Availability of ITER and Fusion Power Plants considering the experience of present tokamaks

- Introduction
- Present tokamaks
  - Operating experience
  - Availability
  - Lesson learned
- ITER
  - Operating scenarios and states
  - Maintenance scheme
  - Availability considerations
- First considerations on FPRs
- Conclusions

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8th IAEA-TM on Fusion Power Plant Safety
12 July 2006, Vienna
Availability (Maintainability & Reliability) is a top level parameter for the design and management of complex plants

Aim of the present work
- Availability assessment of present tokamaks analyzing operating experience, causes and corrective actions
- Lessons learned in view of ITER
- First considerations on the other factors affecting the availability of ITER and FPRs

Present tokamaks
- Few hundreds device-years operating experience
- Different sizes, systems, technologies, hazards
- Limited experience on: S/C and Cryogenics, actively cooled PFCs, complex plasma scenarios
- Pulsed operation, low neutronic fluence, light RH, “simple” safety OLCs
- No significant access limitation for maintenance-inspection/test

ITER (and FPRs)
- Experimental nuclear device, first of kind machine, under design finalization before construction
- Several ITER systems from tokamaks on operation and a few from NPPs-big Lab (significant extrapolation)
- Important activated components with short qualified life: heavy RH
- Safety OLCs to be met
- Significant areas with access limited or prohibited
Operating Experience

Typical tokamak experimental Programme Plan

- experimental campaigns of a few weeks spaced by shutdown periods
- 3 - 5 experimental days / w, 1 prolonged shift or 2 shifts per day
- 50-100 experimental days per year (depending on the budget too)

- Target: produce a good pulse in each minimal experimental time interval: 15-30 min
- If the tokamak is not fired, downtime is charged to the entity that caused the delay

Sources: No standard way to collect and analyze operating experience
- Trouble collection: Engineer in Charge, Session Leader, CODAS and systems diaries-logs
- Analysis and causes: fault analysis, classification of faults in causes family
- Corrective Actions: taken at the managerial level

Main delays

- Sessions lost (≈ 5-25%)
  - Serious troubles in important systems: actively cooled PFCs, vacuum, cryogenics, power supply
  - Failure of essential large components without redundancy, lack of spare parts

- Delays during the experimental session (≈ 2 hr per day, 15-25%)
  - System malfunctions: Power Supply, CODAS, AH. Human Factors

Availability of ITER from present tokamak operating experience
Operating Experience: JET

Delays (hours) per system per operational day along the years
(Sessions cancelled not included)
### Reliability data of JET components

- **Active Gas Handling (AGH)**
  - Amplifier - Erratic/No Output
  - Blower - Blower stop
  - Catherometer - Erratic/No Output
  - Control Unit - Erratic/No Output
  - Controller - Erratic/No Output
  - Fan of electrical board - Fan stop
  - Filter - Blocked
  - Ionization Chamber - Erratic/No Output
  - Indicator - Erratic/No Output
  - Thermocouple - Erratic/No Output
  - Site Power Supply - Loss of power
- **Vacuum**
  - Valve - Pressure Regulator - Diaphragm
  - Valve - Pressure control - Fail to operate
  - Valve - Internal Leak
  - Valve - Fail to open/close
  - Vacuum Pump - Pump stop
  - Vacuum Pump - Fail to start
  - Uninterruptable Power Supply - Loss of power
  - Vacuum Pump - External leak
  - Thermoresistance - Erratic/No Output
  - Transducer - Erratic/No Output
  - Switch - Erratic/No Output
  - Site Power Supply - Loss of power
- **Power Supply**
  - Site Power Supply - Loss of power
  - Site Power Supply - Loss of power
- **NBI**
  - Site Power Supply - Loss of power
- **RF**
  - Site Power Supply - Loss of power

### Methodology

- Classify all components (type, size) and kind of failure
- Total operational time
- Number of failure

### Failure Rates for AGH system (1/h)

<table>
<thead>
<tr>
<th>Component Fai lure mode</th>
<th>Failure rate $\lambda$</th>
<th>Standard error $s.e.(\lambda)$</th>
<th>$\lambda_L(90%)$</th>
<th>$\lambda_U(90%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier - Erratic/No Output</td>
<td>1.2E-06</td>
<td>6.7E-07</td>
<td>3.2E-07</td>
<td>3.0E-06</td>
</tr>
<tr>
<td>Blower - Blower stop</td>
<td>2.2E-05</td>
<td>9.7E-06</td>
<td>8.6E-06</td>
<td>4.6E-05</td>
</tr>
</tbody>
</table>
Availability

No unique definition

• (scheduled time - downtime) / scheduled time
• effective operating time / (effective operating time + troubleshooting time)
• number of pulses / per day / per campaign / per year
• session planned – session lost / session planned

