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Overview of the JET Operation Reliability

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Overview of the JET Operation Reliability

Adrianus Sips[a,b], Eva Belonohy[a,c], João Bernardo[a,d], Lorne Horton[a,b],
Mark Edwards[c], Damian King[c], Trevor Blackman[c], Dragoslav Ćirić[c] and JET Contributors[*]

[a]*JET Exploitation Unit, Culham Science Centre, Abingdon OX14 3DB, UK.*
[b]*European Commission, Brussels, Belgium.*
[c]*CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK.*
[d]*Instituto de Plasmas e Fusão Nuclear, IST, Universidade de Lisboa, Portugal.*
[*] *See author list of X. Litaudon et al, Nucl. Fusion **57** (2017) 102001.*

The JET tokamak has been in operation since 1983. Information on every shutdown, commissioning phase and experimental campaign has been logged electronically since the year 2000, a model for RAMI analyses in fusion experiments. The JET operation reliability statistics record the time taken to install major upgrades, commission systems with plasma, the downtime for maintenance and the achieved experimental campaign days. On average, JET achieves 82% of the planned experimental days during a calendar year. For unplanned interventions the systems that failed are identified together with the impact on machine availability. A total of 14 unplanned interventions are recorded over 19 years with durations of up to 8 weeks. During experimental campaigns, delays from essential subsystems are recorded; computer systems, power supplies, neutral beam systems and delays attributed to human operators. On average 21% of the time is lost due to delays during operations. From the operation reliability data, refurbishments and maintenance are planned at JET to prepare for the upcoming campaigns using deuterium-tritium mixtures.

Keywords: JET, tokamak, maintenance, operation, reliability, statistics.

1. Introduction

The JET tokamak has been in operation for 35 years, producing 92500 pulses so far [1]. Records exist of every shutdown, commissioning phase and experimental campaign since the start of operations in 1983; a combination of paper and electronic documents. However, detailed records are only available fully electronically since the year 2000.

All delays during operations are logged by the Engineer-in-Charge in the control room (~8600 entries) together with electronic logs of faults from essential subsystems, such as computer systems, heating systems, diagnostics and power supplies. These provide the basis for the JET operation reliability statistics during the last 19 years with ~42500 entries.

For experimental campaigns at JET, milestones are set for the operation reliability. Targets are:

- Achieve a high percentage (> 80%) of planned experimental sessions;
- Achieve an average high number (> 7) of good physics pulses per session;
- Achieve good performance of the JET subsystems by having a high availability (> 80%) during campaigns.

This paper summarises the operation statistics of JET in section 2, presenting the time spend on shutdowns, commissioning and campaigns and how many, on average, good physics pulses per shift are obtained. In section 3 the downtime due to unplanned interventions is detailed, together with which systems failed. In section 4, the delays for the various subsystems during campaign shifts are given. Data are available for each subsystem, as well is the components of these subsystem. Examples are presented on remedial actions. The targets and schedule for campaigns at JET up to the end of 2020 are provided in section 5. Conclusions are given in section 6.

2. JET operation statistics

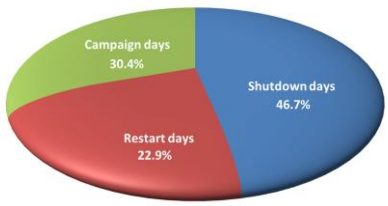

Fig. 1. Separation of calendar time (in %) for shutdowns, restart and experimental campaigns at JET.

At JET, main shutdowns typically take 6 to 12 months, while shorter maintenance period span 1 to 8 weeks. JET uses 47% of calendar time for shutdowns or maintenance. Commissioning and plasma restart phases follow shutdowns and typically take 20 to 22 weeks to bring the systems up to the performance required for experimental campaigns. After short maintenance periods, a restart phase is typically only 1 to 2 weeks. Routine maintenance is also performed during campaigns for the switches of the ohmic circuit (1-day

author's email: George.Sips@jet.uk

maintenance every 6 weeks) and for the systems of the cryo-plant at JET (2-day maintenance every 3 months). Commissioning and plasma restart take 23% of the calendar time at JET. Experimental campaigns take the remainder of the 30% of the time available, as shown in figure 1. Table I details the major shutdowns of JET since the year 2000, the duration of the shutdown in calendar days and the time required to commission the subsystems before experimental campaigns can start.

Table 1. Shutdown and restarts at JET since the year 2000.

