THE NET PROJECT
An overview

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Abstract

THE NET PROJECT: AN OVERVIEW.

The objective of NET is to demonstrate fusion energy production in an apparatus which meets the basic design and operating requirements of a reactor, i.e.: self-sustained DT thermonuclear reactions; extended burn, possibly up to steady state; qualification and testing of components in reactor-like conditions; safe operation of a reactor-like device at significant availability; and energy extraction of high temperature heat and tritium breeding. Since NET is conceived to be the only step between JET and DEMO, it must be capable of conducting a research programme in physics as well as in reactor technology. This requirement has led to an apparatus designed to operate, in the first phase (Physics Phase), with great flexibility with respect to the accessible plasma parameters. NET adopts, as far as possible, reactor relevant technologies (e.g. superconductivity), and it includes provisions and features (e.g. remote handling, access, shielding) which would enable it, in the second phase of operation (Technology Phase), to carry out a programme of qualification and testing of components. NET will be the machine in which the physics and the technology of extended plasma burn pulses will be established. The flexibility of the apparatus therefore allows the incorporation of improvements between the two phases, in particular of the plasma facing components. As for the parameters, two sets have been defined: a reference set to carry out the predesign and to define in sufficient detail the R&D tasks to be performed by the European fusion laboratories, and an alternative set with increased plasma current capability based, however, on the same design solutions and technologies as the reference case.

1. INTRODUCTION

The European strategy towards the demonstration of electrical energy production by thermonuclear fusion includes three main milestones:

— In the long term: to demonstrate that the production of electrical energy from fusion is environmentally attractive as well as technically suitable to utilities and has the potential to become economically competitive (demonstration reactor, DEMO);
— In the medium term: to demonstrate the feasibility of fusion with respect to both physics and technological aspects (Next European Torus, NET);
— In the short term: to establish the scientific and technological basis for NET (JET, new specialized tokamaks; technology programme).

2. OBJECTIVES OF NET

The NET objective is to demonstrate fusion energy production in an apparatus which meets the basic design and operating requirements of a reactor, i.e.:

- Self-sustained DT thermonuclear reaction;
- Extended burn, possibly up to steady state;
- Qualification and testing of components in reactor-like conditions;
- Safe operation of a reactor-like device at significant availability;
- Energy extraction of high temperature heat and tritium breeding.

3. GENERAL DESIGN REQUIREMENTS

Since NET is the only step between JET and DEMO it must be capable of conducting a research programme in physics as well as in reactor technology. This requirement has led to an apparatus designed to operate, in the first phase (Physics Phase), with great flexibility with respect to the accessible plasma parameters, in particular the plasma current. Furthermore, this apparatus should adopt, as far as possible, reactor relevant technologies (e.g. superconductivity) and include provisions and features (e.g. remote handling, access, shielding) which would enable it to carry out, in the second phase of operation (Technology Phase), a programme of qualification and testing of components. The plasma parameters will have to be adjusted to meet specific requirements of each of the two phases, for instance ignition, inductive current drive and high plasma current during the Physics Phase, and finite Q, hybrid current drive, moderate plasma current and long pulse operation during the Technology Phase. NET will be the first machine in which the physics and the technology of extended plasma burn pulses will be established. Therefore it must be possible to incorporate improvements which may become necessary during operation to meet the final performance goals. In particular, it is expected that between the Physics Phase and the Technology Phase the plasma facing components (e.g. divertor plates, first wall protection) may need to be refurbished on the basis of the experience gained during the Physics Phase, in order to meet the more demanding requirements of extended pulse duration and overall operation time during the Technology Phase.

The scientific exploitation of the present tokamaks and their upgrades is likely to be sufficient to establish, by about 1993, the scientific basis for a decision on NET construction. Design solutions and technologies of the basic NET device must therefore be selected having in mind that by this date they will have to be proven feasible and reliable. For this reason a ten year programme aimed at developing the new technologies required in NET was launched in Europe in 1983.

4. NET PARAMETERS

4.1. Main requirements

The main requirements which have guided the selection of the parameter sets are:

- To achieve ignition under a variety of assumptions for plasma confinement and operational limits (e.g. plasma beta, density and safety factor).
- To accommodate several plasma shapes with elongations between 1.8 and 2.2, and single or double null configurations.
- To drive inductively the plasma current for at least 200 s. This pulse length allows the plasma to reach steady state conditions with the exception of current diffusion (≈ 1000 s).
- To perform engineering tests on DEMO-representative blanket sectors/modules. This requirement leads to constraints on the wall loading (≥ 0.6 MW/m^2), on the mode of operation (typical combinations of the burn time/off burn time between pulses are, for example, 300 s/150 s for inductive operation and 3000 s/500 s when current ramp-up and maintenance are assisted by non-inductive current drive), on the total burn time (≥ 4000 h), on the radial build, and on the access to accommodate a full blanket and to permit its remote removal.
- To allow the investigation of the physics and technology of long pulse operation approaching steady state and the assessment of its prospects for reactor applications.