Since mid 2002 JET has introduced also
• number of good pulses / per day / per campaign / per year

as the final aim of the actual tokamaks is
• to produce good pulses to the benefit of the scientific programme

Technical indicators (families)
• Operational days per year
• N.of pulses per day per year
• Delays: per systems/subsystems/components per day
• Delays: Ratio per cause/overall
• AH power: Ratio [delivered power/requested]
• AH energy: Ratio [delivered energy/requested]
• Diagnostic performances
• Fuelling performance
• …..
Availability: Indicators of JET

- 1 pulse each 30 min
- 2 shifts/d
- 5 days a week
Availability: DIII-D

- 1 pulse each 13.5 min
- downtime is charged to the entity that caused downtime > 15 min.
- If a shot is of no value, 15 minutes of downtime is charged to the equipment
- \( A = \frac{\text{scheduled time} - \text{downtime}}{\text{scheduled time}} \)
- Session lost not considered here
Effective net working rate $= \text{eff. operating time}/(\text{eff. oper. time + troubleshooting time})$

- Operation: 9 cycles / y, each cycle $\sim$ 2 weeks
- Operation days / y: $\sim$ 100
- Periodic inspections duration: $\sim$ 2 months
- Troubles: failure or malfunction that interrupts experiment discharge for one shot
- More troubles: after modifications, just before and after pulse, after plasma disruption
Availability of ITER from present tokamak operating experience

- 2-3 operating days per week 8:30 - 18.00
- 75% of the whole PFC surface W coated
- Few unplanned In-VV interventions:
  - Contamination with organic material (by arcs)
  - Passively Stabilising Conductor
  - In-Vessel water leak

\[
A = \frac{N \text{. shots}}{(N \text{. days}) \times \text{max. shots per day}}
\]

max. shots per day = 22

![Availability Graph](Image)
• Dec 99 - mid 01: CIEL project

• **Dominant unplanned shutdown**
  - In-VV water leaks on PFC, ECRH (rec. time 2-3 w)

• **Delays during experiments**
  - TF system dumps (~2 hours)
    - 0.25 events/magnet/y
  - Cryogenics

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![Availability: Tore Supra Impact of in-VV water leaks](image)

Availability out of water leaks

SHUTDOWN FOR MAJOR UPGRADE

Availability of ITER from present tokamak operating experience
Operating Experience: FTU and RFX

FTU Availability
- Any time >20 min. is delay
- One pulse every 20 minutes
- Delays: Power Supply, Codas, preparation of pulse
- Sessions lost not considered here (Vacuum, cryogenics)

RFX Availability
- 1 pulse every 10 minutes
- Sessions lost not considered here (Broken windows, replacement of tiles)

Availability of ITER from present tokamak operating experience
Causes of delays and mid-long term corrective actions for tokamaks in operation

• **Staffing**
  • Assess N. of Personnel supporting key systems and skill. Identify areas of weakness (including risk of loss of individuals). **Extra staff and cross training**

• **Planning and implementation of modifications**
  • Systematically log and assess potential **impact on operations** of all significant modifications: e.g. qualify material for In-VV

• **Operational documentation and procedures**
  • Fixes/improvements must be documented so that problems are not repeated or are fixed quickly in future

• **Spares/Preventative Maintenance**
  • Review/refine continuously **maintenance plans and spares** holding for key systems
  • Check spares: are known to be working and **ready to fit**

• **System improvements**
  • **Design change** to make components/system more reliable
  • Improve **monitoring or diagnostic** capabilities to shorten repetitive problem recovery
Lesson learned and corrective actions
e.g. JET Power Supply Fault Analysis

**Hours lost per Operational Day**

<table>
<thead>
<tr>
<th>Year</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>1.0</td>
</tr>
<tr>
<td>1995</td>
<td>2.0</td>
</tr>
<tr>
<td>1996</td>
<td>1.5</td>
</tr>
<tr>
<td>1997</td>
<td>1.0</td>
</tr>
<tr>
<td>1998</td>
<td>0.5</td>
</tr>
<tr>
<td>1999</td>
<td>1.0</td>
</tr>
<tr>
<td>2000</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**% down time**

<table>
<thead>
<tr>
<th>Year</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>12</td>
</tr>
<tr>
<td>1996</td>
<td>10</td>
</tr>
<tr>
<td>1998</td>
<td>8</td>
</tr>
<tr>
<td>2000</td>
<td>6</td>
</tr>
</tbody>
</table>

**Improvements made as a result of fault analysis**

- Power Supply Personnel training
- Communications
- S4s preventative maintenance
- PVFA fuses and 15V power supplies
- NBI magnet cooling system
- *NBI Pre-charge protection*
- *G3 V&I protection*
Lesson learned from present tokamak to increase reliability

