STUDY OF THE MOTION SCHEDULE FOR ITER REMOTE HANDLING TRANSPORT CASKS*

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Abstract. Simulations concerning the motion schedule of remote handling transport vehicles to be used in the International Thermonuclear Experimental Reactor (ITER), are presented in this paper. Different scenarios for vehicle path layout, simultaneous vehicle motion and unidirectional vs bidirectional motion are analysed and general performance indices compared among them. The results obtained are important to reduce the duration and increase the reliability of heavy radioactive materials transportation.

Key Words. Remote Handling, ITER, Transport Vehicles.

1. INTRODUCTION

This paper presents part of a conceptual study on flexible guidance and navigation solutions for the remote handling transport system to be used in the International Thermonuclear Experimental Reactor (ITER). The transport vehicles under study will operate between the gallery around the Vacuum-Vessel (VV) and the Hot-Cell Buildings (HCB) of the ITER complex, and must be capable of safely moving 20–80 tons of radioactive materials. Details about the buildings and transport operations were taken from several ITER documents, notably (Ribeiro *et al.*, 1997*a*; ITER/EDA, 1996; Mousdell, 1997). The complete study on flexible guidance and navigation solutions can be found in (Ribeiro *et al.*, 1997*b*).

The path to be followed includes line segments and curves of different radius, and requires interfacing the vehicles with the VV docking ports, a lift, and the HCB docking ports. Maximum transfer cask dimensions are 8m × 3.5m × 4m. Loaded casks may weight from 20 to 80 tons. Inside the sealed transfer containers are the component handling systems responsible for the operations of loading and unloading components. Containers will be decoupled from the transportation vehicles.

The transport vehicles motion schedule is an important issue, since the number of casks to be built, the required number of work shifts and the building geometry (e.g., number of docking ports at the HCB, lift location, number of lifts) strongly depend on it. The performance of the transport vehicles motion schedule is discussed regarding two issues: i) bidirectional *vs* unidirectional cask motion in the galleries of the VV building, ii) one transport vehicle moving at a time or more than one moving simultaneously. The study, supported by simulation results, concerns divertor cassettes transfer between the four VV ports and the HCB ports. A complete transfer cycle is considered.

2. SIMULATION SCENARIOS

The initial stage of the transfer cycle is represented in Figure 1 for eight transport vehicles. Notice that the gallery and the HCB are located at different floor levels, connected by the gallery lift.

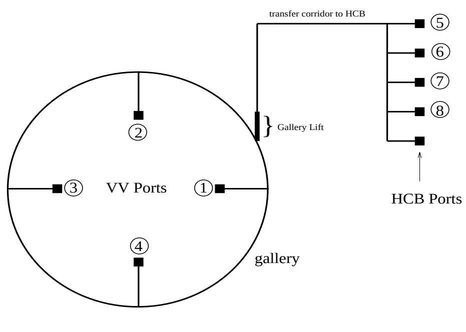


Fig. 1. Initial stage of transfer cycle.

The initial position of each cask for all the simulations is shown in Figure 1. Casks 1,2,3 and 4 belong to set 1. Casks 5,6,7 and 8 are also named as casks 1, 2, 3 and 4 of set 2. The order in which casks are transferred between VV ports and HCB ports is 1-5, 2-6, 3-7 and, finally, 4-8, except if mentioned otherwise.

When bidirectional motion in the gallery is allowed, each cask moving between a VV port and the lift chooses the shortest path. When more than one vehicle moves at a time, traffic congestions may arise. The distances considered in the simulations were taken from the drawings in (ITER/EDA, 1996): gallery path radius= 37m; distance from gallery path do VV docking port=12m; distance from lift to HCB transfer corridor = 25m; length of transfer corridor: 25m. The time spent to overcome the lift, including position on lift and secure, travel between levels and release and free from lift, was taken as 30 minutes, (Mousdell, 1997). The casks velocity was assumed to be 0.125 m/s.
The simulations were also based on the following assumptions:

H1 At the beginning of the transfer cycle, all the casks are undocked, i.e., ready to start moving. The vehicles at the VV ports are loaded with divertor cassettes and the vehicles at the HCB ports are unloaded and ready to move.

H2 During the transfer cycle, neither docking or undocking operations and loading or unloading of components take place.