4.2. Basic machine parameters

A great flexibility concerning plasma parameters, operating conditions and the choice of plasma facing components is the primary feature of an apparatus which aims at meeting the requirements listed in Section 4.1, operating with minimum technical risk and being cost effective. The requirement to achieve ignition inductively has the highest impact on the parameter choice, but it is not much more demanding than steady state operation at appropriate levels of the neutron wall load and current drive power.

The criteria for choosing the parameters of a device aiming at ignition have evolved in the past few years as a consequence of a broader database, produced mainly by the large tokamaks, on confinement and operational limits. The single parameter which best represents the confinement capability of a machine is the plasma current. For given technologies and design philosophy the plasma current also most effectively quantifies the size and cost of the apparatus.

TABLE I. NET PERFORMANCE FOR VARIOUS OPERATING SCENARIOS

	NET I		NET II			
Parameter	1	2	3	4	5	6
Major radius (m)	5.4	5.2	6.3	6.3	6.3	6.3
Minor radius (m)	1.7	1.3	2.05	2.05	2.05	2.05
Plasma volume (m^3)	600	400	1100	1100	1100	1100
Plasma current (MA)	15	11	25	20	25	15
Safety factor, q_I	2.2	2.2	2.1	2.7	2.1	3.5
Elongation	2.2	2.2	2.2	2.2	2.2	2.2
Average electron density (10^{20} m^{-3})	0.7	0.9	0.9	0.7	1.5	0.7
Murakami parameter (10^{19} $T^{-1} \cdot m^{-2}$)	8	9	8	7	15	7
Average burn temperature (keV)	15	15	15	15	7.5	15
Beta factor, g	2.5	3	1.7	1.6	1.2	2.2
Total beta (%)	4.6	4.9	3.4	2.7	2.4	2.7
Magnetic field on axis (T)	4.8	5	6.0	6.0	6.0	6.0
Average wall loading (MW/m^2)	0.5	0.7	1.0	0.6	0.7	0.6
Divertor peak loading (MW/m^2) [a]	3	7	7	7	3	7
Power exhausted through divertor (MW) [a]	60	100	140	140	85	160
Fusion power (MW)	500	400	1100	680	800	680
Fusion power/external power, Q	—	4.3	—	8	14	5.3
Required enhancement factor						
Kaye–Goldston	2.4	1.5	1.5	1.5	1.2	1.9
Rebut–Lallia	1.8	1.6	1.0	0.9	1.0	1.0
Pulse length (s) [b]						
Inductive only	300	—	700	1300	250	—
With RF ramp-up assist	1200	—	2000	3000	700	—
With RF ramp-up assist and non-inductive current drive during burn	—	Steady state	—	6000	800	Steady state

[a] The fraction of the total heating power exhausted via the divertor is taken to be 60%/40% for a burn temperature of 15 keV/7.5 keV.
[b] Without taking a current driven by the bootstrap effect into account.

In 1985 a reference parameter set was chosen having a current capability of up to 15 MA (NET I) in the Physics Phase. The predesign has been developed and the R&D tasks have been defined accordingly [1].

To reach ignition with this parameter set, H-mode confinement or, equivalently, an enhancement of L-mode confinement by a factor of two or more is needed, assuming moderately conservative operational limits on beta and plasma density (e.g. a Troyon factor g of ≈ 2.5 and a Murakami parameter of ≈ 8). Whether such working conditions can be achieved is subject to considerable doubt. For this reason in 1987 the NET Scientific Advisors Committee recommended the NET Team to study a variant (NET II) capable of carrying a considerably higher current, with the aim of reducing the required enhancement of confinement over the L-mode confinement and of increasing the flexibility and the reliability of operation. An important conclusion from this study is that the design solutions and technologies under development for NET I are also applicable to NET II. Reducing the present uncertainties, mainly in confinement physics but also in the plasma–wall interaction area, is a prerequisite for being able to make a definite choice for the NET parameters and to anticipate with some confidence its performance. An assessment of these parameters based on a cost–risk–benefit analysis of the two options is planned for around 1990, at the time when a decision to launch the engineering design of NET will be sought.

