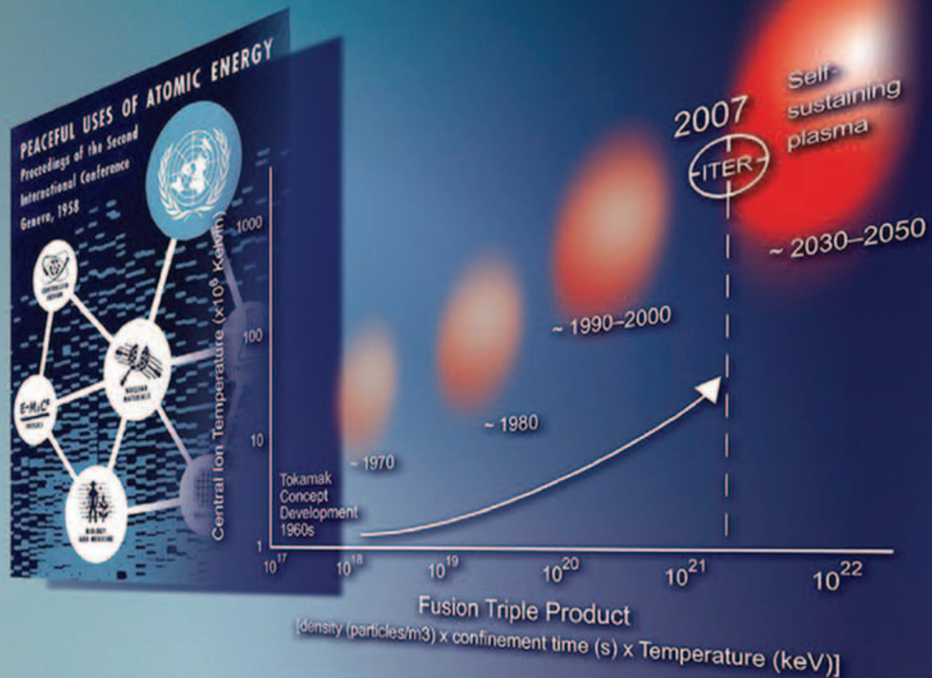

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Organized by the IAEA International Atomic Energy Agency

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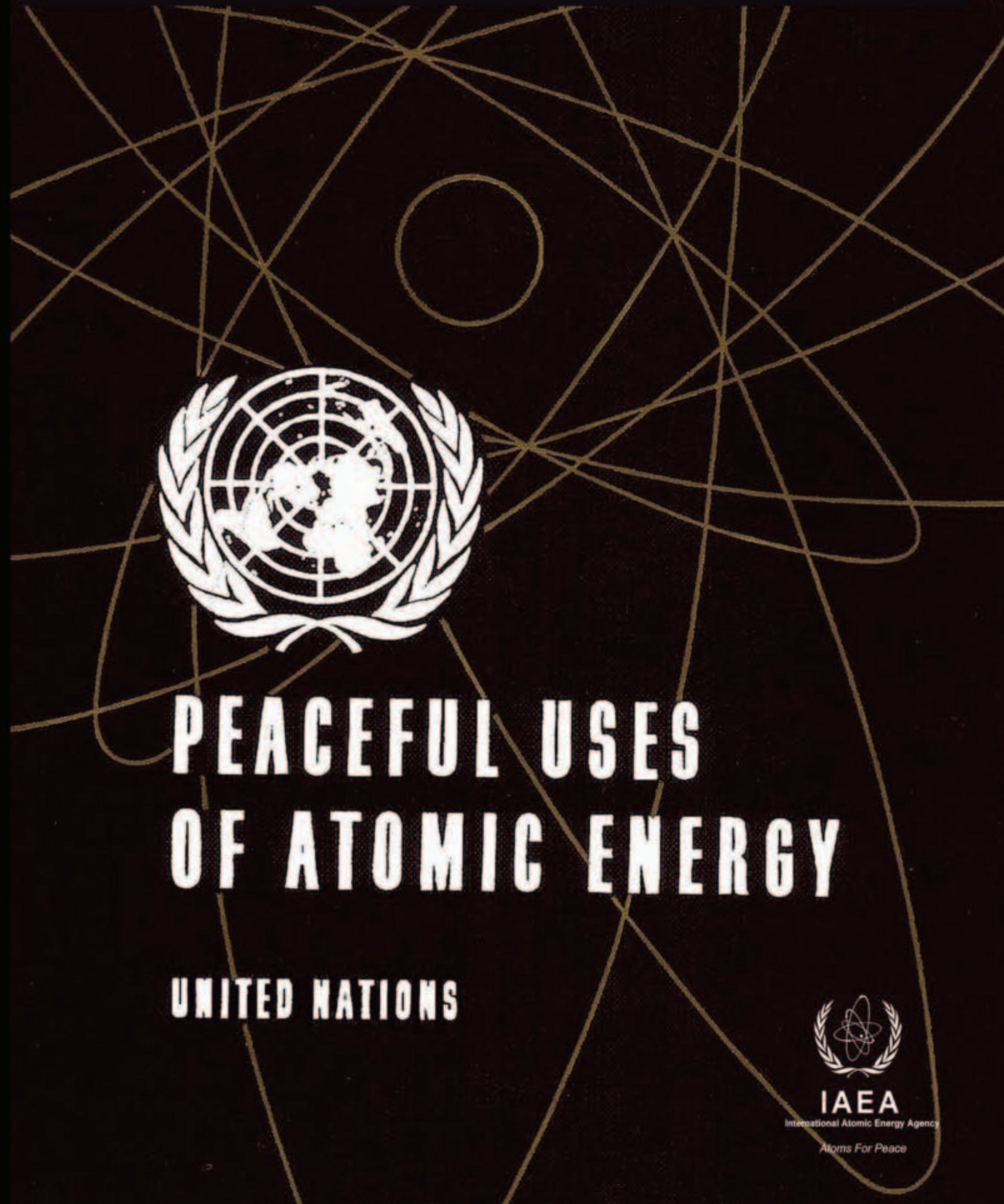
Photography: UNOG Archives Geneva (page 4,5,6,16,17,20,24,25,26), Nuclear Fusion Institute RRC "Kurchatov Institute" Russia (page 9,18,19), KFA Kernforschungsanlage Juelich Germany (page 10,11,15), ORNL Oak Ridge National Laboratory USA (page 6), IAEA Archives Vienna (page 8).

DESIGN

Alan Aqrawi

Fifty Years of Magnetic Confinement Fusion Research – A Retrospective

Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy
Geneva, 1 September – 13 September 1958



Foreword

"Celebrating fifty years of fusion…
…entering into the burning plasma era."

Energy in all its forms has always driven human development. New technologies in energy production, starting from the use of fire itself, have driven economic and social development. In the mid-1950s, nuclear energy created new hope for an abundant source of that energy for the world.

To promote this groundbreaking technology, and to host a neutral ground for substantive scientific debate, the United Nations in 1955 organized the first of a series of conferences in Geneva on the "Peaceful Uses of Atomic Energy". Providing an opportunity for scientists from all countries to showcase their research, these conferences came to be recognized as essential platforms for the further development of nuclear energy.

The main topic of the second UN Conference on Peaceful Uses of Atomic Energy, held in 1958 in Geneva, was nuclear fusion. Imbued with a sense of purpose and hope for the common good, in an atmosphere of innovation and exchange, scientists from different political backgrounds freely discussed their recently declassified results and outlined their expectations for the future. With Sigvard Eklund, the future Director General of the IAEA, serving as Secretary General of the conference, about 5000 delegates, observers and guests discussed over 2150 papers, 105 covering fusion topics. In addition, a number of exhibits highlighted the possibilities of harnessing fusion power. However, it was recognized that technical issues related to the extremely high temperatures involved in fusion and to the neutron and gamma flux were so complex that the prediction by the American physicist Edward Teller that the exploitation of fusion energy would be possible before the end of the 20th century was not likely to come true.

