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Hearing on Nuclear Fusion

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Answers by the Institutes of the HGF Research Collaboration on Nuclear Fusion

A. Status and Foreseeable Development of Fusion Research

Leading questions:

A.1. What are the greatest scientific and technical challenges still to be met from the present perspective ?

IPP	In recent decades, the foundation has been created in many experiments worldwide to demonstrate the basic feasibility of fusion with the next step. This next step will be the ITER experiment. In the past ten years, the concept has been established in an extensive joint programme by the four partners, Europe, Japan, Russia and the USA. The essential components have been developed and built as prototypes jointly with industry. The next task is now to combine all the necessary components into a functioning complete system in ITER. ITER's particular scientific and technical challenge is to generate a plasma and keep it in steady-state operation, in which Q (the ratio of generated fusion power to applied heating power) is for the first time clearly above 1. ITER should reach a value of $Q \approx 10$. The necessary criteria are: achieving a sufficiently good plasma confinement, avoiding or controlling plasma instabilities, avoiding plasma impurities, controlling the intense particle and power fluxes of the plasma-limiting structures, continuous removal of the helium nuclei and continuous fuel replenishment. Most of these rather physical issues are already being dealt with in present-day experiments, but must now be investigated in a reactor plasma of

	adequate size. In particular, scaling of the energy confinement time τ[1] to a plasma having nearly power plant dimensions must be verified. On the other hand, central plasma heating by high-energy alpha particles from the fusion reaction and the collective effects possibly produced by these alpha particles are two important issues which can only be investigated with ITER since they are coupled to the condition of Q >> 1. The technological challenges of the future are, in particular, the development of materials for the fusion components: development of neutron-resistant structural materials with low activation potential as well as heat- and erosion-resistant materials for the First Wall. Moreover, the necessary remote handling technology as well as the components for the breeding cycle must be further developed. [1] *The energy confinement time is a measure of the isolation quality of the plasma. It is calculated as the ratio of energy contained in the plasma to the heating power applied.*
FZK	1. The integration of the physical and technological developments in an experimental facility and the demonstration of safe operation ("Next Step/ITER"). 2. Achieving continuous operation with high availability and the qualification of materials with long service life while minimizing radioactive waste with prolonged decay times ("DEMO"). 3. Extending the use of fusion energy to other applications, optimizing the facilities for the demand situation.
FZJ	<u>Starting point:</u> The generation of hot (100 million degrees) and dense plasmas for the controlled generation of fusion processes is possible today. The physical conditions under which also energy production takes place are reliably known. On this basis, the design parameters of an experimental reactor working in short-time operation have been defined (ITER-FEAT, energy gain factor 10). <u>The greatest challenges:</u> Continuous operation with sufficiently high

	availability as required for economic operation still has to be demonstrated. This concerns above all the technology-oriented topics of thermomechanical load on the wall, erosion of wall material, neutron stability and – for the tokamak – efficient continuous plasma current drive. This further development will take place in ITER-FEAT and other specialized devices and will lead to the definition of a first electricity-producing reactor (DEMO). Further desirable goals: A further development of the present "conservative" plasma parameters for the design of ITER-FEAT towards advanced plasma scenarios (e.g. "optimized tokamak") could in the long term lead to smaller (possibly reduction by half) and less expensive plants (this is still speculative).

A.2. When is the first commercial fusion reactor expected to go into operation?

IPP	The time of commissioning a first commercial fusion power plant depends decisively on the implementation of the next two steps regarded as necessary prior to the construction of a power plant: ITER and DEMO. DEMO (the abbreviation for the not yet precisely specified DEMOnstration power plant) will already produce electric current. Before this, a sufficiently large experiment such as ITER is required to demonstrate the physical and technological feasibility of nuclear fusion. Assuming a start of ITER construction in 2006 and the beginning of experiments in 2014, in the case of positive results, the design of DEMO could already take place in 2021 and its construction in 2029 and would already have the dimensions of a commercial fusion power plant. With an estimated construction time of approx. nine years DEMO could go into operation in about 2037. On condition that five years of operation will be sufficient to begin with the design of a first commercial fusion power plant, the construction of this fusion power plant could start in 2047 and the plant could supply electricity to the grid for the first time after another five to ten years around 2055.

	However, this time schedule presupposes a smooth sequence of the various steps. In particular, there must be a political will to immediately implement the scientific and technical findings from ITER and decide on the construction of DEMO without delay. This will has not always been perceivable in the past, for example. in connection with the ITER decisions: even a decision to construct ITER in 2001/02 already means a considerable – politically induced – delay of several years compared to earlier planning. Such delayed decisions will directly affect the period up to a first fusion power plant and cannot be attributed to fusion research.
FZK	This will depend on technical and political factors. One development step requires approximately 20 years of construction and operation. Hence it follows that a commercial reactor would be available in about 2050. The timescale could be shortened by stronger overlapping of the project flows. In order to limit the increased technical risk involved in such a procedure, additional programmes on component development and further test facilities would be required .
FZJ	Three steps are planned: 1. ITER-FEAT, first experimental reactor with 10-fold energy gain in short-time operation (approx. 8 minutes pulse duration). 2. DEMO, first electricity-producing reactor in continuous operation 3. commercial reactor. The speed will be essentially determined by the construction and utilization times (approx. 10 years of construction, 5-10 years of utilization up to the definition of the next step) and by political decision-making processes. A first commercial fusion power plant could thus be available towards the middle of the century.

Further questions:

Physical Fundamentals

A.3. What is the status of fusion research and what goals are pursued with a further large-scale experiment (ITER) ?

IPP	In the past 50 years, fusion research has achieved considerable progress with respect to plasma theory and experiments, which can be recognized most clearly in the values obtained for the so-called fusion product (the product of the three plasma parameters of density, temperature and energy confinement time). The value of this fusion product, which in a power plant must be greater than $3 \cdot 10^{22}$ million degrees Celsius times second per cubic metre, has been continuously increased by a factor of approx. 5,000,000 from the first experiments up to the present largest tokamak facilities. In the JET joint European experiment, it is only a factor of 5 below the target value for a power plant. In experiments with plasmas containing equal amounts of deuterium and tritium (the optimum mixture for energy production) JET was able to achieve a fusion power of 12 megawatt for about one second in 1997 including a short-term peak power of 16 megawatt. 65 percent of the heating power applied was recovered by fusion (i.e. $Q \approx 0.65$). These results show that fusion research has come very close to its physical goal. For the remaining path to a power plant, however, the existing experimental facilities are not yet sufficient. Although the optimum values of plasma density and plasma temperature for a power plant are achieved today as a standard, the energy confinement time τ, i.e. plasma isolation, must be improved to further enhance the fusion product. Since τ greatly depends on the plasma dimensions, a power-plant-relevant plasma with Q >> 1 can only be generated in a new larger experiment. The mission of ITER, as the next step conceived in international cooperation

	is called, will be to demonstrate the scientific and technological feasibility of fusion and, at the same time, provide the necessary scientific and technological information for the development of a demonstration power plant. To this end, the experiment must be sufficiently large in order to create a plasma for a prolonged time (several 100 seconds) in which the helium particles from the fusion reactions constitute the dominant heating source and a fusion power of several 100 megawatt is generated (see also the answer to A.1.). Furthermore, ITER should contain all the essential technological components of a fusion power plant to demonstrate their compatibility with thermonuclear plasma operation (superconducting coils, remote handling techniques, steady-state plasma heating, tritium technology and other components of the fuel cycle).
FZJ	The magnetic confinement experiments have shown that the generation of hot (100 million degrees) and dense plasmas for the controlled generation of fusion processes is possible today without any major problems. For energy production, however, energy confinement (= thermal isolation of the plasma) must also be adequate. This condition is best fulfilled today by the tokamak; however, a minimum size is required necessitating large-scale equipment not only when constructing a reactor but also for the experimental facilities. The stellarator line has recently been catching up in comparison to the tokamak with new optimized concepts in the field of energy confinement. The physical conditions (empirical data base) which enable energy production (positive energy balance) in a tokamak are known today with great certainty. On this basis, the design parameters of a tokamak with 10-fold energy gain have been defined (ITER-FEAT). In this tokamak, for the first time, the fusion energy released in the form of alpha particles would dominantly heat the plasma (up to now it has been externally heated). Alternatively, there was a precursor design for a larger machine (ITER) which could have done completely without external heating but was abandoned due to the construction costs being twice as high.

	Because ITER-FEAT largely heats itself internally by the fusion processes, although only in short-time operation (8 minutes pulse duration), nearly all prerequisites in terms of physics are given which would make up a fusion reactor. It therefore makes sense to now also integrate and test all technological reactor-relevant components in ITER-FEAT. However, this does not make ITER-FEAT a reactor, because there is a lack of space for a complete breeding blanket for a self-sustaining tritium inventory and especially because it is not yet clear whether this tokamak can also be run in continuous operation. With external current drive it is intended to demonstrate the basic possibility of continuous operation in ITER-FEAT, but then only under the conditions of an energy gain half as high (Q = 5). If this demonstration of continuous operation is successful and if, moreover, the problems of wall loading by heat and erosion will get under control, then there would be almost no obstacle to the definition of a reactor which from the very beginning will be designed for continuous operation and is therefore also suitable for electricity production (DEMO). In ITER-FEAT neutron damage due to short-time operation does not yet play a major role, but for DEMO the materials that are compatible with very intense neutron radiation still have to be developed and qualified. This requires a relevant research programme in parallel with ITER-FEAT. The availability and thus the economic efficiency of a fusion power plant will probably be essentially determined by the lifetime of the most strongly exposed wall components (divertor, breeding blanket). The frequency and duration of the replacement of wearing parts will then determine the availability. Conclusion: Plasma physics and fusion research in the last 50 years have ultimately reached their most important goal today, passing through many different confinement concepts: the plasma-physical conditions and thus also the minimum size of a tokamak for the generation of reactor-relevant fusion plasmas are known. We are now entering a physico-technological era, above all in the form of ITER-FEAT, dominating the next decades, in which it will be

	important to realize the continuous operation of a fusion reactor.

A.4. How long has a plasma burned in the past, how much energy has it generated and how much energy had to be supplied for heating? Is it really possible to draw conclusions from these short-time experiments with respect to a longer-lasting plasma confinement (continuous operation)? What burning time and delivered energy amount do you expect of ITER ?

IPP	The longest discharge phase with significant D-T fusion energy production was achieved in JET, where a fusion power of approx. 5 MW – with a total energy production of 22 MJ – was maintained over 5 seconds. The externally supplied heating power was 24 MW, the heating energy supplied during this time 120 MJ. (The energy previously needed for heating up to burning temperature was small compared to the energy supplied during this phase.) The highest fusion peak power – 16.1 MW – was also achieved in JET. For this purpose, 25.7 MW was supplied to the plasma from outside, i.e. 65 percent of the power applied was recovered by fusion. The aim of these special experiments was to demonstrate and study plasma heating by fast, fusion-produced helium atoms. The results were in agreement with expectations, but are not informative enough for a fusion power plant, for which the fusion power must be significantly higher than the heating power supplied from outside (Q >> 1, see A.1.), a condition which will only be achievable in an experiment of ITER size. These investigations are thus the physical main goal of ITER. Sustaining a tokamak plasma by energy supplied from outside has been adequately demonstrated. In a small Japanese plant, for example, discharge times of two hours have already been achieved. Informative for continuous operation are discharges in which the temperature and plasma current profiles have adjusted to a state of equilibrium. Adjustment times depend on the size of the plant and amount to a few seconds (temperature adjustment) and more than 100 seconds (current adjustment) in ITER. In its burning time, ITER has been designed so that it can be demonstrated that equilibrium is

	achieved. In a mode of operation in which the current is driven by a transformer ITER will supply 500 MW fusion power over approx. 400 seconds, i.e. an energy of 200,000 MJ per pulse. Energy supply from outside will only be 1/10 of this value. In other forms of operation – involving lower power multiplication – pulse lengths of 2000 seconds and probably even genuine continuous operation can be achieved in ITER.
FZJ	The data In JET, a peak value of 16 MW fusion power was achieved for a short time with 26 MW external heating and an ion temperature of 300 million degrees. JET is thus within 10 % of the so-called break-even (Q = 1), where as much energy is produced as must be supplied from outside for plasma heating. In comparison to the first fusion experiments in the fifties this is an improvement by 12 orders of magnitude (1000 billions) *[Wesson in "The science of JET"]*. Of particular importance is also the quasi-continuous operation reached in JET with a constant fusion power of 4 MW for 5 seconds with 26 MW plasma heating and a plasma temperature of 80 million degrees. This equals a power gain factor of Q = 0.15. The totally released fusion energy was 20 MJ. Significance of the DT experiments When a 50:50 mixture of deuterium and tritium was filled into JET, the physicists had no doubt that fusion energy of the order of MW could be produced. The preliminary experiments with deuterium alone had already provided sufficient evidence for this result. It was not known whether the energy confinement changed with these amounts of tritium in the plasma and how the heating by alpha particles exactly acted. The new findings obtained in DT operation now provide important data complementing the empirical data base underlying the extrapolation to ITER-FEAT. Furthermore, the aim was to learn to control the tritium cycle – an important technological milestone on the road to ITER-FEAT.

	Significance of the pulse length The constant production of 4 MW fusion power over 5 seconds actually represents a more important result than the record value in energy gain. The duration of 5 seconds may be regarded as quasi-continuous in terms of plasma physics. On the other hand, no equilibrium is established as yet with respect to heat exposure of the wall or even the erosion processes for these pulse lengths. Even more difficult is the investigation of damage to the wall material due to neutron radiation, which even in a fusion power plant only becomes gradually evident after many months. In this respect, only special experimental facilities still to be built for neutron irradiation with reactor-relevant energies can be helpful. The longer pulses in ITER-FEAT (8 minutes) will be useful to answer many questions (heat removal by active cooling), but can only help to solve the neutron problem to a limited extent due to the low neutron fluence.

A.5. Are the behaviour of a deuterium-tritium plasma (in contrast to a pure deuterium plasma as used e.g. in Greifswald), the impacts of the high neutron fluxes and the breeding process sufficiently explored, especially for a large-scale plant ?

IPP	The investigations with deuterium-tritium plasmas in JET, and also in TFTR, Princeton, have shown that these plasmas basically do not behave differently than the normally used pure deuterium plasmas. The improvement in energy confinement expected by replacing hydrogen by deuterium and finally tritium also occurred. However, the specific aspects of a deuterium-tritium plasma (above all the self-heating at $Q >> 1$) – as already discussed above – are the physical main investigation goal for ITER. The summed-up neutron flux in ITER is limited to a level which can be handled without problems with established and tested materials. The breeding process (for generating the tritium fuel from lithium) will only be tested in replaceable modules. Fuel breeding is not a prerequisite for successful ITER operation because the fuel for ITER-FEAT is available in

	sufficient quantities even today – produced e.g. as waste product by the Canadian fission power plants of the CANDU type.
FZJ	Concerning this question, the requirements for ITER-FEAT and DEMO must be differentiated. In ITER-FEAT the neutrons will cause much less damage due to short-time operation. Specific neutron processes, for example, in the breeding blanket modules, however, can be examined. Conventional materials are still used without exception. For the continuous operation of DEMO, sufficiently neutron-resistant materials with low activation should already be used for the highly exposed components. This means that the necessary material developments and material tests must be largely advanced up to the start of DEMO construction.

A.6. Is deuterium/tritium fusion the most promising approach to a power reactor? Are alternative fuel concepts ("advanced fuels") conceivable? What advantages and disadvantages would be involved ?

IPP	The deuterium-tritium reaction is the only one with which a power plant based on proven physical solutions could be built. All other reactions (D-He^3, D-D, p-B) require a quality of energy confinement which, from the present perspective (physical experience, known technologies of superconducting magnets) is not achievable in plants of an acceptable size. D-He^3 and D-D would make tritium breeding superfluous. D-He^3 would, moreover, more than halve the neutron flux. Only the p-B reaction would be feasible without any neutron production. However, the demands made on confinement quality by these three alternative concepts are exorbitant. The confinement triple product, $nT\tau$, which is the best measure of the physical requirements, would have to be

	increased by a factor of 50 for a D-He^3 power plant (which, moreover, would have to rely on He^3 fuel supply from the moon), by a factor of 100 for D-D and a factor of 1000 for p-B compared to a deuterium-tritium power plant.
FZJ	Apart from the envisaged fusion of deuterium and tritium, whose reaction products are one neutron and one helium nucleus, there are still other fusion reactions which do not emit neutrons. For various reasons, this neutron-free or low-neutron fusion is considered unattainable as yet today: 1. The fusion of hydrogen and boron-11 requires almost ten times higher temperatures and significantly higher plasma densities than are achievable today. 2. The fusion of deuterium and helium-3 fails due to the lack of helium-3, which is found in large quantities on the moon and could only be brought to earth at huge efforts. 3. Neutron-free fusion would dramatically increase the heat removal problem. The neutrons from normal DT fusion are very suitable for distributing the major fraction of the fusion energy over relatively deep regions of the entire wall. Without neutrons, the total fusion power concentrates on relatively small regions of the first wall, which would lead to heat loads that are uncontrollable today. Neutron-free fusion is still science fiction.

A.7. ITER will be a tokamak. What ranking does the simultaneous development of the stellarator concept have? Is the plasma physics for both concepts sufficiently understood ?

IPP	In physical terms, the two plant variants differ in that the tokamak needs an internal plasma current in addition to external magnet coils for stabilizing its plasma, whereas in the stellarator the plasma is stabilized by the magnetic fields of external, specifically shaped coils alone. The plasma current in the

	tokamak has advantages – it serves for initial plasma heating – but also disadvantages: It is a source of plasma instabilities. Moreover, the plasma current limits the discharge duration if it is generated conventionally, i.e. inductively. A tokamak operated in this way can only work in a pulsed mode, which would be unfavourable for a power plant. It is therefore intensively investigated how the plasma current in a tokamak can be generated in a different way, e.g. by intrinsic currents (bootstrap current) or by current drive with radiated particles or radiofrequency waves. The investigation of such concepts is also planned for ITER. In its conceptional design, the stellarator is basically suited for steady-state operation. It therefore represents a promising alternative to the tokamak and will be thoroughly explored in the WENDELSTEIN 7-X experiment in Greifswald. Due to the steady-state feature and because the above instabilities cannot occur, the stellarator concept could well lead to a more efficient system, but the theory-based, optimized confinement concept must first be verified experimentally with W7-X. For historical reasons, however, the tokamak is already further advanced than the stellarator and reaches plasma values even today which come close to the values expected for a power plant. Therefore, only the tokamak was a candidate principle for ITER. However, the European fusion strategy provides for a further development of the stellarator line (in Europe essentially with Wendelstein 7-X) in parallel with ITER. For DEMO, therefore, the question is still open whether the plant will be a stellarator or a tokamak. This is also based on the fact that all technological developments still necessary are independent of the confinement concept so that the developments tested in ITER can later be directly used for the stellarator. With respect to plasma physics it must be borne in mind that – apart from the mechanism for the generation of the confining magnetic fields – the two confinement concepts are based on the same physical principles, so that a great deal of plasma-physical knowledge can be transferred from one confinement concept to the other. Incidentally, it is a strength of IPP as the

	only fusion institute worldwide to investigate both tokamaks and stellarators. From a comparison of the results with the two magnetic configurations synergetic effects are obtained which lead to an in-depth understanding of the properties of magnetic configurations.
FZJ	Both concepts, tokamak and stellarator, are based on the principle of magnetic confinement with toroidal magnetic fields. <u>Differences:</u> The magnetic field configuration in the tokamak is predefined, among other things, by a plasma current. The drive of this plasma current is generally pulsed in present-day experiments. A tokamak can only be run in steady-state operation with additional expenditure (external current drive). Relevant techniques working with sufficiently high efficiency are under development. A completely external current drive has already been demonstrated in several smaller tokamaks. In contrast, a stellarator runs continuously without additional expenditure. The tokamak concept has shown a better energy confinement in the past and is thus much further developed than the stellarator. However, recent findings which have led to an optimized stellarator concept (Wendelstein 7-X) give new impetus to this line so that it is hoped that the stellarator could displace the tokamak due to the attractiveness of natural continuous operation. <u>Common features:</u> Many issues relating to fusion reactor technologies do not differentiate between tokamak and stellarator; e.g. plasma-wall interaction, diagnostics, heating method, breeding blanket, wall materials, superconducting coils, tritium cycle or control of steady-state operation. In view of the scope of these topics it becomes apparent that the common

	features predominate. Findings obtained in ITER-FEAT will therefore also be transferable to a stellarator. The decision whether DEMO will be a tokamak or a stellarator is in no way anticipated by the construction of ITER-FEAT.

A.8. Can the characteristic parameters of the plasma near the expected operating point of a fusion reactor and the physical aspects of thermonuclear plasma heating be adequately tested in ITER-FEAT ?