Shutdown	*Days*	*Restart days*
2001-2002 (various)	*228*	*105*
2004-2005 (divertor)	*206*	*123*
2010-2011 (ITER-like Wall)	*348*	*104*
2014-2015 (W samples)	*226*	*115*
2017-2018 (pre-DT)	*359*	*119*

The schedule of shutdowns, commissioning phases and experimental campaigns is based on the (long-term) goals of the JET experiments. Each phase is planned in detail about one year in advance, together with targets for system performance. Restart targets specify the systems requirements during plasma commissioning, such as available heating power, minimum vacuum leak rate and minimum performance required from other subsystems. The operational schedule is compared with the time that was actually required for the shutdown or maintenance, the time required for commissioning and the number of experimental days achieved. These planned versus achieved comparisons provide a high-level overview of JET operations as shown in figure 2. Shutdowns are, on average 11% longer than planned and restart phases are on average 21% longer. Experimental campaigns, although in duration not compromised by the extra time required for shutdown and restart (just delayed), on average achieve only 82% of their scheduled days. This is due to unplanned interventions.

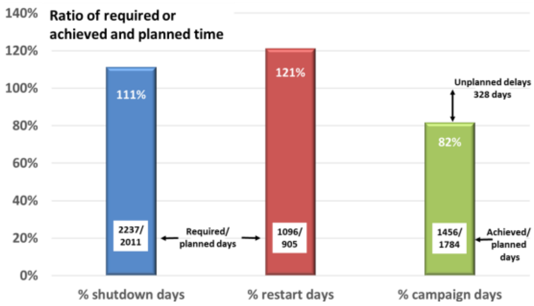

Fig. 2. Ratio (%) of the time required and the scheduled time for the shutdowns and commissioning (restart), together with the ratio (%) of the number of experimental days achieved to days planned.

At JET each operational day has two shifts (early and late shift) and typically five operational days are planned per week. Each JET pulse is rated by the session leader in the control room to provide feedback on the quality of the discharges obtained. The pulses can be rated from zero to three stars; "0" is given to a pulse of no scientific value, ∗ to a pulse with only limited scientific value, ** for a pulse of scientific value to the program objectives and *** to pulses with high scientific value. Good physics pulses have 2 stars or 3 stars and these are counted for each shift. Figure 3 gives an overview of the average number of good physics pulses per shift, for each calendar year (note that in some years, there is no operation). Typically, 65% of JET pulses are good physics pulses, with a typical pulse rate of two pulses per hour. There are also records on number of plasma pulses that disrupted, number of pulses that had failed breakdowns or pulses that failed due to technical reasons.

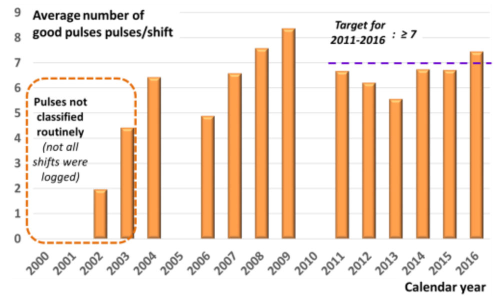

Fig. 3. The average number of good physics pulses per campaign shift (y-axis) for each calendar year.

3. Unplanned interventions at JET

Despite system refurbishment, maintenance and detailed planning of the experiment schedule at JET, unplanned failures of systems do occur. Since the year 2000, these events have been logged, documenting what happened and which systems or events were the cause of the fault. In figure 4 the duration of the interruption to JET operations is shown, when the fault occurred, and which system or event caused the intervention.

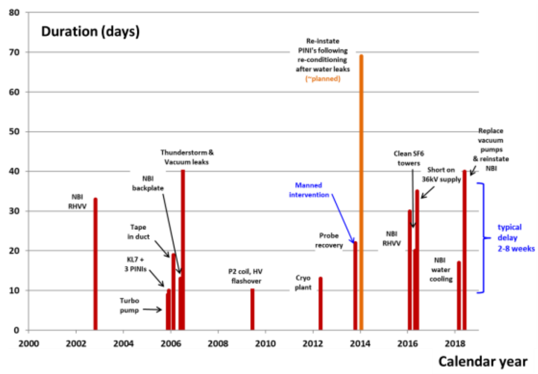

Fig. 4. The duration of unplanned interruptions to JET operations, when they occurred and cause of the event.