The major breakthrough finally came many years later with the invention of the tokamak. Since then, a doubling of fusion quality, described by the fusion triple product, has been achieved every 1.8 years. New developments in science and engineering have led to an optimized magnetic prototype reactor, with corresponding cost savings. Inertial confinement experiments have achieved similar progress. The culmination of international collaborative efforts in fusion is the start of construction of the International Thermonuclear Experimental Reactor (ITER), the biggest scientific endeavour the world has ever seen involving States with more than half of the world's population.

The IAEA has been closely involved in the area of nuclear fusion, mainly through its biennial Fusion Energy Conferences. Fifty years of international cooperation in fusion research is being celebrated this year at the 22nd Fusion Energy Conference, held at the Palais des Nations in Geneva, the starting point of discussions back in 1958. This commemorative booklet contains a brief history of international fusion research activities as well as anecdotes by distinguished scientists.

Nuclear fusion continues to attract attention as a clean and reliable source of energy, holding promise as a global solution for tackling the problems of poverty, economic development and climate change. Fusion energy, as developed through ITER, has the potential to play an important role in humanity's intensified quest for adequate energy sources.

Werner Burkart

Deputy Director General,
Nuclear Sciences and
Applications,
Werner Burkart

"With the beginning of ITER construction now in sight, this long term objective will likely be receiving serious attention."
IAEA Director General,
Mohamed ElBaradei

THE CONFERENCE - INTRODUCTION

The 2nd Geneva Conference - Introduction

"Monster Conference", Time Magazine, 15 September 1958

THE 2nd INTERNATIONAL CONFERENCE ON PEACEFUL USES OF ATOMIC ENERGY

The 1955 United Nations Conference on the Peaceful Uses of Atomic Energy, which became known as the 'First Geneva Conference', was notable for the unaccustomed fraternization between scientists from Communist and non-Communist countries that took place there. The conference also removed the shroud of secrecy that had surrounded the technology of fission reactors. Nuclear fusion was mentioned only in the opening address by Homi Bhabha,

Opening session of the 2nd Geneva Conference

President of the First Geneva Conference: "It is well known that atomic energy can be obtained by fusion processes as in the H-bomb and there is no basic scientific knowledge in our possession today to show that it is impossible for us to obtain this energy from the fusion process in a controlled manner. The technological problems are formidable, but one should remember that it is not yet fifteen years since atomic energy was released in an atomic pile for the first time by Fermi. I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens the energy problem of the world will truly have been solved forever for the fuel will be as plentiful as the heavy hydrogen in the oceans."

"Geneva was a fair of ideas"

Any developed countries that were not already engaged in nuclear fusion research certainly took notice of these words. Laboratories around the world began to explore the subject.

Then came the 1958 United Nations Conference on the Peaceful Uses of Atomic Energy, the 'Second Geneva Conference', held on 1–13 September 1958. This conference performed the same kind of 'unwrapping' for controlled nuclear fusion as the First Geneva Conference had done for fission in 1955. The 1958 conference was probably one of the largest scientific conferences that has ever been held, and it was certainly huge compared with the other conferences held up to that time. Time Magazine politely called it the 'Monster Conference', and this view was shared by most participants.

According to an official estimate, 5000 scientists from 67 countries, 900 accredited correspondents from all over the world, 3651 observers from industrial concerns and an even larger number of interested public observers attended the Second Geneva Conference. Providing accommodation for so many participants was a challenge for Geneva's hotels, which contained 6500 beds at the time, and some participants had to be accommodated in cities like Evian, some 50 km away. To prepare the fusion exhibit, many scientists had lived in Geneva for several months, sometimes with their families.

"This problem seems to have been created especially for the purpose of developing close cooperation between the scientists and engineers of various countries." L.A. Artsimovich

Overall, 2137 nuclear science papers on 150 topics of research, with 15 000 illustrations, were submitted by authors from 46 countries and 6 intergovernmental agencies. Of the papers submitted, 600 were presented orally. In the field of nuclear fusion research, 109 papers were submitted from 11 countries, including the United States of America (65), the Soviet Union (14), the United Kingdom (9), France (4), Sweden (4), Japan (2), Denmark (1), the Federal Republic of Germany (1), Poland (1), Romania (1) and Switzerland (1).

Although the conference programme contained more papers and sessions on fission than on fusion, fission took a back seat for most of the time. From the start of the opening session on fusion, 'Possibilities of Controlled Nuclear Fusion', fusion and its declassification were the focus of interest for the remainder of the conference — in the sessions, the exhibits and the discussions. Large exhibits — both commercial and technical — were held, presenting models of nuclear reactors and possible thermonuclear machines, as well as real fission and fusion machines. Declassification had gone so far that the thermonuclear machines and experiments were set up in working condition, some of them flashing with light when the crews of scientists switched them on. The largest contribution to the exhibits was that of the USA. It had cost a total of US $4.5 million and involved the shipment of four real fusion devices. The US exhibit was clearly the focus of attention.

Conference Premises – Palais des Nations

Declassification

"The main achievement of this conference is going to be the occasion of the complete elimination of secrecy in this last outpost. The communications on this subject will be by far the most striking revelations of our meetings and the crowning event of the exhibition will be the spectacular presentation of devices permitting the temperature of gases to be raised to several million degrees.“ Dr. F. Perrin, president of the Second Geneva Conference, in his opening speech.

BEHIND THE CURTAIN – Not only was attention high at the Second Geneva Conference, so were the expectations for a future with nuclear fusion energy offering endless energy resources. Large press conferences, mostly dealing with fusion — predictions, estimates, its chances of being realized — were held in the press rooms of the Palais des Nations, with live radio broadcasts and translations in five languages.

The nuclear powers of that time — the Soviet Union, the United Kingdom and the USA — were the major players in the field of controlled nuclear fusion research. This was simply due to the fact that these were the nations actively engaged in hydrogen bomb research, and only these countries had the necessary knowledge and experience in this field. Since research was at first closely tied to the development of hydrogen bomb weaponry, developments in the field of controlled nuclear fusion were classified. The mist of classification concealed how fruitful the research endeavours had been on both sides of the Cold War divide.

Conference President F. Perrin in a press conference

Ironically, the announcement in 1951 by the President of Argentina, Juan Perón, that experiments by the physicist Ronald Richter had succeeded in producing a “controlled release of atomic energy at a super-high temperature of millions of degrees without using uranium fuel” stimulated the research programmes in the Soviet Union and the USA. For example, it resulted in an immediate increase in communications and a restructuring of the controlled nuclear fusion programme in the Soviet Union. Although the claims turned out not to be true, nervousness on both sides persisted, since the promise of controlled nuclear fusion was undoubted.

A Soviet (left) and a US (right) delegate

This promise and the realization that major difficulties lay ahead on the road to a thermonuclear machine made it clear to the nuclear powers that it was time to declassify their research so that problems could be discussed and tackled by the international scientific community.

The Second Geneva Conference played a unique role in the history of nuclear fusion research. For the first time, the countries engaged in thermonuclear fusion programmes openly revealed and described the latest status of their efforts towards the ultimate goal of achieving controlled nuclear fusion reactions. The lifting of classification revealed to the conference participants and indeed to the world that, despite the secrecy, these nations were following similar approaches to the problems of plasma stability, magnetic radiation losses and attaining the necessary multimillion-degree temperatures. The similarities in the development of fusion research and in the instrumentation used became clear.

DECLASSIFICATION

“A portentous rumor is spreading fast through U.S. atomic industry: that a ‘controlled fusion’ reactor has been or may soon be achieved...the rumors have enough substance to worry electric power companies. In the absence of assurances to the contrary, some of them are afraid that the fission (uranium) power plants they intend to build in the near future may be hopelessly outmoded before they are finished.” Controlled Fusion, Time Magazine, 25 July 1955

“Greatest contribution of the conference: declassification”

The greatest contribution of the conference towards a controlled thermonuclear reaction was not the scientific progress made but the declassification itself, this being the starting point of international collaboration. This was expressed very well by Academician L.A. Artsimovich in the overview paper from the Soviet Union: “For the first time, these results will be discussed on an international scale, and this is probably the most important step that has been made towards the solution of this problem. The importance of this fact is greater than that of the separate investigations, which as yet have not brought us very much nearer to our goal.”