IPP	ITER-FEAT has been designed so that it can provide conclusive physical information for a power plant in a very cost-efficient manner. The physical similarity or variability of different plants can be described by dimensionless parameters (analogously e.g. to the Mach number known from aeronautics). Pure plasma physics is dominated by three characteristic parameters, two of which can be widely varied in any experiment. The third parameter (called $\rho*$) is that by which previous experiments differ most strongly from ITER-FEAT and a power plant. JET, the largest existing experiment, typically operates at a value which is greater by a factor of three than that of a power plant. ITER-FEAT, however, will also be able to achieve the power plant values with respect to this parameter. For the specific aspects of thermonuclear burning, however, above all Q is also important, which is the ratio between the power produced in the plasma by fusion reactions and the power supplied from outside. One fifth of the fusion power produced in the form of fast helium ions simultaneously serves for plasma self-heating. In order to successfully investigate this aspect, self-heating must be greater than the heating power supplied from outside. At Q equalling 10 – the selected working point of ITER-FEAT – self-heating is twice as high as the heating power supplied from outside, which is considered to be sufficient. Other physical key questions of a power plant, which must also be answered by ITER, are continuous operation as well as removal of the power and the helium arising as "ash". In this respect, ITER-FEAT is equipped with systems

	which should be regarded as prototypical of a power plant.
FZJ	The plasma-physical conditions and thus also the minimum size of a tokamak for the generation of reactor-relevant fusion plasmas are known today. To immediately construct a fusion reactor, however, would be too great a step because never in a tokamak have all reactor-relevant technologies ever been integrated and because the development and qualification of wall materials compatible with the high neutron radiation to be expected are still outstanding. An interim step is therefore planned: an experimental device with enough leeway for testing different plasma scenarios, which does not yet have to fulfil all the requirements of a reactor (e.g. continuous operation, tritium breeding). The first design of such an ITER experimental device was intended to make the next jump ahead in development as great as possible according to the present state of the art (1500 MW power). Due to cost pressure, a second design has been evolved (ITER-FEAT, 500 MW), which is now oriented to the minimum necessary development step size. Accordingly, ITER-FEAT fulfils the following requirements: • generation of a fusion plasma burning over a longer time (300 - 500 seconds,) • 10-fold energy gain, i.e. the plasma heating by alpha particles is twice as high as external heating • continuous operation with external current drive at lower power (five-fold energy gain) • higher energy gain not excluded • wall components for steady-state heat and particle removal • sufficient flexibility with respect to different plasma scenarios; extension and improvement of the physical data base in the reactor-relevant region; sufficient diagnostic equipment • remote-handling tools e.g. for the replacement of wall materials and components • superconducting coils

	• tests of breeding blanket modules (DEMO-relevant)

Technology and Reactor Operation:

A.9. Is it ensured that fusion technically functions as an energy source? Are the necessary technologies and materials available? What technologies and materials still have to be developed? How long will these developments take? What technological milestones will probably be achieved at what times ?

IPP	As explained above, it is precisely the task of ITER to demonstrate the physical feasibility of an energy-producing plasma and test part of the technically necessary components. DEMO must then demonstrate the technical feasibility of a fusion power plant. This question can therefore not be answered today. In none of the previous fusion experiments, however, has a basic problem appeared which excludes the technical realization of nuclear fusion as an energy source. As described in A.1. - A.8., a key demand for a fusion power plant is the availability of materials withstanding the loads due to the plasma and the high-energy neutrons. Over the past twenty years, an important aim of the global fusion programme has been to develop these materials and components – in cooperation with industry and other research institutions – in parallel with plasma physics. Many technologies have already been evolved and tested in JET. These activities in critical fields of fusion technology show that most technological problems can be solved on the basis of the experience and findings gained. Among the technologies still to be developed are: the plasma-facing materials of the first wall, the structural materials for regions of high neutron exposure, the breeding blankets (for producing the tritium fuel from lithium), methods for plasma diagnostics and for the inspection and maintenance of the plasma vessel. The materials and components must ultimately withstand the high neutron exposure as well as the high temperatures and coolant pressures needed for the

	thermodynamically efficient operation of a power plant. The service life of the components must be long enough to limit necessary replacements to an economically reasonable extent. In addition to these requirements, the materials used in a fusion power plant should be optimized towards low activation in order to fully exploit the ecological attractiveness of a fusion power plant. Based on previous work there is agreement that only a limited number of combinations for structural material with breeding and coolant fluid and neutron multiplier exist for the envisaged breeding blanket concept integrated into the first wall. These can be divided into two categories: rigid ceramic and liquid metal blankets. Three different structural materials, ferritic-martensitic steels, vanadium alloys and SiC/SiC ceramics (silicon carbide fibre reinforced silicon carbide) are under consideration which fulfil the condition of low activation. Strategies for the further development of these materials and their qualification for use in a fusion power plant were drawn up so that the timescale fits the development of fusion power plants. The development programme for these materials and other technologies will require the construction of a special high-intensity fusion neutron source complementing existing irradiation possibilities, i.e. mainly in nuclear fission reactors. Such a source, the accelerator-driven D-Li neutron source IFMIF (International Fusion Materials Irradiation Facility), was conceived and proposed in a worldwide cooperation within the framework of the International Energy Agency (IEA). The irradiation tests of the materials for DEMO in an IFMIF-like plant up to an irradiation dose of at least 80 dpa (displacements per atom) must be successfully completed in good time during the design phase of DEMO so that these materials may then also be used.
FZK	The demonstration that a fusion device can be technically realized is the main goal of present research and development. The next milestone is ITER where the essential technologies are brought to functioning in one arrangement. The results of extensive R&D work for ITER

	confirm that the technical basis for the construction and operation of ITER is given. Due to the short integral plasma operating time and the low accumulated neutron fluence (0.1 MWa/m^2 in ten years of operation) the material exposure for the structural materials cannot be simulated in ITER. Material development must therefore be advanced in parallel with ITER. This requires extensive irradiations in material test reactors and in an accelerator-based fusion neutron source to be realized in the future. The finally qualified material must not only satisfy high requirements with respect to service life, but should also exhibit low long-term activation so that a recycling of the waste materials becomes possible. The results from ITER operation and from the simultaneous material development form the basis for the demonstration reactor (DEMO). In DEMO it will be possible to test materials and components in long-term experiments. If the decision for ITER construction will be made in 2003, the information required for DEMO will be available in about 2020.
FZJ	Plasma physics defines the machine size, magnetic field configuration and other plasma-relevant parameters required for the fusion process. Besides many variants, in 20 years of fusion research on tokamaks of different size, a reliable data set has been developed for a specific plasma scenario which now forms the basis for the design of ITER-FEAT. It may thus be safely assumed that the plasma conditions for significant energy production will be achieved. However, these plasma-physical conditions alone are not yet sufficient to ensure continuous operation. Continuous operation depends on the solution of a number of technological problems; e.g. wall materials for highly stressed components, methods for external heating and for current drive, technology of the breeding blanket, superconducting coils and the tritium cycle. For the construction of ITER-

	FEAT it is not at all necessary to adequately answer all questions. ITER-FEAT itself is the test bed for the various technologies and will, in particular, make an essential contribution to matching physics and technology by the integration of all relevant techniques. Special problems which cannot be studied in ITER-FEAT must be dealt with in suitable test facilities and smaller fusion experiments (tokamak, stellarator). This applies e.g. to the development and testing of wall materials under reactor-relevant irradiation with neutrons or to the further development of optimized tokamak scenarios. For the construction of DEMO, reliable knowledge must then be available ensuring continuous operation. The technical feasibility of nuclear fusion depends on this know-how. Some highly stressed wall components will probably belong to the "wearing parts" of a fusion reactor and require regular replacement. This will essentially govern the availability and thus the economic efficiency of a fusion power plant. The technological challenge is to ensure an availability as high as possible. The frequently asked question of whether fusion will function at all is thus not so important today as the question of whether fusion technology will ensure sufficient availability. *See also A.1., A.2. and A.12.*

A.10 Can all the technologies and components relevant for a fusion reactor be integrated in the ITER-FEAT project and be examined with a view to their compatibility with a thermonuclear plasma operation ?

IPP	ITER-FEAT was designed in accordance with the specifications of the ITER Council. This includes, in particular, a cost reduction compared to the first ITER design with a corresponding reduction of the technical aims. In spite of the thus reduced plasma target values and the smaller scope for the scalings used for the plasma parameters (especially for the energy confinement time), the initial programmatic goal of ITER should be maintained: the demonstration of the physical and technical feasibility of fusion as an energy

	source. Some aspects, above all in connection with the operation at Q $\rightarrow \infty$ and with the technological demands on a fusion power plant, are not contained in the requirements for ITER-FEAT. The ITER design team succeeded in integrating all the technologies and components necessary for achieving these goals. The additional critical aspects in a fusion power plant compared to ITER-FEAT concern higher power production (i.e. operation at higher Q) and the continuous operation needed for a power plant over long times. Moreover, ITER-FEAT will not yet have a complete tritium breeding blanket, but the relevant solutions proposed will be examined in test modules. The optimized materials (see A.9.) will not yet be available for ITER-FEAT either. Both technologies are currently still under development and will only be applied in DEMO.
FZK	Important technologies indispensable for the design of fusion reactors will be integrated in ITER. These are, in particular, superconducting magnets, tritium process technology, remote handling technology, plasma heating techniques and fuel injection. For the further development of the plasma-facing components the operating experience in ITER is to be utilized. ITER is also a test bed for breeding blanket modules. Due to the limited integral burning time of ITER, however, no data can be obtained on radiation damage to structural materials. These can only be obtained by irradiations in material test reactors and in a future special fusion neutron source (see also A.9.). All relevant technologies for a fusion reactor producing energy will be integrated in ITER-FEAT: heat and particle removal, heating techniques, current drive, breeding blanket modules, materials, superconducting coils, tritium cycle, fuel injection, remote handling techniques, control of steady-state operation, diagnostics. The techniques required for energy conversion

	(such as steam extraction for electric energy production) are not considered in ITER-FEAT. The effect of neutrons in the breeding blanket can be basically studied, but the short-time operation of ITER-FEAT is not sufficient to test the complete damage of wall components by reactor-relevant neutron radiation.

A.11. By how many years will time planning be prolonged after the year 2050 if ITER-FEAT is built instead of the originally planned full version and thus part of the development risk is shifted to the DEMO reactor ?

IPP	Essential for timing up to power plant level is the number of plant generations needed. The target planning of ITER-FEAT also proceeds on the assumption that the facility can provide all prerequisites for the construction of a DEMO so that initially no time delay will be involved. ITER was and is intended as the only intermediate step towards DEMO with a certain degree of freedom in segmenting the overall interval. In the design presented by the ITER team in 1998 it was envisaged to already penetrate with ITER into the dimension of a genuine power plant (approx. 1500 MW thermal power). The segmenting chosen now in fact shifts a certain development risk concerning the technology towards the step from ITER to DEMO, but this is considered tolerable. From the physical aspect, it is to be expected that the possibilities of computer simulation will make great progress in the period under consideration up to the start of planning and/or constructing DEMO (see answer C.14.). Although simulations cannot replace experiments, if new problems must be investigated *qualitatively*, as is the case of the dominating self-heating in ITER, they will provide much higher reliability in extrapolation and can thus also bridge the quantitative difference between ITER-FEAT and DEMO. From the technological aspect, ITER will basically test the integration of all necessary technologies – with each other and concerning their compatibility

	with a burning plasma. It was not envisaged either for the "large" or for the present "small" ITER that the individual technologies (superconducting magnets, high-heat-resistant wall materials, fuel cycle including breeding the tritium fuel from lithium, operation, service and modifications by remote-controlled robots) will already be optimally refined in detail for DEMO or a series power plant. Above all, this will also require further material developments and tests, as described in the answer to question A.9.
FZK	The change in the structural design of ITER will have no influence on a future introduction of nuclear fusion as an energy carrier. The essential goals will also be achieved in the compact ITER version. The necessity of an accompanying materials development programme has already been pointed out (A.9., A.10.). From the ITER results and from materials development sufficient data will be obtained for the construction of a demonstration reactor. This development step will be the basis for planning a first commercial reactor generation.
FZJ	There should be no shift in time. However, the jump ahead from ITER-FEAT to DEMO is greater than with the originally planned more powerful ITER (1500 MW, 17 minutes burning time). The risk involved is not quantifiable in terms of time.

A.12. Is the "first wall" controlled in terms of technology and material ?

IPP	Research Centre Karlsruhe is intensively concerned with the development of materials for the First Wall and blanket of fusion reactors and significant progress has been achieved in recent years. As part of these activities, (ferritic-martensitic) steels (designated EUROFER) are being developed with tailor-made element composition and structure. According to the data available on irradiation behaviour, a stability of these steels up to a neutron exposure of at least 150 dpa (displacements per atom) is expected. In a

	fusion reactor, the annual exposure will be 30 dpa per year. Since these steels can be manufactured even today with high purity and tailor-made element composition, they already exhibit favourable deactivation behaviour after operation at the present stage. The envisaged steels can be processed by "conventional" methods such as welding techniques or hot isostatic pressing into structural units and components.
FZK	The First Wall is stressed both by various plasma impacts and by neutrons carrying energy. The effects directly caused by the plasma only affect a relatively thin layer of the First Wall, whereas the effect of the neutrons extends to the region of the entire blanket (approx. 0.5 to 0.7 m depth). The interaction of plasma and wall is already intensively studied today (ASDEX-U, TEXTOR, JET experiments). In ITER, these investigations can be continued under reactor-relevant plasma conditions and suitable technical solutions can be derived. On the other hand, the investigation of bulk damage due to neutrons requires separate studies in special neutron sources (material test reactors, future accelerator-based fusion neutron source).
FZJ	The First Wall, i.e. the area directly exposed to the plasma, is subjected to a particular load whose control is decisive for continuous operation with high availability. The following types of load are distinguished: • Thermomechanical load: High heat flux densities (10 MW/m^2) on relatively small areas in the divertor and moderate heat flux densities (0.2 MW/m^2) on the remaining wall must be removed via cooling systems in normal operation. Deviating from normal operation, very high local loads (e.g. during disruptions) can also occur for short times (milliseconds). Irrespective of the choice of wall materials, these events lead to irreversible material damage (sublimation, melting, formation of

cracks) and, if occurring too often, also determine the lifetime of the first wall and the divertor).

- Erosion of wall material: Wall material is eroded due to the influence of the plasma. This can lead to damage of wall components, on the one hand, and, on the other hand, the eroded materials contaminate the plasma, which, in the most unfavourable case, can even quench the plasma. Since a fusion plant represents an almost closed system, most of the eroded material is redeposited on the First Wall. In these deposited layers, tritium can also be stored, which would undesirably increase the total tritium inventory (see also B.1. and B.12.).

- Neutron radiation leads to activation of the materials; fast decay is an important aspect for the selection of First Wall materials. Material damage due to neutrons distributes over a larger depth of the wall components (0.5 metres) and affects above all the mechanical and thermal properties of the structural material (e.g. embrittlement, thermal conductivity).

In the fusion experiments existing today (e.g. JET, ASDEX-Upgrade, TEXTOR) these problems are selectively being dealt with. Neutron damage cannot be investigated in these facilities. There are realistic solution approaches for all issues.

- Actively cooled components capable of continuously removing peak values of 20 MW/m^2 and even withstanding extreme thermomechanical loads due to cycling have already been successfully tested.

- Methods of radiative cooling with selectively injected impurities have been developed to relieve the most strongly exposed areas in the divertor.

- The erosion properties of different materials as well as their influence as impurities on the plasma properties are systematically examined. The specific properties of impurity transport play a key role because in many cases more than 99 % of the eroded material is found to be redeposited

	at its location of origin – the effective erosion rate thus becomes 100 times lower. • Methods for the removal of thick deposited layers are under development and strategies for reducing this effect are currently being evolved. • The neutron damage to be expected is simulated in accelerator facilities and fission reactors, and various materials, especially also the new European EUROFER alloy with particularly low impurities, are examined with respect to their thermomechanical properties. For a final qualification of these materials, however, irradiation with neutrons in the reactor-relevant energy range is necessary. The construction of a corresponding neutron source is an essential element on the road to a fusion power plant. The right choice of materials with their specific erosion properties, their different effects on the plasma and the suitable development of the plasma properties in the boundary region represent a typical optimization problem dealt with at present in a comprehensive research programme in Europe.

A.13. How long do the wall components last before they must be replaced ?

IPP	According to the data available on the irradiation behaviour of steels developed specifically for fusion, the materials already available today can withstand a neutron exposure of at least 150 dpa (displacements per atom). In a fusion reactor the annual exposure will be 30 dpa per year. This means that an operating time of five years can be envisaged even today for the First Wall. Investigations under way at Research Centre Karlsruhe are to reveal whether these materials can also be used for longer operating times.
FZK	The answer to this question is only to be found as the result of a long-term materials development programme.

	For a first reactor generation, a service life of about 3 to 5 years is assumed for the First Wall (corresponding to a damage rate of 150 dpa). These values apply to the plasma-facing inner shell. Less damaged regions at greater depth have correspondingly longer service lives. Individual components such as limiter or divertor elements can have shorter lifetimes due to direct plasma effects. Experience in ITER will provide more detailed information.
FZJ	The control of erosion or thermomechanical load should be sufficiently good so that the service life is only determined by the neutrons. A replacement of the most strongly stressed components is expected after approx. 3-5 years. These figures are based on estimates and can only be specified more precisely with the results of ongoing research activities.

A.14. How long is the downtime to be expected for replacing the first wall and how often will this be necessary? What problems can occur at the man-machine interface when replacing the divertor cassettes ? What will be the standby capacities required during downtime ?

IPP	Precise data on downtimes presuppose detailed knowledge concerning the design of a fusion power plant, which is not yet available. It is clear, however, that this replacement will be carried out by remote handling and in a largely automated manner. Experience with such technologies is already available from JET, where the entire divertor was replaced by remote handling techniques, and from the research and development work for ITER, where a detailed concept was drawn up on replacing the divertor cassettes, which was also experimentally tested in a demonstration plant (in Brasimone/Italy). Initial estimates for a fusion power plant provide downtimes of approx. three months which, however, are only considered necessary every 3 to 5 years. These downtimes are taken into consideration in current power plant studies (see answer to C.2.) and included in the availability of a fusion power plant of about 75 % cited there.

FZK	The calculation of the downtimes requires experimental experience and a detailed knowledge of the plant. The first positive experience was gathered in replacing the entire divertor in JET. Testing suitable techniques is a technological main goal for ITER. In the design of ITER-FEAT a particularly detailed process is planned for replacing the divertor components. Replacement is largely automated. Initial estimates for a reactor have shown downtimes of 3 months. Since this would only be required every 3 to 5 years, the overall availability would be similarly high as in conventional power plants. The downtimes are normally scheduled for periods of low demand so that no standby capacities are required. Moreover, the interconnected supply systems are flexible enough to compensate the shutdown of individual units.
FZJ	The aim is a replacement of components in the form of large modules as rapidly as possible to minimize removal time. With a replacement rhythm of 3-5 years an availability could be achieved similar to that of conventional large power plants.

A.15. Is a tokamak on account of its physical properties suitable for continuous operation for energy supply ?

IPP	A tokamak power plant could work either in pulsed (with a pulse duration of three to four hours interrupted by an intermission of 100 - 200 seconds) or in genuine continuous operation. Even in the pulsed mode, the power plant would be capable of continuously discharging energy since the heat capacity of the plant or an interconnected heat accumulator could bridge the discharge breaks. Genuine continuous operation of a tokamak discharge can be achieved if the necessary plasma current is partially driven by radiated wave fields or by

	particle beams. This second operational regime has meanwhile been demonstrated by experiments in all tokamaks equipped with relevant auxiliary devices. This is also the form of operation underlying most power plant designs (see also A.4.).
FZK	Resetting the magnetic field, which drives the plasma current, periodically interrupts the operation of a tokamak reactor. Interruption takes place typically once per hour for a few minutes. By means of a buffer tank provided in the steam cycle it is basically possible to achieve continuous power discharge. Cyclic operation can lead to material fatigue. Efforts therefore aim at prolonging the cycle duration. By external energy supply and additionally by generating a bootstrap current it is basically also possible in a tokamak to generate a continuously burning plasma. This mode of operation is envisaged for ITER. A stellarator confinement would allow continuous operation. The principle is to be demonstrated in Wendelstein 7-X.
FZJ	In principle, yes. However, the plasma current necessary for the tokamak must be maintained by external non-inductive current drive after an induction phase which, at present, generally determines the pulse length of a tokamak. Such a 100 % current drive has already been basically demonstrated in several experiments. Energy could also be continuously produced by a tokamak without external current drive, but the short breaks for recharging the transformer would then have to be bridged by suitable heat buffers. A disadvantage of this solution would be the much higher load on the tokamak due to many thermal cycles. In this respect, a stellarator is simpler because continuous operation is naturally given and no additional energy would be required for current drive.

	However, it remains to be demonstrated for the stellarator whether it has the same good plasma confinement as a tokamak.

A.16. What will be the energy demand of ITER during operation for heating and magnets ?