A total of 14 unplanned intervention took place over the period January 2000 to July 2018, with the loss of

313 campaign days from the scheduled program. This amount to a 18% loss of experimental days, as shown in figure 2. Five of these unplanned events were related to JET vacuum systems, including two failures of the rotary high-vacuum valve (RHVV) of the neutral beam boxes. Five faults were related the neutral beam systems, mainly due to water leaks in the cooling systems. The other events occurred on the high-voltage systems (2 events), cryopump (1 event) and diagnostic systems; a manipulator probe fell into the divertor. None these interventions required the use of the remote handling system in-vessel, which requires a minimum intervention of about three months.

4. Delays during experimental campaigns at JET

For the period 2000 to 2016, the JET operation statistics contain ~6000 entries for subsystem delays during operation (~2750 campaign shifts). Any pause (delay) in JET operations is logged with the entries grouped by main systems, such as pulsed power supplies, heating systems, computer systems (CODAS), diagnostics and others, including delays due to human thinking time during operations.

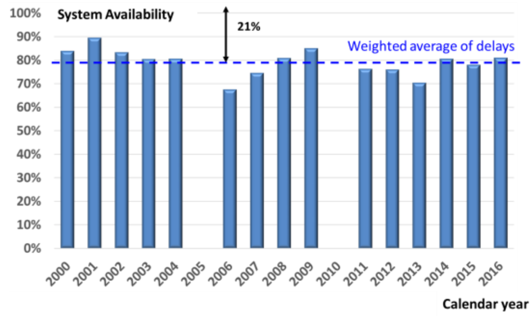

Fig. 5. The system availability during JET campaigns.

The availability of all systems is defined as the percentage of time JET is operational of the total time available shift for a shift (7½ hours). Figure 5 gives an overview of the average availability per shift for each calendar year. The overall system availability has not varied much over 17 years and has a weighted average of 79%. The average delay during campaign shifts is 1 hour, 22 minutes over the last two decades. Hence, campaign planning has 20-25% contingency.

Figure 6 provides an overview of the percentage of delays caused by the main subsystems. Delays due to pulsed-power-supply systems dominate the statistics, causing 40% of the delays. Computer systems give 11% of the operational delays as many are essential for real-time control and data collection. Heating systems constitute 10% of the delays. Delays for extra thinking time in the control room account for 6% of the delays during experiments.

Each of the subsystems has sub-categories. For example, pulsed power supplies are sub-divided into OH-circuit, toroidal field-circuit, generators, power supplies for additional heating, and other components, given a wealth of detailed information. Figures 7a – 7d give the breakdown of the delays of each subsystem (as percentage of the subsystem delays). These detailed overviews highlight, that in some subsystems specific components are susceptible to faults. For example, the OH-switches for pulsed power supplies, the “PF” computer systems for CODAS, session leader thinking time for “human thinking” and delays and the neutral beam system for the heating systems.

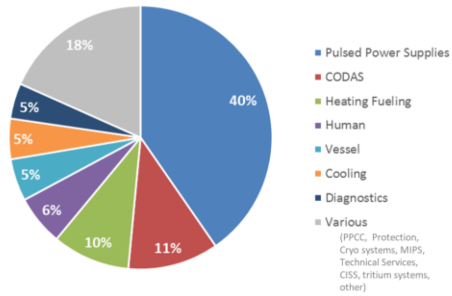

Fig. 6. Contribution (%) of various sub-systems at JET to delays during experimental campaigns.

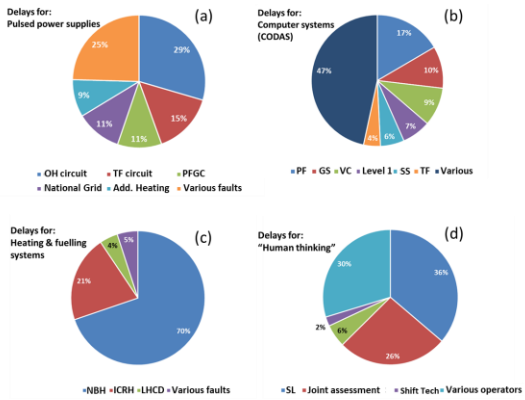

Fig. 7. Delays in the components of four main subsystems at JET. Given are the % contribution to the delay for each subsystem: (a) puled power supplies, (b) CODAS, (c) heating systems and (d) “human thinking”.

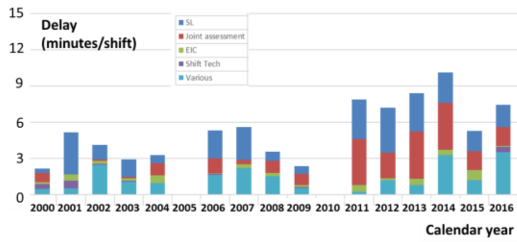

Fig. 8. The extra thinking time required in the control room over time.