The way to declassification had been laid out during the preparations for the Second Geneva Conference that followed the First Geneva Conference in 1955. At the outset of the Second Geneva Conference, the United Kingdom and the USA declared “total declassification”. In a press conference, the US delegation declared that ideas in the thermonuclear field should never again be “born classified”. In September 1958, IAEA Deputy Director General H. de Laboulaye wrote, in an interoffice memorandum to IAEA Director General Sterling Cole: “The Geneva Conference highlight was expected to be nuclear fusion, and indeed the intense declassification on the matter was of great scientific and technical interest, as was also the remarkable U.S. exhibit on the subject. Nevertheless, the conference confirmed openly what was already clear to all specialists, that is to say that ‘industrial fusion’ is very far away if any of the research paths followed up to now are to be successful at all. Complete exchange of information and coordinated research on an international scale appears to be the only means to get things going faster.”

Paper Contributions

- **(65) USA**
- **(14) USSR**
- **(9) UK**
- **(4) France**
- **(4) Sweden**
- **(2) Japan**
- **(1) Denmark**
- **(1) Germany**
- **(1) Poland**
- **(1) Romania**
- **(1) Switzerland**

ENTHUSIASM versus SCEPTICISM

Enthusiasm versus Scepticism

"A sun of our own – and it's made in Britain!", British newspaper headline, 1958

WILL THERE BE LIGHT AT THE END OF THE TUNNEL? – At the beginning of the Second Geneva Conference in 1958, the estimation of H. Bhabha, President of the First Geneva Conference in 1955, that a thermonuclear device would be built in the following 20 years was still very much present in people's minds, but no one could give an exact answer as to whether a machine could indeed be built within that time frame. So the Second Geneva Conference started as a hotchpotch of predictions driven by enthusiasm, excitement and public pressure.

This had many reasons. One was that, given the impressions created by the advent of the atomic era and the fast evolution of both

"A hotpot of predictions"

nuclear power reactors and atomic weaponry, controlled nuclear fusion was seen to be merely the next, imminent achievement of the nuclear sciences. In the light of all that had been done in the two preceding decades, the ultimate goal of a nuclear fusion reactor was thought by some to be a reality attainable in the not too distant future.

Another reason lay in simple public relations disasters. Reservations and resentments were expressed and overheard, and in some cases, words were not chosen carefully enough. For example, early in 1958, Sir John Cockcroft gave a statement to the press that he was "90 per cent certain" that a controlled nuclear reaction took place in the United Kingdom's Zeta machine. What followed during 1958 were triumphant newspaper headlines, such as "The Mighty Zeta", "Britain last night became officially the first country to prove H-power", "To Britain a Sun is Born" and "To Britain, this discovery is greater than the Russian Sputnik." While Cockcroft's statement had been a reasonable, honest estimate, and Zeta was indeed a technical milestone in nuclear fusion research, the cascade of reactions that followed this announcement was not entirely warranted.

A third reason for the intense interest in predictions for fusion's future was that the wealth of ideas and approaches to the feasibility of controlled nuclear fusion was in itself a cause of great excitement. Academician L.A. Artsimovich rightly called the conference "a fair of ideas".

"The analogy of flying, 100 years ago"

However, the euphoria at the start of the conference began to vanish as science made its way through to the speaker's podium and scientists like Edward Teller, L.A. Artsimovich, Lyman Spitzer and P.C. Thonemann called for a more realistic view of the matter. Teller, for example, made his famous comparison with flying: "I have mentioned an analogy and I mean it. The analogy of flying 100 years ago. At that time the question was to understand a very difficult subject, namely the subject of hydrodynamics and in particular the subject of turbulent hydrodynamics. We are now similarly trying to understand the subject of magnetohydrodynamics...I personally believe that there will be such a time, but that there will be surprises on the basis of the general situation of questions of new facts which we shall learn by the very kind of experimentation which we are undergoing today. Today we are not even clever enough, I believe, to recognise the surprise if it came along. We haven't started to ask the really significant questions and we have to go farther on the straight forward way, and it is not coincidence that we are all going more or less in that direction."

Bust of H. Bhabha at the IAEA Headquarters in Vienna

"However, I agree with Academician Artsimovich that [the origin of the neutrons] is not the important question. The origin of the neutrons will become clear enough if we can increase the temperatures in our plasmas. The important question is whether we can maintain stability in our plasmas as we feed in more and more energy, and whether we can, in due course, reach the break-even point where the energy generated by fusion equals the energy input. Dr. Thonemann thinks this may well take ten years, and that even if we are successful it is likely to take at least another ten years before we know whether an economic fusion power station is practicable. I agree with this. Dr. Teller's timescale is even longer." J. Cockcroft, Summary of the Conference, 12 September 1958

'"Euphoria gave way to realism"

At least when the conference ended, the situation had become clear: No matter how long it might take, the as yet 'unwritten chapter' on plasma physics had to be written. In his overview paper on the status of the Soviet research programme, L.A. Artsimovich wrote: "There begins to emerge a rough outline of the scientific foundation on which the methods of solving problems on controlled nuclear fusion reactions will probably rest...We do not wish to be pessimistic in appraising the future of our work, yet we must not underestimate the difficulties which will have to be overcome before we master thermonuclear fusion...The solution of the problem of thermonuclear fusion will require a maximum concentration of intellectual effort and the mobilization of very appreciable material facilities and complex apparatus. This problem seems to have been created especially for the purpose of developing close cooperation between the scientists and engineers of various countries."

L.A. Artsimovitch and I.V. Kurchatov

J. Cockcroft visits I.V. Kurchatov's home

Interview with Professor Eduard Hintz

“The overall impression of the conference was just overwhelming for all of us.“

BIOGRAPHY

Born on 2 October 1929 in Solingen-Gräfrath, Germany, Eduard Hintz studied physics from 1949 to 1956 at the University of Bonn and at Aachen University of Technology. From 1956 to 1958 he was a research associate at Aachen University of Technology (Institute of Physics, working group on nuclear fusion under Professor Wilhelm Fucks). He later worked on his PhD thesis, Experiments on the Production of a High-Temperature, High-Density Deuterium Plasma by Fast Magnetic Compression, at the Institute for Plasma Physics at the newly founded Kernforschungsanlage (KFA) Jülich. From 1962 to 1968 he was on the faculty of the University of Maryland, USA, and was a consultant to the Naval Research Laboratory in Washington, DC, USA. In 1968 Professor Hintz was appointed director of KFA Jülich. In 1976 he was appointed to a professorship at the University of Bochum, a post he held until his retirement in 1995.

Portrait of Professor Eduard Hintz in 2006

INTERVIEW WITH PROFESSOR E. HINTZ

What were the reasons for your participation at the Second Geneva Conference?

To answer this question I have to take myself back in time to the end of the year 1956, when I had to accept a drastic change in my career because of a death. I then joined a small group of young physicists and technicians that had just been formed at Aachen University of Technology. Under the direction of Professor Wilhelm Fucks and Dr. Hermann L. Jordan, they had started working on the development of high temperature plasma physics in order to follow the worldwide efforts to make the nuclear fusion of hydrogen isotopes available to society as a new kind of primary energy source. The starting conditions for this enterprise were poor, with respect to both the knowledge required and the resources needed, but all of us were determined to work towards this common goal as long as necessary.

Our first object of research was a Z-pinch experiment. However, we soon recognized that this configuration was not very promising, because it tended to instabilities. At that early time we did not want to decide on a definite plasma heating and confinement scheme. Instead we planned in a more general way to generate and study high temperature (in 1958 this was about 100 eV) and collision dominated plasmas in a simple geometry. For this purpose, the ‘theta pinch’ concept appeared promising. In the middle of 1958 we decided to build a rather ambitious experiment of this type that would permit us to generate and study high temperature, high density plasmas of 100 eV and even more, including the control of impurities and the development of the necessary diagnostics. When we

"Our first object of research was a Z-pinch. However, we soon recognized that this configuration was not very promising.“

learned about the intentions and the programme of the Second Geneva Conference, it was obvious for the research group that at least some of us had to attend. Because we would be unofficial visitors, it was clear that a major part of the costs had to be borne by ourselves. Eventually I joined a group of three colleagues, one of whom owned a private car, and we decided to drive to Geneva.

