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Chapter 10 - Final Observations

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About the ITER Basis Engineering Handbook

This handbook consists of two volumes which describe the ITER design from its inception up to the design, construction and assembly in 2025.

The handbook is not designed to be read as a continuous sequence of chapters. Instead, it is composed of focused, self-contained sections that address specific topics. Each chapter can be read and understood independently, allowing readers to engage with the material most relevant to their needs without requiring familiarity with preceding chapters. As a result, the reader will find certain overlapping content in chapters.

It is to be noted that at the time of writing, the design for some systems is still on-going. Therefore, the reader should consider that whilst there is significant value of this important point-in-time study, an update would be required as the Project progresses.

A broad Project overview is given in the first volume, to provide the reader with background information necessary to understand the context in the subsequent more-detailed chapters of the second volume, dedicated to the individual systems composing ITER.

For the overall table of contents of the Handbook and to access each one of the chapters, please refer to https://www.iter.org/scientists/iter-technical-reports.

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Volume 1
GENESIS, DESIGN AND EVOLUTION

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FINAL OBSERVATIONS

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Chapter 10

Final Observations

ITER, conceived at a time of cold war tensions to tackle ground-breaking high technology in a worthy aim for humanity, is without parallel in demonstrating the positive results of international scientific collaboration. These include:

- participants in different programmes bringing complementary approaches, skills and knowhow to the table, often shortening the path to highly innovative and practical joint solutions;
- pooling of fundamental plasma physics knowledge and experimental results to more rapidly and more securely lead to new insights and exploratory paths;
- successful design and procurement of plant systems with unprecedented performance requirements, and unparalleled mechanical and installation challenges;
- proving that disparate cultures and languages are not a barrier to effective collaborative working, and lead to greater respect and understanding among the physicists, engineers and administrators concerned, and the long-term benefit of wider mutual appreciation;
- showing that the different economic involvement of participants in the global economy is not a barrier to finding a fair sharing of contributions;
- effectively withstanding fluctuations in support by stakeholders, as economic or political changes occur (such as financial upheavals or political or even constitutional shifts), to maintain continuity over long development time periods;
- pooling of resources and openness of science and technology exchange to ensure that development to an initially hazy objective converges as efficiently as possible, for each participant, to an effective concrete proposal and its realisation;
- keeping an open scientific collaboration channel of exchange even between countries with political differences;
- sharing new experience in licensing of a fusion-based nuclear installation valuable for all when fusion power generation becomes a reality.

Notwithstanding these definite advantages of international collaboration on ITER, in hindsight, while some good practices were developed and implemented of relevance to future projects, several aspects ranging from organizational to technical could have been better managed.

Cost remains a significant consideration in the development of fusion, and the costs associated with building ITER turn out to be considerably higher than expected. If this were indicative for subsequent devices, it would be undesirable for their widespread adoption. As explained in outline below, and in more detail in the dedicated sections of Volume 2 of this handbook, the causes of high costs in ITER are partly technical, as would be expected for first-of-a-kind component and system manufacture, but are significantly driven by the organisation of ITER and its procurement, which was intentionally set up in this form in an unprecedented effort to share detailed cutting-edge technical knowhow across international boundaries.

In Section 10.1, a valuable insight from a management perspective on the particular characteristics of ITER that make it a challenging project to realise efficiently is given by the current ITER Director-General. Section 10.2 highlights a number of major lessons affecting multiple systems and components that the editors of this handbook see have been learned over previous years. Section 10.3 then concludes Volume 1 with some final remarks.

10.1 Overoptimization creates Fragility

All large projects contain interfaces, but in highly integrated scientific facilities these interfaces form dense, many-to-many networks. At ITER, interfaces are both geometrical and functional. Components must physically align with extreme precision while simultaneously satisfying performance dependencies across multiple subsystems.

