments have indicated conditions under which the tokamak configuration can provide a plausible foundation for a power station, with costs comparable to existing energy sources. Artsimovich would have cause for some pride in these achievements.

How has international co-operation helped our progress?

In the domain of international collaboration, one can surmise that Artsimovich would have been encouraged as well. The vitality of these biennial conferences bears witness to the exchange of **"results of calculations, experiments and engineering developments"** called for by Artsimovich.

The efforts in Europe to integrate the fusion programmes of the different European nations have borne fruit — most noticeably in the establishment and achievements of the JET machine, but no less importantly in the breadth and balance of the Contract of Association programmes. Indeed the integrity of the Euratom fusion programme is now taken so much as a given that one can easily underestimate the scale of the challenge that its establishment and nurture presented. Even with the benefit of the pre-existing institutional structure of Euratom, it required exceptional vision, wisdom, persistence (and a little luck) to seize and exploit the opportunities.

A growing network of inter-continental relationships has developed, largely under the auspices of IAEA and IEA, and has involved significant flows of staff, equipment and funds across the regional boundaries and oceans. These interchanges have yielded programmatic benefits both directly, for example, by allowing specific tools developed in one programme to be applied to another, and indirectly, through the cross-fertilisation of ideas which always occurs when diverse groups work together at the frontiers of their discipline. Equally important, they helped to develop the trust and mutual confidence needed to venture on more ambitious collaborations.

ITER (and its precursor - the INTOR Workshop) has its origins in a common recognition of comparable positions reached in the major programmes and a shared overall view that the time was due to take as the next challenge that of demonstrating the scientific and technology feasibility of fusion power — indeed to provide the data base in physics and technology necessary for the design and construction of a demonstration fusion power plant. From this common position, the attractions of taking the next step in the frame of a single, collaborative project provided a compelling incentive to establish the joint venture.

The progress of the successive stages of ITER has been presented at recent IAEA conferences and the results at the end of six years' Engineering Design Activities, as embodied in the ITER Final Design Report, Cost Review and Safety Analysis (FDR), will be elaborated in the ITER sessions of this conference. Let me therefore synthesise what I see to be the overall achievements of the project to date and reflect on the particular benefits that have derived from the "I" of ITER.

What have we achieved with ITER?

The efficient collaboration between the ITER JCT and Home Teams has successfully delivered the products requested of them:

- a complete, fully integrated design of the ITER machine is available;
- the technology R&D done to date has resulted in the qualification of the technical solutions;
- the safety and environmental analyses have shown that ITER can be safely and reliably operated and will indeed demonstrate the safety and environmental potential of fusion as an energy source.
- cost studies from industries throughout the Parties confirm that the total estimated costs have remained within the targets set at the start of the EDA.

In short one can be confident that ITER could be built, operate safely and fulfill its objective to demonstrate the scientific and technical feasibility of fusion.

How have we benefited from ITER being international?

By pursuing the ITER EDA as a quadri-partite co-operative project, the Parties have undoubtedly realised major financial savings to reach the present point. But, from a programmatic point of view, the impetus to pool experience, expertise and results within a focussed framework has provided an added value to the ITER Activities that is the most important benefit from the joint approach.

For instance, in Physics, the voluntary contributions from all present experimental facilities have led to the building of large, reliable and authoritative databases as the basis for extrapolation and now provide a vital and critical frame of reference for further development and testing of theory and modeling work. In technology, development at the laboratory level has been followed by manufacturing of models and prototypes of ITER systems by industrial firms in all four Parties, in several cases, with components transferring between Parties for the various stages of manufacture. This multi-Party process has led to an open and rigorous development process — including intensive joint problem-solving — and has broadened confidence in the feasibility and cost estimates for ITER construction.

In the area of Safety and Environmental analysis, the need to design ITER to be site-able in the territory of any of the Parties has set demanding standards and has ensured that the design takes full benefit of the inherent safety advantages of the fusion process. The multi-party nature of the activity offers a unique opportunity for the Parties to pursue jointly a harmonised approach to the regulation of fusion power plants.