How were the journey and your accommodation at the conference in Geneva?

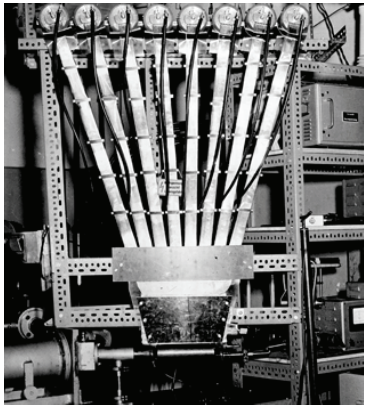
All of us still have a good memory of the journey, but we do not recall the details. The same is true for our stay in Geneva.

Young plasma scientists from Jülich and Aachen on their way to Geneva. From bottom to top: Joachim Schlüter, Hermann Fay, Eduard Hintz and Herbert Förster

Can you describe the size and quality of the conference?

The overall impression of the conference was simply overwhelming for all of us. The titles of the lectures as well as their content were quite new and impressive. The lectures were accompanied by an exhibition that was even more interesting. But the most exciting experiences were the discussions with our colleagues from foreign countries, in particular with English-speaking scientists. We all had the impression that we had to collect a wealth of knowledge and information that we then had to carry home for further exploitation.

The presentations at the conference covered the transport properties of high temperature magnetized plasmas as well as careful studies of critical questions on plasma instabilities. In addition, new methods of plasma heating were proposed. Special emphasis was given to plasma confinement in a variety of geometries. Altogether the conference participants were quite enthusiastic and highly satisfied with the outcome of this important event.



A theta pinch experiment at KFA Jülich with advanced low inductive energy feedlines and fast high voltage switches (end of the 1950s)

INTERVIEW WITH PROFESSOR E. HINTZ

"For the first time the critical problems of nuclear fusion could be discussed freely without any restrictions."

How much influence did the conference have on your young career as a physicist?
The influence of the conference was very strong. At Aachen University of Technology we had been working to prepare ourselves for performing successful research in the field of high temperature plasma physics since the end of 1956. At the Second Geneva Conference we were offered presentations by experts on almost all the critical questions and problems. Completely new experimental approaches were also proposed. For us young scientists it was important to learn that our own ideas regarding the main direction of future experimental research were confirmed and supported by what we read in the conference papers and by what we saw at the exhibition of experiments. A critical prerequisite for our planned theta pinch experiment was a very fast electrical circuitry, preparations for which were well advanced. Our small group from Aachen returned home from the conference with new ideas and an enormous amount of optimism. I believe the strongest impact from the Second Geneva Conference was the unbelievable enthusiasm of most of the participants. This observation was confirmed by the IAEA personnel as well.

What influence did the declassification of fusion research have on the general atmosphere at the conference and how positive was its impact on the atmosphere of scientific discussion?
Declassification in general was quite welcome and had a very positive effect on the atmosphere of the scientific discussions, in particular those between scientists from the USA and the Soviet Union.

How would you compare those scientific discussions with the discussions of today?
According to my experience over the decades since 1958, there is not much difference.

Would you agree, looking back, that the Second Geneva Conference was the initiation of international collaboration?
I think that there had been some small degree of international collaboration before 1958, but collaboration on a worldwide scale received a strong impulse for the future, especially collaboration across the political borders between East and West. For the first time, the critical problems of nuclear fusion could be discussed freely without any restrictions.

Was the general opinion correct that, with declassification, progress would be accelerated not only because of the free interchange of information that would result, but also because of the opportunity for additional qualified people (particularly those in academic life) to participate actively in the research?
I fully agree with that opinion, and it has been borne out quite obviously by the remarkable progress in thermonuclear research since the Second Geneva Conference.

How did this relate to your own remarkable career in nuclear fusion?
In 1958 I and my colleagues were complete newcomers to nuclear fusion. We had to absorb the knowledge and the experience offered at the conference in a relatively short time, and we had to work hard in order to get started with our own experiments. The next IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research was held at Salzburg, Austria, in 1961. By then our efforts at Aachen and later at Jülich had been very successful, and we were able to present results from our new theta pinch experiment

"For me the second Geneva Conference in a certain sense was the foundation stone of this wide range of plasma research."

as had been planned in 1958. We achieved temperatures of about 100–200 eV at particle densities of (1–2) × 10^{17} cm^{-3}.
Until about the years 1970–1975, experiments of the theta pinch type were successful and popular almost worldwide; there were even fusion reactor models based on this principle. In 1971 we at KFA Jülich succeeded in producing a thermonuclear plasma showing an ion temperature of 10 keV, or 100 million degrees Celsius, for the very first time. Although pinch dimensions varied between 10 centimetres and 10 metres, it became obvious that an extrapolation to reactor dimensions would be unrealistic. As a consequence, theta pinch experiments were brought to an end at our laboratory, and the tokamak era began. At KFA Jülich the TEXTOR tokamak was built, with the aim of conducting a research programme in the important field of plasma–wall interaction. For me the Second Geneva Conference in a certain sense was the foundation stone of this wide range of plasma research.

Looking back at the multiple designs for confinement systems (Z-pinch, theta pinch, toroidal pinch, steady state or pulsed mirror confinement systems, stellarator), was there a favoured direction in the nuclear fusion community? Which one would you say was the most advanced design at the time?
The best answer to this question was given by Academician Artsimovich during the 1958 conference. He emphasized that "at that time not a single one of the various magnetic confinement concepts was decisively superior to any other, and therefore, investigations had to be carried out in all different directions."

In your view, what would you say was the scientific highlight of the conference regarding Nuclear Fusion? And why?
The answer to this question is already covered by the quotation of Academician Artsimovich. There was no concept at hand that outperformed all the others. Basic research in a variety of directions seemed necessary and unavoidable. Perhaps one might add that the special scientific highlights of the conference were, in particular, the improved general theoretical understanding of plasma confinement by magnetic fields and the discovery of the 'cooperative phenomena'. However, they were not yet understood at that time.

To what extent was it obvious that the 'chapter on plasma physics' first had to be written before the scientific feasibility of nuclear fusion could be addressed?
In 1958 we were not really aware of the large field of basic plasma physics research that was lying ahead of us, but the necessity of writing that chapter became more than obvious in the following 10 to 20 years. A lot of fundamental knowledge had to be generated before we could even think of building a fusion power plant. The current design of ITER is based not only on results from many plasma confinement experiments over four decades, but also on the considerable progress in understanding the physics of hot plasmas that has been achieved since 1958.

How far did the seemingly universal Bohm diffusion burden the optimism of the scientists at the conference?
We did not regard Bohm diffusion as a burden, but rather as a scientific challenge. Its experimental existence was a fact. If we really intended to build a fusion power plant, we had to solve this problem, and in the end we did.

INTERVIEW WITH PROFESSOR E. HINTZ

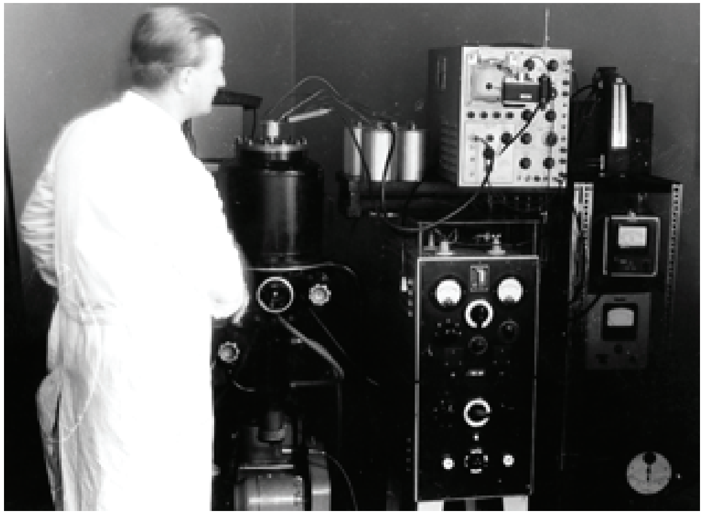
"After 50 years of intensive research, it appears to me now that the realization of nuclear fusion as a reliable energy source is no longer mainly a problem of physics or technology, but is rather a psychological and most of all a political issue."