IPP	At its nominal working point, ITER will produce a fusion power of 500 MW – with a power gain factor of Q ≈ 10 – i.e. a heating power of about 50 MW (in the form of radiofrequency radiation and particle beams) will be required in the plasma. An electric power of 60 to 100 MW will be needed for the magnet system, about 150 MW for total plasma heating. In addition, an electric power of 100 MW will be provided for other purposes (among other things, to enable the control system to respond to changes of the plasma parameters via the magnetic coils). Since ITER is only operated in the pulsed mode, this total power of approx. 350 MW will not be continuously required from the grid but also partially provided from storage systems (e.g. flywheel generators) for short-time operation. The grid connection power of the ITER project will be approx. 120 MW.
FZK	A differentiation must be made between the grid connection power of the plant and internal power fluxes. These values differ for the individual systems due to the pulsation of the plant. The grid connection power of ITER-FEAT is 120 MW. The superconducting magnets (main field) are continuously supplied. The connection power of the refrigeration systems is in the range of 34 MW. The power required for the superconducting coils for vertical stabilization and plasma heating is provided by pulsed power supplies. Their contribution to the overall connection power is relatively low due to the short total operating

	time of these systems. *Source: ITER EDA Doc No. 19, IAEA, Vienna 2000*
FZJ	The electric power required for operating the tokamak is composed of: • 60 - 100 MW for the magnet systems • 100 - 150 MW for plasma heating and current drive • 100 MW for other purposes • 260 - 350 MW in total. The grid connection power will be approx. 120 MW. The lacking grid power will be provided by storage systems during short-time operation.

A. 17. To what extent is the ITER Final Design Report (1998) and complete information on the slimmed-down design of ITER-FEAT available to the public? Was the ITER-FEAT design examined by independent experts ?

IPP	In principle, all reports and studies on fusion research are available to the public either in peer-reviewed scientific journals or in publication series of international or national organizations. Informative internal reports can also be requested from the respective research institution. Both the ITER Final Design Report [1] and the ITER-FEAT Outline Design Report [2] are published by the International Atomic Energy Agency, IAEA, in its ITER documentation series and available. The ITER-FEAT Final Design Report is currently in preparation and will also be published in this series after handing over to the ITER partners. In addition, the physical basis underlying the ITER design has been published in one of the most important scientific journals on fusion research [3]. This very detailed publication (a special number with over 500 pages) was reviewed – as is common practice – by a group of independent scientists prior to publication. All ITER design reports – by each of the ITER parties – were evaluated in

	detail by groups of independent experts from fusion research and industry. These panels confirmed that each design completely fulfilled the scientific and technological requirements of the respective design phase. The reports by these panels have also been published by the IAEA in the ITER documentations series.
FZJ	All information is available to the public. The ITER design as well as the ITER-FEAT design was reviewed in all phases several times and in parallel by independent experts from science and industry in the respective partner countries.

<u>B.</u> <u>Opportunities and Risks of Nuclear Fusion for Humans and the Environment</u>

Leading questions:

B.1. What are the important radiological and non-radiological risks in operating a fusion reactor and how are they to be classified in comparison to other forms of energy production ?

IPP	Fusion power plants will not contain any high radioactive inventory (such as fuel rods) and there is no risk of uncontrolled energy release. Since the energy content of the plasma is very low, a destruction from inside is to be excluded; only external destructions of the power plant (e.g. due to an aircraft crash) are conceivable. This could lead to a release of emissions, which will be discussed further below. In fusion power plants, the emission of tritium[2] and activation products[3] involves a radiological risk. The term 'risk' is generally understood to contain two elements: the consequences of an event and the frequency with which this event can occur: - The most important risk for persons inside or outside the power plant is radioactive radiation. However, possible doses are comparatively low both in normal operation and during accidents (s. further below). - The frequency of accidents with major consequences is also very low for fusion power plants (s. further below). - The combination of small consequences and low frequency leads to the conclusion that the radiological risks in operating fusion power plants are also low. For the normal operation of a fusion power plant the answer to question B.10. contains numerical values expected for emissions and doses.

These values are low and of the order of the doses caused by coal-fired power plants. The latter also emit radioactive substances since potassium-40, thorium-232, uranium-235 and uranium-238 are contained as natural radioisotopes in coal. Added to this is the fact that these isotopes accumulate in coal ash and, depending on its use, can cause further dose commitments.

The above doses caused by fusion and coal power plants are, moreover, also in the range of values for best-developed fission power plants.

Details on accidents with fusion power plants will be given in the answers to questions B.16. through B.20. On the whole, the risk is low since only comparatively low energy inventories are stored in a fusion power plant. Even on very pessimistic assumptions, they are not sufficient to heat significant material quantities to high temperatures or to even melt them. The energies are not sufficient either to break all confinement barriers.

The consequences of accidents with fission power plants can – on the pessimistic assumptions usually made in the analysis of fusion accidents – reach values higher by several orders of magnitude than in fusion. For fission power plants, therefore, 'active' safety systems are extremely important and 'passive' safety can only be approximately achieved at very great effort.

This is due to the energy inventory in a fission power plant. It is higher by several orders of magnitude than in a fusion power plant and can be rapidly released under unfavourable circumstances. The countermeasures in the event of an accident must therefore take effect much more quickly in a fission power plant, for some events within seconds. For fusion, these times are in the range of hours.

Non-radiological risks of nuclear fusion are basically similar to those in other technical systems of the same order of magnitude. Details will be naturally different; in nuclear fusion, for example, risks could arise due to the use of beryllium.

	[2] *Tritium (a radioactive hydrogen isotope with two neutrons in the atomic nucleus) is one of the two fuels in a fusion power plant.* [3] *The neutrons produced during the fusion reaction of deuterium and tritium can activate the atoms of the metallic structures around the plasma, i.e. transform them into – then radioactive – nuclei.*
FZK	Non-radiological risks play a minor role in the safety considerations. Individual studies concern the presence of high magnetic fields and the chemotoxicological risk in handling beryllium in individual reactor designs. A radiological risk arises from (1) the presence of tritium, (2) the radiation (spontaneous and remanent) in the core region of the device. In both cases, numerous studies are available, deepened especially in the preliminary work for ITER.[1)] Relevant experience was gained by the long-term operation of the TFTR (Princeton, USA) and JET large-scale experiments. A risk in handling **tritium** is only given in the event of incorporation. This risk is minimized by effective confinement and retention systems as well as a monitoring system specifically qualified for tritium. The process development serving this goal is being carried out – first of all for JET and ITER – in the tritium laboratory of Research Centre Karlsruhe. The risks caused by **radiation** (neutron and gamma radiation) are restricted to the core of the plant inside the biological shield. They are to be delimited by shielding measures and appropriate operating instructions. The **environmental contamination in normal operation** cannot be exactly specified for a commercial reactor. This requires a detailed plant design and

	precise knowledge of the flow of operations. As in the case of currently operated nuclear fission reactors, no significant contribution towards environmental contamination is to be expected owing to appropriate construction and operational measures (see question B.10.). The release of radioactive substances during **accidents** is the subject matter of numerous studies[2)]. None of these studies presents accidents with catastrophic consequences. In this case, too, quantitative statements going beyond present estimates can only be expected in connection with detailed plant layouts. Model studies provide the following picture: • The fuel quantity contained in the plasma compartment is depleted after less than one minute without further supply. • The afterheat can be removed without forced-circulation cooling, the structures remain intact. • The energies that can be released do not suffice to destroy the confinement. Summary in: *I. Cook et al., The Safety and Environmental Impact of Commercial Fusion Power Stations, UKAEA, t.b.p. [16]* [1)] *Technical Basis for the ITER Final Design Report, Cost Review and Safety Analysis, ITER EDA Doc. Ser. 16, IAEA, Vienna, Dec. 1998 [1]* [2)] *D.A. Petti, H.W. Bartels: The Ultimate Safety Margins of ITER. A Demonstration of the Safety Potential of Fusion, Fusion Eng. and Design 46 (1999), 237-242*
FZJ	Current safety studies [SEAFP-95] and the SEAFP-2 follow-up study to be published soon deal in detail with all safety and environmental aspects of future fusion power plants. These studies were carried out with the participation of science and industry in Europe. The basic assumptions of the study are oriented to the technical solutions evolved in detail in the ITER design, and the differences between the ITER experimental reactor and a fusion power plant were taken into account by moderate extrapolations. The studies arrive at the following important conclusions:

	• The total tritium inventory will remain moderate (< 2 kg). • The energy inventory cannot destroy the confinement vessel even in the event of a cooling failure. • Any uncontrolled burning of the fusion plasma is impossible according to the laws of nature (no chain reaction). • The dose to the population will be very low: in normal operation the exposure will be less than 2.5 % of natural radiation exposure. • An evacuation of the population is not necessary even in the event of beyond-design accidents in the frequency range of up to approx. 10^{-7}/a examined. • Even on the assumption of a complete release of the easily mobilizable tritium fraction, the dose values remain limited to 250 mSv even under unfavourable release conditions, i.e. the intervention level for evacuation is reached but not significantly exceeded. • The volume of activated materials will be similar to that of fission reactors, but with significantly lower long-term radiotoxicity: i.e. a very large portion of the material can be reused and long-lived waste only arises to a very small extent. • Non-radiological risks are to be classified as very low. These conditions are also to be regarded as design requirements for ITER-FEAT. For DEMO or even commercial reactors there are no concrete designs as yet for which a detailed analysis of safety issues could be performed. With respect to the radiological hazards it must be basically borne in mind that, in contrast to fission reactors, there are always only very small fuel quantities (in the gram range) in the burn chamber, which entails a considerable reduction in potential energy and thus also potential hazard.

B.2. Where do you see the ecological advantages of fusion ?

IPP	A great ecological advantage of fusion is the fact that definitely no gases are

	produced during operation, which can damage climate or have other toxic effects. Another great ecological advantage is the high density at which the fusion energy is stored in the fuel of the deuterium-tritium process, so that only small amounts are consumed within the lifetime of a power plant, i.e. only some ten tonnes of deuterium and lithium fuels are required. Their production does not involve any major mining activities or other significant environmental damage. Added to this is the fact that deuterium and lithium quantities that would last extremely long for fusion are contained in water, especially in sea water. Freedom from catastrophe in the event of accidents is a declared design objective for a fusion power plant, whose attainability is hardly doubted. Quite obviously this also involves a great ecological advantage since damage to the environment associated with catastrophes cannot occur. The large majority of materials used for the construction of fusion power plants are conventional: steel, possibly vanadium alloys, copper, some other commonly used metals, ceramics, concrete. Other materials used in comparatively small quantities are not particularly unusual either, unless beryllium, lead, niobium and titanium were to be regarded as unusual materials. The total mass used for constructing a fusion power plant may be about twice that used for other energy systems according to the current state of the art with the same power. It is thus of a normal order of magnitude. This therefore also applies to the associated mining and the subsequent processing and logistics. Added to this, the recycling of materials for use in new power plants is a declared aim and field of work in fusion research. On the whole, fusion would not lead to novel or additional environmental burdens within the framework of materials supply, which does not seem to be certain for all the other innovative technologies and has not yet been systematically studied for them.
FZK	Nuclear fusion plants

	• do not release any climatically harmful and ecotoxic gases during operation, • use fuels with extensive resources, • do not require transports of large quantities of goods during operation, • do not produce noise pollution. • involve a fuel production with low effort and risk, • leave only small amounts of long-lived radioactive waste, • involve little landscape consumption and do not required exposed sites.

B.3. How does energy production with nuclear fusion fit into the concept of Sustainable Development ?

IPP	Answers to this question are also given in connection with other questions, especially under B.2. The low fuel consumption described there and the freedom from climatically harmful emissions during operation are extremely important contributions towards precaution for future generations of humans, animals and plants. Extremely important in connection with fuels is the fact that the operation of fusion power plants would reduce the combustion of fossil materials. This is not only important because of the emissions thus avoided. In fact, fossil resources should not be wasted as fuels, but they are important raw materials which must not be irretrievably snatched away from future generations. The range of the fuels for deuterium-tritium fusion is extremely long, of the order of millions of years. The quantity of construction materials is in the range of that which is normal for energy systems. The large majority of the materials is conventional so that future generations are not deprived of vital raw materials. Added to this is the possibility of recycling important materials for use in new power plants. The radiotoxicity of the radioactive materials decays quickly with time – except for a percentage fraction – which is very important with respect to

	sustainability. Future generations will therefore only be exposed to a limited extent and especially not for extremely long periods of time. It is quite possible that nuclear fusion is not only equal to other, innovative energy supply technologies with respect to sustainability but even superior. It would therefore be necessary to evaluate all technologies as comprehensively and thoroughly as has already been the case for nuclear fusion for a long time. Nuclear fusion is probably rightly regarded as that technology of the future which is investigated best concerning its implications. Thus, a US study designates fusion as "possibly the most reviewed science and technology program in history" (*page 41 in Ref. [4]*).
FZK	See answer to question B.2. (ecological advantages of nuclear fusion).
FZJ	Nuclear fusion is among the few outstanding examples of sustainable development. • In electricity production with nuclear fusion no CO_2 is emitted; the amount of energy for constructing the plant is recovered in approx. 6 months of fusion power plant operation. • The operation of a fusion power plant does not entail severe damage to humans and the environment even upon the occurrence of severe accidents. • In dismantling a fusion power plant, radioactive materials arise which, however, can be reused almost completely after approx. 50 to 100 years. • The raw materials of fusion (deuterium in water and lithium in rock) last infinitely according to human criteria. • Potential conflicts about energy resources are avoided due to the globally uniform availability of the fusion raw materials.

B.4. How do you assess public acceptance of fusion technology ?

IPP	Fusion is very likely to find broad public acceptance due to good safety properties and acceptable environmental impacts. Fusion will make it

	possible for currently still less developed parts of the world to achieve a lifestyle corresponding to that of the West without industrialized countries having to cut back their development or without unacceptable environmental changes having to be tolerated. Environmental protection, good safety properties and maintenance of the comfort one is used to are guarantors of high acceptance. However, quantified statements on public acceptance are difficult at present. Even methods of empirical social research do not allow any statements to be made on the acceptance of a future technology in the future. We will obtain the first clear insights when ITER is built. The response by the local population will be a first test for the acceptance of fusion. In a joint study with the Academy for Technology Assessment in Baden-Württemberg under the leadership of Professor Renn [5] the MPI of Plasma Physics has attempted to explore the opinion of the population on fusion and fusion research. The statements were disaggregated but in all cases the good safety and environmental properties of fusion were appreciated. We were surprised to note that especially young people did not see any solution approach in the possibility of saving energy.
FZK	The level of knowledge about nuclear fusion among the general public is low although the media and research institutes frequently report on this technology. If a public opinion is expressed, polarization caused by the nuclear energy debate is pronounced. Schoolchildren (a large number of pupils visit us during the year, generally from grammar schools with physics courses in the upper classes) display a rational, largely objective attitude to nuclear fusion (not necessarily found with the teachers). An informative study was carried out by the Academy for Technology

	Assessment in Baden-Württemberg[1)], in which clear differences were observed in the evaluation of nuclear fusion by different groups (teachers, environmental groups, young people, creative artists, science journalists, managers). The institutes involved in fusion research have intensified their information activities and at the EU level new initiatives to inform the public are also in preparation at various levels of access. The Internet will be of particular significance as a dissemination medium. [1)] *G. Hörning, G. Keck, F. Lattewitz, Fusionsenergie – eine akzeptable Energiequelle der Zukunft, Jahrbuch 1999, Akademie für Technikfolgenabschätzung Baden-Württemberg*
FZJ	Today, research into nuclear fusion and its basic technical implementation is of major significance. The experience made at Research Centre Jülich with many visitor groups shows that the acceptance of research is very high with respect to such ambitious and fascinating topics as the generation of 100 million degrees hot plasmas and their potential contributions towards solving the world's energy problem. Only future generations faced with the construction of the first commercial fusion power plant will have to decide whether they wish to embark on this new technology. It is hardly foreseeable how public opinion, global policy boundary conditions, ecological and economic constraints as well as the Zeitgeist illuminating everything will change until then. In view of the advantageous properties of nuclear fusion with respect to the environment and safety, the chances of high acceptance are good.

Further questions:

B.5. What conditions (site, jobs, infrastructure, waste management, cooling) must be fulfilled for a possible large power plant ?

IPP	Where similarities to the requirements of ITER are to be expected, the following data were taken from the corresponding ITER documents: the siting conditions for ITER-FEAT (and earlier for the "large" ITER) are documented in a very detailed manner and can serve as a basis for extrapolation. The preliminary site report for Cadarache [6], which has been noted by the competent European panels, describes the features of Cadarache in the South of France as a possible site of ITER-FEAT and documents the suitability of the proposed site. For the large ITER (which should come close to the conditions for a power plant enumerated in the question) 70 ha of fenced-in premises was required; during the construction phase, in addition, the availability of an adjacent terrain of 60 ha. During the construction phase up to 3000 people would work on the plant site. For the operating phase, the personnel data for ITER – as a research facility – are no useful reference criteria for a power plant, but the operating crew required for a fusion power plant should be comparable to that of a nuclear power plant of identical electric power (in France these are, for example, about 600 persons per power plant, averaged over 57 power plants). For ITER – and correspondingly for a power plant – an industrial infrastructure must be available in the region, as would appear necessary for the construction of any large and complex industrial plant. For "conventional" waste management an estimate of 200 m^3/day was specified for industrial effluents from ITER. During operation the cooling requirements are governed by the thermal power of the facility and will range between 2000 and 3000 MW per power plant unit. The question concerning radioactive waste is dealt with in B.11. In connection with the site requirements it is assumed that during operation no transports of activated materials from the site should be made. Activated

	waste will arise during operation due to the routine use of some components (divertor; blanket modules). The quantity thus arising over the entire operating time is estimated to be approx. 25,000 tonnes for first-generation fusion power plants. These replaced components would be stored during operation and for a subsequent cooling time at the site of the power plant and then disposed of together with the inner, plasma-facing components according to the principles specified under question B.11. No cooling of the activated waste is necessary during storage at the site.
FZJ	The power class of future fusion power plants is comparable to present-day conventional large-scale power plants; i.e. most conditions will also be similar. A first positive qualification of boundary conditions for ITER-FEAT was performed in a preliminary assessment of the Cadarache site. *[EFDA, ITER at Cadarache, Preliminary Site Assessment, Jan. 2001].*

B.6. How does nuclear fusion in a life cycle analysis compare with other forms of energy production ? Are there studies investigating the advantage of fusion reactors over fission reactors with respect to the CO_2 balance in the extraction and production of fuels and materials ?

IPP	As part of the European SERF-1 study, a life cycle analysis has been established for fusion power plants [7], estimating for all materials the energy requirements and emissions for the complete life cycle – production, transport and waste management. This provided an energy return time of 0.5 years for a fusion power plant. Specific emissions were 5.5 g of CO_2, 0.004 g of SO_2, and 0.006 g of NO_x, each per kWh. These values are above those of a fission power plant by about a factor of two due to the higher mass of concrete needed. This assumption valid for ITER, however, is rather conservative for a fusion power plant. A similar life cycle analysis for fusion power plants has also been established

	by a Japanese group and compared with corresponding analyses of other energy sources, including alternative energies. Due to the clearly higher energy requirements, however, all other energy sources except hydropower are clearly inferior to fusion concerning emissions.
FZJ	The energy recovery time of a fusion power plant is approx. 6 months. This is a very good value in comparison to other conversion technologies. Nuclear fission is slightly more favourable than fusion (approx. by a factor of 2).

B.7. Do you consider energy production with nuclear fusion to be compatible with the concept of sustainability ?

IPP	In a very general form, the concept of sustainability calls for justice between the generations but also within one generation. The resources for the construction and operation of a fusion power plant are sufficient and available all over the world. Present-day use will not impair use by succeeding generations. Especially the lithium and deuterium fuels are sufficient for several million years on the assumption of present electricity consumption. Fusion can be used everywhere in the world. It is neither dependent on climate nor on special deposits. Conflicts such as those over petroleum will not arise. Even today, the rapidly developing countries in Asia, China, India and above all Korea endeavour to take part in the development of fusion research, so that these countries will also acquire the know-how to construct fusion power plants at a later point in time. The operation of a fusion power plant cannot lead to an accident with catastrophic consequences for basic physical reasons. Subsequent generations will not be significantly burdened by the waste from fusion. The radioactive waste of a fusion power plant, measured via its radiotoxicity (see answer to question B.9.), decays within a few decades by

	many orders of magnitude. Fusion thus fulfils all criteria of sustainability. Neither are the resources for future generations used up in an irresponsible manner, nor are intolerable polluted sites produced.
FZJ	*See B.3.*

B.8. In your opinion, should the public be involved in the discussion about fusion research ?

