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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002)).*

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ABSTRACT
Estimates of worker dose for future fusion machines have suffered from a lack of an experiential database from operating tokamaks. The need for occupational radiation exposure (ORE) experience was the motivating factor for the present study, which focused on the JET machine. This study of the JET ORE experience has started to address the above needt. Much more needs to be done, however. Although preliminary, the results of this initial study are encouraging [1]. We have found that, on average, the machine was in the shutdown state almost 50% of the time; while most of the shutdown time was planned for maintenance or modifications, about 18% of the total shutdown time, on average, was due to unplanned machine interventions; it would appear about two thirds of the JET annual dose, on average, was accrued by the maintenance staff; about 15% of the average, annual worker dose was accrued during the machine operating state; annual worker doses were significantly reduced after the implementation of the ALARP policy during the 1997 tritium plasma campaign; the long-term averages of the collective and individual worker doses are low (96p-mSv/a and 0.153mSv/a); and, on average, since 1997, the tritium dose has been about two percent of the total worker dose.

1. MAINTENANCE HISTORY

Maintenance has been performed on the machine on an on-going basis, in between plasma physics runs, at the end of the operating day, or during weekends. Intensive maintenance periods, however, have been scheduled between plasma physics campaigns. These can be of a few weeks duration, or longer. During these shutdown periods the machine was repaired and prepared for the next campaign. At the end of the physics campaigns, there has usually been a longer maintenance period lasting several months, or more. Significant in-vessel repairs and modifications were made during these long maintenance periods. The type of work included, for example, replacement of damaged in-vessel components (RF antennae, tiles, etc.) and changes to the machine configuration, such as installation of different divertors. Accordingly, the maintenance effort has varied significantly from month to month and from year to year. On a long-term basis, however, the machine was in the shutdown state almost 50% of the time. Moreover, on average, the number of unplanned machine interventions account for about 18% of the total shutdown time.

The following Figure 1 provides an indication of the variability of shutdown time. Also, as shown in this graph, annual shutdown time has been in a slight upward trend, but there is very significant variation from year to year. In 1993, the machine was shutdown for the entire year to perform major machine upgrading, such as divertor replacement.

As shown in Table 1, from 1983 to 2002, the machine was in the shutdown state about 44% of the time, on average.

As shown in Table 1, during the 1983-2002 period the machine was in the shutdown state 3,229 days. Of these 2,656 were planned and 573 unplanned. Therefore, on average, the number of unplanned machine interventions account for about 18% of the total shutdown time.

2. WORKER DOSE HISTORY

Given the variability in the annual shutdown time, it is not surprising that the JET annual worker doses have varied significantly over the study period (see Fig. 2). Interestingly, though, even as shutdown time has been in a slight upward trend (graph in Fig. 1), and machine dose rates have also been trending upwards (see Fig. 3), annual worker dose has been in a general downward trend.

JET started operating in 1983 and performed its first Deuterium-Tritium experiment in 1991. During 1997 the JET operations included a three-month campaign of D/T plasmas. The long-term averages of the collective and individual worker doses are 96p-mSv/a and 0.153mSv/a. The post 1997 averages are lower. The average collective annual dose was 30p-mSv/a and the average individual dose was 0.058mSv/a.

3. ANALYSIS RESULTS

As noted above, tritium was injected into the machine initially in 1991 and then again in 1997. The quantity injected in 1991 was only 5mg. That injected in 1997 was 35g. The impact of the 1991 D/T plasma operation on worker doses was negligibly small. The impact of the 1997 D/T plasma operation on worker doses was also small, but worthy of some considerations. As shown in Table 2, during the 1997 D/T plasma shots, and immediately afterwards, the tritium dose was less than 6% of the total worker dose. On average, since 1997, the tritium dose was about two percent of the total worker dose. This results shows that radiation protection measures used at JET (typically, zoning of areas, ventilation controls, remote techniques and fully pressurized plastic suits), worked well at reducing the tritium dose to a small percentage of the total dose.