What scientific mindset prevailed after the conference: enthusiasm or scepticism?
There is no general answer. It would depend on the mental attitude of each of the individual participants, but on the whole I presume that a high degree of optimism and enthusiasm was the leading mindset for most of the participants.

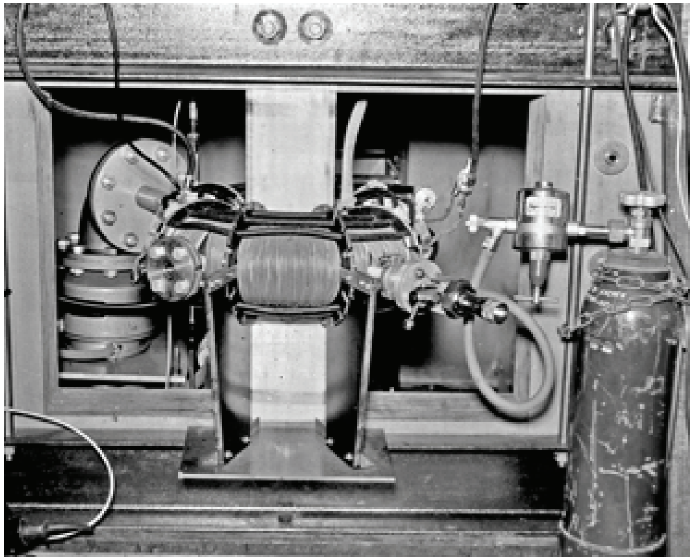
Nuclear fission was developed in a relatively short time. To what extent did the public and the media suffer the misimpression that nuclear fusion research would quickly succeed? To what extent did nuclear fusion scientists contribute to that misimpression?
In 1958 and for many years afterwards we were not at all able to give a solid and reliable prediction about when nuclear fusion would be ready for industrial use, but the media — just as today — strongly insisted on our answering their questions. They simply did not accept statements like, "we don't know, too much has to be clarified, so let's wait and see." Fusion scientists then spoke of "20 years or more", because nobody was able to predict what would happen during such a long time period. Looking back, it might have been a mistake to give numbers at all, as at that time we did not even know of one concept of confinement being superior to any other.

As one of a few, Edward Teller spoke of a more distant future regarding fusion energy production: *"The irradiation of materials by neutrons and gamma rays will cause the properties of these materials to change…These and other difficulties are likely to make the released energy so costly that an economic exploitation of controlled thermonuclear reactions may not turn out to be possible before the end of the twentieth century."*
Obviously, Teller's assessment of the situation has been borne out by the fact. Owing to his experience with other major nuclear projects before 1958, Teller probably had the best insight into the complexity of the task.

Your final thoughts: What is the likelihood that the ambitions of nuclear fusion research will be realized?
After 50 years of intensive research, it appears to me now that the realization of nuclear fusion as a reliable energy source is no longer mainly a problem of physics or technology, but is rather a psychological and most of all a political issue. For me the crucial question, therefore, is whether society — in particular the politicians and financial administrators — will be ready to support the efforts towards a nuclear fusion demonstration power plant in the flexible and unbureaucratic manner that is necessary for success.



The Aachen research group's first plasma experiment with a toroidal geometry in 1958



The first pinch experiment of the Aachen research group on nuclear fusion in 1957

Atmosphere of Scientific Discussion '58-'61

"We are not in the institute for noble girls here. Here, we have come together in order to clarify the truth." L.A. Artsimovich, translated by K.A. Razumova

BIOGRAPHY

K.A. Razumova, born in 1931, studied at Moscow University and later took up a post at Kurchatov Institute. She worked in the small group of scientists that proposed the tokamak idea, developed the tokamak construction and then investigated the first tokamak plasma. She was appointed Head of the Laboratory for the Tokamak Physics Problem within the Plasma Physics Department of Kurchatov Institute, investigating plasma confinement, MHD stability, disruptive instability, 'fan' instability and runaway processes. She, together with V.V. Alikaev, realized ECR heating and current drive. Today her interests lie in the field of plasma self-organization.

ARTICLE by PROFESSOR K.A. RAZUMOVA

The Style of the Scientific Discussion between 1958 and 1961

Reflections on the 1958 United Nations Conference on the Peaceful Uses of Atomic Energy and the IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research 1961

As a result of participating in contemporary international meetings, I became accustomed to being able to discuss both usual and novel ideas, and to having these ideas listened to politely and with kind indifference. The discussion of controversial ideas never exceeded a calm level. I never expected that, after energetically discussing my results with others, we would come closer to the truth than before. Instead the discussion helped to stimulate new ideas. It seems that in modern society, criticism is considered bad manners. It may be that, in the era of computers, people have become more isolated in their own world, or perhaps the world has changed.

Portrait of K.A. Razumova

The situation was different in my youth. I began work on thermonuclear studies at a time when everything was secret. Despite our attempts to find information about plasma investigations in the literature, we did not succeed. As a small group of scientists, we dreamed of finding 'intellectual brothers'. As more governmental restrictions were put on people's activities, people became more determined to overcome them. After the lecture on thermonuclear research in the Soviet Union given by I.V. Kurchatov at Harwell Laboratory, United Kingdom, in 1956, information gushed out from various laboratories. This of course determined the

Discussions on the lawn at the Palais des Nations

SCIENTIFIC DISCUSSION 1958-1961

"...locking the door, only to find out the plasma is going out of the window." H. Alfvén, chairperson of the session on Diffusion of Plasma at the Second Geneva Conference

Discussions in the hallways during the conference

scientific activity at the Second Geneva Conference in 1958. After the delivery of the papers, discussions were held in the conference hall, outside of it and at small special meetings which arose after the official proceedings. This provided an opportunity for a young girl like me to discuss ideas such as the nature of negative spikes on a loop voltage oscillogram (now known as 'disruptive instability') with a respected and well-known scientist like Lyman Spitzer.

"Finding 'intellectual brothers' "

The IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research held in Salzburg, Austria, in 1961 went beyond the usual bounds of an official meeting.

Academician L.A. Artsimovich strongly criticized the optimism of some scientists who believed that they had measured thermonuclear neutrons in their devices. Artsimovich had had prior experience (working with N.V. Filippov and V.I. Sinitsin) in measuring neutrons as a result of the instabilities in the inertial electrode pinch. He argued that, in their measurements, the authors had mistaken instrumental or instability effects for a heating effect.

The discussion became heated, and Artsimovich was asked to be more tolerant. He replied, "We are not in the institute for noble girls here. Here, we have come together in order to clarify the truth." His criticism was not meant to be personal, but was rather aimed at the ideas. The outcome of the discussion was

On the Way to Declassification - Kurchatov's Guidance

"The Second Geneva Conference can be viewed as having been a real 'fair' of ideas on nuclear fusion research that promoted the active development of the work being done in many countries today. The contribution of I.V. Kurchatov to the success of the idea of the conference — declassification and international cooperation in nuclear fusion research — cannot be overestimated."

that no resentment remained, but rather respect for those people who are able to look deeper into a problem. The result was that the partners became friends, and the conference stimulated scientists to work with increased interest and to continue their contact and discussions after the meeting.