IPP	An issue of such great significance for society as is the possibility of shaping future energy supply must be publicly discussed. The Max Planck Institute of Plasma Physics therefore makes every effort to continuously inform the public. This includes, on the one hand, continuous contact with newspapers, radio and television, which led to more than 450 articles on nuclear fusion in the print media last year (corresponding to a circulation of 20 million). On the other hand, the Institute offers various brochures on the status and objectives of fusion research, a newsletter on energy research, an information and question service on the Internet, guided tours of the Institute for schoolchildren, students and the general public, papers before the most diversified audiences, open days, exhibitions, trade fair presentations and numerous other events where contact and exchange of opinion with the public is sought.
FZK	Fusion research is supported from public funds. The research results are basically published. A participation of the public in the discussion is absolutely necessary. The research institutes intensify their efforts by offering information and opportunities for discussion with the different groups of the general public.
FZJ	Yes. It must be made clear what major aims are involved in present-day research and that we do not yet speak of the introduction of a new commercial technology, let alone a short-term contribution to energy supply.

	The primary aim of fusion research is to make a completely new energy source available as a further option in the energy mix to solve the global energy problem of future generations. The exploitation of deuterium (water) and lithium (rock) – the actual fuels of nuclear fusion – as a new long-lasting, clean primary energy source available to everybody would represent a quantum leap in the energy supply of mankind, only comparable to the discovery of coal, oil, gas or uranium as primary energies.

Radioactive Inventory and Waste

B.9. How high is the radioactive inventory ?

IPP	It is important to assess the inventories not according to 'radioactivity' but according to 'radiotoxicity'. Radioactivity just indicates the number of decays per unit of time, irrespective of what isotope decays and what type of radiation is emitted with what biological hazard. Activity therefore tells us very little about radiological effects. It is therefore meaningful and common scientific practice to use radiotoxicity as the measure, whereby the activity is determined for each individual isotope of the material, multiplied by the dose conversion factor and then summed up over all isotopes. The dose conversion factors are stipulated and updated by the international radiation protection bodies. Depending on the issue to be dealt with, the conversion factors are used for inhalation or for ingestion. In the assessment of consequences over long periods of time it is meaningful to determine the radiotoxicity for the uptake of radioactive material with food (i.e. by 'ingestion') into the human body. Radiotoxicity is a hypothetical dose and provides direct information about the hazard potential of a material, which practically cannot be read from the activity of a material. The radiotoxic inventory upon shutting down a fusion power plant is lower by

about a factor of 10 than the inventory in a fission power plant (if both power plants have released the same amount of electric energy). In the following 100 years the radiotoxicity of the fusion material steeply decreases at least by a factor of 1000. Details chiefly depend on the structural materials.

The toxicity of the material from a fission power plant declines at most by a factor of 2 during the same period and also decreases only little during the centuries thereafter.

These differences are due to the completely different production mechanisms for radioactivity:

- A fission power plant has radioactive materials (with a mass of several tonnes) in its fuel rods from the very beginning, and these materials are partially transformed during operation, basically and inevitably producing long-lived actinides.

- A fusion power plant initially does not contain radioactive materials, except tritium fuel. Tritium has a half-life of 11.3 years. 10 to 100 grams of tritium are contained in the plasma and tritium cycle. The activated material is only produced by neutron bombardment during operation, which has two important consequences:

  1) the properties of the activated materials depend on the composition of the plasma vessel (not on physical laws) and are thus – to a certain degree – selectable. The development of low-activation steels is one aim of materials research, for example, at Research Centre Karlsruhe.

  2) The half-lives of most steels are in the range of a few years and thus significantly lower than those of the actinides (up to 100,000 years). Therefore, the radiotoxicity of a fusion power plant – as discussed above – also declines by several orders of magnitude within 50 to 100 years.

	A comparison of the radiotoxic inventory in the fusion power plant materials with that in the ash of a coal-fired power plant shows that both inventories have become equal after 50 to 500 years. (The cause of the radiotoxicity of coal ash is, of course, potassium-40, thorium-232, uranium-235 and uranium-238 contained as natural isotopes in coal and accumulating in the ash.) After that time, fusion power plant materials can even drop below the level of coal ash. Details depend again above all on the structural materials. The mass of coal ash significantly exceeds the mass of fusion material by about a factor of 300.
FZK	It is assumed that this question relates to a commercial reactor. It must be distinguished: a. at what time the inventory is determined, especially how it decays after shutting down the plant (waste problem) b. what type of activity is involved (tritium, tightly bound activity) The total **tritium inventory** contained in a fusion power plant is estimated to be a few kilograms, of which 1 to 2.5 kg can be present in the First Wall - blanket region.[1)]. The processes leading to tritium retention are not yet sufficiently understood, they are being investigated in the JET facility, Concerning the issue of waste treatment and material recovery, in particular, the decay behaviour of the **activity induced by neutrons** in the materials and its nature in the first 50 to 100 years after shutting down the plant are of significance. The total amount of radioactive material produced during the operation of a fusion reactor amounts to approx. 50,000 to 100,000 t[1)] and is thus of the same order of magnitude as in fission reactors. The **radiotoxic activity**, which is decisive for assessing the hazard potential, differs significantly in level and decay behaviour over time from that of a fission reactor: there are no long-lived actinides.

Studies on different fusion reactor concepts have shown that with suitable materials choice the radiotoxicity of the fusion waste materials can be lowered by 3 to 4 orders of magnitude within 50 years (Fig. B.9.-1).

The **contact dose**, which is decisive for handling the waste materials, also declines by several orders of magnitude in the same period so that the large majority of waste can be recycled (s. also question B.11.).

Finally, there remains a residue of approx. 1 %, which has to be transferred to a repository. In order to achieve this goal, concentrated long-term materials development is required including the qualification of industrial methods for the production of materials with low impurities and their recycling.

[1)] *N.P. Taylor, C.B.A. Forty, D.A. Petti, K.A. Mc Carthy: The Impact of Materials Selection on Long-term Activation in Fusion Power Plants, J. of Nucl. Mat. 283-287 (2000), 28-34*

	Fig. B.9.-1 concerning question B.9. Radiotoxic inventory for various fusion reactor designs in comparison to fission reactors of various design (upper set of curves) and to a coal-fired power plant (horizontal line). The data were normalized to equal energy production and plotted as a function of time after shutdown. *Source: I. Cook et al., UKAEA, t.b.p. [16]*
FZJ	Tritium In ITER-FEAT a total of approx. 2 kg of tritium will be contained, of which only a few grams are present in the plasma. The total inventory in a reactor will amount to a few kg. Activated materials Neutron radiation will activate major volumes of the structural material in the region of the First Wall and the breeding blankets. This material only arises upon replacing components or dismantling the plant. In total, about the same volume (mass) is activated as in a fission reactor. Radiotoxicity In fusion there is the freedom to choose suitable materials with low radiotoxicity. Radiotoxicity is the measure of the hazard potential. There are two decisive advantages over fission: - an approx. 10-fold lower radiotoxicity during operation, - an approx. 1000-fold lower radiotoxicity 100 years after shutting down the plant.

B.10. Are there any up-to-date studies with clear boundary conditions and basic assumptions available on the radioactive dose in continuous operation for the employees and the environment ? What are the results of these studies ?

IPP	For fusion power plants there are no such studies as yet since the details of a power plant have not yet been investigated with sufficient accuracy. For ITER, however, such studies were drawn up especially within the framework of the Engineering Design Activity (EDA). The investigations on the '1998 ITER Design' are published [1, 9, Volumes 4 and 5], the most recent study is concerned with the latest ITER design and will be officially available in mid-2001. A relevant interim report can be found in [2]. These studies have not only evaluated a finished design but also intervened in the design process and helped to optimize the design from safety aspects. The ITER studies provide maximum values to be expected according to current judgement since the consequences are assessed very carefully and because the ITER materials (especially conventional steels) and water as the coolant (which corrosively erodes steels and thus activation products to a certain extent) will not be used in future fusion power plants. The materials preferred in future are probably low-activation steels and helium as the coolant. Another conservative element in ITER is the fact that both the emissions into the environment and the exposure of the staff are dominated by maintenance and repair work. The extent of such work is certainly higher in the innovative ITER device than in a developed power plant. The latest ITER study specifies the following values for the emissions into the environment: 0.05 g of tritium as tritiated water (HTO) in air per year, 0.0003 g of tritium in water per year, less than 0.06 µg of radioactive argon-41 per year, 61 µg of radioactive carbon-14 per year, 0.25 g of activated metal dust from the plasma chamber per year, 0.85 g of activated, metallic corrosion products from the cooling loops

	per year, 4 µsievert of direct radiation at 250 m distance, about 0.1 g of beryllium (non-activated) per year. These values are clearly below the targets stipulated for the project. A very conservative extrapolation of these values provides similar (possibly even lower) values for a fusion power plant. This is due to the fact that a power plant can be built up somewhat more simply compared to an experiment and that the procedures for the replacement of components will be standardized. Detailed dose calculations on radioactive emissions have not been performed in the ITER project to date since they would vary significantly depending on the site and, moreover, depend on national calculation rules. However, it globally follows from the above figures that the annual dose to the public (i.e. persons outside the power plant) due to emissions is of the order of one percent of the average natural effective dose equivalent, which is about 2 millisievert per year in Germany. The radiation exposure of the staff is also systematically investigated in the ITER project. The values so far available lead to an annual dose of 5 millisievert per year and person and collectively (summed up for all employees) 0.5 person-sievert per year, which is below the target values of the project. Emissions into the environment and exposure of the staff have already been examined in the EU studies on a power plant (SEAFP) and will continue to be investigated. They also showed low values, but the accuracy of the ITER results is higher due to their level of detail.
FZK	For a commercial fusion reactor no precise statements can be made at the present state of development. This would require detailed knowledge of the system and the flows of operation. However, recent studies are available for ITER. They show that the

	radioactive dose in continuous operation to the staff and the environment is below the target values of the ITER project. The ITER target values themselves correspond to or are below the target values defined e.g. by the European operators of future nuclear reactors (European Utilities Requirements[1]). Since both the emissions into the environment and the exposure of the staff are essentially caused by repair and maintenance work, which is more extensive in a first-of-its-kind and test facility such as ITER than in a future reactor, it is to be expected that the radioactive exposure due to a fusion reactor will not be higher than that caused by ITER. *1) P. Berbey: Consolidating the European Utility Requirement Document, 7th International Conference on Nuclear Engineering, Tokyo, April 19-23, 1999, ICONE-7009, to be published in JSME.*
FZJ	*See B.1.*

B.11. What volumes of radioactive waste will arise during operation and in dismantling the plants ? How high is the fraction of long-lived nucleotides in the waste ?

IPP	The material from a fusion power plant is not automatically radioactive waste in its entirety. In fact, radiotoxicity decreases from the fusion plasma to the outside. Components far away from the plasma are thus practically not activated any more. Moreover, radiotoxicity decreases rapidly with time after shutting down the power plant (s. answer to B.9.). This topic must therefore be considered in a differentiated manner. The total mass of radioactive materials from a fusion power plant is known from power plant studies and detailed work in the ITER project. It is in the range of 65,000 tonnes for a power plant. Only the use of lithium-lead material in the blanket envisaged for certain concepts would lead to about 95,000 tonnes due to the specifically heavy lead.

	30 to 40 percent of the radioactive material can be cleared without limitation after a maximum decay time of 100 years ('clearance' is the official nomenclature for this procedure in Germany), if relevant recommendations by the International Atomic Energy Agency (IAEA) are accepted. For about another 60 % of the material a whole range of measures can be applied. Depending on the desired effort (activities 'by hand' up to 'complex remote handling'), complete recycling and use in new power plants is possible as well as partial recycling up to final storage of the materials. The rest of the material (one to a few percent) is 'long-lived'. This fraction is so small because fusion-specific materials have been developed which do not contain alloying elements such as nickel, molybdenum, cobalt, niobium, from which long-lived activation products could be produced. These elements are only contained in minor trace amounts. On the whole, all contaminations that would lead to appreciable long-lived radiotoxicity will be limited to very low concentrations. Practically the entire periodic system of chemical elements was systematically evaluated in this connection by studies under the EU Fusion Programme, especially by the Culham Laboratory. The very small fraction of 'long-lived' radionuclides specified above follows from the permissible and feasible concentrations.
FZK	Studies on future fusion reactors[1)] proceed on the assumption that radioactive waste in a volume of 50,000 to 100,000 t will arise over the entire lifetime of a fusion reactor. This volume is comparable to that arising in a fission reactor. However, the quality of the waste is different. In the waste from fusion reactors no actinides are present, which are responsible for the long-term activity of fission reactor waste. The activation of fusion reactor waste will be governed – after separating the tritium fraction – by neutron reactions with the materials of the plasma-facing components. Long-lived nucleides can be reduced by suitable materials

	choice. The cited reactor studies show the potential for recycling most of the of waste produced during operation and in decommissioning a fusion plant after a decay time of a few decades. The activity has then decayed by 3 to 4 orders of magnitude. The fraction of long-lived waste constituents can thus be reduced to a few tonnes (approx. 1 % of the initial volume)[2).] The development of low-activation materials assumed to be used has only just been started. A qualification of these materials is a main task of future technological development. This also includes making suitable material production and recycling techniques available on an industrial scale. 1) *W. Gulden, I. Cook, G. Marbach, J. Raeder, D. Petti, Y. Seki: An Update of Safety and Environmental Issues for Fusion, Fus. Eng. and Design 51-52 (2000), 419-427* 2) *N.P. Taylor, C.B.A. Forty, D.A. Petti, K.A. McCarthy: The Impact of Materials Selection on Long-term Activation in Fusion Power Plants, J. of Nuclear Materials, 283-287 (2000), 28-34*
FZJ	Activated waste that would have to be transferred to a repository is only produced by admixtures or impurities in the materials, which form long-lived nuclides when activated. If the fraction of these elements is sufficiently small, the activated material could be completely reused after a decay time of 50 - 100 years. Minimizing these undesirable admixtures is a goal in the development of new materials (e.g. EUROFER). It is realistically assumed today that almost 99 % of the entire activated material will be reused.

B.12. Can a first wall be conceived so that no radioactive waste is produced ?

IPP	Concerning this question see also the answer to B.11. The radiotoxicity of the First Wall is determined by the structural material and can therefore be both high and low. A wall which would not entail any radioactive waste is not possible according to present knowledge. Power

	plant design takes account of activation by minimizing the amount of wall material to be replaced in the event of a defect. The First Wall only contributes little to the mass of radioactive materials from a fusion power plant. Including the parts replaced during operation, it accounts for about one to three percent of the total waste. Materials to be used for the First Wall are steels whose composition minimizes the consequences of neutron irradiation. The essential elements of these steels are iron, chromium, manganese, vanadium, tantalum, tungsten, carbon and silicon. Significant progress has been achieved in recent years in both theoretical understanding (especially EU/Culham) and practical development (especially EU/FZK Karlsruhe and in Japan). For all steels it is important to keep the impurities as low as is technically and economically possible. In addition to steels vanadium alloys are being investigated since they are particularly little activated by neutrons. Low impurity levels are particularly important for the activation of these alloys, for material stability and also to prevent the favourable activation properties of the base material from being covered up. Apart from these metal alloys, ceramic materials are also being developed, in particular, silicon carbides which also display low activation.
FZK	No, the wall materials are activated by the neutrons produced in the deuterium-tritium fusion reaction. By suitable materials selection, however, it is possible to influence the type of activation and thus the quality and volume of arising waste (see question B.11.). <u>Note:</u> If it is possible to generate fusion reactions whose products are only charged particles, these could be slowed down giving off their energy to an electric field to such an extent that no radioactivity is produced. However, the realization of such a fusion reactor requires plasma-physical parameters out

	of reach today ("aneutronic fusion").
FZJ	Activated materials are inevitably produced. By a restriction to low-activation materials or by avoiding critical isotopes as alloying partners or impurity elements, however, the activation of the components used can be minimized; long-lived activation products can thus be suppressed. In dismantling the plant or replacing components these activated materials arise and must be treated separately. Almost everything can be reused: a) The tritium stored in the components can be outgassed and further used. b) The activation of the wall material by neutrons is unavoidable; the choice of suitable materials allows the decay time to be minimized. The candidate alloys will have decayed after approx. 50 - 100 years so that they can be largely reused.

B.13. How and where will the radioactive materials be disposed of ?

IPP	Concerning this question see also the answer to B.11. Among the most important goals of fusion research is the development of materials for the power plant structures, which display low or short-lived activation by neutrons. At present, martensitic steels are leading in practice, whose chemical composition has been selected and optimized according to this goal. Only a few percent of these materials would be 'long-lived' after use in the reactor (as discussed under question B.11.). According to present concepts within the EU concerning safety and radiation protection, these materials would be transferred into a repository which, due to the comparatively low radiotoxicity, would probably not have to be deeper than about 50 metres. A final strategy cannot be formulated at present, since not only technological

	but also political, legislative and economic aspects become decisive, probably differing from country to country. Further candidate materials are, in particular, alloys of vanadium with titanium and chromium, which would make the picture outlined above even much more favourable.
FZK	*See questions B.11., B.12.* On the assumptions of current reactor studies, the waste to be disposed of after a suitable decay time does not make particular demands on final disposal either in terms of volume or in terms of activity. It may be assumed that repositories will exist for fission reactor and other radioactive waste, which can accommodate the remaining waste.
FZJ	The activated materials intended for reuse would have to be stored for decay for several decades. The very small quantities of long-lived materials should not represent a major problem for long-term storage due to their small volume.

Tritium

B.14. What hazards are inherent in radioactive tritium ?

IPP	Tritium is a gas emitting electrons ('beta radiation') of low energy. Since tritium is a hydrogen isotope, it takes part in biological processes. In radiological terms, it is characterized by 'half-lives': (1) After a 'physical' half-life (12.3 years), in each case half of the tritium

starting quantity has decayed, the decay product (helium-3) is not radioactive.

(2) Tritium, which is taken up by the human body, is excreted again by half within a global 'biological' half-life of about 10 days. The global biological half-life is short since tritium chemically behaves like hydrogen and thus participates in the rapid water exchange in the body. There are two other biological half-lives amounting to about 30 and 300 days. They describe the behaviour of tritium bound to organic substances in the body. This tritium contributes about 10 % to the total dose caused by incorporated tritium.

Because of the comparatively short biological half-lives tritium does not accumulate appreciably in the body. Due to the low beta energy, tritium only has a radiological effect in the body in the case of incorporation, and this practically only applies to tritium in the oxidized (HTO) or organically bound form. The radiotoxicity of tritium (expressed by the radiation dose in sievert per unit of incorporated activity in bequerel) is comparatively low. For example, it is approximately one ten thousandth of the radiotoxicity of plutonium-239.

Since a fusion power plant will confine a significant tritium inventory (about one to three kilograms), there is the possibility of release. It is therefore necessary to apply retention technologies, thorough monitoring and safety analyses. The latter have been carried out in great detail above all as part of the work for the ITER fusion project. The calculated releases in normal operation per year are far below the target values of the ITER project, which amount to 1 g of tritium as HT and 0.1 g of tritium as HTO.

Extremely conservative analyses (especially with a view to assumed weather conditions) reveal that only the release of the total mobilizable inventory in the course of an accident can lead to the German intervention levels for evacuation being exceeded, but this only on an area of about one square kilometre.

FZK	Tritium is a radioactive isotope of hydrogen. It only occurs naturally in extremely small quantities and is technically produced by neutron reactions with lithium in fission reactors. The range of the beta radiation produced is short, it can already be shielded by thin foils. A hazard to humans is therefore only given upon incorporation into the body. In the human body, tritium behaves like water and half of it is therefore excreted about 10 days after incorporation (biological half-life of 10 days). A small fraction of the incorporated tritium is bound to organic substances and has a biological half-life of up to one year. But this fraction only accounts for about 10 % of the total dose. Tritium decays with a half-life of 12.3 years. It is therefore not relevant for an assessment of the waste problem after long periods of time. Tritium is contained in a fusion reactor in a closed loop. Tritium consumed during reaction is replaced by neutron reactions with lithium. In a fusion plant, the inventories of the tritium contained in the loop are minimized. The total tritium inventory in ITER will be approx. 2 kg, in a commercial reactor an inventory of approx. 5 kg will be needed. The largest portion of this inventory will be contained in systems outside the actual reactor. Any release to the outside can be effectively prevented by a double confinement and, in the event of possible leakages, by additional retention systems. Experience with large-scale plants, e.g. tritium separation plants in Canada, which recover tritium from the cooling water of CANDU reactors, has shown that an effective confinement of tritium is practicable. Positive experience was also made with the tritium-operated JET and TFTR experimental fusion devices. Demonstration of the safe handling of tritium and the development of suitable techniques for purification, storage, balancing and monitoring are main goals of work in the European tritium laboratory located at Research Centre Karlsruhe.

B.15. What technologies exist to remove tritium passed into the cooling system ?