A preliminary analysis of worker doses from 1995-2002 by work group indicates that the maintenance dose has been, on average, two thirds of the annual dose. This implies the non-maintenance dose accounts for one third and is spread over the six non-maintenance groups, of these, the engineering support group receiving the largest dose. However, a proportion of the overall dose arises due to the sum of small doses of the large number of workers (~400) under routine monitoring, many of whom only work occasionally in a radiation environment. Also some doses are received by workers not in the maintenance group but are nevertheless involved in technical or inspection activities that take place in a radiation environment.

The above results lead to the possibility that non-maintenance doses can be accrued during machine shutdown periods, in support of maintenance activities, or during non-shutdown periods, in support of operations activities. That is, some worker dose could have been accrued with the machine in the operational state, but not during plasma operation. This possibility was tested by a detailed analysis of each non-maintenance group dose in relationship with the maintenance group. The underlying assumption being that the maintenance group dose was accrued only during the machine shutdown state, (although this simplification needs to be further tested given the pseudo-dose effect due to the large numbers being monitored). To illustrate the approach, the neutral beam group dose was plotted against that of the maintenance group. As shown in the following Figure 4, the neutral beam group dose is well correlated with that of the maintenance group. The correlation index is about 92%, indicating a strong correlation. When the maintenance group dose is zero, however, the neutral beam group dose is non-zero, implying that some of the neutral beam group dose was incurred when the machine was in the operating state (i.e., not shutdown).

Following the same approach for all other non-maintenance groups, it was possible to determine that, while small (of the order of 10-15%), worker doses accrued while the machine is in the operational state are not insignificant.

The graph in Figure 5 illustrates another important result – the maintenance group doses have dropped to very low levels in the most recent years of JET operation. As can be seen in the following figure, despite the general upward trend of the estimated work effort (NP T) (where NP = number of persons and T = working days) and elevated machine dose rates since 1997, the annual maintenance group (MG) dose has been constant, or trending slightly down. This demonstrates the success of the ALARP policy implemented following the D/T operation in 1997, which required the use of remote-handling equipment, for in-vessel work, to the extent practical.

The above result is also important from an ITER perspective, as it illustrates the success of remote-handling equipment in maintaining worker doses ALARP, in a period of increasing maintenance activities.

4. SUMMARY AND CONCLUSIONS

This study represents the first attempt at collecting, documenting and analyzing the JET occupational radiation exposure experience using a systematic approach. The present study has demonstrated that the approach works well and has produced some valuable information for estimating fusion machine worker doses. It would appear that the non-maintenance dose accounts for about one third of the total worker dose, on average. and almost one half of the non-maintenance dose could be attributed to periods when the machine is in the operating state. However this finding is based on a number of assumptions due to very limited data, and future refinements using detailed data may show a more complex distribution partly explained by the dose measurement method. Further, JET's experience is that tritium doses have accounted for only a small fraction of the total dose.

We have also found that, on average, the machine was in the shutdown state almost 50% of the time; and, while most of the shutdown time was planned for maintenance or modifications, about 18% of the total shutdown time, on average, was due to unplanned machine interventions.

Annual worker doses were low. The long-term averages of the collective and individual worker doses are 96 p-mSv/a and 0.153mSv/a, respectively. Moreover, annual worker doses were significantly reduced after the implementation of the ALARP policy during the 1997 tritium plasma campaign. The post-1997 averages are 30p-mSv/a and 0.058mSv/a, for collective and individual doses, respectively.

It can be concluded, from this study, that the ALARP policy, introduced during the 1997 tritium plasma campaign, which promoted remote handling in preference to manual work, has been effective in reducing worker doses. This conclusion is supported by the fact that worker doses have dropped even during periods of increasing maintenance effort, although there is a need to investigate more closely in a future study the benefits and disadvantages of remote handling in terms of the reduced dose but increased maintenance times. Further, given that a large proportion of the JET dose is due to in-vessel exposures, further work is required to extrapolate the relevant features of the dose distribution to future large scale tokamaks.