In the concluding remarks of the conference, Artsimovich said:

"It is now clear that all our original beliefs that the doors into the desired region of ultra-high temperatures would open smoothly at the first powerful pressure exerted by the creative energy of physicists have proved as unfounded as the sinner's hope of entering Paradise without passing through Purgatory. And yet there can be scarcely any doubt that the problem of controlled fusion will eventually be solved. Only we do not know how long we shall have to remain in Purgatory. We shall have to leave it with an ideal vacuum technology, with the magnetic configurations worked out, with an accurate geometry for the lines of force and with programmed conditions for the electrical parameters, bearing in our hands the plasma, stable and in repose, heated to a high temperature, pure as a concept in theoretical physics when it is still unsullied by contact with experimental fact."

Finally I should like to note that we should keep up this attitude of discussion in order to allow us to find new and more progressive ideas, to move forward more quickly and to at last leave this Purgatory, where we have already spent too long.

Portrait of Professor V.P. Smirnov

BIOGRAPHY

Born on 2 October 1937, V.P. Smirnov graduated from Moscow Institute of Physics and Technology and joined the Kurchatov Institute fusion programme. From the beginning of his scientific career in 1961, V.P. Smirnov was involved in research on MHD wave propagation for plasma heating and diagnostics development. From 1969 his activity shifted to the physics and technology of high current charged particle beams for inertial confinement fusion (ICF). He proposed the approach to high power pulsed generators for ICF adopted in the Soviet Union, and in 1978 headed the construction of the largest pulsed generator in the Soviet Union, Angara-5-1, at TRINITI (formerly a branch of Kurchatov Institute). V.P. Smirnov and his

ON THE WAY TO DECLASSIFICATION

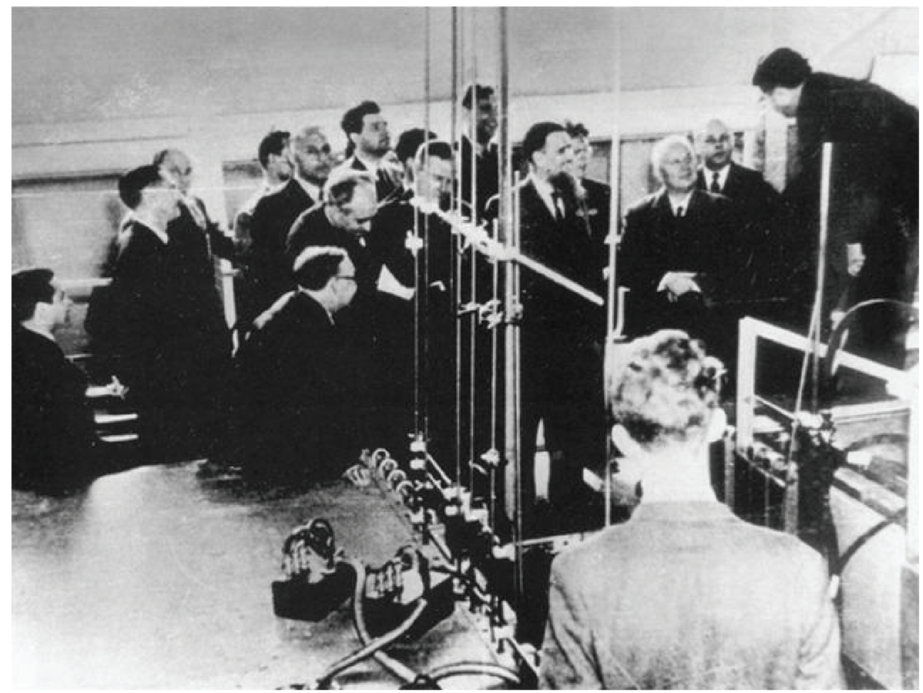
"I think that the papers to be presented at this conference, and the discussions which follow them, will show that it is still impossible to answer the question, 'Can electrical power be generated using the light elements as fuel by themselves?' I believe that this question will be answered in the next decade. If the answer is yes, a further ten years will be required to answer the next question, 'Is such a power source economically valuable?" P.C. Thonemann

colleague S. Zakharov developed and tested the modern approach to fusion pellet ignition by Z-pinch radiation. This result initiated worldwide research on strong radiative super-fast pinches for ICF. In 1998 he was invited to return to Kurchatov Institute, and succeeded B.B. Kadomtsev as director of its Nuclear Fusion Institute. At present the main part of his activity is directed towards ITER project development and fusion research in the Russian Federation.

ARTICLE by PROFESSOR V.P. SMIRNOV

On the Way to Declassification: Kurchatov's Guidance

In 1951, Academician I.V. Kurchatov, Head of the Soviet Atomic Project at the time, proposed to begin major studies into the problem of controlled thermonuclear fusion. His proposal was actively supported by Igor Tamm and Andrei Sakharov (future Nobel Prize winners). One of Kurchatov's closest



I.V. Kurchatov's 1956 visit to Harwell Laboratory, where he also gave a surprising lecture in which previously classified experimental material was presented

"I think that it can be done, but do not believe that in this century it will be a thing of practical importance. This view may be much too conservative and may be proved wrong within the coming decade, but I shall tell you why I believe what I believe..." E. Teller

colleagues at the time, L.A. Artsimovich, was appointed as the head of the new programme. The work was carried out under conditions of top secrecy, as was also the case in the United Kingdom, the USA and other countries.

"1956: Kuchatov's proposal to declassify all nuclear fusion research"

At the beginning of 1956, Kurchatov addressed the authority of the country with a remarkable proposal to declassify all nuclear fusion research activities, explaining that fusion power would have a strictly peaceful purpose and that the undoubted advantage of international cooperation should be the solution for this major task. As a result of this, in April 1956, Kurchatov, who had accompanied a Soviet Government delegation on a visit to the United Kingdom, delivered a report, On the Possibility of Producing Thermonuclear Reactions in a Gas Discharge, at Harwell Laboratory, and invited British physicists to visit the plasma laboratories of his institute.

The report made a great impression, and not only on the audience at Harwell. Subsequently, the studies of high temperature plasma started to be declassified in other countries that were also doing work in these areas.

"Fusion power would have a strictly peaceful purpose"
- I.V. Kurchatov

At the Second Geneva Conference in 1958, more than 100 reports devoted to controlled fusion issues were submitted. Academician I.V. Kurchatov did not himself participate in the conference, but all reports of the Soviet scientists passed a special selection process that was under his guidance. The head of the nuclear fusion programme, L.A. Artsimovich, submitted the overview paper. Some of the reports were dedicated to the results of experiments on the Soviet toroidal installation TMP, the first tokamak.

Delegates W. Heisenberg and L. Biermann, Federal Republic of Germany, examining the Soviet OGRA machine at the Second Geneva Conference

Highlights of 50 Years of Magnetic Fusion Research

"The international fusion programme is well positioned to demonstrate the scientific and technological feasibility of fusion energy by 2025, and to deliver on the promise of a new energy source to provide clean, plentiful energy envisioned at the Second Geneva Conference 50 years ago."

BIOGRAPHY

D.M. Meade began fusion research as a graduate student at the University of Wisconsin in 1962. His primary interests have been experimental research on plasma confinement in toroidal systems, and fusion device design, construction and operation. After moving to Princeton University in the early 1970s, he was Head of PDX, Head of TFTR, Deputy Director of Princeton Plasma Physics Laboratory and Head of the US design team for FIRE.

Professor Dale Meade in 2002

ARTICLE by PROFESSOR D. MEADE

Highlights of 50 Years of Magnetic Fusion Research

After almost a decade of research carried out in secrecy, magnetic fusion research was declassified in 1958. Scientists from opposite sides of the East–West political divide gathered in Geneva that year for the first international fusion meeting to find that they had identified the same barriers to achieving fusion, and that neither had a solution to the vexing plasma instability problems. The collegial bond formed in the early years led to five decades of strong international collaboration on one of science's greatest challenges — harnessing fusion energy on Earth. Supported by that collaborative structure and spurred on by friendly rivalry within it, dramatic technical progress towards fusion conditions has been achieved, providing the basis for pooling the world's resources to build ITER, the first fully international scientific mega-project.