In Table I the main parameters of NET I and II are summarized and typical operation conditions are given. Also listed are the enhancement factors over the global Rebut–Lallia and the Kaye–Goldston scalings needed to reach the operating conditions (taking explicit account of radiation losses). The flux swing available in NET I and NET II, for the higher currents, is 190 and 360 V·s, respectively. In the Technology Phase operation at lower plasma current is attractive to optimize the trade-off between confinement capability, long pulse operation and power exhaust requirements. The thickness of the inboard shielding structures (vacuum vessel and shield/shielding blanket/first wall) is 90 cm, sufficient for both the Physics and the Technology Phases. It allows operation at an average neutron wall load of 0.7 MW/m^2, in Net II, for at least 8000 h. For the Technology Phase only the replacement of the divertor plates is probably necessary to meet the more severe requirements on lifetime (e.g. erosion).

5. BASIC MACHINE CONCEPT

The basic machine (Fig. 1) consists of the supporting system, which allows separate assembly of all components, the cryostat, the toroidal and poloidal field coil system, and the vacuum vessel/shield. All the machine components are self-supporting and an oblique access through cryostat, coils and vacuum vessel is provided for maintenance of plasma facing components. The outer containment of the machine is formed by the biological shielding. This structure also acts as the outer containment for the cryostat vacuum. This double function keeps the active machine

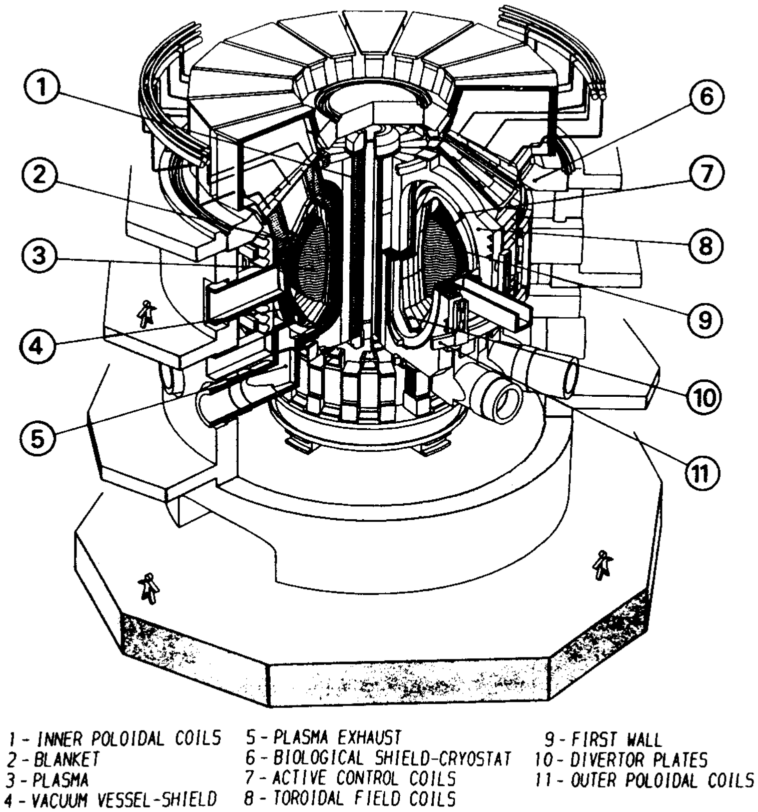

FIG. 1. An isometric view of NET device showing the main components.

volume to a minimum and allows hands-on access to many of the auxiliary systems. The central solenoid is independent of the TF coils, and the central vault formed by the inner legs (no bucking cylinder) supports the centripetal forces acting on the TF coils.

All the coils are superconducting. Superconducting cables are being developed along two lines: the react and wind process for 16 kA and the wind and react process for 40 kA, both for NbSn cables to be used at 12 T. Short length, full size samples are in an advanced stage of fabrication. The radiation resistance of the insulator is being tested up to 10^{10} rad (10^8 Gy) and structural materials are being qualified at 4 K. The first facility to test conductors at full current and 12 T is under construction.

The plasma containment is provided by a vacuum vessel inside the TF coils. This vessel also incorporates part of the permanent radiation shield and, with a thickness of about 30 cm, constitutes a very robust structure. The vacuum vessel is, in fact, the primary containment of activated materials, provides support to the removable shielding/blanket sectors and is able to resist very severe loads, in particular plasma disruptions.

Serious difficulties arise in the design of the first wall and the divertor plates because of the still uncertain operating conditions, which are anticipated to be very demanding (see Section 6). A solution for the Physics Phase based on a protection made of a graphite–carbon composite seems to meet the requirements for the operating time of this phase ($\approx 10^6$ s) and for a limited number of disruptions (<100). Samples of a first wall protected by mechanically attached (both conductive and radiation cooled) graphite tiles are under test.