In such systems, change does not remain local. A modification in one component propagates through adjacent systems, which in turn propagate further downstream effects. The result is not a linear increase in complexity with size, but a combinatorial growth of interdependence.

Traditional project decomposition methods implicitly assume partial independence between subsystems. In highly coupled environments, this assumption breaks down, and local optimization can produce global fragility.

A recurring pattern in first-of-a-kind projects is the pursuit of tight optimization during early design phases. Geometry is compressed, tolerances are minimized, and performance margins are reduced to improve apparent efficiency.

However, designs that are optimal under idealized assumptions are often brittle under real-world variability. Manufacturing deviations, supplier limitations, and integration constraints are not exceptional events; they are intrinsic features of industrialization at the frontier of technology.

When margins are eliminated at the conceptual stage, even small deviations can propagate into system-wide redesigns. The result is not efficiency but fragility masked as optimization.

Unlike mature industrial systems, first-of-a-kind projects operate in a regime where uncertainty is structural rather than incidental. Materials behave differently at scale, manufacturing processes reveal unforeseen constraints, and interfaces evolve as subsystems mature at different rates.

In this context, deviations are not anomalies but expected events. The relevant question is therefore not how to prevent variation, but how much variation the system can absorb without destabilizing downstream integration.

This reframes margins not as inefficiencies, but as functional elements of system design.

Technical, spatial, and schedule margins provide the buffer capacity required for complex systems to remain stable under uncertainty. While they may appear to increase cost or duration in early planning, their absence typically results in significantly larger downstream penalties through redesign, rework, and integration delays.

The key principle is proportionality: the more novel and less validated a system is, the greater the margin it requires.

In this sense, margins are not deviations from optimal design; they are prerequisites for achieving it in practice.

A similar misconception applies to schedule management. It is often assumed that aggressive compression and minimal contingency will shorten overall project duration. In highly coupled systems, the opposite is frequently observed.

When schedules contain insufficient slack, local delays propagate rapidly through dependent activities. This effect is particularly pronounced during assembly and integration phases, where multiple supply chains converge and site activities become tightly interdependent.

Rather than accelerating delivery, excessive compression reduces system robustness and increases coordination overhead, often extending total duration.

Schedule compression also affects organizational behaviour. Under sustained pressure, teams may delay reporting of non-conformities or accept temporary deviations to preserve short-term milestones. While locally rational, such decisions shift costs downstream, where correction is more complex and expensive.

In extreme cases, deferred issues can compromise system performance or require extensive late-stage rework. Thus, schedule pressure is not neutral: it actively shapes technical decision-making.

Large projects are also social systems. Once significant delays accumulate, a psychological transition can occur in which differences between “late” and “very late” appear negligible. This can erode motivation and weaken coordination discipline, reinforcing underperformance.

Recovery in such environments depends not only on revised plans, but on restoring credibility—demonstrating that execution is again tractable and that progress is measurable.

The recent trajectory of ITER illustrates these principles in practice. Following a period of sustained underperformance prior to 2023, during which SPI (schedule performance index = earned value/planned value) against the 2016 Baseline remained around 0.6, a series of corrective measures was implemented across technical, organizational, and planning domains.

A defining feature of this shift was not a single intervention, but a change in operating philosophy. Greater attention was given to technical interfaces, particularly those with significant knock-on effects, through the explicit management of technical uncertainties and schedule margins. This was complemented by enhanced transparency, including on non-conformities, more rigorous reporting, and more direct communication across the project.

Performance improved steadily, with the SPI rising above 1.0 with respect to the 2024 baseline. By 2025, annual earned value had reached a record level, nearly doubling that achieved in any previous year.

The ITER experience suggests that in highly coupled first-of-a-kind systems, performance is determined less by the absence of uncertainty than by the capacity to absorb it. Margins—technical, spatial, and temporal—are not inefficiencies to be minimized but structural requirements for stable integration.

Ultimately, the measure of success in such projects is not adherence to an initial plan, but the ability to maintain controlled progress when reality inevitably diverges from it.