Drawing on the knowledge gained through the development of nuclear weapons, the great potential, general technical requirements and critical issues for the peaceful production of fusion energy were identified in the early 1950s. Various experimental configurations, such as the tokamak, stellarator, pinch and mirror, were developed and presented at the 1958 conference. Instabilities and anomalous transport plagued confinement experiments into the 1960s, however. Nearly all toroidal experimental results could be characterized in terms of the pessimistic Bohm scaling. Gradually, a new field of science — fusion plasma physics — began to emerge, as theorists developed more refined analyses and experimentalists began to carry out more detailed experiments with improved diagnostics designed to yield an understanding of instabilities. Following the predictions of theory, interchange instabilities were stabilized

"The collegial bond formed in the early years led to five decades of strong international collaboration on one of science's greatest challenges — harnessing fusion energy on Earth."

by adding minimum |B| on a mirror machine and by minimum-average-B in toroidal multipoles. Natural self-organization in Zeta produced a reversed field region with high shear near the plasma edge, creating a transient quiescent phase with improved confinement. Slowly but steadily, plasma confinement in modest temperature plasmas began to exceed Bohm scaling by factors of 5–10.

The IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research held in Novosibirsk in August 1968 provided the first hint of a major advance in fusion, as soft X ray and diamagnetic loop measurements on the Soviet T-3 tokamak indicated T_e in the kiloelectronvolt range. If true, this would mean that the barrier of Bohm diffusion had been broken in a hot plasma. Almost immediately, an international collaboration was formed between Culham Laboratory in the United Kingdom and Kurchatov Institute in the Soviet Union to use a new diagnostic technique, laser Thomson scattering, to definitively measure T_e on T-3. The results of this effort, brought together very quickly despite the prevailing political climate, were reported at a special meeting held in Dubna, Soviet Union, in August 1969. Soon after the results confirming $T_e \approx 1$ keV were presented, the phone lines were buzzing, as laboratories in the West began analysis and design of a new series of tokamaks.

'"IAEA Conference Novosibirsk 1968: indications that the Bohm-diffusion barrier had been broken"

In the USA, the Model C stellarator was converted into the Symmetric Tokamak (ST) within six months, and quickly confirmed the improved confinement observed on T-3.

During the early 1970s, researchers around the world built several T-3-scale tokamaks, such as ORMAK, Alcator and ATC in the USA; TFR and Pulsator in Europe; and JFT-2 in Japan. These devices extended the breadth of tokamak physics and provided a test bed for auxiliary heating using ICRF and neutral beam injection. The construction of medium scale tokamaks (PLT and T-10) was initiated.

When the oil crisis arose in 1973, the international fusion research programme already had momentum and was ready with proposals to advance. The US fusion budget increases were spectacular, as they were in other countries. The confidence in tokamaks increased when PLT produced very high ion temperatures through neutral beam heating. Several medium scale tokamaks — DIII, DIVA, PDX, Alcator C, ASDEX, TEXTOR, FT, JFT-2a (DIVA) and T-7 — were built to investigate specific areas: cross-section shaping, divertors, high field, and the challenges of auxiliary heating and superconducting coils. The advances in tokamak performance also spurred advocates for other configurations — magnetic mirror, theta pinch and toroidal pinch — to propose and construct medium scale experiments. A major outcome of the progress achieved in the tokamaks of the 1970s was the initiation of the construction of the large tokamaks (TFTR, JET, JT-60 and T-15) embodying roughly a tenfold increase in size over the previous generation and costing in the range of US $500 million. Each had the ambitious goal of achieving near-fusion-plasma conditions to allow the study of fusion plasma phenomena and to extend technology for fusion.

As the medium scale tokamaks began operation with auxiliary heating in the early 1980s, Bohm-like diffusion reappeared,

50 YEARS OF MAGNETIC FUSION RESEARCH

"He also showed us a very tantalising photograph at the end, of an apparatus looking very much like Zeta, perhaps a little bigger, but he didn't tell us how well it was performing — perhaps you can ask him that question." J. Cockcroft, commenting on the report of V.S. Emelyanov

"Laughter in the conference room. An amiable reflection of the cooperative spirit of this great Conference." This Week at the United Nations, 5 September 1958

however, this time in the guise of 'L-mode scaling', with its pessimistic projections for tokamak power plants. Fortunately, the 'high confinement' H-mode was discovered on ASDEX in 1982 and was quickly exploited on other medium scale tokamaks. TFTR, JET and JT-60 came into operation in the early to mid-1980s. Despite the huge increase in size and complexity, they were each built in about six years. Within three years, new regimes of plasma behaviour with fusion plasma temperatures (10–20 keV) and values of the Lawson product $n\tau_E$ 300 times larger than those of T-3 were achieved. Construction of JT-60U was initiated in 1989 and completed in 1991. JT-60U came into full operating capability during the 1990s, achieving record performance in deuterium plasmas using several advanced modes. The scientific base of the programme was strengthened by results from medium scale tokamak experiments, including ASDEX-U, Tore Supra and DIII-D, as well as results from the broader supporting programme in stellarators and other configurations. It was a period of outstanding scientific progress made possible by the large investments in fusion research made during the late 1970s and early 1980s.

"Reykjavik 1987: agreement to design what later became ITER"

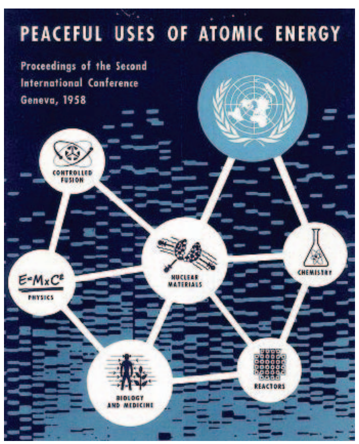
With new results in hand, each of the major participants in fusion began to plan for a major next step. The idea of a global collaborative experiment for fusion research was first discussed by Chairman Gorbachev and President Reagan at the Geneva Summit in 1985. Then, at the 1987 Reykjavik Summit, an agreement was reached for the European

Opening session of the Second Geneva Conference

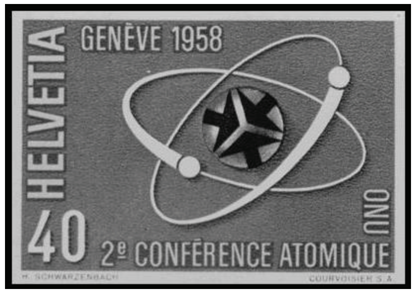
"Zeta and other experiments were classified because of the fact that they could be neutron sources to produce fissile material, but my criterion was not, so it was allowed to be talked about...Sharing an office with Peter Thonemann I saw what the fusion problem was. I produced the criterion, produced the report, and then I got involved with lots of other discussions...I wrote one or two other papers surveying the other ideas that had been suggested and showing that most of them wouldn't work. I also knew that I wouldn't see fusion power in my own lifetime, although most people were talking about it coming in 20 years or so. They still are. My work was always negative and was tending to be showing things that wouldn't work, or surveying an area to see whether it might possibly be feasible." J.D. Lawson, interview published in December 2005 on the JET web page to mark the 50th anniversary of the Lawson Criterion

Union, Japan, the Soviet Union and the USA jointly to pursue the design for a large international fusion facility, which became the International Thermonuclear Experimental Reactor (ITER). The Conceptual Design Activity (CDA) of ITER started in 1988 under the auspices of the IAEA with an international team sited in Vienna.

The first experiments to investigate fusion power production in a tokamak were carried out by JET in 1991 using 10% tritium in a deuterium plasma, resulting in a peak fusion power of 2 MW. TFTR began the first tokamak experiments with 50/50 DT fuel in 1993 and achieved fusion powers of 11 MW in 1994.