H3 There is a turntable in the lift so that transfer casks may turn to approach the ports (at VV or HCB) with the correct orientation, i.e., cask's door facing the port door.

In the simulation results, the values of several different variables are presented with the following meanings:

- **Total transfer time** – Time needed to accomplish a complete transfer cycle.
- **Waiting time** – Time spent by each cask waiting for other cask at a crossover location or in the gallery near the lift due to traffic constraints. The total waiting time is the sum of all casks' waiting time. It should be stressed that during a waiting period, a cask is stopped at a place different from a port or the lift, with low power consumption and reduced safety problems.
- **Moving time** – Time spent in motion by each cask plus the time spent entering and leaving the gallery lift (20 minutes). Total moving time is the sum of all casks' moving time.
- **Distance** – Distance travelled by each cask. Total travelled distance is the sum of all casks' travelled distance.

3. RESULTS AND DISCUSSION

For the graphic display of the simulations, a square schematic representation of the gallery (Figures 2–3 and 7–13) is used to simplify implementation, although maintaining the correct perimeter length.

3.1. *One Cask Moving at a Time (A)*

With only one cask moving at a time, no traffic problems arise, since all the paths are free to be used by the moving cask. The first consequence of this is a null waiting time for all casks. The first step is to move a loaded cask from the VV to the HCB. In this situation, there are four unloaded vehicles in the HCB ports. Therefore, a fifth port at the HCB must be available to park the first loaded vehicle, just arrived from the VV.
The initial position of each cask is shown in Figure 1 and the order in which casks are transferred between VV ports and HCB ports is 1-5, 2-6, 3-7 and, finally, 4-8.

Unidirectional motion in the gallery (A.1)
In Figure 2, the results of the cask transfer simulation are presented for the case where only unidirectional motion is allowed in the gallery.

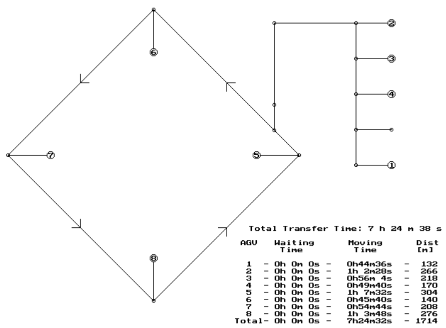


Fig. 2. Simulation results for unidirectional anticlockwise motion in the gallery and one cask moving at a time. Final stage of transfer cycle.

The total transfer time is 7h24m38s. The consequences of having only one cask moving at a time are null waiting time for all casks and total moving time equal to total transfer time. Total travelled distance is 1714 meters.

Bidirectional motion in the gallery (A.2)
With bidirectional motion in the gallery the results of the simulation are those presented in Figure 3. The total transfer time is 6h22m46s. Null waiting time for all casks and total moving time equal to total transfer time are, once again, consequences of having only one cask moving at a time. Total travelled distance is 1250 meters.

Discussion
Bidirectional motion in the gallery reduces about one hour the total transfer time and reduces the total travelled distance from 1714 to 1250 meters, because the shortest gallery path to/from the lift is chosen for each cask. No safety level decrease results from these reductions, since only one transfer cask is moving at a time.

Cask	Direction of motion in the gallery
1	anticlockwise
2	clockwise
3	clockwise
4	anticlockwise
5	clockwise
6	anticlockwise
7	anticlockwise
8	clockwise

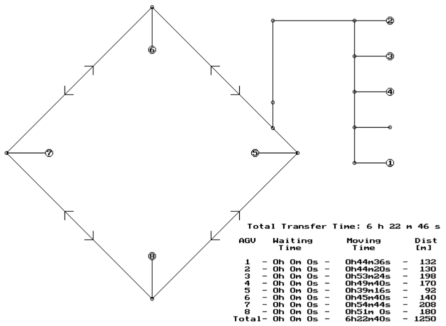


Fig. 3. Simulation results for bidirectional motion in the gallery and one cask moving at a time. Final stage of transfer cycle

3.2. *More Than One Cask Moving Simultaneously (B)*

Increasing the number of casks moving simultaneously is expected to decrease total transfer time. However, when more than one cask moves at a time, traffic congestions may arise. Three different solutions to handle this problem are analysed:

- Cask crossover using an extra path between the gallery lift and the HCB;
- Cask waiting state in the gallery, near the lift;
- Combination of the first two solutions, i.e., cask crossover and waiting state.