10.2 Major Lessons Learned

10.2.1 A First-of-a-Kind Project requires Innovation, which affects Project Execution

Accessing a new physics regime in ITER requires pushing the engineering requirements of available technology to and beyond proven limits. This requires innovation for instance in the use of new materials and material combinations, and in previously untried and untested design solutions. The ITER design phase identified these innovations, and addressed many of them in the Large Projects (see sec. 7.3) in 1994-2001, covering superconducting model coil testing, vacuum vessel sector manufacture to high tolerance, plasma-facing component fabrication and testing, and remote maintenance demonstration at scale. These have ultimately decreased cost risk and shortened manufacturing time. Since the start of construction, further innovations have been identified and tested, for instance the development of industrial scale prototypes by previously uninvolved Members prior to their procurement actions, development of non-destructive testing schemes for the vacuum vessel joints, fatigue life and critical heat flux testing of first wall components, and hypervapotron development and brazing of W/Cu tiles in the divertor dome. More recently innovations have become necessary for instance to allow the replacement of Be by W as the first wall plasma-facing material, and to change the logic and method of first wall replacement. Such innovations, particularly those since the start of construction, have needed time to develop as far as manufacturing qualification, which has in some cases impacted the project schedule, and it should be expected others may do so in future, sometimes more than expected. However, from today's perspective, the 2024 baseline operation plan now looks attainable, given what needs to be achieved.

10.2.2 Project Infrastructure and Organization have to be set up so as to ensure Quality Delivery

Ensuring that the Project meets the quality standards required for a highly integrated nuclear facility requires a strong effective central organization propagating the use of common engineering management tools and QA/QC requirements to all Members of the project and their suppliers involved in the procurement and construction of the device. The decision to produce project hardware in kind instead of by a "just return" approach, without a systematic, integrated approach to quality management, effectively outsourced quality control to the DAs and their suppliers, as the IO were generally not the procuring organization. ITER Field Teams were originally proposed in the implementation agreement to support this, but were never implemented (see sec. 7.2). This sometimes led to IO responsible staff not being able to monitor production at key points in the supply chain.

An additional issue was the very long processing time needed to assess quality issues faced during production, generated mainly by the double layer of IO +DA reviewers and, occasionally, from the lack of expertise in terms of technology and the ability to appreciate the impact of the issue on performance. This led in some cases to an overconservative approach causing unnecessary delays in the production, and in others the opposite approach overlooking important quality aspects.

To avoid both these issues in future it would be essential to establish upfront single teams of properly trained and mutually trusting technical and QA staff from both the IO and DA, able to efficiently follow up production and processes and to assess efficiently and thoroughly any type of quality issue arising.

10.2.3 Industry needs to participate earlier in novel Engineering Design and Manufacture

Engaging suppliers early during the design of novel components or systems ensures manufacturing processes are better reflected in design choices. Such involvement needs to be carefully structured to ensure adequate procurement competition and to protect development intellectual property. Over-specification to obviate risk can also thereby be avoided, preventing unnecessary costs. In particular overly strict tolerance specification often has a large impact on cost, component performance, and the manufacturing approach, and in some cases even feasibility. Avoiding this requires closely working with the vendors during vendor selection and at contract start to fully qualify the manufacturing process, and subsequently realistic management and correction of non-conformities.

The need for industry to make costly and time-consuming manufacturing prototypes before series production was not always planned for the most technologically complex components and conventional components in new configurations or conditions, and contributed to production of non-conformities during series production which were expensive to correct. Successful prototype construction could have been used in more cases to screen for capable manufacturers prior to main contract placement, as parallel prototyping and qualification in particularly challenging cases (e.g. radial plates, first wall panels) in different suppliers did ensure manufacturability while maintaining competition. In contrast to the difficulties associated with parallel procurement for the same component (or parts thereof) described in 10.2.6, splitting serial procurement steps among several suppliers was also used successfully to minimise risk transfer to suppliers, minimising costs (e.g. EU TF Coil).