IPP	The ability of detritiating water in a cheap and rapid way (i.e. removing tritium from water) is a prerequisite for experiments with tritium and, in particular, for the operation of a fusion power plant. For this purpose, isotope separation methods have been developed at Research Centre Jülich and Research Centre Karlsruhe. Thus, for example, the complete removal of tritium from water has been experimentally demonstrated for small amounts of water at Research Centre Karlsruhe. This is achieved by a combination of cryogenic distillation and catalytic isotope exchange in the liquid phase. On a large scale, the detritiation of water is carried out in the CANDU reactor industry in Canada. The Institut Laue Langevin (ILL), the European neutron source in Grenoble, also uses large facilities to remove tritium from the heavy water used in the cooling loop. A detritiation system of a quality producing drinking water was used at the Savannah River research institute in the USA. There are thus no difficulties perceivable at present which would prohibit the complete detritiation of water at moderate costs – and inside the power plant.
FZK	The depletion of tritium from the cooling water of CANDU reactors has been an industrial process operated for years. For ITER, in which a large water recooling system is to be provided, the depletion of partial flows in which an elevated tritium concentration is found takes place in a special facility working according to the CECE (**c**ombined **e**lectrolysis and **c**atalytic **e**xchange) process. An optimization of the techniques for fusion plants – especially for ITER – is part of the R&D programme of the European tritium laboratory at Research Centre Karlsruhe.

Incidents / Accidents

B.16. What accident scenarios have so far been explored ? E.g. cumulative failures in several subareas ? The consequences of so-called "human error" ? The hazards during startup and shutdown ? Accidents due to third party actions ?

IPP	In various safety studies [1, 9, Volumes 7 and 8] dealing with ITER, the systematic identification and investigation of possible accidents is an integral part. The problem of the completeness of the accident spectrum is tackled in different ways: For each system, the possible abnormal behaviour and its impact on the entire plant is investigated. A complementary method postulates the release of hazardous substances and investigates the failure necessary for such release in the plant. Another possibility is to systematically examine all energy sources in a fusion plant and analyse the greatest possible damage that can be caused by these energy sources. All these investigation methods are constantly refined and, independently of each other, provide similar lists of possible accidents which can then be analysed in detail. The following list gives a survey of the most important accidents in a fusion plant: - increased fusion power due to elevated plasma temperatures or plasma densities, - loss of coolant inside and outside the plasma vessel, - failure of coolant flow (pipes blocked by foreign bodies or failure of pumps), - ingress of air into the plasma chamber or into the cryostat for the magnets, - dropping of heavy components or stuck components during transport or repair activities, - leakages and hydrogen explosions in the tritium systems,

	- electric arcs and unforeseen electromagnetic forces in the magnets, - failure of penetrations inside the safety barriers (e.g. valves), - electric supply failure. In addition to the postulated accident, the following is assumed in each detailed accident analysis: All systems to which no safety relevance has been ascribed are not available. Furthermore, failure is assumed in an arbitrary further safety system. It is additionally assumed that electric power supply fails at the time of the accident. These investigation methods cover cumulative failures. In addition, it is ensured that further failure of another arbitrary safety system will not lead to a dramatic deterioration of the accident sequence. Result: even under such extreme conditions an evacuation of the surrounding population is not necessary for all accidents for technical reasons. The impact of human error is minimized by the automatic actuation of active safety systems whenever deviations from normal operation are measured. Detailed statements on possible errors of the operating personnel are not yet possible at present since this requires more detailed knowledge about the operation of a fusion plant. Reliable findings can only be obtained in operating a demonstration plant. On the basis of the studies currently available it is expected, however, that the impacts of human error are covered by the spectrum of accident sequences since in safety studies it is assumed for each system anyway that it could fail. Similar statements can be made concerning accidents due to third party actions. Accidents are considered in all operating states. The startup and shutdown of a fusion power plant does not represent any particular safety risks to the public or staff. During startup and shutdown only the probability of a disruption is to be assessed as higher. However, such a disruption is automatically included in any accident analysis. Abnormal behaviour of plasma heating during startup has also been investigated and does not represent a particular safety hazard. All the other energy and hazard potentials are lower during startup and shutdown.

B.17. How high is the accident risk in a tokamak reactor ?

IPP	Unlike nuclear fission, no chain reaction can occur in fusion. In a fusion plasma the fuel is continuously fed in. The inventory is about 1 gram. Energy production can be stopped within about 10 seconds by switching off fuel supply. On the whole, it is very difficult to reach the state in which fusion is possible in a fusion plasma. Any disturbance of the system – for example, an increase in temperature or density – will therefore cause a departure from this narrow parameter range and the fusion reactions will be quenched. The power plant is thus automatically shut down. A fusion power plant is therefore also automatically shut down upon loss of electricity. All heat sources still available will dissipate their heat to the environment by passive cooling without pumps. Even a complete loss of coolant cannot lead to the release of considerable amounts of radioactive material. The temperature in the fusion plant would remain well below the melting temperature of the structural materials even during this accident. However, this positive feature of fusion power plants is only achieved by carefully selecting the structural materials and choosing a suitable construction. This feature has been demonstrated for ITER. In normal operation, the two innermost regions of a fusion power plant are under vacuum for technical reasons. On the one hand, this is the plasma vessel and, on the other, the so-called cryostat containing the superconducting magnets. In the event of minor leakages, it is thus impossible to lose radioactivity from the interior of a fusion plant to the outside since the direction of such a leakage is naturally from outside to inside. A hazard to the public can occur if the safety enclosures are damaged. According to present knowledge, it appears impossible to destroy the

	multiple layers of the safety enclosures from inside, since the energy inventories of a fusion plant are too low. If, however, an accident due to an unforeseen external event (e.g. an earthquake which considerably exceeds the intensity of historical earthquakes) is postulated, the safety enclosures of a fusion plant could be destroyed to a large extent. Nevertheless, the impacts on the environment would be limited. (Only those impacts are considered here which would be caused by the fusion plant.) If German guidelines for the evacuation of the population are taken as a basis, a few square kilometres could be affected under unfavourable weather conditions. The long-term impacts on the affected environment would also be limited. Released tritium has a biological half-life of about 10 days. After that time it almost completely disappears from the organisms of humans, animals and plants. Long-term measurements of tritium in soil have shown that the tritium content decreases by a factor of 1000 within one year. Greater dilution has not been demonstrated due to experimental limitations.

B.18. What happens in a tokamak reactor if the plasma current is suddenly quenched ?

IPP	Quenching of the plasma current in a tokamak plasma leads to a sudden loss of the thermal plasma energy which flows towards the inner wall of the plasma vessel within about 10 milliseconds. The high plasma energy involved (about 10^9 joule in a power plant plasma) will lead to an incipient melting of surfaces. This can limit the total lifetime of the components of the First Wall, if it takes place too often. In addition, the rapid drop in plasma current – on a time scale from 10 to 100 milliseconds – will induce currents in the plasma vessel which cause high forces acting on the vessel. Analyses of the ITER design have shown, however, that these forces are below the load limits for the vessel; it will be possible to design a fusion *reactor* in the same way. Since the occurrence of current quenches (so-called disruptions) is

	inconsistent with continuous power generation in a power plant, it is being investigated intensively worldwide – and with considerable success – how the plasma can be controlled so that current quenches are not very frequent. In addition, techniques have been developed to "smoothly" run the plasma down in time if the control system recognizes an impending current quench. The aim is to ensure that current quenches involving the above problems occur at most once a year. In this way, the lifetime of technical components is not shortened; only the availability slightly deteriorates.
FZJ	Plasma current disruptions should be avoided as far as possible because due to the additional thermomechanical load the lifetime of some structural components will suffer. The fusion process is immediately quenched upon the occurrence of a disruption. Disruptions are therefore rather a hazard to the availability of the machine than a direct hazard to humans and the environment. Techniques to avoid such disruptions or to attenuate their effects are currently being developed in a promising way. A stellarator has the advantage over a tokamak that no plasma current is necessary and therefore no disruptions can occur.

B.19. Are there any risk studies by independent experts on fusion reactors in general and tokamak reactors in particular ? How is the accident risk assessed there ?

IPP	In the German-speaking area there is material on this question if the terms of 'risk study' and 'expert' are not interpreted too narrowly: Reports [10] and [11] as well as reports [12] and [13] are each correlated with one another. On the whole, the reports provide assessments on the German, Swiss and Austrian part, which can certainly be referred to as independent and which bear a sceptical basic attitude. Many individual assessments in [13] of physical, technical and radiological facts are substantiated so insufficiently or are even incorrect that they have been

	commented in detail in writing on the part of SEAFP [14] and were subsequently discussed in detail several times and corrected by staff members of the Institute for Applied Ecology and of IANUS. The reports confirm and acknowledge that it is impossible to quantify all properties of future fusion power plants in detail today and that this also applies to the accident risk. For a basic assessment of the accident risk, in most cases a comparison with fission power plants is used. This comparison turns out to be positive up to very positive and generally uses the toroidal magnetic confinement (exemplified by the tokamak) as the basis. In detail, especially with respect to the safety analyses on the part of fusion on future power plants, the sceptical basic attitude of the reports naturally leads to criticism, which is justified above all by details of the assumptions made and lack of completeness of analyses.

B.20. Are there any findings concerning the safety and environmental properties of a fusion reactor aimed at going beyond the information contained in the SEAFP study from the year 1995 ? How far are these results documented ? How far are they available to the public ? Have the results of the SEAFP study been verified independently or is this envisaged ?

IPP	There are studies available on the safety and environmental properties of nuclear fusion, which have been published after the SEAFP study and go beyond this study. All these studies are available to the public. As far as this is meaningful, the material is published in the scientific literature, where this does not seem meaningful, it has been or will soon be published in laboratory reports or reports by the International Atomic Energy Agency (IAEA). The by far most comprehensive analyses have been and will be carried out within the framework of the ITER project. ITER is a facility of power plant dimensions, but not yet a power plant from all aspects. Since ITER in terms of engineering is designed in detail, the associated analyses on safety have an extensive basis and are prototypical in many respects. The ITER studies

	are very likely to be conservative with respect to the safety of power plants, since the consequences are very carefully assessed and because the ITER materials (especially conventional steels) and water as the coolant will be replaced by more advanced materials in future power plants. Further details are given in the answer to question B.10. In December 1997 the NSSR-2 report [9] was completed which documents the safety analyses for the 1998 ITER Design. This report comprises 11 volumes and covers all relevant aspects. A summary of NSSR-2 has been published by the IAEA in [1]. Safety is dealt with in chapter IV "FDR Safety Assessment". For the most recent ITER design the GSSR report (Generic Site Safety Report) is currently being prepared and not yet published. It also comprises 11 volumes dealing with all relevant safety aspects. In the EU Fusion Programme, the study of power plants was continued within the framework of SEAFP. The interim report "Safety and Environmental Assessment of Fusion Power – Long Term Programme (SEAL)" was published in December 1999 by the EU Commission in Brussels [15]. The final report of the SEAFP-2 project, "The Safety and Environmental Impact of Commercial Fusion Power Stations", is in its final phase and should therefore be published soon [16].
FZK	The SEAFP study of 1995 was complemented by follow-on work. A summary of the activities in the past few years will be published in the near future [1)]. The results of work obtained within the EU Fusion Programme are published on principle. The results of the SEAFP study have been presented in various publications, at conferences etc. [2,3)] and have therefore also been available for independent verifications. 1) *I. Cook, G. Marbach, L. di Pace, C. Girard, N.P. Taylor: The Safety and Environmental Impact of Commercial Fusion Power Stations, report, t.b.p. [16]* 2) *W. Gulden, E. Kajlert: Safety and Environmental Assessment of Fusion Power –*

	Long Term Programme (SEAL), Summary Report of the SEAL Project, EUR 19071 [3] *I. Cook, G. Marbach, L. di Pace, C. Girard, P. Rocco, N.P. Taylor: Results, Conclusions, and Implications of the SEAFP-2 Programme, Fusion Eng. and Design 51-52 (2000), 409-417*

Proliferation Risks

B.21. Tritium is an important weapons material for advanced nuclear weapon designs. It is so far not subject to IAEA safeguards. On the other hand, there are international efforts at excluding weapons-grade nuclear materials (fission materials such as highly enriched uranium or plutonium) from civil uses to achieve a more proliferation-resistant use of nuclear technology. This leads to the question of how the proliferation risk of fusion reactors breeding tritium is to be assessed ?

IPP	Concerning the possibilities of diverting tritium from a fusion plant, it is of fundamental importance that tightness is an inherent property of such plants. The plasma vessel, its extensions and the primary cooling system must be extremely tight to fulfil the extreme demands on the vacuum absolutely required for plasma operation. In the section of the tritium cycle outside the plasma vessel, in which the tritium is extracted from the exhaust air and blanket and purified, the tightness of all components is also extremely important to avoid tritium releases. Any withdrawal of tritium would require the opening of all barriers confining the tritium-bearing systems. Incidentally, tritium and also enriched lithium (which is needed for tritium production) can be supplied much more simply and cheaply by already existing technologies (including heavy-water reactors).
FZK	Within the meaning of the Nuclear Non-Proliferation Treaty, NPT, proliferation is understood to be the passing on of materials, equipment and know-how enabling third parties to gain possession of nuclear weapons. Potential proliferation risks of fusion technology are breeding and the use of tritium as the fuel, the physical possibility of breeding fission material suitable

	for the production of nuclear weapons as well as the disclosure of know-how that could serve non-peaceful purposes. Tritium alone is not a nuclear weapons material, but it only gains strategic significance in conjunction with fissionable material (e.g. plutonium-239, uranium-235, uranium-233). The safeguards measures of the International Atomic Energy Agency (IAEA) therefore concentrate on safeguarding fissionable material and so far do not stipulate any comparable safeguards for tritium. International efforts at excluding weapons-grade material from civil uses simultaneously reduce the proliferation risk of tritium. The proliferation of tritium and tritium facilities is subject to the export restrictions on dual-use materials of the Nuclear Suppliers Group. Furthermore, there are relevant IAEA guidelines (INFCIRC/254) which, however, are not binding. In the European Union, tritium is covered by the dual-use regulation, which stipulates an obligatory notification of exports to specific sensitive countries. In Germany, this regulation is implemented in the Foreign Trade and Payments Regulation and, moreover, the Nuclear Weapons Control Act is applicable, which penalizes any kind of support for the development of war weapons. In the member states, tritium is safeguarded by EURATOM on the basis of special arrangements in bilateral supply contracts. For the worldwide situation see [1)]. The increasing use of tritium as the fuel in future fusion power plants could lead to a different assessment of the proliferation risk than is the case today. This could require further safeguards approximately comparable with the present IAEA safeguards regime. On the basis of the existing safeguards infrastructure and experience in the practical implementation of safeguards, it may be assumed that the proliferation risk of tritium can then also be effectively limited. The scenarios "clandestine breeding of fission material" and "disclosure of know-how" will be dealt with under questions B.22. and B.23.

	[1)] *Lars Colschen, Martin Kalinowski, Jan Vydra: "National Regulations of Accounting for and Control of Tritium", JANUS, TH Darmstadt, April 1991*

B.22. Fusion neutrons can also be used for breeding fissile materials (such as plutonium). Can such breeding be excluded ?

IPP	Although the use of fusion power plants for breeding fissile materials of weapons-grade isotopic composition is technically possible in principle, it should make demands on power plant operation that are contrary to its actually intended application. For example, it would imply an opening of the barriers including the plasma vessel, since the breeding material would have to be brought very close to the plasma. As already mentioned in question B.22., this would endanger the tightness of the plant and thus plasma operation. A possible misuse of neutrons for breeding fissionable material is already covered by the international safeguards since they comprise comprehensive controls of the uranium and thorium breeding materials both by the IAEA and by Euratom in the EU. Possible undeclared activities are also detected by the new extended IAEA safeguards system.
FZK	In a fission reactor plutonium is produced during normal operation. In principle, weapons-grade plutonium can also be produced in a fission reactor without requiring significant modifications of the plant or mode of operation. In a fusion reactor, in contrast, no nuclear fuels are used. Breeding weapons-grade fissile material would require significant changes in the design of the plant and the use of special components. Clandestine breeding in a fusion power plant faces the following additional barriers, provided that there exists a safeguards regime: a) The starting material, e.g. natural uranium, must be diverted from peaceful uses or clandestinely imported, in both cases infringing the NPT. b) The bred uranium/plutonium mixture must be clandestinely transferred to

	a reprocessing plant. c) In the reprocessing plant, the plutonium must be separated and diverted again infringing the NPT. This scenario thus presupposes that the safeguards under the NPT are dodged several times without being discovered. In view of the short detection time for plutonium and the associated near-real-time accountancy in reprocessing plants, there is a high probability of being detected.

B.23. How are other proliferation risks of fusion reactors to be assessed (tritium production, know-how transfer, militarily relevant research ?

IPP	It can be generally stated that in a fusion power plant with magnetic confinement, apart from the above-mentioned possibilities (tritium and fissile material production), no new physical findings and technical details play a role which could directly contribute to the development of nuclear weapons. The processes of plasma generation, confinement and heating take place in a time interval without relevance to nuclear weapons. Computer codes allowing the calculation of these processes cannot be used for the development of nuclear weapons either from the present perspective.
FZK	Fusion research in Europe aims at providing the scientific and technical fundamentals for fusion power plants according to the principle of magnetic plasma confinement. Apart from the already mentioned potential risks of breeding fissile materials and using tritium as the fuel, no physical and technical developments are to be expected which could contribute to the production of nuclear weapons.

B.24. Are there already concepts for safeguards and are these sufficient ? Will there also be preventive measures in addition to safeguards ?

IPP	An increasing use of tritium in connection with progressing fusion research can lead to safeguards for tritium (probably within the framework of the IAEA). Such a safeguards regime does not exist at present under the Nuclear Non-Proliferation Treaty. Tritium, some tritium-related technologies

	and lithium-6 are currently only subject to less formal requirements by the IAEA specified in the Annex to IAEA INFCIRC/254/Rev. 1 "Guidelines for transfers of nuclear-related dual-use equipment, material and related technology".
FZK	In member states of the NP Treaty all fissionable material within the territory of a state – unless explicitly exempted from the application of safeguards measures – is safeguarded by the IAEA under the INFCIRC/153 Model Agreement. Added to this since 1997 has been the INFCIRC/540 Additional Protocol, which aims at verifying the correctness and completeness of the specifications of states concerning all their nuclear activities. The concrete safeguards measures in a nuclear facility are determined in detail on the basis of the design information in the so-called facility attachments. The fuel for fusion power plants is a mixture of deuterium and tritium, both materials do not belong to the category of fissionable materials. A fusion power plant is therefore not to be regarded as a nuclear facility as defined today. Whereas deuterium as a possible moderator for nuclear fission reactors is subject to certain IAEA safeguards, there is at present neither a mandate nor a legal basis for the application of safeguards to tritium by the IAEA. For the development of a safeguards concept by national authorities it must first be clarified how fusion power plants should be classified within the meaning of the NP Treaty and what safeguards criteria and goals should be fulfilled. Moreover, the design of a fusion power plant is not available at present in the depth of detail required to develop a safeguards concept. Therefore, there is no safeguards concept for a fusion reactor at present. The question of preventive measures can only be appropriately discussed in connection with a safeguards concept and, moreover, it must be defined what is to be understood by preventive measures.

1) *Lars Colschen, Martin Kalinowski, Jan Vydra: "National Regulations of Accounting for and Control of Tritium", IANUS, TH Darmstadt, April 1991*

2) *"Non-Proliferationsaspekte der Kernfusion", Abschlussbericht der Arbeitsgruppe des Forschungsverbundes Kernfusion der Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren, September 2000 (to be published)*

C. Competitive Position of Germany and Europe, Costs of Fusion Research and Need for Political Action

Leading questions:

C.1. What steps with what estimated costs in what period must be taken until an economically usable fusion reactor will be available ?

IPP	ITER-FEAT would be followed by a demonstration power plant (DEMO), which would produce electricity for the first time and would display a closed fuel cycle breeding the tritium needed for operation within the plant. Necessary prerequisites at defined times during planning and licensing are the experience with the construction and operation of ITER as well as developments and tests of materials in a dedicated neutron source (called IFMIF). DEMO would then be followed by the construction of a prototype power plant, the first commercial plant, which could go into operation at the beginning of the second half of this century. The costs of these steps are described in answer C.6.
FZJ	Three steps are planned: 1. <u>ITER-FEAT</u> as the first experimental reactor with 10-fold energy gain in short-time operation. Research on ITER-FEAT allows the variation of important parameters in physics (e.g. magnetic field configuration, plasma current drive) and technology (e.g. wall materials), whose optimization will then lead to the design of 2. <u>DEMO</u>, a first reactor in continuous operation (producing electricity), in which the technological concepts of a fusion reactor are to be verified. These will then form the basis for the construction of the 3. first <u>commercial reactor</u> towards the middle of the century. For this period, the total costs of fusion research in Europe will have to be adjusted to a level of approx. € 500 million. These costs will be borne on a pro rata basis by the European Framework Programme and by direct national funding (at present in a ratio of about 2:3). These costs comprise the

	construction and use of ITER and DEMO as well as complementary research on concept improvements (stellarator, tokamak), materials research and other special issues.

Further questions

Costs / Economic Efficiency

C.2. How is the economic efficiency (cost) of fusion reactors to be rated ? What costs will be included in the cost efficiency calculations (research, operation, safety systems, waste, dismantling) ? What are the uncertainties in the cost estimates ? What is to be borne by the public sector ?