Due to structural constraints, the best place to create the extra path that allows cask crossover seems to be in the way between the gallery lift and the HCB transfer corridor as illustrated in Figure 4. The actual stage of Tokamak Building design does not accommodate that extra path. The required space will impose some changes in the laydown hall level between the gallery lift and the transfer corridor. Should a flexible guidance system be used, space for two near parallel paths is required. For instance, if inductive guidepath is used, two wires (one per path) should be installed.

Using the second solution, a cask remains at a waiting state in the gallery (near the lift) when it is willing to use the lift to go up and another cask is already using the lift to come down. If only unidirectional motion is allowed in the gallery, this situation will require no manoeuvres, as referred in Figure 5 for the possible situations when (a) the lift occupies the gallery, (b) the lift is apart from the gallery.

Bidirectional motion in the gallery is used to minimize the travelled distance between each VV port and the lift entrance. The minimum distance path is the one to be followed by the cask leaving the VV port (and going to the HCB) and also by the cask

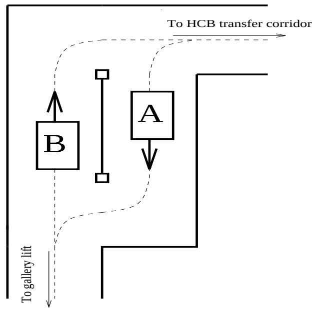
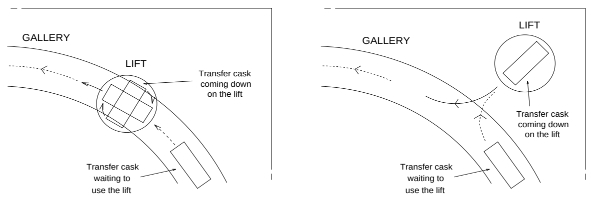


Fig. 4. Schematic representation of two paths between lift and transfer corridor.

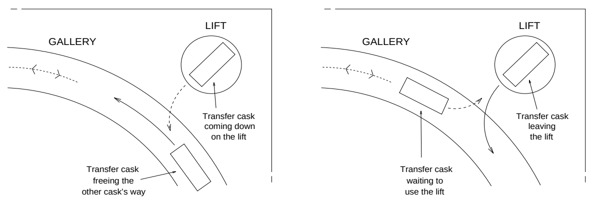


(a) The lift occupies the gallery
(b) The lift is apart from the gallery

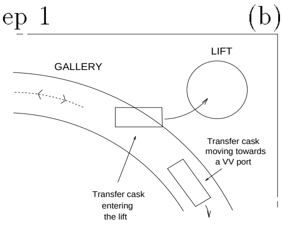
Fig. 5. Waiting state when only unidirectional motion is allowed in the gallery.

that left the HCB and travels towards that VV port. If the first cask (VV $\longrightarrow$ lift) travels clockwise in the gallery, the second (lift $\longrightarrow$ VV) will have to travel anticlockwise on the same physical path. As such, this strategy requires manoeuvring as illustrated in Figure 6. Such manoeuvres are only possible if the lift is not in the gallery, but at some distance from it, in order to allow casks to pass by the lift.

With more than one cask moving simultaneously, when one cask leaves a VV port, another cask leaves an HCB port, freeing it. Thus, the complete transfer operation can be accomplished with only four ports in the HCB.



(a) Step 1
(b) Step 2



(c) Step 3

Fig. 6. Waiting state and manoeuvring when bidirectional motion is allowed in the gallery.

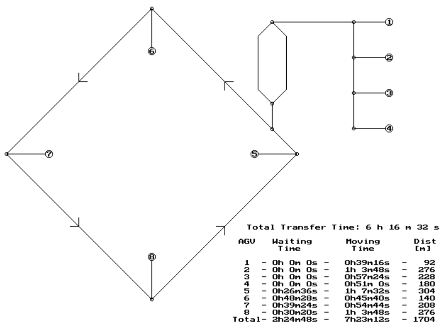


Fig. 7. Simulation results for cask crossovers between the lift and HCB corridor and unidirectional anticlockwise motion in the gallery. Two casks moving simultaneously. Final stage of transfer cycle.