ACKNOWLEDGEMENTS
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Table 1: Annual Summary of Machine Operation

Year	Operating days	Shutdown days	Total	Shutdown / Total
1983	226	139	365	38%
1984	224	141	365	39%
1985	248	117	365	32%
1986	334	31	365	8%
1987	236	129	365	35%
1988	258	107	365	29%
1989	131	234	365	64%
1990	200	165	365	45%
1991	253	112	365	31%
1992	75	190	365	79%
1993	0	365	365	100%
1994	256	109	365	30%
1995	116	249	365	68%
1996	236	129	365	35%
1997	302	63	365	17%
1998	236	129	365	35%
1999	219	146	365	40%
2000	243	122	365	33%
2001	127	238	365	65%
2002	151	214	365	59%
Totals	4071	3229	7300	44%
Average	204	161	365	44%

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Table 2: Internal doses vs Total doses

Year	Operating days	Shutdown days	Total
1997	72	1.4	1.9%
1998	35	2	5.7%
1999	41	0.7	1.7%
2000	24	0.7	2.9%
2001	37	0.4	1.1%
2002	13	0.1	0.8%
Avrerage	37	0.88	2.4%

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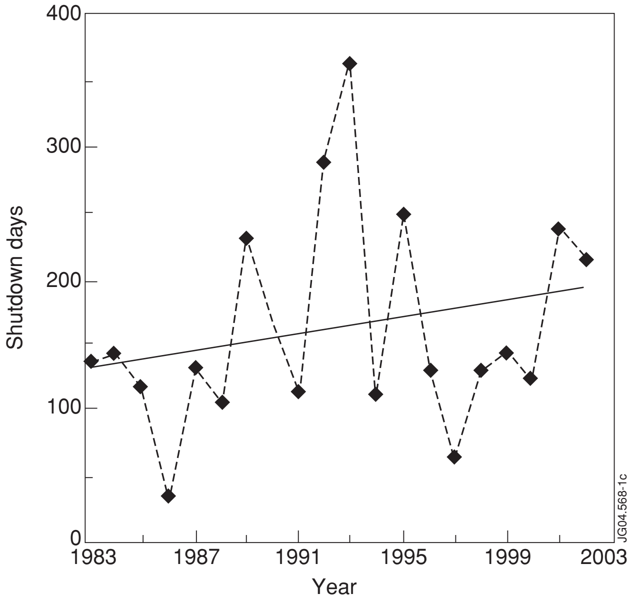