10.2.4 Fusion Regulation needs to be Evolutionary

A staged approach to regulatory approval geared to operational phases needs to be taken a) to question and then remove where appropriate unnecessarily over-conservative regulation of design and manufacturing, b) to obtain first-of-a-kind operational data under real operating conditions to underpin assumptions, and c) to build trust between the project and regulators' technical teams. In the case of ITER, the lack of understanding of the need for this approach particularly in the period 2016-2022 led to difficulties between licensing authorities and the project until it was recently addressed[1].

The classic case of (a) is the Vacuum Vessel (see more explanation in Volume 2 of this handbook). The early decision for this confinement-critical item to follow nuclear pressure equipment codes, required 100% weld examination and any detected defect to be repaired. Such a huge burden of repair also can cause more damage than good. It has led to a 20-year procurement phase, due to reasons including, amongst others, changes in management and delays due to Covid, with the corresponding difficulty of maintaining expertise. Only at the end of this period it has been possible to negotiate a more balanced approach with licensing authorities, taking account of the increased ability to detect defects since the design code rules were established, and using fracture mechanics to establish the need for defect repair. This will help future fusion device construction.

10.2.5 Design Coordination and Integration need to be carried out Project-Wide

In addition to the impact of over-optimization through the reduction of margins described in Section 10.1, when the IO was established in 2006, many auxiliary systems (ranging from the water-cooling systems to diagnostics and additional heating systems) were at a low level of design maturity, and they were still not sufficiently designed when long lead items went into procurement, resulting in poor definition of the interface requirements and costly adaptations during manufacturing. For a highly integrated device such as ITER, it is important instead that the planning of the design activities of ALL systems, and their interfaces (which often turn out to be more challenging than the systems), be driven to converge at integration milestones.

One example of this (again more details will be found in the respective sections of Volume 2 of this handbook) is in the nuclear buildings, where too early attempts to optimise (i.e. minimise) building size and supporting floor thicknesses with the idea to reduce cost, before the full requirements of subsystems (particularly ancillaries) were fully known, were counterproductive. The number, location and design of anchoring points, penetrations, shielding and service routing in the tokamak buildings were not developed with sufficient margins to allow cost-efficient adjustments to be made as detailed systems designs evolved. It would have been valuable to have established simplified system interfaces, and control them well, as well as to pay more attention to standardising assembly processes at the design stage.

Over-attention to broad measures such as raw material consumption (e.g. concrete) also led to well-intentioned but eventually costly design changes, when shielding and floor strength were sacrificed. The buildings' procurement contracts issued early by the responsible DA to qualified suppliers to secure their expertise and demonstrate progress before detailed specifications were complete also posed a risk to the suppliers, resulting in offers well beyond the value attached to the procurement packages by the project. Along with the expensive material usage and extra structure needs to compensate for ill-advised space savings, which caused licensing concerns and require special monitoring measures, this has ended up causing the nuclear building unit costs to reach several times the expected level.

10.2.6 Developing Multi-Member Procurement Expertise has Cost and Schedule Consequences

With in-kind procurement, the aim was that each ITER Member would be better prepared for the step after ITER, the conception and realization of a fusion facility that will demonstrate industrial-scale fusion electricity. On the plus side this approach has provided all the ITER Members with the opportunity to develop their industries and personnel expertise in cutting-edge areas of technology. Irrespective of their contribution levels, the ITER Members obtain full and equal access to the intellectual property generated during the construction and operation of this facility, with the minimum possible investment. The continued development of ITER to its construction and eventual operation would not have been possible without the participation of all the main countries involved in fusion research with a free exchange of information. The technological spin-offs from this experience in fabricating the ITER tokamak components are potentially immense and are one of the motivations for the Members to participate. Sharing procurement can also reduce risk in case of manufacturing failures or lack of production capacity.