The fact that the ITER EDA addressed a specific machine with specific objectives provided invaluable focus and discipline to the activities. But the results arising from the EDA are not only valid specifically for ITER. Advances in physics and technology stimulated by the discipline and focused effort are of general application in a wide domain of possible integrated next step devices.

The ITER-EDA has brought together Artsimovich's two pillars. The Parties now have at their disposal the first comprehensive design of a fusion reactor based on well established physics and technology. The FDR and its accompanying documents would be sufficient, when complemented by site-specific adaptations of the design, to provide the necessary technical basis to a construction decision.

Looking to the future

Artsimovich said in 1970, **"There can be no doubt that our descendants will learn to exploit the energy of fusion for peaceful purposes even before its use become necessary for the preservation of human civilisation."** How does this claim now stand up?

Has the case for fusion energy development changed?

As noted above, reactor studies and economic assessments have shown no reason in principle preventing fusion from fulfilling its potential as a safe, environmentally acceptable and economic large-scale source of energy.

From the external perspective, essential aspects of the general world view underlying the case for fusion energy development remain no less valid than when Artsimovich surveyed the field:

- ineluctable continuing growth in world population and the legitimate aspirations of the billions in the developing and transitional countries for improved material well-being seem certain to lead to continuing growth in global energy demand at least for the next century; recent studies project a doubling by about 2050:
- the perception of physical depletion of oil and gas has receded, masked for now by low prices and current market gluts. While this may provide some immediate short-term comfort, it would be myopic and irresponsible to base energy research policies on this happy state continuing; indeed reputable experts are already discerning from detailed statistics evidence of turning points in production profiles which lead them to conclude that, while **"the world may not be running out of oil - at least not soon, what our society does face, and soon, is the end of the abundant and cheap oil on which all industrial nations depend."**
- moreover, in recent years, there has been widespread growing concern over the possible effects of mankind's ongoing experiment with the world's atmosphere and climate, — a concern most recently manifested in the 1997 Kyoto protocol to the United Nations Convention on Climate Change, under which the nations of the World agreed, inter alia, to implement policies including **"Research on and promotion, development and increased use of, new and renewable forms of energy, ... and of advanced and innovative environmentally sound technologies."** I submit that the development of fusion energy for the benefit of all mankind fits precisely into that description.

The report of the Japanese Special Committee on ITER most recently captured the essence of the continued overall case when it argued the value of establishing fusion as one of the real energy options that we should place at the disposal of future generations.

Have we made the necessary technical progress ?

From the technical perspective, the progress in fusion over in the twenty five years since Artsimovich's death could be seen to bear out his bold prediction. Throughout this period we have all developed a good grasp of the likely scale, scope and complexity, and hence the order of cost, of a significant next step. Success of the ITER EDA, with a design compliant with its original performance objectives and cost target, shows that we are now ready to take such a step. By virtue of its integration of fusion science and engineering, its effective likely contribution on the path to prototype power reactors is well defined.

Indeed the recent change in title of this biennial occasion from a "Conference on Plasma Physics and Controlled Nuclear Fusion" to "a Fusion Energy Conference" symbolises neatly our state of readiness.

Can there be "no doubt"?

The problem is not technical. Proposals such as those embodied in the ITER FDR can readily be modulated within the given programmatic objective, for instance to meet different financial perspectives.

There are, of course, uncertainties attached to the projected performance of a next step device. This should not be seen as a criticism of the proposal. A next step machine will be an experiment and it is the nature of experiments — indeed of the scientific method — that the outcome cannot be predicted with 100% certainty.

But the nature and dynamics of international co-operation does raise questions and challenges to be addressed.

The nature of international collaboration

International collaboration to address difficult problems in science has a self- evident general appeal. United efforts in the scientific domain help to offset international tension arising from political or economic rivalry. Collaboration provides the only practicable means to conceive and to enter into projects that are beyond the capacity - in terms of both finance and expertise - of individual national programmes. It provides the means to build balanced teams able to address all the challenging aspects of designing and constructing the devices needed to carry fusion development to the next level.