IPP	There is a variety of cost estimates for fusion, e.g. in [17,18]. The calculation of the electricity generating costs includes construction, operation, dismantling and storage. The costs should range between 12 and 20 pf/kWh for the tenth plant of its kind according to the above-mentioned studies. These estimates are based on various studies on the construction of future fusion power plants and the considerable experience gathered in developing the ITER experiment in close cooperation with industry. For the critical components of the ITER experiment, prototypes were built in industry, which provide a relatively reliable basis for cost estimates. Some US studies [19,20] estimate the cost of fusion-generated electricity even more favourable than cited above. These studies are also based on the physically feasible, but presuppose great progress in plasma physics and plasma technology. In comparison, the European studies proceed rather more conservatively. However, the economic attractiveness of an energy source is not only determined by the price of the electricity produced, but also by other factors such as acceptance, resources and environmental aspects. From this

	perspective, fusion represents a nearly inexhaustible – and thus quasi-renewable – energy source with favourable environmental properties: the toxicity of fusion waste decays in fifty to a hundred years by orders of magnitude (B.1.-B.3., B.9.) A public financing of fusion power plants is not envisaged. Only the preceding fusion research and technology development is paid from state resources as precaution research.
FZJ	Economic efficiency will essentially depend on the ratio of the electric power produced to the construction investments and operating costs. Fuel costs do not play a role. a) The <u>construction investments</u> are essentially given by the absolute size of the plant, for which there are reliable data according to the present state of knowledge. b) The <u>operating costs</u> will be determined by the availability of the plant, i.e. by the service life of wall components, of the breeding blanket and of other highly stressed components. The development of these components for steady-state operation is the subject matter of current research. Estimates of the total cost of a fusion reactor assume an availability comparable to present-day conventional power plants (at least 75 %). The electricity generation costs are in the range of competitive 15 pf/kWh. Industry would financially play a role only at the stage of a commercial reactor.

C.3. Is it true that the plant costs for a fusion reactor will be about two to three times higher than for a fission reactor and significantly higher than for a breeder reactor ?

IPP	Instead of the pure plant costs, normally the electricity generating costs – in pf/kWh – are discussed, and the plant costs and the costs for operation, dismantling and waste management are allocated to the total energy produced by the power plant. The costs for electricity from a fusion power plant are then above the values for a conventional nuclear power plant by a factor of about two according to present studies [17,18], see also C.2. As also mentioned under C.2., however, the attractiveness of an energy source is also governed by factors other than the price.
FZJ	The investment costs of a fusion reactor will be higher than for a fission reactor (today approx. 3000 DM/kW (electric) for the EPR pressurized water reactor 4 GW thermal) because of the mass being about twice as large alone. However, the differences in electricity production costs amounting today to approx. 6 pf/kWh (fission) versus estimated 15 pf/kWh (fusion) could be adjusted by a sharply rising price of the fuels in the future. The share of the costs for fuel is negligible in fusion (below 0.1 pf/kWh), whereas the fuel share in a fission reactor is already approx. 13 % of the electricity cost today and shows a rising trend.

C.4. What have been the costs of total fusion research up to the present ?

IPP	The total expenditure of all OECD countries in the period from 1974 to 1998 amounted to US$ 28.3 billion (in 1999 US$) according to the IEA, i.e. roughly US$ 1.1 billion per year on average.

C.5. What have been the costs of preparing for the ITER project since 1985 ? How much is publicly financed and how much comes from industry ?

IPP	During the ITER-EDA from July 1992 to July 1998 the Home Teams spent US$ 550 million on research and development (R&D tasks), another

	US$ 110 million for the three-year extension until July 2001 (source: TAC-16 Progress Report). Part of the contracts were executed by industry, but financing was purely public. In addition, a total of 950 person-years were calculated for construction work during the design phase.

C.6. How high are the costs estimated for a first test reactor, a later planned second test reactor and the further development steps up to first commercial electricity production ?

IPP	The construction costs of ITER-FEAT (which is to be regarded as the first test reactor) are expected to be below 4 billion euro. (A more precise estimate by EFDA and the European industry is currently under way.) The international ITER Design Team has merely made an estimate of the relative expenditure, which confirms that the goal has been reached – 50 percent reduction of the costs compared to the original "large" ITER design. For DEMO, the next development step, no design activities have so far been carried out that would permit a similarly precise cost estimate. Concerning its dimensions and the stored magnetic field energy (significantly pushing up costs) DEMO is likely to be in the range of the "large" ITER, but would exhibit a higher fusion power. Since additional installations (needed for electricity generation) will be added, its investment costs (at 1000 MW electric power) should be in the range of approx. 8 billion euro. DEMO will already be able to supply electricity to the grid, so that part of these costs – or, for example, the operating costs – could be covered by electricity supplies. The costs for the IFMIF neutron source simultaneously required are estimated at approx. 600 million euro. In addition to these investments, operating costs for personnel, consumables, services and extensions will arise for ITER, IFMIF and DEMO, which are estimated for ITER-FEAT at approx. 240 million euro including extensions to be carried out during operation. In parallel with these central expenditures, a research programme also remains necessary in the individual fusion institutes in order to evaluate the

	results arising in the central facilities, develop proposals for improvements and test them in advance in smaller units. However, these activities will be greatly reduced – above all concerning the operating expenses – in comparison to the previous expenditure in the research institutes.

C.7. Can the costs of approx. DM 150 billion – including over DM 50 billion estimated to arise in the EU – specified in the recent TA study "Advanced Nuclear Systems" by the Swiss Science Council for the ITER path be confirmed ?

IPP	At present, in Europe, Japan and the USA approx. 1.1 billion euro are spent on fusion research – mainly with magnetic confinement. (The expenditures on inertial fusion, above all in the USA, are covered essentially from the military budget.) In the case of an effective international cooperation which avoids unnecessary duplication of efforts, the construction and operation of ITER should also be possible within this frame. (The construction costs of the large-scale ITER-FEAT experiment currently under planning were calculated to be 3.5 billion euro to be distributed over 10 years; accompanying costs for project management and ITER-specific research and development tasks should total approx. 0.7 billion euro. The operating costs of ITER are later expected to be 0.22 billion euro per year.) The difference between the annual costs calculated therefrom and the (inflation-adjusted) assumed constant budget would serve for a follow-on technology programme (development of materials) and simultaneous physical investigations, which should also comprise the research and development of the stellarator line. The planning and construction of the next step (a DEMO demonstration power plant) would take place simultaneously with the operation of ITER, the start of construction being conceivable in approx. 2025. A power plant which regularly supplies electricity to the grid could thus be put into operation in 2050. The further extrapolation of the expenditures greatly depends on whether further steps (such as DEMO) are also internationally coordinated or will take place in competition. In the former case, the entire research and development costs up to commissioning the first series power plant could remain below those specified in the Swiss study by approx. 30 percent.

FZJ	This sum is also obtained by a simple calculation: Assuming that the expenditure on fusion by the countries involved in ITER-FEAT would be DM 3 billion per year and would be extrapolated for the next 50 years up to the construction of the first commercial fusion reactor, the sum of DM 150 billion is obtained. The same calculation for Germany alone with at present approx. DM 300 million per year incl. EU funds provides a sum of DM 15 billion in half a century.

C.8. How will the costs for the ITER project be allocated to the international partners ? Has the allocation key changed or will it change ? What does the ITER construction mean for the national and European fusion research budgets in the medium term ? What consequences for an increase of the expenditure from the federal budget (national and European financing) are foreseeable ?

IPP	The contributions by the individual partners to the ITER development activities were made in kind, and their relative value was specified in so-called ITER units of account. The contributions by EU : Japan : Russian Federation : USA were approx. 33 : 33 : 16 : 16 with a total value of approx. 970 million euro. The construction of ITER is also largely planned through contributions by the partners in kind, and the allocation key should be the subject of negotiations and will also depend on the site. A differentiation is made between contributions that can be made by each partner (the common-area part of the expenditures) and contributions firmly bound to the site (non-common area). The Russian Federation has announced that it would participate in the construction expenditure on a scale comparable to the preparation activities. In case ITER will be constructed in Europe or Japan, therefore, an allocation among the host partner (50 %), the second partner (35 %) and the Russian Federation (15 %) would be conceivable. As mentioned above, however, this remains to be negotiated.

	It is expected that Canada will present itself as a candidate site in the next few months in the form of an offer. Apart from the developed terrain, this offer is expected to contain also a contribution of approx. 20 % of the construction costs, so that a splitting into Japan : Europe : RF : Canada = 32.5 : 32.5 : 15 : 20 would appear possible. If ITER is constructed outside Europe, the participation in ITER could be borne from a European fusion budget constant in money value. A construction in Europe would require considerable savings in other parts of the European Fusion Programme but possibly also a slight increase of the total budget.

C.9. Has the fusion research community or the EU proposals as to where the funds for the ITER path should be raised ? In more concrete terms: Are there any proposals concerning research priorities in which funds to the corresponding amount should be saved (the question encompasses both cuts and the omission of increases) ?

IPP	The answer under C.8. suggests various possible scenarios. Some figures can delimit the approximate total frame: for planned construction costs of about 3.5 billion euro distributed over 10 years of construction, annual investment costs of about 250 million euro are obtained, whose allocation to the partners still has to be determined. The European fusion budget in the 5th Framework Programme amounts to roughly 197 million euro, of which about 70 million are currently used for the operation of JET. As mentioned under C.8., in the case of constructing ITER outside Europe, the participation in ITER could well be borne from a fusion budget constant in money value. A construction in Europe would require a reorganisation of the European Fusion Programme and possibly a slight increase of the annual European budget. At all events, the construction and operation of ITER will lead to a modification of the European research landscape which, however, must be retained, in principle, in order to maintain the European expertise and the training of young people.

	Although the boundary conditions for this restructuring of the European fusion associations are thus by far not clear, a working group composed of the heads of various European fusion research institutions was set up in February to work out initial concepts.

C.10. How high is the share from Euratom funds financed indirectly through federal funds ? How high would be Germany's share in Euratom funds that would be expended on ITER-FEAT ? What would be Germany's total costs (related to construction and operating costs) for ITER-FEAT, composed of national research funds and share in Euratom funds ?

IPP	The German contributions to the European institutions – and thus also to Euratom – are proportionate to the annually redetermined share in the gross national product. At present, this share is approx. 26 %. This figure should be compared to Germany's 42 % share in the money allocated by Euratom to the associations. The German share in the financing of ITER cannot yet be calculated at present since it depends on the share to be paid by Europe to ITER and, moreover, on how much of the preparatory work is awarded to German associations requiring national research funds (see also C.8., C.9. and C.34.)

C.11. Is it being considered to involve European energy utilities in financing in the case of a European siting of ITER-FEAT ? If yes, how far have these considerations progressed ? If no, why not ?

IPP	Up to the present, there have been no such considerations because the utilities are not willing to finance such long-term research, which is generally regarded as precaution research under state responsibility. With the deregulation of the electricity market, the willingness of the utilities for medium- or long-term investments has decreased even further so that their participation in ITER financing must appear to be beyond all hope (one should only think of the present situation in California).

C.12. Do the US utilities through their EPRI association (Electric Power Research Institute) support the nuclear fusion activities of the Department of Energy from the aspect of the competitiveness of this new method of energy production ?

No answer by the HGF institutes.

C.13. The stellarator in Greifswald may provide information within about the next 15 years of whether this path promises a higher probability of success than the tokamak path. Would it not be more meaningful from the aspect of cost efficiency to wait with the construction of the tokamak until it is clearly perceivable whether the stellarator or the tokamak path is more promising ? How high would be the misguided investments if it were found after the construction of the ITER tokamak that the stellarator path would be more promising ?

IPP	As stated above (see answers to A.1. and A.3.), ITER will investigate for the first time plasmas with Q >> 1, especially the new effects occurring due to the alpha particles, such as self-heating, the possibility of collective effects and helium removal, and at the same time provide the technological information necessary for the development of a demonstration power plant. These investigations are only possible with a tokamak today. The physical findings and technological developments obtained, however, are independent of the confinement concept used. They can thus be directly transferred to the stellarator. There is therefore no reason to stop the construction and operation of the "next step" today. This would also set the stellarator line back by decades. The European strategy for the development of fusion research, in contrast, provides for a development of the stellarator line simultaneously with the physical investigations and technological developments with ITER to a level where the question of "tokamak or stellarator" can then be discussed on a well-founded basis.
FZJ	The simultaneous development of ITER-FEAT and Wendelstein 7-X is meaningful. The competition between tokamak and stellarator is greatly determined by physics, i.e. the better energy confinement, where the tokamak has so far

	been more successful, but the stellarator is catching up. On the other hand, most technological issues such as plasma-wall interaction, heating method, breeding blanket, wall materials, superconducting coils, tritium cycle, control of steady-state operation or diagnostics are the same for tokamak and stellarator. DEMO would in any case benefit from the technological progress achieved with ITER-FEAT, irrespective of whether DEMO will be a tokamak or a stellarator. Abandoning ITER-FEAT, on the other hand, and waiting for the results of Wendelstein 7-X would lead to considerable time losses in fusion technology and thus also have an effect on the timing of DEMO. Moreover, it will also be possible in ITER-FEAT to thoroughly investigate the physics of alpha-particle heating, which would be important for corroborating the physics-based design parameters for DEMO.

C.14. Can computer simulations perform part of the research tasks until a decision is made between tokamak and stellarator and, if applicable, the American path of laser fusion ? What findings can or cannot be obtained through computer simulations ?

IPP	Fusion research has been and still is one of the pioneers of computer simulation. The total planning of fusion research is based on lasting, dramatic progress in computer simulation which, in fact, will make many experimental investigations superfluous. However, computer simulations cannot replace experiments if qualitatively new effects such as the self-heating of the plasma by thermonuclear burning are to be studied. Simulation results will continue to require a case-by-case confirmation by experiments, since the models underlying the calculations are always only approximations. With the continuous refinement of the models, however, we expect, for example, that computer simulations – calibrated on the results of the stellarators Wendelstein 7-X and LHD (pure deuterium plasmas in which self-heating does not play a role) and on the ITER results (self-heating of a deuterium-tritium plasma in a tokamak – would allow a reliable extrapolation to a DEMO stellarator.

FZJ	A reliable theory of the transport in magnetized plasmas is not yet available and not in sight in the near term. The design of ITER-FEAT is therefore based almost exclusively on empirical data obtained in the past 20 years in fusion experiments of different dimensions and not on computer models of plasma confinement. The further development of theory requires close cooperation with experiments. Computer simulations are meaningful in subareas where they can sometimes even replace experiments. In view of the complexity of the total tokamak or stellarator system, however, the computer codes for comprehensive modelling have so far been completely insufficient.

C.15. How often and in what form is the German and the European fusion programme evaluated by independent bodies ?

IPP	The European Fusion Programme is evaluated every five years by a panel of independent experts from science and industry. The last evaluation was performed in 2000 by the Airaghi Panel (named after its chairman, Dr Airaghi) [21], the last but one in 1996 by the Barabaschi Panel [22]. The German fusion programme, for example, was evaluated last year by the Science Council within the framework of its evaluation of German energy research [23] and showed a very positive result.

Research Policy

C.16. What is the status of German fusion research in comparison to that in Europe and other countries ?

IPP	European fusion research occupies a leading position worldwide, not only with the JET joint European experiment, which plays a special role as the currently largest tokamak and due to its deuterium-tritium experiments, but

also on account of the many – in special fields of work very successful – fusion experiments in the associations.

Within European fusion research, German fusion research holds a top position. This will be demonstrated here by the special case of the Max Planck Institute of Plasma Physics (IPP):

In the field of fusion-oriented plasma physics, the IPP is a leading institute worldwide both due to the wide range of research (as the only institute, the IPP conducts research in the field of tokamaks and stellarators) and due to outstanding results which have strongly shaped global fusion research. To mention a few results from the past years:

- At the ASDEX tokamak it was possible for the first time to successfully demonstrate divertor operation (in which the plasma is limited by additional magnetic fields), which has meanwhile gained acceptance worldwide for the extraction of energy and particles. Practically all large fusion experiments have since used a divertor. The JET joint European project, which originally had only been built with a material plasma limitation, a limiter, was subsequently equipped with a divertor on account of the ASDEX results and achieved great scientific successes.

- ASDEX also served in 1982 to find a plasma state with improved energy confinement, the so-called H-mode, which has very rapidly gained acceptance worldwide as a standard working mode. The H-mode makes the development of an economic fusion power plant possible and is indispensable for achieving an energy-supplying plasma in ITER.

- The IPP's expertise in the field of divertor physics as well as the extensive and very successful investigations at ASDEX Upgrade also led to an intensive participation of the IPP in the design of the ITER divertor. ASDEX Upgrade has anticipated the ITER divertor by the investigations into an improved divertor. This is supported by internationally coordinated numerical modellings of the divertor.

- In 1998 ASDEX Upgrade demonstrated for the first time quasi-steady-

	state plasmas with good energy confinement and high energy content in discharges with a so-called "internal transport barrier" intended to allow more economic power plant operation. - With the first "pure stellarator operation" at Wendelstein 7-A in 1980 and the successful work by the Garching stellerator theoreticians the IPP has gained an exceptional position worldwide in the field of stellarator research. - The concept of modular coils developed at IPP up to the application stage, realized for the first time successfully with Wendelstein 7-AS, is a precondition for the technical realization of stellarator power plants. The positive results of stellarator research at IPP in theory and experiments also led to a renaissance of stellarator research in the USA in recent years. - The basis of stellarator optimization, so-called quasi-symmetry, was developed at IPP. - The interaction of materials with plasmas is being studied at IPP at a leading edge worldwide. - On the whole, the IPP is internationally recognized as one of the leading institutes of fusion research.
FZJ	Europe is leading worldwide in fusion research (see JET and others). German fusion research occupies a top position as an integral part of European fusion research. This is also demonstrated by an overproportionate return of European research funds.

C.17. What is the experience with fusion research and how does it develop in the USA, Japan, Russia and other countries ?

IPP	Japan and Russia are running a power-plant-oriented fusion research programme similar to Europe. Both countries are therefore also greatly interested in the construction and operation of ITER.

	In the USA the goal direction has slightly changed in the last few years. The focus of the American fusion programme – with magnetic confinement – is now rather on basic research. Fusion research with inertial confinement essentially serves military research and "stockpile stewardship" (i.e. maintenance of the atomic arsenal), although in recent years the aspect of energy production has also been increasingly emphasized. Korea and India have started intensive fusion research programmes in the last few years, in both cases with the long-term goal of developing a new energy source.
FZJ	Europe, Japan and Russia pursue a joint research strategy. The USA have embarked on a dual strategy pursuing, on the one hand, alternative concepts of magnetic fusion (e.g. spherical tokamak) and, on the other hand, inertial confinement fusion coupled closely to military research in connection with the "Science Based Stockpile Stewardship and Management Program" (US$ 4.5 billion) to compensate for the Comprehensive Test Ban Treaty. India, Korea and China with their hunger for energy have launched ambitious research programmes on magnetic fusion.

C.18. Can you confirm that the USA conduct scientifically oriented fusion research and spend 252 million dollars on this in 2001 alone ? Does the US Department of Energy spend 199 million dollars per year on laser fusion and has the construction of a reactor of the NIF type been started, which is to be completed at the Lawrence Livermore National Laboratory in 2008 ?

IPP	It should be left to Dr Decker, DOE, to confirm and complement or correct these statements. Our state of knowledge, which is essentially based on information from the

	Internet, is as follows: For the year 2001, the Department of Energy (DOE) has applied for US$ 248.5 million for scientific research into nuclear fusion. This includes about US$ 240 million for fusion with magnetic confinement and approx. US$ 9 million for inertial confinement fusion. It should be borne in mind, however, that about another US$ 500 million was made available, for example, from the DOE's Defense Program in 1999. For the construction of a National Ignition Facility (NIF) – according to the principle of inertial confinement fusion – at the Lawrence Livermore National Laboratory, construction costs totalling US$ 2.05 billion are estimated by the DOE. Assuming a project term of 10 years this would mean an annual expenditure of US$ 220 million (without adjustment for inflation). The National Ignition Facility has originally been started as part of the Stockpile Stewardship Program, but is meanwhile classified as a reactor-oriented project. It is interesting to compare the NIF total cost of about US$ 2 billion with those of ITER. It should be borne in mind here that NIF is a national programme without international partners. Moreover, from the IPP's point of view, inertial confinement fusion is much further away from the realization of a commercial power plant than magnetic fusion.

C.19. Why did the USA in 1997 adopt a fusion programme without deciding on a new fusion experiment and why did they withdraw from the ITER project ?

IPP	This question can certainly be answered in detail by Dr Decker. It should be pointed out, however, that the USA's decision to abandon a power-plant-oriented programme in magnetic fusion for the time being corresponds to the view prevailing in the USA that there will be neither a global energy crisis nor a global climate problem coming up. Thus, for example, Congressman James Sensenbrenner, former chairman of the House Science Committee, commented on the Kyoto climate protection convention: "The Kyoto Convention is based on incomplete scientific findings, costs too much, leaves

	too many procedural questions open, is grossly unfair since the developing countries do not have to participate, and will not solve the alleged problem of climate change."