However, while this procurement sharing principle enabled the ITER collaboration to go ahead, it also resulted in a major challenge for the project. Allocating parallel procurement of the same parts of components to multiple different Members has ended up being extremely challenging and costly by creating additional artificial interfaces within the same component's manufacture, sometimes utilising different manufacturing methods (limiting the expected knowledge transfer), and sometimes resulting in a variable quality product overall-. This is in contrast to the benefits of sharing production steps referred to in 10.2.3.

10.2.7 Cost and Schedule Estimates depend significantly on Organization and Design Maturity

As illustrated by the above, several contributing factors have affected the project cost and schedule performance, including lack of design completeness and maturity at the time of the signing of the ITER Agreement, changes in scope due to design changes after the premature signing of procurement contracts (e.g. buildings), risks and uncertainties associated with constructing a novel highly integrated facility, the emergence of new physics understanding, and lack of sufficiently early consideration of the optimum staging of operation phases in relation to hardware readiness and performance. More attention needed to be given from the beginning to generating a better understanding and acceptance of cost and schedule uncertainties given the level of technical maturity, which would have helped all Members make a more realistic assessment of their possible financial risks.

The original 10-year schedule (with no schedule margin) connected with the construction decision in 2006 was known at the technical level inside the project to be extremely technically challenging. The large influx of new construction-experienced staff trying to understand and implement a design they were unfamiliar with, it was inevitable that new issues would emerge requiring further investigation and design detailing, leading to construction delay.

Schedule is strongly affected by the quality of the decision-making and integration processes as well as by the expertise and leadership qualities of the people in charge. Earlier establishment and orientation of the team in the IO and DAs of highly skilled people covering QA, procurement strategy, integration and coordination, in support of their technical counterparts, would have helped mitigate technical and commercial uncertainties, and enhanced schedule adherence and cost control.

10.2.8 Design Solutions Need to be Able to Change Radically Even After Construction Starts

Large projects which take a long time to build are vulnerable to changes in underlying physics understanding or technology development. For example, the inclusion of internal vessel coils to ensure plasma stability, and of internal ELM control coils to reduce the expected pulsed heat loads on the divertor targets and ensure a reasonable lifetime, increased cost and added complexity. Another example is the switch from beryllium to tungsten as plasma-facing armour which has allowed a more reliable approach to first wall remote maintenance to be adopted, removing the onerous requirements related to beryllium handling, and reducing hot cell requirements and their timing, with only minor schedule impact. The impacts on cost and schedule can be positive or negative, but margins allowing major systems as well as supporting systems to adjust (mentioned in 10.2.5) can significantly help.

10.2.9 An Early Site Decision would have facilitated faster creation of a functional Project Organization

A considerable time is necessary after site selection for a functional project construction organization to emerge, as key staff adapt to managing procurement, and new expertise is brought in to help their role transition while maintaining technical knowledge across project phases. An early site decision exposes site-specific technical and regulatory requirements and gives useful time for adaptation, and allows better integration of DAs and their suppliers into the practical aspects of the organization culture and its management, and for an understanding of the project to develop with the regulators. Further, the required site-specific regulations were not fully defined or understood.

Changing at a critical point in the development of ITER to a new organization at a new location composed of a central team and new Domestic Agencies worldwide required these organisations to recognise the need to interface with an integrated set of engineering and project management tools adopted by the central team to cover the full design, procurement and delivery process. However, it took a long time for these common tools and processes to be agreed on or developed sufficiently, and later for access to them in both the IO and the DAs/suppliers to be arranged, and for the tools to become familiar to them. In addition, good features of the integrated approach to project personnel, financial and technical systems infrastructure adopted in comparable projects needed to be learnt from and incorporated earlier. Furthermore, settling so many new incoming staff at new locations simultaneously, without well-established infrastructure, added further disruption. This impeded establishing the coordination/integration team mentioned under 10.2.7.