Proceedings cover 2nd Geneva Conference



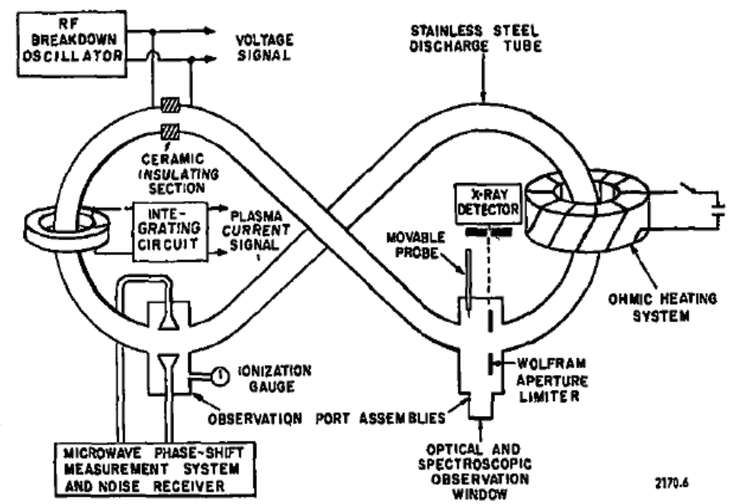
Special edition stamp, Switzerland 1958

The major physics results from these experiments were first measurements of heating by the α particle fusion products, measurements of the confined α particle transport and instabilities driven by the α particles. In October 1997, JET resumed DT operation and extended the peak fusion power to 16 MW and the fusion energy per pulse to 22 MJ. All the large tokamaks achieved values of the Lawson product $n\tau_E$ during short pulses within a factor of 10 of that required for a fusion power plant, and together with the medium scale tokamaks provided a strong technical basis for the design of ITER.

"2005: decision to build ITER"

The focus of the world's programme then shifted towards the science and technology for sustaining high performance plasmas. The Large Helical Device (LHD), a long pulse superconducting helical system comparable in size to the three large tokamaks, began operation in Japan in 1998. Also in Japan, the small tokamak TRIAM-1, with a superconducting toroidal field coil, achieved pulse lengths of over five hours with the plasma current driven by lower hybrid waves. Tore Supra continued to extend pulse duration and power handling capability. As they expanded their magnetic fusion programmes, the Republic of Korea, China and India each took on the ambitious task of constructing advanced medium scale tokamaks, namely KSTAR, EAST and SST-1, with superconducting magnets to address steady state plasma research and development. An optimized superconducting stellarator, W-7X, is now under construction in Germany with the goal of high performance long pulse operation.

Meanwhile the ITER Engineering Design Activity (EDA), which began in 1992, was carried forward by the European Union, Japan and the Russian Federation. When the EDA was completed in 2001, the goal shifted to selecting a construction site and establishing an Implementing Agreement. It was decided in June 2005 to build ITER in Europe at Cadarache, France, with a satellite tokamak to be built in Japan as part of a broader approach programme agreement between the European Union and Japan. By the end of 2005, China, India, the Republic of Korea and the USA had joined the collaboration. All seven parties had signed the ITER Implementing Agreement by October 2007. As the ITER organizational structure was being finalized, the world fusion research programme was mobilized to support ITER through the International Tokamak Physics Activity (ITPA). EAST and KSTAR have recently begun operation to address long pulse issues.
In support of ITER, a major modification to JET will be made to study the plasma first-wall issues, and a new Japanese tokamak, JT-60SA, is being designed to study the behaviour of high performance long pulse



Schematic diagram of instrumentation of the B research stellarator, in "The stellarator concept", by L. Spitzer

"I wish I could know and tell you more about this, and I hope suggestions will come forward; because this needs imagination and I am lacking in imagination." E. Teller

deuterium plasmas.

The construction of ITER and preparation for its operation are occurring as recent steep increases in the price of oil are, once again, spurring the development of non-petroleum energy sources. Furthermore, concerns about the impact of all fossil energy use on the environment are increasing the desire for non-CO2-emitting energy sources. In the evolving energy future, the fusion programme will be well positioned to fulfil its potential of demonstrating the scientific and technological feasibility of fusion energy by 2025, if the nations of the world continue to support the science and engineering that have propelled the tremendous progress we have made since the world's fusion community assembled for the first time in Geneva fifty years ago.

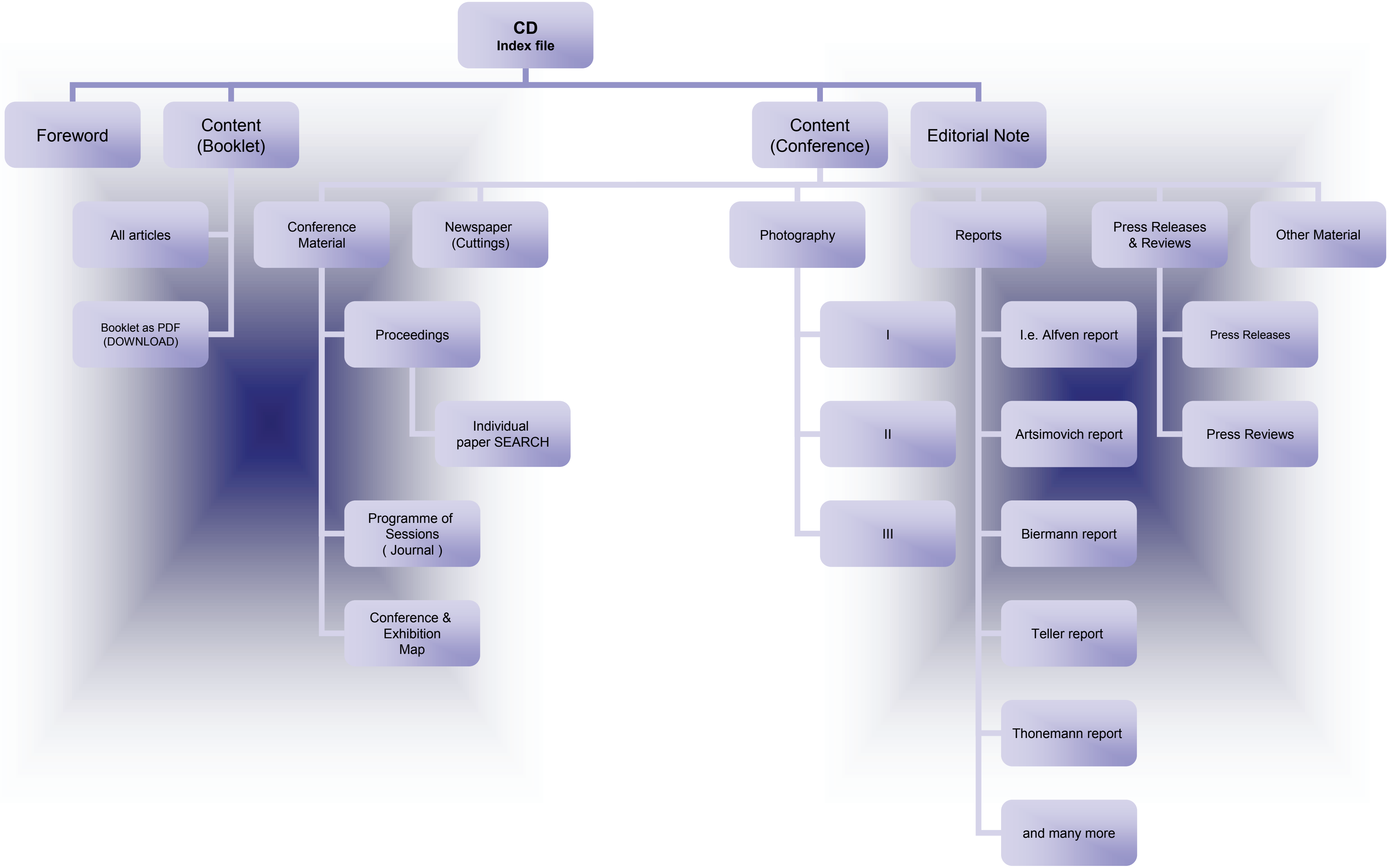
The Second Geneva Conference: the United Kingdom's exhibition on the left and that of the USA on the right

Editorial Note

FUSION ENERGY 2008
IAEA, VIENNA, 2008

Produced by the IAEA in Austria
September 2008

CONTENT OF THE RETROSPECT CD



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