In addition, for each of the subsystems and their components, the evolution of delays over time can be analysed. These statistics show typical fault behaviour over time, with more frequent failures or delays for systems that are new or significantly upgraded and faults that occur due to age. Figure 8 shows the change in time for “human thinking” in the control room, detailed for various control room personnel. During the carbon wall phase of JET (up to 2009) the delay due to thinking time in the control room was, on average, 3 to 5 minutes/shift, while thinking time has increased to 8 to 9 minutes/shift for experiments with the new ITER-like Wall, equivalent one-minute thinking delay for each pulse. This increase is mainly required for the interpretation of infra-red and visible camera data for the protection of the Be/W wall.

The information from JET operational statistics is used to plan maintenance and repairs. In the shutdown of 2009 to 2011 the cryo-systems were upgraded at JET, since then delays from this subsystem have reduced from ~10 % in 2009, to < 1% of total delays each year since 2011. Recently the OH-heating switches were refurbished, the computer systems for the poloidal field control upgraded, the gas introduction software was updated, and key diagnostics repaired (such as magnetics and interferometry) A refresher course for session leaders and other control room staff was organised. Furthermore, procedures and restrictions for deuterium-tritium operation in JET are being rehearsed [2].

The neutral beam system deserves special attention. Five unplanned interruptions to the campaign were caused by faults of the neutral beam systems, the neutral beam cause 7% of all delays during campaigns as this system is essential for high power plasma operation and diagnostics using the neutral beams. Figure 9 provides an overview of the maximum and averaged neutral beam power achieved in JET since the year 2000.

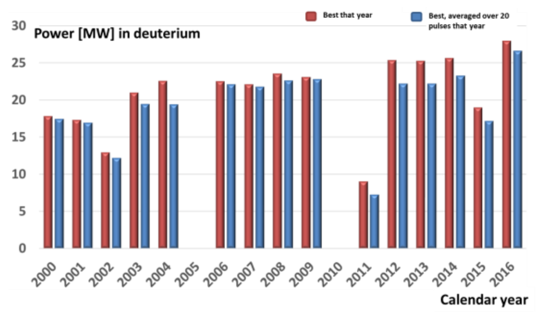

Fig. 9. The neutral beam power in JET over time. Maximum power achieved for three seconds in a discharge (red) and the average beam power (blue) obtained during the best 20 discharge that year.

The performance of the neutral beam system in the last 5 years with maximum input power of ~ 25 MW in deuterium is below the design value of 34 MW [3]. Components giving reduced performance or reliability were replaced, such as the dump plates for molecular ions, the closing mechanism of the two rotary valves and water-cooling hoses. Delays during campaigns were attributed to faults on the cooling and the control of high-voltage power supplies and auxiliary systems for neutral beam heating. These have now been addressed in preparation for operations in 2018 to 2020.

5. Future JET campaigns

JET has finished the shutdown required to prepare for deuterium-tritium operations [4]. The main campaign elements until the end of 2020 are:

- A deuterium campaign for the preparation of high performance scenarios and studies of disruption and run-away election mitigation using a new shatter-pellet system;
- Hydrogen and 100% tritium campaigns combined with reference pulses in deuterium for the study of isotope effects; and
- A final deuterium-tritium campaign with the aim of producing 10 to 15 MW of fusion power for 5s in stationary conditions.

Targets have been set (Table 2) for JET operations for the upcoming campaigns, based on the operation statistics over the past two decades and the expectations of machine availability and reliability up to 2020.

Table 2. Operational targets for campaigns in 2018-2020.

Campaign target	*Goal*	*Achieved 2000-2016*
Campaign days	*90 %*	*82 %*
System availability	*80 %*	*79 %*
Good physics pulses/shift	*7*	*6 to 7*

6. Concluding remarks

JET operations have been evaluated since the year 2000. There have been 14 unplanned interventions in the last 18 years. Hence, campaigns achieve on average 82% of the planned days. On average there is a 79% system availability during operations, giving an overall availably for JET of 65% during campaigns. JET performance has not deteriorated over the past years, if anything, the technical know-how is increasing with the extensive performance information now available.

Acknowledgements

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References

[1] P.H. Rebut et al, Nucl. Fusion **25** (1985) 1011.

[2] E. Belonohy et al, Fusion Eng. Des. **123** (2017) 196.

[3] D. Ciric et al, Fusion Eng. Des. **82** (2007) 610.

[4] X. Litaudon et al, Nucl. Fusion **57** (2017) 102001.