C.20. How realistic is a participation of the USA, Japan and Russia in ITER-FEAT and in the whole ITER path including financing ?

IPP	We expect a participation of Japan in the construction and operation of ITER-FEAT. Discussions in the Japanese science public concerned above all the question of whether Japan will invite the partners to construct ITER in Japan. In Russia, ITER has a high ranking both in science and in research policy. Thus, for example, the Russian Federation provided services to the equivalent of approx. 150 M € during the design and development phase. For the construction phase, too, the Russian Federation promised a similar percentage contribution. Since it intends to provide these contributions above all in those subareas in which it has already demonstrated its capability during the development phase (e.g. provision of superconducting material), the technical quality and equivalent of these contributions is guaranteed. A participation by the USA is not envisaged at the current stage of planning. However, high US government officials repeatedly indicated that the withdrawal of the USA was above all caused by the slow progress in project implementation and that a definite construction decision by the ITER partners could induce the USA to join again. After the conclusion of an ITER contract, a partnership participation by the other countries is also to be expected in simultaneous programmes (materials development). It has not yet been discussed, however, whether these partners would also join in the further steps (DEMO). However, a successful cooperation during the construction and operation of ITER would certainly provide a strong stimulus for a continuation of this joint development with DEMO. It cannot be excluded, however, that the partner countries will go separate ways after DEMO to provide their national industries with greater starting advantages.

C.21. What significance should be given to the support of fusion research in the overall concept of a European energy research policy within the 6th Framework Programme for Research and Development ?

IPP	Since the catalogue of questions for the hearing was established, the first draft of the 6th EU Framework Programme has been published and presented to the ITER Committee of the European Parliament. In the Euratom part, a continuation of the European Fusion Programme is aimed at because "controlled nuclear fusion represents one of the options for long-term sustainable energy supply, especially for the centralized supply of base-load electricity." Furthermore, it is stated: "Since the activities for establishing a detailed design for the Next Step within the framework of the international ITER project are completed, a decision on the project start and construction of the device can now be taken. The exact modalities for the implementation of the project will depend on the result of the negotiations conducted at present within the framework of international cooperation and on its further developments." The prominent position of ITER in the draft of the 6th Framework Programme is due to a majority of positive opinions expressed by the EU research ministers at an informal meeting this January (see interview with EU Commissioner Busquin in "Die Welt" 22.02.2001). In parallel to the realization of ITER it is intended to continue the JET experiment while simultaneously preparing for waste management after its decommissioning. Research into magnetic confinement will also be continued from physical and technological aspects, however, generally above all at Wendelstein 7-X in Greifswald. For the fusion part of the Euratom budget a sum of 700 million euro including 200 million euro for ITER is earmarked. In the 5th Framework Programme 788 million euro were budgeted for fusion. Unfortunately, the sum of 800 million euro initially envisaged by DG Research was cut by 100 million euro on the initiative of EU Commissioner Schreyer (Agence Europe 21.02.2001). Other items in the Euratom budget mainly concern the topics of nuclear safety and waste management in the field of nuclear fission.

	In the thematic area "Sustainable development and global changes" of the 6th Framework Programme priority will be given, among others, to the fields of renewable energies, intelligent transport and traffic, fuel cells, hydrogen technology, photovoltaics, biomass and climate changes induced by environmental factors. As far as we are informed, 1.8 billion euro will be available. Added to this would probably be further expenditure by DG Energy and Transport on energy research programmes with short-term achievable goals to the amount of approx. 600 million euro in the same period. As a longer-term option for the future, thus, fusion will be adequately supported within the framework of the European energy research policy, although the reduced budget estimate (as of February 2001) may involve great difficulties for the non-ITER share of the fusion programme, above all for the activities at the national level, for example, in Garching and Greifswald. Such national fusion programmes will continue to be necessary, however, in order to carry out supporting experiments and integrate young scientists. The fusion research programme in Germany is by far the most successful in Europe.

C.22. Is it possible to incorporate ITER-FEAT into the 6th Framework Programme firming up the international organization structure, financial participation by the EU and the individual partners as well as the final siting of ITER-FEAT ?

IPP	This question was in part answered under C.21. A final firming up of the international organization structure, financial participation by the EU and the individual partners as well as the final siting of ITER-FEAT in the 6th Framework Programme will probably not be possible for reasons of time, although – as mentioned above – 200 million euro are already earmarked for ITER as the European contribution in the years 2003 to 2006. The negotiations with the ITER partners on a possible legal entity have not yet started and there is no concrete site offer as yet. However, the French CEA offered its Cadarache research centre in the South of France as the ITER site in July 2000. It is expected that France will propose to the EU countries

	in the course of the next months that Cadarache should be chosen as the European site. Japanese and Canadian site offers are also likely in the next 12 months.

C.23. What consequences would an abandonment of the new ITER large-scale experiment have for basic and applied research in the field of nuclear fusion ?

IPP	If the longer-term goal of an overall research programme – in this case ITER – does no longer exist, the field of activity will lose its dynamics, scientific work will stagnate and there will soon be no young scientists any more. Within a few years the experience, know-how and human potential in the field of nuclear fusion would disappear. An abandonment of ITER would have catastrophic consequences for the development of a fusion power plant. The later resumption of a power-plant-oriented programme as a response to a further growing global energy crisis would – if at all – only be possible with immense money and time losses. But also basic research would suffer from an abandonment of ITER, especially in Germany which may be regarded as a stronghold of high-temperature plasma physics. Although the fundamentals of plasma physics were evolved by classical physics in the 19th century, as in other scientific disciplines such as fluid dynamics or chemical reaction kinetics, there is currently great interest in the nonlinearity of the systems with which bifurcation, turbulence and chaotic behaviour can be studied. Due to the significance and complexity of these nonlinear systems, their study actually ranks among the most challenging physical research topics. (Richard Feynman, for example, called it the "most important unsolved problem of classical physics".) Within the framework of work on fusion research, high-temperature plasma physics has decisively contributed towards the understanding of such nonlinear phenomena and thus also stimulated work in other fields such as astrophysics or hydrodynamics. Apart from contributions to chaos theory, many examples of nonlinear instabilities were

	studied, which are of general interest due to their complexity (interaction of electromagnetic waves with electrostatic turbulence), self-consistency (nonlinear feedback of various parts of the system) and bifurcation phenomena. In order to quantitatively understand turbulent processes, extremely powerful computers are required, as have only been available for a few years. Fusion research has performed leading-edge work for the development of new numerical methods for the solution of nonlinear differential equation systems and the efficient utilization of supercomputers (massive parallelization). This impetus would be stopped by a desolation of fusion research. The same also applies to the development of mathematics and mathematical physics, to which plasma physics has also furnished decisive contributions such as the development of the Lagrange field theory (gyrokinetics), the theory of complex functions (Landau damping) or differential geometry (for the description of the complicated geometry of magnetically confined plasmas).
FZJ	• The time at which nuclear fusion can contribute to energy supply would inevitably be shifted significantly. • Demotivation of a generation of researchers and associated loss of know-how. • Fusion research would lose its technological impetus; withdrawal to basic research would be the consequence. • Leaving technical progress to Korea, China and India and an associated credibility loss of the industrialized countries with respect to their sense of responsibility and will to solve the world's energy problem.

C.24. What is the ratio of research funds used to the success expected in comparison with other research priorities ?

IPP	Controlled nuclear fusion is considered to be a task of national precaution research because it will only represent an important option for global energy

	supply in the base-load range in the second half of our century. Before it is clear whether this option is needed, it is not appropriate to contemplate on price/performance ratios in an issue vital for the future of mankind and in view of unreliable forecasts. Added to this, it is nearly impossible to obtain reliable figures on the financing of other priorities in energy research or the market introduction of new energy forms in other countries (for fusion, in contrast, the figures are relatively well known worldwide, see answer to question C.4.). It should be noted that at present the expenditure on fusion research in Germany accounts for approx. 7 % of national energy expenditures (research plus subsidies) and even less than 2 % if the subsidies for the domestic hard coal industry are included.
FZJ	What type of success is to be compared here? If it is a matter of developing a completely new primary energy source, the realization of nuclear fusion would be an <u>unrivalled</u> success since all competing primary energy sources (e.g. Renewables) have long been developed and many more or less far developed conversion technologies are available for them. The exploitation of deuterium (water) and lithium (rock) – the actual fuels of nuclear fusion – as a new long-lasting, clean primary energy source available to everybody would represent a quantum leap in the energy supply of mankind, only comparable to the discovery of coal, oil, gas or uranium as energy sources.

C.25. What does a decision in favour of ITER mean for the priorities and scope of German energy research ?

IPP	ITER creates a clearly power-plant-oriented priority and strengthens European – and thus also German – energy research. The scope of a future ITER-related fusion programme – if the question refers to the financial consequences for Germany – will not change significantly so

	that the consequences for the scope of German energy research will also be moderate. Direct German financial participation in ITER is not expected. However, consequences for all national research centres in Europe must be expected. Their extent will depend on whether ITER is realized in France, Canada or Japan. With the exception of the stellarator programme concentrated in Greifswald, the IPP will increasingly engage in preparatory work for ITER. This also applies to the medium-sized ASDEX Upgrade tokamak whose configuration is reflected in the ITER design and which will gain increased significance as the largest European experiment after closing down the joint European JET experiment in Culham, Great Britain.
FZJ	If the budget for fusion research remains more or less the same, as is hoped, and with an otherwise constant total budget for energy research, there would be no consequences for research areas outside fusion. A more precise analysis must be carried out to determine the influence of the siting of ITER-FEAT on the total budget.

C.26. What would be the influence on the development of the Renewable Energies and climate protection if the funds earmarked for the ITER path were additionally available ?

IPP	This question should be answered in two parts. First of all, it should be assessed what impact the funds of fusion research could have on shaping the energy supply. In studies by the World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA) it has been estimated that about US$ 34,700 billion (1990 US$) are invested in energy supply in the period between 1990 and 2050 [24]. If instead of the investments flowing primarily into fossil energy carriers in this scenario, renewable energy carriers are supported, much more money would have to be raised if the same energy demand should be covered. The funds

	for fusion in this period amount to about US$ 50 billion – much too little for a marked modification of the energy system. Concerning the second aspect of the question: What would be the consequences for humans in the future if one option of electricity supply had not been developed? Probably higher energy costs and less flexibility. Fusion also differs clearly from most renewable energy technologies in that fusion power plants can fit without problem into the existing energy supply structures. Quite generally it should be stated that German economy is in a position to develop a variety of future energy technologies simultaneously, which is demonstrated by the great support of energy research in the early eighties. The competition between different technologies in the future will reduce the costs more significantly and relieve our economy more than it is burdened by funding. On the international financial markets, the fact has long been known that options can also have a high value, and this should also gain entry into research policy. The considerable cost reductions in telecommunications should be an example of how competition is to the benefit of all people.
FZJ	• The concentration of the financial resources on specific options and the exclusion of others (e.g. fusion) involves a risk with respect to solving the global energy problem and is therefore imprudent. • Every option must be adequately pursued. • The global energy problem, which will dramatically expand in the future, requires responsible and adequate research. The expenditure on energy research and subsidization allocated to the price of electricity in Germany today provides about the following picture: fusion 0.06 pf/kWh (with EU) / EEG 0.2 pf/kWh / coal subsidy 1.5 pf/kWh. *see also D.6. and D.9.*

Industrial Policy / Utilization / Spin-Offs

C.27. What expectations do you have concerning the development of key technologies by fusion research ?

IPP	Many key technologies have already profited from developments in European fusion research. This progress is due to the pressure on fusion research to develop the technologies in many areas up to their limits. Examples are: - the production of steels with very high specifications, which practically do not have any imperfections - the production of novel carbon-fibre-reinforced carbons of high homogeneity and thermal conductivity, but at economical prices - the near-net-shape processing of high-purity beryllium components to achieve savings in material and in costs - the development of the most powerful cryopump ever built with a pumping capacity twice as high as that of earlier pumps and the highest trapping coefficient ever achieved (47 % of the theoretical value of a black hole) - the development of flexible cryopipes for the transport of liquid helium with lower losses than hitherto achievable - for radiofrequency heating systems new high-performance tetrodes and new coaxial transmission lines for high operating voltages were produced in cooperation with industry. One of the essential goals of the industry involved in the construction and operation of JET was to gain experience with respect to planning, quality and quality control. The expectations for ITER would be similar. The very stringent specifications and the strict control of product and time schedule have forced many companies to introduce completely new forms of organization and new procedures to fulfil the requirements imposed.

	However, these changes have led to improvements in production and production control allowing those companies to enter the world market in fields in which they were not competitive before. The branches of industry benefiting from this situation are very widespread and comprise many high-technology enterprises at the leading edge of the European technology industry.

C.28. What importance do you attach to the utilization of findings from fusion research by the German and European industry ?

IPP	This was described under C.27.

C.29. What spin-offs do you expect from the ITER experiment ? Should such possible synergies be selectively supported ?

IPP	In detailed studies, four classes were identified for the benefit resulting from basic research, as is also represented by the ITER experiment [24]: • the possibility of discoveries of great economic and practical significance, • equipment and techniques also useful in other fields and stimulating the industry, • education • contributions of cultural significance. All four classes increase the prosperity of society and can therefore be classified as spin-offs. Many studies show how expenditure on basic research leads to discoveries of high economic and practical significance, which are very profitable and rapidly pay for themselves [25–27]. Most of these spin-offs are unexpected; there is often a prolonged delay between fundamental discovery and use. It is therefore not possible to specifically plan spin-offs and/or encourage their "production". However, the early identification of possible spin-offs and their selective support is also a strong recommendation by the CFI (a committee advising the European Commission on industrial matters of fusion research), which is

accounted for by the introduction of suitable structures.

Moreover, it is to be doubted that the presentation of long spin-off lists can be regarded as a justification for high future expenditures. Such lists have been drawn up in many areas of research, among others, in elementary particle physics (CERN), in space research (ESA, NASA) and also in the field of fusion research (JET, DOE Office for Fusion Research). A justification on the basis of expected spin-offs, however, is not possible since it is difficult to quantify the coming economic benefit. It would also have to be analysed what benefit would have been achieved if this money had been spent otherwise. On the other hand, it may be assumed, however, that the expenditure of similar sums in different high-technology areas produces similar levels of spin-offs. The fact that fusion research requires very complex, specifically developed instruments in various technological areas makes it so to speak destined for the generation of spin-off products.

Due to the demand for products whose properties are at the limit or beyond the respective state of the art, large-scale research in general plays an important role in stimulating the industry. Various studies have attempted to quantify this effect [28–30]. For this purpose, the authors use the quantity of "economic utility" = "sales increase + cost savings (for high-technology contracts)".

With the data provided by industry (and not by CERN or ESA) an "economic utility" of 3.0 was obtained for the contracts awarded by CERN, i.e. for every euro CERN pays to industry the latter generates 3 euro [28–30]. Normalized to the total CERN budget this gives a value of 1.2. In another study (again normalized to the total budget) a value of 1.6 was obtained for ESA [31,32].

Research for the next generation of fusion experiments provides excellent training and working opportunities for scientists and engineers in applied research, technology development and industrial management. The constant urge to extend the technological capabilities together with the highest quality and precision requirements and with the pressure of an industrial

	environment creates an exceptional environment for scientists and engineers. This experience is ultimately also to the benefit of industry.

C.30. What branches profit in particular from the ITER experiment ?

IPP	Among others, the following branches of industry will above all profit from ITER: - mechanical engineering - cryotechnology - vacuum technology - electrical engineering (high-performance technology, control technology) - materials technology - superconduction - robotics and remote-handling technology - geodetics - semiconductor and detector technology - software development - "virtual reality" - information technology - safety technology - safeguards technology

C.31. What advantages would ITER in Europe have for the European industry ? What significance has a European ITER site for Germany's future competitiveness in research and industry ?

IPP	Irrespective of the site selection it may be safely assumed that the European industry would succeed in obtaining a considerable portion of the contracts for ITER high-technology components. A European site would additionally strengthen the competitive position of the European industry and also provide it with the special know-how on the construction and operation of a fusion experiment.

- A particular strength of the European industry is the integration of different technologies. This is also the greatest challenge for a fusion power plant, and ITER will be new and different from previous high-technology projects concerning its requirements. In this field, the host has a great advantage since he can best pursue the simultaneous development of different subsystems. Moreover, there is a strong connection between systems integration and the licensing procedure which must be handled in close and effective interaction with the local authorities. The resulting competitive advantage of "local" consortia is evident.

- Although the fabrication of individual components can take place far from the ITER site, the industry also gains a great deal in connection with such new systems from the combination of manufacturing experience and observation and analysis of the operating performance. This provides a great advantage for the industry of the host partner. Especially in Japan there exists already a strong interaction between the government authorities and large industrial firms, which would make it very difficult for the European industry to obtain similarly good access to all necessary details of operating experience.

- Within the framework of licensing, all ITER components will have to be qualified according to the standards and codes of the host partner. Whereas these criteria will be largely the same everywhere concerning their technical aspects, in the case of siting ITER in Japan, the formal aspects would mean additional effort for the European subcontractors. This experience would, moreover, not be directly transferable to Europe later. In the event of a European site, the interaction with the licensing authorities would be of great significance for the future development.

- The total infrastructure (buildings, power supply, cooling etc.) will be provided by the host partner integrating the "local" industry. This provides these enterprises with the competence necessary to later construct

	complete power plants within a reasonable time.

C.32. What consequences would the realization of ITER in Cadarache (France) have for the other European fusion research institutions ?

IPP	The financial constraints will require an extensive reorganization and reduction of the remaining fusion activities. However, this would also be necessary for a construction of ITER in Japan or Canada. We expect that a continued operation at least of one medium-sized tokamak device in Europe is necessary during the ITER construction phase in order to keep the operational know-how for the tokamak alive, train young people and be able to test conceptual improvements as well as new theoretical models. ASDEX Upgrade is very suitable for this purpose, since the device has been constructed relatively recently and – on a smaller scale – equals ITER. During the ITER construction phase, the associations will, moreover, be concerned with setting up the diagnostics and heating systems of ITER. After the commissioning of ITER we expect that the associations will play a role similar to that of the European research institutes at CERN. Teams will be delegated to the ITER site for limited experimental campaigns; after their return, they will work on the evaluation of the results and the comparison with computer simulations. This form of operation is currently already practised at JET and has proved very successful for the scientific utilization of the machine. Future progress in data transmission will, moreover, also enable an effective participation in ITER experiments from the sites of the individual associations.

C.33. What can fusion research contribute in the next decades towards promoting the competitiveness of Germany and of the EU ? Is it possible to assess the extent to which the competitiveness of Germany and the EU would decrease if these funds were saved in other energy research, nanotechnology or biotechnology ?

IPP	In questions C.29. and C.31. the positive effects for the European industry

	and the strengthening of its competitiveness were described in detail. Especially a European ITER site would mean great advantages for the whole European high-technology industry. Quite generally, the long-term development of fusion as one of the few options of CO_2-free and sustainable energy supply should decisively contribute to the competitiveness of Germany and the EU.
FZJ	The primary aim is to solve the global energy problem which will become dramatic in the course of the century. In the second place, competitiveness according to the then valid boundary conditions must also be given. *See also C.24. and C.26.*

C.34. In Germany there are about 30,000 jobs in the field of Renewable Energies as well as, on estimate, a few hundred fusion researchers. Is it possible to approximately estimate how these two figures would change if the funds which Germany had to raise for the ITER path were to flow into either of these areas ?

IPP	Strictly speaking, roughly 1,500 staff members are concerned with fusion at the IPP, FZ Jülich and FZ Karlsruhe research centres as well as at several universities. Added to this are on estimate the same number of jobs in subcontractor and service functions. These jobs are especially important in the eastern part of Western Pomerania where unemployment is currently over 20 %. The fact that there are ten times more jobs in the field of the Renewable Energies reflects the fact that the state spends ten times more money on research and subsidies for other forms of energy. Mention should also be made of the subsidy of DM 8 billion paid to the German hard coal industry, which creates even more jobs, but this is a somewhat unproductive discussion! On the whole, question is misleading because it implies that there would be a direct financial participation of Germany in ITER. There is only an indirect participation through the 26 % payment by Germany into the EU budget (see

	C.10.) The question of whether funds earmarked for ITER could flow into the Renewable Energies, if ITER were not approved can be answered by the example of the fusion budget in the first draft of the 6th Framework Programme: The cut of 100 M euro initiated by EU Commissioner Schreyer flows back into the total EU budget; it is of no benefit to the research budget.
FZJ	The primary goal of fusion research is to provide a completely new energy source as a further option for the solution of the world's energy problem. Economic competition and jobs are initially secondary, all the more since only future generations will decide on the integration of fusion in the energy mix under the then valid economic, ecological and global policy boundary conditions. The jobs created in Germany in the field of the Renewables are primarily due to subsidies and hardly to research in this field. The construction of ITER-FEAT in Europe with a total investment of approx. € 3.5 billion, which will be raised by the EU, Japan and Russia, would also create many new jobs. The construction of ITER-FEAT would be borne by the industry. A European industrial consortium, EFET, composed of Ansaldo (I), Belgatom (B), Framatome (F), Ibertef (Sp), Fortum (Fin), NNC (GB) and Siemens (D) is closely integrated into the design of the next large machine even today.