For the Technology Phase (operating time $\gtrsim 1.5 \times 10^7$ s) the erosion of a graphite based divertor target is a serious concern. However, by sweeping the separatrix (0.1 Hz; $\Delta = \pm 30$ cm) and considering that redeposition is expected to reduce the effective erosion by at least a factor of 20, it appears that a lifetime of about 0.5×10^7 s for the divertor plate may be a realistic expectation. Then an operating time of 1.5×10^7 s would be possible with two replacements of the divertor plates. For this it is also essential that the number of disruptions be kept very low (<100). Using high Z materials such as tungsten for the divertor target would be a possibility only if in front of the divertor a high density, low temperature plasma ($\lesssim 15$ eV) can be maintained ('high recycling regime'). This may be possible for operation at comparatively high plasma density (e.g. 1.5×10^{20} m^{-3}) and low temperature in a pulsed mode (see Section 6.1). For strongly driven working conditions ($Q \approx 5$), as are typical for steady state operation, on the other hand, the divertor target is subject to very demanding requirements (see Section 6.2).

6. OPERATION SCENARIOS

6.1. Pulsed operation

NET I and II have sufficient volt-second capability (190 and 360 V·s, respectively) for inductively driven burn of 300 and 700 s (see columns 1 and 3 of Table I). Obviously, already on these time-scales it is essential that excessive impurity accumulation (whose characteristic time is of the order of 10 s) be avoided. This imposes a constraint on the admissible confinement regimes. Such burn times could be extended considerably (to 1200 and 2000 s) with the assistance of radiofrequency waves for current ramp-up to avoid loss of resistive volt-seconds during this phase and generating another 50 V·s. However, in this case the minimum off burn time between pulses will increase and may approach 500 s. Using non-inductive current drive during burn allows the burn pulse to be extended further, up to steady state operation. Long pulse operation with full or partial non-inductive current drive is best obtained by somewhat reducing the current.

In NET II, using a current drive power of 85 MW would allow a burn pulse of 6000 s (see column 4 of Table I). If the neoclassical bootstrap current drives 20% of the plasma current, the power could be correspondingly reduced. Note that for times approaching or exceeding the global current diffusion time (≈ 1000 s) partial non-inductive current drive may in any case be required for current profile control; however, at a low g value, as considered, this need will be minimized.

In the pulsed mode the accessible plasma parameter range is wider than in the steady state mode. This flexibility could be very useful to ameliorate the operating conditions of the divertor plates during the Technology Phase. For instance, a low temperature (≈ 7.5 keV) and high density ($\approx 1.5 \times 10^{20}$ m^{-3}) operating point (see column 5 of Table I) would lead to a plasma temperature at the divertor of about 10 eV and a peak power load on the plate of about 3 MW/m^2. A similar goal could be achieved by letting the helium concentration increase; in this case also the He pumping would be eased, but attention has to be paid to enhanced sputtering by He^{2+} ions. Alternatively, diluting the plasma with some amount of H would also favour the high recycling regime but not lead to enhanced sputtering conditions. This high density pulsed operation could be adopted in the Technology Phase. The maximum pulse length could approach 1000 s, if the external power of about 50 MW is used also for non-inductive current drive and 20% of the current is generated by the bootstrap effect, with an off burn time of 150 s; then about 2×10^4 pulses would be needed in the Technology Phase.

6.2. Steady state operation

Steady state operation in NET would be attractive because it allows a more in-depth and reliable analysis of blanket tests, and it would demonstrate the feasibility of a mode of operation which is desirable for a reactor. However, this regime poses serious engineering problems. Moreover, there is so far only limited operational experience available for this regime.

To achieve an acceptable efficiency in driving the current, operating with a low density, high temperature plasma is necessary. Nevertheless, high external heating powers (typically 130 MW) are needed for non-inductive drive of the full current. These conditions are very demanding with respect to power and particle exhaust and erosion of the divertor plates, and considerable contamination of the bulk plasma by impurities may occur. In fact, at the divertor plates a plasma temperature higher than 100 eV is anticipated. Again, if part of the current is generated by the bootstrap effect, the power requirements decrease correspondingly and the divertor working conditions become less demanding. Conversely, the presence of a bootstrap current could also be used to increase the plasma current and, consequently, the confinement capability. Note that for a low plasma current, favourable from the point of view of reaching steady state operation, ripple induced alpha particle losses are a concern.