However, following this path brings new demands and lays heavy additional responsibilities on the fusion communities and their leaders. In his address to Kyoto meeting in 1986, at an earlier stage in the co-operative process, John Clarke spoke of the wisdom, courage, skill and dedication to a common aim manifested in Artsimovich and other respected leaders in fusion development. He characterised the issue as follows:

"Reaching agreement on the necessity of working together is difficult because it involves many non-technical factors. It involves the personal ambitions of scientists as well as institutional ambitions of laboratories. The dedication to a common aim must be very strong to motivate an appropriate balance between such ambitions and more efficient pursuit of our common goal"

Having agreed to common action, then the instruments for implementing need to hold hard to the underlying objective. In the words of a US politician whose influence has recently been felt: **"Any agreement for international co-operation requires well-defined and enforceable goals from the outset. Without such parameters, international co-operation will not succeed."** Having embarked on a joint project, one must then accept the continuing obligation to attend to the potential dichotomy between the centralised demands of the project and the perceived local interests of the different constituencies involved. Maintaining a satisfactory balance is a demanding and delicate charge; but one may be sure that there will always be forces pulling away from the centre that need to be actively countered.

The dynamics of co-operative projects

The dynamics of an international project also raise new issues. The investment needed to build an effective international project team and the special commitments demanded of the Team members and their families generates additional management responsibilities. Whilst one can appreciate the need, at political level, to limit formal commitment to the stage-wise implementation of a major project, those responsible for its implementation must be ready, as they enter each stage, to accept responsibility for moving towards succeeding stages. For the dynamics of these projects are such that we rapidly reach the point at which simply to stop means to retreat. Once the teamwork and mutual confidence built up in a joint project is allowed to dissipate, we shall lose at all levels — from the older team members whose years of training and experience may be irreplaceable, to the enthusiasm and talents of the younger cadre of developing leaders that we need to bring our quest to fruition. It will take many years and much money to reach the same state again, if indeed such a restitution proves possible at all.

One lesson that my experience as ITER Director during in the EDA has taught is that, if you give dedicated groups of fusion scientists and engineers a difficult task to achieve, then you must always prepare yourself for the eventuality of them succeeding.

Such considerations demonstrate that international collaboration - whilst undeniably attractive from many points of view is not an easy path to pursue. In embracing it as the best, or only practicable, way forward we must ourselves be ready to adapt our modes of behaviour to the new dimensions and realities that it brings to the task of programme direction and management.

In conclusion

The ITER co-operation was established at a time when the four Parties (and the other nations that chose to join ITER by association) were ready and able to articulate a common aim and, in John Clarke's words "**had the courage to act to make the co-operation possible**". The progress under that common aim has brought into our reach the option, within balanced overall programmes, to embark on the next step together. To be realistic, the initiative should perhaps best come from one country with an invitation to others to participate at different levels consistent with their capacities and interests. But, whatever the prospective geometry of co-operation might be, we must not shrink from the opportunity to progress that it offers.

The general lines proposed by Artsimovich — both technical and organisational — remain the right ones to follow. The scientific and technological basis is well-established. Having embraced the principle of co-operation, with the clear backing of our political masters, we understand the peculiar responsibilities and obligations that this brings. We know that technical co-operation must go hand in hand with high level political co-operation so as to realise the necessary confluence of technical readiness and political commitment. We also recognise that, with each stage of major projects, if we do not prepare ourselves to progress to succeeding stages we imperil what we have managed to achieve and run the risk of irreversibly harming future prospects of scientific collaborations in fusion and beyond.

What remains now is to re-affirm our common aim and then to accept our responsibilities throughout the community to develop together and to promote and implement the policies and programmes that will lead most efficiently towards the realisation of the promise of fusion energy for the benefit of all mankind.

I should like to acknowledge the assistance of my colleague Martin Drew of the ITER Joint Central Team in the preparation of this lecture.