D. Future Role of Nuclear Fusion in Energy Supply

Leading question:

D.1. How does nuclear fusion fit into future supply and consumption structures ?

IPP	Nobody can say today with certainty how the supply and demand structures will develop in future. The most diversified developments are conceivable. It is therefore reasonable to prepare for the potential diversity of challenges with many different options. Nevertheless, a clear increase in global energy demand can be predicted for several reasons. First of all, the world's population will considerably grow to nine, ten, or even twelve billion people. Secondly, most people are living today under very modest or completely unacceptable social and economic conditions. If all these people – and this should be everyone's desire – wish to participate in prosperity, a significant increase in energy demand must be expected. India alone is likely to increase its energy consumption sixfold during this century and a similar statement can be made for China, to say nothing of many countries in Africa. At present, about 90 % of the energy demand is covered from fossil energy carriers. There is every reason to believe that this high share of fossil energy carriers in energy supply will still be maintained for several decades because there are fixed energy supply structures in the industrialized countries which only change slowly; in the threshold and developing countries the shortage of capital makes it necessary to implement the cheapest solution. This means – at least for India and China – the intensive use of domestic coal. However, for the well-known reasons of climate change, scarce resources and avoidance of geopolitical conflicts, the energy supply must be converted in the long run away from fossil energy carriers. Fusion is an important option here, especially because it excellently fits into the existing supply structures: wherever there is a large coal, gas or nuclear fission power plant today, a

	fusion power plant can be constructed in the future. Lithium and deuterium will only be consumed in such small quantities that fuel supply will not pose any problem. Apart from these general remarks, reference should be made here to a very detailed study by the Dutch energy institute ECN [17]. In this study, the question was raised as to the conditions under which fusion – provided that it exists in the year 2050 – may find entry into the European energy market. The answer was that fusion is needed if the emission of greenhouse gases is to be markedly reduced and nuclear fission will not be further expanded.
FZK	Statements on future supply and consumption structures are highly speculative. On account of its particular properties, nuclear fusion is particularly suited for the production of electricity in base-load operation. Nuclear fusion plants therefore fit into major interconnected grids which are being continuously expanded. A particular demand will arise in future for the supply of regions of high population density. Global population growth is expected to lead to a strong increase of urban regions with population figures of over 10 million inhabitants. In total, a 2- to 3-fold higher electricity demand is expected worldwide by the end of the century in comparison to the present situation[1)]. On a global scale, fusion energy can complement solar energy and other sustainable energy supply structures which, on their part, present advantages in the supply of regions of low population density. However, fusion power plants can also be used for the generation of process heat, for seawater desalination, for the exploitation of raw materials and in combined-cycle plants (cogeneration). [1)] *Source: Global Energy Perspectives, IIASA/WEC, 1998*

	(see also D.3.)
FZJ	For physical reasons, fusion power plants only have a positive energy balance above a certain minimum size, i.e. there will be no small fusion power plants. The typical power class will be in the range from 1 GW to 1.5 GW electric and thus be comparable to present-day conventional large power plants which essentially contribute to the base load in a largely interconnected electricity supply system. It is to be assumed that interconnected electricity supply will also play an important role in the future, especially for the Renewables whose local unsteadiness can only be compensated by the balancing effect of the grid. In fusion research there are approaches to smaller compact fusion plants. The prospects for the success of these development lines which, at best, could lead to halving the plant size are still very uncertain (e.g. tokamak scenarios with internal transport barriers, which can also be tested in ITER-FEAT, or the spherical tokamak). It appears impossible to ever use fusion reactors also for decentralized supply.

Further questions:

Electricity Market

D.2. Can a fusion reactor economically produce electricity under the boundary conditions to be expected (supply, demand, deregulated markets, costs of environmental protection) ?

IPP	Economic efficiency can always only be defined within a specific regulatory framework. We assume for the future that the external costs will increasingly be incorporated in the direct costs, whether through taxes or other regulatory tools such as environmental standards. This will make conventional energy technologies more expensive. In addition, on a medium- and long-term basis, only those technologies will be applied which do not emit greenhouse gases.

	In such a regulatory framework, fusion will certainly find its economic place, as was demonstrated in a study [17] by the Dutch energy institute ECN. Other studies in Japan [34] and the USA arrive at similar conclusions.
FZK	This question can only be answered today as a trend. Added to the considerable difficulties in predicting future boundary conditions are problems in determining, assessing and allocating the external costs, which also include the expenditure for infrastructure measures and environmental protection. Initial studies show that the cost of electricity production in fusion plants compares well with that of other future energy carriers if direct and external costs are taken into account. *References: T.C. Hender, P.J. Knight, I. Cook, Fusion Eng. and Design, Dec. 1996* *STOA report on "Operational Requirements of a Commercial Fusion Reactor" PE 166.793/Final, EU Parliament, Luxembourg, Dec. 1997*
FZJ	Reactor studies predict electricity costs of approx. 15 pf/kWh, which is naturally affected by uncertainties in view of the lack of a detailed reactor design as yet. If this target value is reached, fusion would range at a level about twice as high as present-day conventional electricity producers (coal, gas, nuclear fission) and approximately equal to wind power. It must be assumed, however, that fuel prices will significantly rise in the course of the century. Depending on price increase and cost share of the fuels in electricity costs (at present, gas approx. 40 %, coal approx. 20 %, nuclear approx. 13 %, fusion approx. 0.7 %), electricity costs from fusion will then be able to adjust to those from the other energy carriers. Additional changes in boundary conditions difficult to predict at present, such as • strict global restriction of CO_2 emissions, • drastic increase in the prices of coal, gas, oil, uranium due to geologically or politically induced scarcity • restricted access to certain raw materials (political crises),

	would make the advantages of fusion very apparent.

D.3. What power will a fusion reactor have and how does this potential fit into a future structure of energy supply ?

IPP	ITER should – in a first design – reach a thermal power of 1500 MW. A power plant based on this design would produce an electrical power of about 500 MW. In most power plant studies, electric power levels from 1000 to 1500 MW are assumed. Conventional coal, gas and nuclear power plants are of similar unit size. Fusion would thus fit well into the existing system of electricity supply.
FZK	Fusion power plants according to present-day concepts are larger units in the range from 500 to 2000 MWe. Such units fit well into existing and constantly expanding grids. A large proportion of future plants will have to supply conurbations whose number and size continue to increase worldwide. This will be an adequate and necessary supplementation of a decentralized energy supply for which some of the renewable energy carriers are suited. (*see also D.1.)*
FZJ	*see D.1.*

D.4. What share in the electricity market is expected for fusion reactors in 2050 and 2100 ?

IPP	As already mentioned under question A.2., there will be no fusion power plants before 2050. According to a study by the Dutch research centre ECN [17] it is expected that fusion will cover about 20 to 30 % of the European electricity demand in the year 2100. Similar values are specified in Japanese studies.
FZK	Nuclear fusion is an investment for the more distant future. The availability of nuclear fusion is an essential back-up of future long-term planning. In 2100

	nuclear fusion can already contribute significantly to base-load electricity supply, in particular, where corresponding grids for feeding in are available.
FZJ	*See D.2.*

D.5. With what energy carriers would nuclear fusion mainly compete in the decades 2050 ff ?

IPP	The main competitors of fusion are coal and nuclear fission. This is also a result of the work [17] by the Dutch energy research centre ECN. Whereas a strong growth of coal or nuclear power plants would prevent the expansion of fusion, fusion and Renewables develop in parallel, which is explained by the considerably different characteristics of these technologies. Fusion will primarily contribute to the base load, for which wind and solar power plants are not suitable due to their intermittent power output as long as there are no storage systems of high capacity available.
FZK	In view of the emergence of global deficiency and the greatly differing conditions in the individual regions, it will be hardly possible to speak of competition. Nuclear fusion would rather be an important supplementation of other energy carriers (e.g. solar power).
FZJ	The primary goal of fusion research is to provide a completely new energy source as a further option for the solution of the world's energy problem. Its application within the energy mix will be decided by future generations under the then valid economic, ecological and global policy boundary conditions. *See also D.2.*

D.6. Is nuclear fusion necessary at all in view of the fact that recent studies (e.g. LTI Research Group: Long-Term Integration of Renewable Energy Sources into the European Energy System, Heidelberg 1998) consider a 100 percent coverage of the energy demand in Europe to be possible from Renewable Energies by the year 2050 and that on the other

continents the potential of the Renewable Energies is even greater in most cases ?

IPP	The results of the LTI study presuppose that humans will considerably change their lifestyle. Phrases such as: *"The world of the Sustainable Scenario is, thus, not characterised by having more but by feeling better off"* sound good, but are not likely to be approved by a majority of people in practice. In particular, many young people are very consumption-oriented today. In a study [5] prepared by the IPP together with the Academy for Technology Assessment in Baden-Württemberg, especially young people did not consider energy saving to be an acceptable option. If, therefore, the LTI study claims that there should be no inner-European air traffic in 2050 any more and the maximum speed for trains should be restricted to 200 km/h and for cars to 100 km/h, this is theoretically conceivable but practically not very likely. The study, moreover, does not assume that new appliances could be installed in households. The list of items (page 66 Table 2.7) consuming energy in households does not even comprise a computer as an electricity consumer. But especially the development of new appliances has led to a continuous increase in electricity consumption in the past. Only on the basis of these and similar assumptions that are more than questionable does the LTI study then succeed in reducing the energy demand by 63 % up to the year 2050. The benchmark is thus not set high for the Renewables all the more since the anticipated cost reductions for photovoltaics and solar heating are very optimistic. But the assumptions made in describing the energy supply are also rather questionable. In spite of BSE it is not very likely that people in the long run will really reduce their meat consumption and thus create more space in agriculture for the cultivation of biomass. Since the occurrence of most prerequisites of the LTI study is highly improbable, it would be presumptuous to base future planning on this study

	alone. The mendicant friars' sermons in the Middle Ages about the pursuit of happiness in a simple and poor life were only obeyed by a few people even then.
FZK	Nuclear fusion has prospects within the framework of global energy supply. The forthcoming climate change, a progressive scarcity of affordable raw materials in conjunction with a considerable further rise in global energy demand require an availability of processes that can be adjusted to the respective situation. A creation of island solutions increases the differences between the world regions with the consequence of political and social tensions. A conversion of Europe's total energy economy to Renewable Energies up to 2050 without considerable repercussions on the standard of life – if technically feasible – is not very realistic.
FZJ	The answer is oriented towards the assessment criteria for the development and (later) use of energy technologies. In addition to the "official" target triangle (economic efficiency, security of supply, environmental compatibility; Energiedialog 2000) there will be further criteria such as the conservation of resources, quality and reliability from the consumer's perspective, resilience to political supply disturbances, social and international compatibility (Forum 1997), all under the overall concept of "sustainability". Furthermore, there are also current political boundary conditions to be observed such as competition and globalization as well as the medium-term goal of an energy supply without subsidies (Energiedialog 2000). The Renewable Energies have problems in Europe (and not only here) with satisfying all these aspects although a contribution increase from 6 % today to 12 % primary energy until 2010 in the EU is the political goal (EC 2000). Those studies which advocate sole regenerative energy supply within a few decades for Europe do not observe some of the above criteria, especially (international) competitiveness as well as the limited (private) willingness to pay for energy.

The following should be borne in mind to justify fusion research:

From the present perspective, precautions should be taken for a new "workhorse" that will be needed after about 2050 for electricity supply because

- large amounts of base-load current will probably be needed (industry, conurbations),
- fossil contributions will probably be greatly reduced due to the climate endangerment (and possibly also due to other environmental or resource reasons),
- nuclear (fission) energy may no longer be sufficiently accepted,
- domestic (German, possibly also EU-wide) supply by the Renewables is not thought to be sufficiently capable (insufficient exploitable potential perhaps also including efficient energy utilization in the long term),
- predominant electricity supply from non-EU regions ("electricity import") may be politically mistrusted so that any strong dependence on such supply is not acceptable).

Sources:

EC 2000: European Commission: Brochure "Energising Europe", European Communities, 2000

Energiedialog 2000: Energiepolitik für die Zukunft. Leitlinien zur Energiepolitik, Schlussdokument – Energiedialog 2000, Friedrich-Ebert-Stiftung, Berlin, 5 June 2000, ISBN 3-86077-918-4

Forum: Forum für Zukunftsenergien: Langfristige Aspekte der Energieversorgung, Folgerungen und Kriterien für die Energiepolitik heute, Bonn, February 1997, ISSN 0944-6753, ISBN 3-930157-30-6

D.7. Can nuclear fusion compete with renewable energies which, even today or in a few years, involve the electricity production cost of less than 15 pfennigs/kWh expected for fusion in the year 2050 ? In case Renewable Energies should not cover total energy demand in the future either, would modern coal power plant technology with CO_2 emission (cf. the USA's clean coal strategy) e.g. not be a less expensive alternative to nuclear fusion ?

IPP	Yes, because the comparison of different energy carriers cannot be done via the energy costs alone. In fact, the consumer demands power from the electricity grid in the form of a defined amount of energy at a defined time interval. In the case of wind and solar power, however, there may be considerable differences between power demand and power supply, which have to be covered by extensive storage or back-up capacities. This involves considerable costs. But irrespective of this aspect, especially in the case of photovoltaics it is still completely unclear whether it will ever supply electricity at costs of 15 pf/kWh; in any case, present costs are higher by a factor of 10. The comparison must be made on the assumption of a defined load demand. This was precisely done in the study [17] by the Dutch energy research institute ECN. And although a considerable cost reduction was assumed here, for example, for photovoltaics, fusion was able to win considerable market shares. Advanced coal-fired power plants with CO_2 separation and storage represent a competition for fusion. However, these technologies will substantially increase the cost of electricity from coal so that competitiveness will be reduced. Moreover, this technology cannot be applied without scruple because safe storage must be ensured for CO_2. Many experts doubt whether storage in the ocean is possible. Although this technology is taken into account in the study [17] by the Dutch energy research institute ECN, fusion (whose electricity generating costs will amount to approx. 12-20 pf/kWh according to present studies, as described in C.2.) achieves a high market share. Moreover, a factor speaking against the further use of fossil fuels, as

	proposed in the question, is also their limited availability and high raw material value.
FZJ	• Coal has limited resources in comparison to fusion. • Sustainable CO_2 storage at acceptable cost has not yet been demonstrated. *concerning competitiveness see also D.5., D.6. and D.2.*

D.8. What other significant novel alternatives to nuclear fusion are under discussion for future energy supply ?

IPP	A detailed answer to this question would exceed the scope of this comment. We therefore refer to the relevant literature. An extensive reply to this question can be found e.g. in the study "Energy technologies for the 21st century" of the International Energy Agency (IEA) in Paris [35].

D.9. Will other essential potentials for future energy supply be neglected by investments into nuclear fusion ?

IPP	First of all, the question arises of whether the budget for energy research is a "natural constant". In fact, the budget for energy research has significantly varied in the last two decades, decreasing from a very high value in the eighties to low values today. The question, therefore, is not whether the energy technologies compete with each other but why the important topic of energy research is equipped with such low national funds. In its recommendation [23] the Science Council arrives at the conclusion with respect to energy research that this field should generally be equipped with significantly more funds; cuts in the field of fusion research, for example, are not recommended. A joint comment [36] by leading energy researchers in Germany also comes to a similar result. The expenditure on fusion thus does not only compete with other expenditures on energy research but should be regarded in proportion to all

	government expenditure including, for example, domestic hard coal funding with 8 billion DM/a. Other potentials for energy supply are only neglected if energy research in general is not adequately funded.
FZJ	If displacement effects between the different energy research areas were to arise concerning important aspects, the total budget for energy research would be too low. Political responsibility must keep all important options of energy supply open for succeeding generations and conduct appropriate research adapted to the existing research potential.

D.10. Enormous energy consumption increases will occur especially in countries of the Third World. What contribution can fusion energy make to cover this increase in the developing countries ? Do you believe that the implementation of fusion power plants in the Third World is an alternative to coal, oil and Renewable Energies which the population in these countries can afford ?

IPP	The increase in energy consumption during the last 30 years was caused for the major part by the fact that less developed countries became highly developed countries. Japan, South Korea and Malaysia can be named as examples in chronological sequence. Their energy demand increased with rising prosperity. In parallel, a society has developed with the potential for introducing advanced technologies. It may be expected that this trend will continue and that the majority of people with a European standard of living will consume energy on a European scale and will have an expertise in handling advanced technology on a European level [24]. There are thus neither financial nor know-how problems in covering the large energy increase expected for the threshold countries at least in part by fusion energy.
FZK	The forecasts assume a demand for electricity that will be twice to three times as high in the 2nd half of the century as present electricity production[1)].

	The demand will be coupled to an also greatly increasing economic output. Consequently, the term of Third World, as it is understood today, will then only be applicable to a few regions. It is a matter of experience that for an efficient national economy it is first of all necessary to invest a relatively large portion of the GDP into the energy sector [1)]. Availability, price and – if not already allocated to the price – follow-up costs will determine the energy mix that will be available in future economic areas. Taking the restrictions on the individual energy uses into account, nuclear fusion can definitely be an important alternative. [1)] *WEC/IIASA study, Global Energy Perspectives, 1998*
FZJ	The increasing energy demand in the course of the century is caused by the transition of many Third World countries to a standard of living which adjusts more and more to that of Western industrialized countries. Such an increase in the standard of living will proceed hand in hand with an improvement in education, infrastructure and generally in the use of high technology. *concerning affordability see D.2.*

Climate Protection

D.11. The Study Commission "Protecting the Earth's Atmosphere" has considered a 50-percent reduction of CO_2 emissions until 2020 and an 80-percent reduction until 2050 as necessary in Germany. What percentage of CO_2 emissions can be saved by nuclear fusion in this century ?

IPP	The goals and conclusions of the Study Commission "Protecting the Earth's Atmosphere" are shared by us and should be guidelines for energy and environmental policy. Nevertheless, the goals are ambitious and it is by no means ensured that they will be fulfilled. Research policy should not least open up a further option by promoting fusion, also in the sense of an insurance against imponderables of future developments.

	Until 2050 fusion as planned today will not contribute towards reducing CO_2 emissions. Of course, the development of fusion could be accelerated – ideas [37] how to proceed directly from ITER to a power plant are being discussed. Certainly (as discussed in answer A.2.), the political will to rapidly develop fusion is decisive. The earlier and the more determined the construction and support of ITER, the earlier the contribution by fusion to reducing greenhouse gases. The study by the Dutch energy research institute ECN [17] shows very clearly, however, that fusion wins most market shares where the required reduction of greenhouse gases is the strictest. In this respect, fusion cannot be considered separately but must be seen in connection with other possible savings technologies. In the short and medium term, for example, savings of CO_2 emissions are possible through replacing coal by gas since the specific emissions of gas are much lower than those of coal. Added to this, gas-fired power plants have higher efficiencies today than coal power plants. In the second half of this century, however, it will be necessary to replace the gas-fired power plants, and fusion is a suitable option. The significance of an option such as fusion becomes even more apparent on a global scale. In countries such as India and China, coal-fired power plants will be built almost exclusively in the next decades and planning can hardly be changed any more. Power plants and infrastructure are designed for lifetimes of 30 to 40 years. DEMO will then just start to supply electricity. Added to this is another aspect. The significance of electricity as an energy carrier will increase more and more strongly. This development is unbroken in all regions of the world. If, therefore, fusion will successfully cover 30 % of the electricity supply in the year 2100, it will thus secure the base load replacing the most important energy carrier by that time.
FZJ	Nuclear fusion can only contribute to the reduction of CO_2 emissions in the second half of this century. How fast nuclear fusion can then contribute

	towards electricity supply will also depend on economic, ecological and global policy boundary conditions.

D.12. Carbon dioxide emissions worldwide will increase by approx. 70 % until 2020 according to the International Energy Agency, above all due to the developments in China and other threshold countries. What contribution can fusion energy make until 2020 to slow down this increase ? What contribution do you expect until 2050, until 2100 ?

IPP	Nuclear fusion can only make a contribution when it is fully developed, that is to say after 2050. Nevertheless, this contribution is of great significance for two reasons: On the one hand, an increase in global electricity consumption is also to be expected after 2050. Reference should be made here to the global studies by the World Energy Council (WEC) together with the Institute for Applied Systems Analysis (IIASA) [24]. On the other hand, part of the reduction of greenhouse gases will be achieved in a cost-optimized manner with short- and medium-term interim solutions, especially by substituting gas for coal. The use of gas will then have to be replaced again, and fusion is an adequate option here.
FZJ	*see D.11.*