7. ENGINEERING TESTING REQUIREMENTS

The requirements of blanket engineering testing lead to important constraints for the operating time, availability, pulse scenario, wall loading, radial build and access. The basic performance tests include neutronics, thermohydraulics, heat recovery and tritium recovery.

In a short pulse regime (300 s burn, 100 s off burn) a test run of 20–30 h of continuous operation is needed to reach 60–80% of the quasi-steady-state tritium release. In steady state operation these conditions would be reached in a test run of 2–3 h.

Long pulse operation is to be preferred because it allows longer off burn times and considerably reduces the testing time. For example, during only one pulse of 3000 s duration 30–50% of the quasi-steady-state tritium release would be reached; with an off burn time as long as 500 s, a run of just 5 h (typically five pulses) would be needed to obtain 60–80% of the quasi-steady-state tritium release.

The duration of a test run previously estimated must be increased by a factor of two to cover different wall loads, blanket temperature distributions and materials properties. Hence the duration of the basic run for the long pulse reference scenario is taken to be about 10 h. The testing will have to be repeated for, say, five different operating conditions (e.g. temperature, wall load, cooling conditions), and each blanket concept may have to undergo one design iteration. The testing of the tritium release of a blanket concept will then require ten runs. Actually 50 runs are foreseen to provide for the contingency of changes in the programme and for repetition of not fully successful tests, which corresponds to a total testing time of about 500 h. Several blanket concepts will be tested in NET. In addition long term phenomena such as tritium permeation and inventories, corrosion and tritium release on a full blanket sector will have to be investigated. For these reasons the duration of the Technology Phase of NET is taken to be 4000 h, and the basic machine is even designed for at least one full power year of operation. The Technology Phase with 4000 h of integral burn time can be carried out in five to six years, with an actual successful testing time during the scheduled operation time (i.e. excluding planned shutdowns to prepare the experiments) of about 15%. Each blanket concept under test will receive a neutron dose of less than 1 dpa, which is anticipated to be too low by at least an order of magnitude to have a significant impact on the blanket performance. Therefore, endurance tests of these concepts cannot be a realistic objective for NET, owing to the too high requirements on availability and operation time as well as cost. However, shielding blankets and specific test devices may accumulate several dpa, providing a valuable basis of comparison with irradiation experiments in fission reactors and with simulation experiments, if the operation of NET is extended up to one full power year.

The admissible thickness of the blanket under test depends on the plasma cross-section. With the highest current and largest cross-section, as used in the Physics Phase for ignition studies, the blanket test sector located on the outboard side can have a thickness of about 40 cm in NET I and 80 cm in NET II. In addition, horizontal ports 2 m high can be used. The reference value of the average neutron wall load chosen for the first wall/blanket design of 1 MW/m^2 can cope with the present uncertainties in the plasma performance.

The quantity of tritium burnt during 4000 h of operation is about 20 kg, if the testing programme is performed in an optimum way (e.g. minimizing the wall load requirements and ensuring the reliability required for continuous operation runs). Present information indicates that tritium will be available for civil applications at a rate of up to 1–2 kg per year starting in the second half of the 1990s; therefore breeding significant quantities of tritium in NET may not be absolutely necessary. However, the supply of tritium in such a large quantity is a matter of concern and therefore the option of a breeding/shielding blanket that could supply a substantial fraction of the tritium needed (say 50%) has been included in NET. This blanket must have a high reliability for it to be included in the basic machine. Two options — aqueous lithium salt and low temperature water cooled ceramic — are being developed.

The tritium supply as well as the cost of the plant suggest that the total power produced during the Technology Phase must be minimized. A trade-off between opposing requirements such as confinement and wall loading needs has led, for the Technology Phase, to a value of about 700 MW.

8. CONCLUSIONS

The performance requirements of NET are defined by its main objectives, which are to demonstrate controlled ignited burn of a DT plasma, to demonstrate reliable operation of a fusion plant and to provide a test bed for the development of nuclear and plasma facing components. Great flexibility during operation is an essential feature of the NET device and increases the confidence that the objectives of NET can be achieved. The predesign of NET is now in an advanced stage, and the design solutions adopted are being validated by an extensive technology programme in the European fusion laboratories and industry. The greatest difficulties are encountered in the design of the plasma facing components for long integral operating time, in particular for steady state operation. As for the machine parameters, two sets have been defined: one as reference for the design and R&D activities and an alternative based on the same design solution and technologies but with high plasma current capability. Before the engineering design phase is entered both these options will form the basis for an assessment of the NET parameters scheduled for 1990.

REFERENCE

[1] THE NET TEAM, Next European Torus, Fusion Technol. **14** 1 (1988).