**DESIGN**
Availability Target
- Overall plant
- Main systems
  - Power supply
  - CODAS
  - AH
  - PFC cooling
  - Cryogenics
- Design criteria
  - R&D
  - Code & Standards
  - QA

**MANUFACTURING**
Highest QA & Quality Control
- PFC cooling circuits
- In-Vessel material components
- Critical prototypes
- Cryogenics
Diagnostic on Components
  - trouble diagnosis/ data for mainten.
- Build up component database
  - Spare parts
  - Training/Trials

**ASSEMBLING**

**COMMISSIONING**

**OPERATION**
- Tools & effort to collect, analyze Operating Experience
- Classify Causes
- Corrective Actions
  - Refine maintenance & Spare parts policy
  - Operating procedures
    - Training/cross training
  - Design changes

- Review availability against target at significant stages of design and construction
- ITER will benefit also from experience of NPPs for nuclear systems and from large Research Labs for complex systems e.g. CODAS

Availability of ITER from present tokamak operating experience
ITER Availability

Operating scenarios
- H2 phase: 2.5 Y
- D-D phase: 1.5 Y
- D-T phase: 10 + 10 Y

Operating status
- Long Term Shutdown
- Short-Term Maintenance
- Test and Conditioning
- Short-Term Standby
- Plasma

Operational transitions (max number and duration)
- Baking operation (tens h) 200
- TF magnetisation (tens h) 1000
- VV vacuum pump-down (60 + 40 h) 30
- Cryostat vacuum pump-down (60 + 100 h) 15
- Magnet cool down/warm-up (30 days + 30 days) 100
### ITER Operating Plan

**Construction Phase**

<table>
<thead>
<tr>
<th>Milestone</th>
<th>1st yr</th>
<th>2nd yr</th>
<th>3rd yr</th>
<th>4th yr</th>
<th>5th yr</th>
<th>6th yr</th>
<th>7th yr</th>
<th>8th yr</th>
<th>9th yr</th>
<th>10th yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Plasma</td>
<td>Full Field, Current &amp; HCD Power</td>
<td>Short DT Burn</td>
<td>Q ~ 10, 500 MW</td>
<td>Q ~ 10, 500 MW, 400 s</td>
<td>Full Non-inductive Current Drive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Installation & Commissioning**

- Basic installation
- Commissioning
- Achieve good vacuum & wall condition

**Operation**

- Machine commissioning with plasma
- Heating & CD Eqpt.
- Reference scenarios with H

**Equivalent Number of Burn Pulses (500 MW x 440 s)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Burn Pulses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
</tr>
<tr>
<td>4</td>
<td>2500</td>
</tr>
<tr>
<td>5</td>
<td>3000</td>
</tr>
</tbody>
</table>

**Fluence**

<table>
<thead>
<tr>
<th>Year</th>
<th>Fluence (MW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.066</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**Blanket Test**

- System Checkout and Characterization
- Performance Test

- Electromagnetic test
- Hydraulic test
- Effect of beryllium steel etc.
- Neutronics test
- Validate breeding performance
- Short time test of breeding
- Thermomechanics test
- Preliminary high grade heat generation test, etc.
- On-line tritium recovery
- High grade heat generation
- Possible electricity generation, etc.

*The burn time of 440 s includes 400 s flat top and equivalent time which additional flux is counted during ramp up and ramp down.

**Average Fluence at First Wall (Neutron wall load is 0.56 MW/m² in average and 0.77 MW/m² at outboard midplane)*
ITER availability is affected by

- **Need to replace important** in-VV and in port cells **components with short life**
  - Remote operations for scheduled/unscheduled maintenance and planned upgrades, including replacement of PFCs
- **Unreliability of systems and components** (present tokamkas operat. experience)
  - PFC Cooling circuits, Cryoplant, including Magnet Systems, Power supply, CODAC (it will have a very demanding target), HFs are the main contributors
- **Respect and verification of OLCs**
- **Frequency of changing operating status**
  - above events
  - various experimental programmes

The **quality of scientific results** ("good pulses") affected also by

- Availability of AH systems
- HFs in preparing the experiments and in managing the control room
ITER Maintenance Scheme

Present reference plan for ITER machine in-vessel components maintenance
• series operations on all its components, except for divertor where series/parallel operations are foreseen