Figure 1: Variability of JET shutdown time

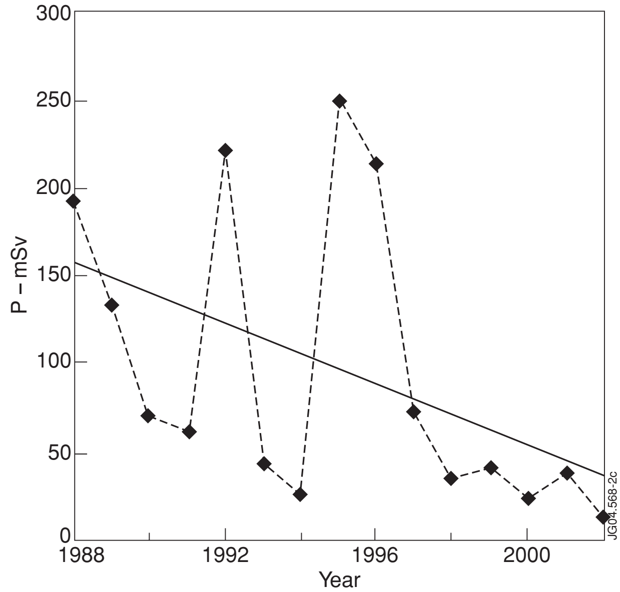

Figure 2: JET annual worker doses

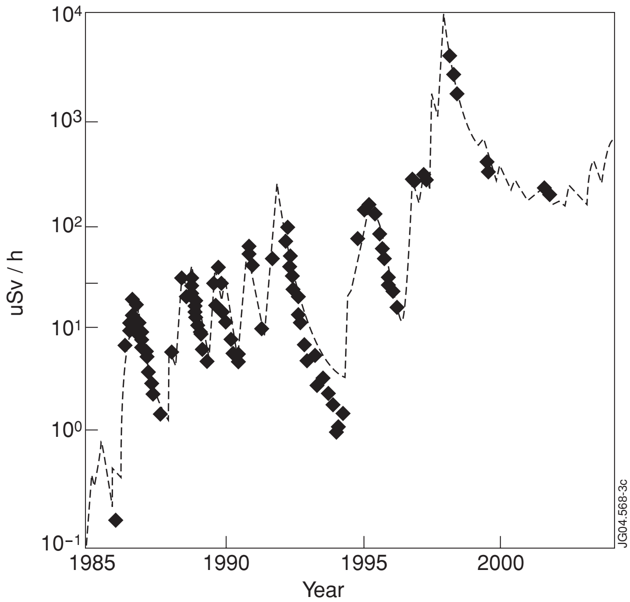

Figure 3: JET machine dose rates

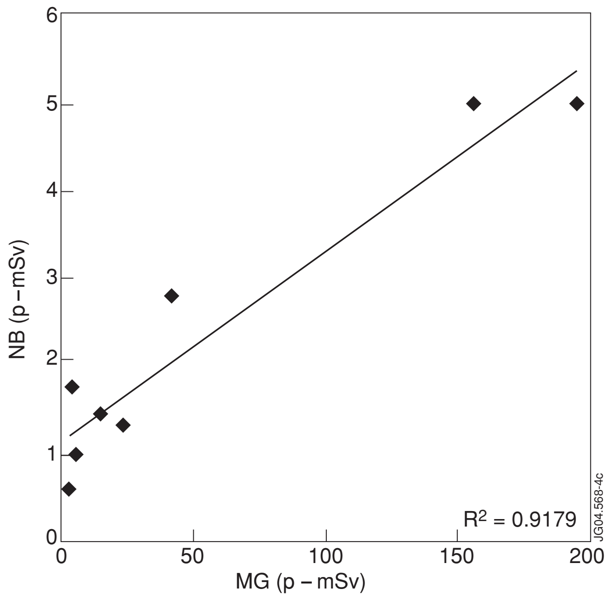

Figure 4: Correlation between MG and NB group

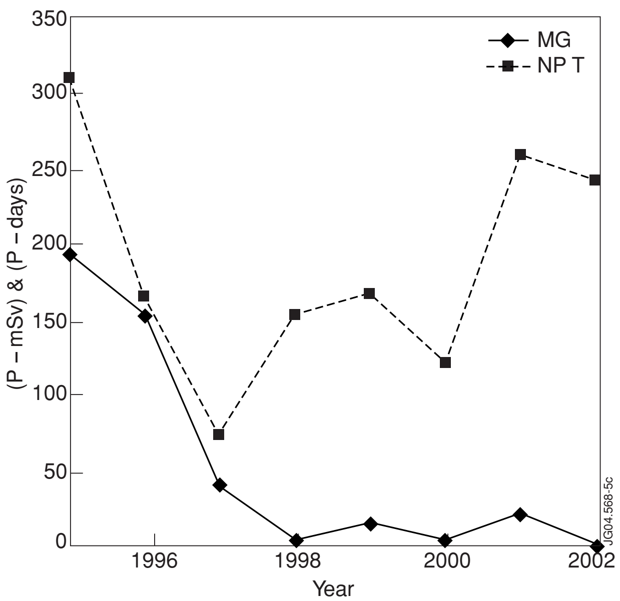

Figure 5: Comparison of annual MG dose and work effort trends