10.2.10 Multi-Generational Projects Require Special Efforts to Preserve Knowledge

The evolution of ITER has taken place against a background of intense worldwide technological development from the analogue to the digital age. Due to good housekeeping, the editors of this handbook have found it just possible to retrace the steps of the past nearly 40 years of development and to extract the essential facts and lessons learned. In the last few years the IO has taken increasingly active steps to expand its knowledge management actions, of which producing this handbook is but a part. Given the long term nature of the project, exceeding an individual's working lifetime, the handbook authors strongly support this effort, particularly in the establishment of an easily searchable targeted knowledge base/archive of project participants' expertise and knowhow, installation guides and handbooks, and other such documents considered worth preserving to aid their successors. This is particularly necessary in this finalisation phase of the construction as an essential aid to commissioning and eventual operation.

10.3 Concluding Remarks

The ITER Project is one of the most complex, challenging, and far-reaching scientific and technological endeavours humanity has ever attempted. The aim of this handbook has been to document the technical experience of those who participated at various stages in attempting to realise this project over the years it has taken to bring it to its present state on the verge of operation, with a view to guiding those involved now and in the future. It has highlighted the major accomplishments of ITER over a range of domains encompassing political, social, organisational, cost sharing and technical aspects.

Although, in hindsight there is a lot that could have been done better, the progress made is impressive in view of the considerable and sometimes unique challenges met along the road, including:

- The first-of-a-kind nature of the design and, even more, of nearly all major components and subsystems: taking such a leap has relied upon the experience and foresight of its designers and the ingenuity of the scientists who have planned its operation scenarios.
- The international nature of ITER and the underlying structure of the project, with the consequent difficulties in reaching consensus and the resulting delays: this has required the development of a good spirit of cooperation between the IO and the DAs, which has taken considerable time to develop but is now much improved.

Like all experimental facilities, there is always a risk that the eventual performance could fall short of the objectives. Nevertheless, the design of ITER mitigates this risk by being based on and taking advantage of decades of progress made in all the fusion facilities worldwide, giving greater assurance that it will meet its scientific and technical objectives of demonstrating the practical feasibility of fusion power.

ITER has been the unwavering flagship of fusion for decades, keeping the dream alive often over a fluctuating support environment. This has helped create a positive international public attitude to fusion with a wave of excitement and expectation. There are currently many higher risk/higher reward private and public ventures aiming to develop, build and operate a fusion reactor within the next decade or two, which could then be commercialized. For these ventures, even if they were to come to market earlier, much can be learned from ITER, and information flow from ITER has been set up to share on issues ranging from organisational ones to the many technical ones these ventures also have to address. The many lessons learned already from ITER highlighted above, and in more detail in Volume 2, also provide invaluable information for professionals designing and building new fusion facilities.

The technical issues, schedule delays and cost increases ITER has experienced provide lessons for other teams developing fusion energy. The imperative for the design has always been to adapt to feedback derived from technology and plasma physics R&D, prototyping and testing, as well as making better informed cost estimates, ensuring a continuous process of refinement. The evolution trajectory has at times been intricate and characterized by numerous critical decision points. The overarching implementation strategy advocates regular assessments, adaptability, inclusive feedback and pro-active recovery planning. In this regard, over time, ITER has converged to more realistic objectives based on more detailed and better-informed technical, integration, cost and schedule considerations.

The editors and authors of this handbook are fully aware of the challenges and limitations of ITER. Nevertheless, they firmly believe that ITER will be a success overall, not only as an experimental facility, but as a model of international cooperation. Once ITER becomes operational, it will finally push back the boundaries of plasma physics knowledge far beyond what has been possible to date and provide technical data on the performance and reliability of its first-of-a-kind components, essential for technologists and investors pursuing commercial fusion power.

References

[1] ITER progresses to a new baseline, P. Barabaschi et al., Fusion Engineering and Design 215 (2025) 114990.