CLASS 1
Divertor
✓ 54 cassette 3 (54 cassette) exchanges/first 10 year, 5 (54 cassette) exchanges/second 10 year
Test Blanket Modules
✓ 1 exchange/year. 3 TBM plugs
NB filaments / caesium oven
✓ 2 exchanges/year
Equator port limiter plugs
✓ 10 exchanges/20 years. 2 port limiter plugs.
Equator RH diagnostic plug
✓ 10 exchanges/20 years. 4 equator RH diagnostic plugs.
Class 2
Blanket modules (all or outboard region)
  • once only change over at the end of 10 years operation
Blanket modules (a few)
  • Requirements: 3 – 6 modules/year
Cryopump
  • 2 – 3 replacements/20 years    Assume replacement of all 8 cryopumps.
ECH/ICH
  • \leq 5 times each/20 years    3 equatorial plugs, 4 upper plugs
Equator/upper ports diagnostics
  • \leq 5 times each/20 years    12 upper plugs
NB ion source grid cleaning
  • \leq 1 time/year.
NB isolation valve replacement
  • \leq 1 time/20 years.
Availability: further factors

Downtime has to be quantified also for
• In-Cryostat inspection and repair
• Localization of failure (e.g. leaks of PFC cooling circuits or vacuum)
• Safety OLCs periodic control, e.g.
  • In VV Tritium measurements, control/removal
  • In-VV dust measurements, control/removal
  • Containment leakages
  • Etc…

Systems to mitigate downtime
• E.g. provide secondary vacuum barriers
  • at all vulnerable vacuum feedthroughs to form interspaces that can be monitored to reveal leak location and leak rate and connected to the Service Vacuum System to allow differential pumping of a leaking interspace until the next planned shutdown
• Making possible some important maintenance with plasma on (also moving to backup plasma scenarios, e.g. for un-schedule maintenance)
Availability of ITER from present tokamak operating experience

**ITER availability influencing factors**

### Short life of components
- Maximization of good pulses
- Accuracy in PFC life consumption measur. (erosion, ...)
- Parallel maintenance
- Maximize maintenance with operation on Adequate maint. equipment
- Training/Trials

### Unreliability of systems and components
- Design criteria (red&diver)
- Highest QA & Quality
- Diagnostic on Components
- Leak detection
- Spare parts
- Training/Trials
- Operating experience an. Corrective actions

### Respect and verification of OLCs
- R&D on safety issues (reductions on number, uncertainties, then of frequencies (i.e.In-VV Dust and T amount)

### Frequency of changing operating status
- Optimization of the other factors
- Planning of operating modes with minimum change of system configurations

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ITER availability maximization
75% as availability target (essential for commercial reasons) is quite challenging

- Large module segmentation (PPCS solution): the total number of blanket modules to a value lower than 200
- Scheduled and unplanned outages due to in-VV component replacements
- Heavy need of complex RH operation
- Many complex systems (e.g. AH, cryogenics, power supply, CODAS) essential

Areas of improvements

- Alternative maintenance scheme (e.g. vertical maintenance scheme)
- Maximization of parallel maintenance

ITER will give an important contribution on that respect
Conclusions: Availability of present fusion machines

Availability depends on reliability and maintainability

Availability of present machines mainly affected by unreliability of components and upgrades (maintainability, quite simple, plays a minor role)

Availability ultimate limits

- design choices
- reliability of components
- budget constraints

- Planned experimental time $\approx 100$ d/y ($10$-14 h/d)
- Availability $\approx 75\%$ planned exp time
- Lower values (55%) in presence of actively cooled PFCs and S/C magnets (ITER relevant)
- Good pulses: $\approx 50\%$ of total pulses

Operating experience

- Experimental sessions lost: 5-25%
  - Critical systems: PFC cooling circuits, Vacuum, Cryogenics, no redundant essential components
- Delays during the experimental sessions: 15-25%
  - Critical systems: Power Supply, CODAS, AH, Human Factors

$\checkmark$ All over the years the present tokamaks have maintained or slightly increase their availability also with more complex experiments and aged components
Conclusions: ITER availability

ITER is a complex experimental nuclear machine with short qualified life of important activated/contaminated components

• Maintainability is very demanding for frequency, complexity and nuclear environment
• Respect of safety OLCs
• Changing of operating status (demanding also in terms of time)
• Reliability will be lower than in present tokamakas because of more complex systems with lack of operating experience

ITER availability to be evaluated and maximised through

✓ Minimization of maintainability time
  ✓ accurate in-vessel maintenance techniques and time estimates assessments
  ✓ adequate-reliable maintenance equipment
✓ Maximation of system/component reliability
✓ R&D to simplify/shorten OLCs verification
✓ Minimization of frequency of operating status changes and component exchanges
Conclusions

• An adequate availability is requested to accomplish ITER important and strategic scientific mission but also for the complex organization and the high political visibility

• Economic considerations ask for the highest availability possible too

*Put availability among the top criteria in all phases particularly in Design and Manufacturing, Maintainability, Operation Plan and OLC verification, to make ITER sufficiently available in spite of complex maintenance, critical events and nuclear environment*