3.2.1. *Cask crossovers between the lift and HCB corridor (B.1).* The simulations consider the situation when two casks (the one leaving a VV port and the one moving towards that port) move simultaneously. As the only considered possibility for crossover is on the way from the gallery lift to the HCB transfer corridor (see Figure 4), the lift is first used by the cask going up. The two physical paths represented on Figure 4 support the crossover, no manoeuvres being required.

The initial position of each cask is shown in Figure 1 and the order in which casks are transferred between VV ports and HCB ports is 1-5, 2-6, 3-7 and, finally, 4-8.

Unidirectional motion in the gallery (B.1.1)

Figure 7 presents the results of the simulation with crossovers between the lift and the HCB corridor and when only unidirectional motion is allowed in the gallery (see Figure 4). It shows that the total transfer time is 6h16m32s, the total waiting time of the casks are 2h24m48s and the total moving time is 7h23m12s. The total travelled distance is 1704 meters.

Bidirectional motion in the gallery (B.1.2)

If bidirectional motion is allowed in the gallery, the results are presented in Figure 8. It shows that the total transfer time is 5h14m40s, the total waiting time of the casks are 2h04m00s and the total moving time is 6h21m20s. The total travelled distance is 1240 meters.

Discussion

The total travelled distances in simulations **B.1.1** and **B.1.2** are 10 meters smaller than those of simulations **A.1** and **A.2**, respectively, because with casks moving simultaneously only four ports are required in the HCB.

These simulations show, once again, that it is advantageous to allow bidirectional motion in the gallery, as far as total travelling time is concerned. Only the casks moving from the HCB to the VV have waiting times – each of them has to wait between the HCB corridor and lift for a cask coming from the VV.

Cask	Direction of motion in the gallery
1	anticlockwise
2	clockwise
3	clockwise
4	anticlockwise
5	clockwise
6	anticlockwise
7	anticlockwise
8	clockwise

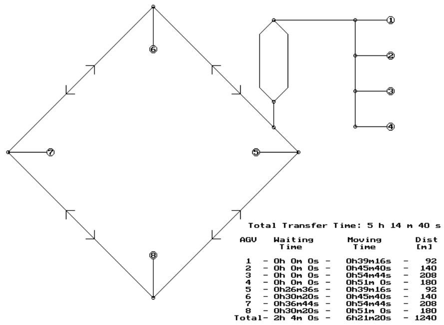


Fig. 8. Simulation results for cask crossovers between the lift and HCB corridor and bidirectional motion in the gallery. Two casks moving simultaneously. Final stage of transfer cycle.

3.2.2. *Cask waiting state in the gallery near lift (B.2).* The simulations for situation **B.2** consider that a single pair of casks leaving/reaching a specified VV port is moving at a time, coincidently with the assumptions made for situation **B.1**. When **B.2** is considered, the pair of casks will have to cross each other at the gallery level, near the lift. Therefore, the cask travelling from the HCB to the VV port will be the first to use the lift, while the second cask (the one that left the VV port) will be waiting near the lift to go up.

The initial position of each cask is shown in Figure 1 and the order in which casks are transferred between VV ports and HCB ports is 1-5, 2-6, 3-7 and, finally, 4-8.

Unidirectional motion in the gallery (B.2.1)

With cask waiting state in the gallery near the lift and with unidirectional motion in the gallery, the simulation results are those presented in Figure 9. Total transfer time is now 5h11m42s, total waiting time is 1h40m02s and total moving time is 7h23m12s. The total travelled distance is 1704 meters.

Bidirectional motion in the gallery (B.2.2)

Allowing bidirectional motion in the gallery, the results are those presented in Figure 10. Here, total transfer time is 5h22m22s, total waiting time is 1h56m34s and total moving time is 6h41m36s. The total travelled distance is 1392 meters.

Discussion

When waiting states are allowed in the gallery near the lift but not crossovers between the lift and the HCB corridor, the advantage of bidirectional motion in the gallery concerns only the total travelled distance. The smaller travelled distance requires, however, manoeuvres for the casks going up. When bidirectional motion in the gallery is allowed, the total transfer time becomes slightly higher. This is

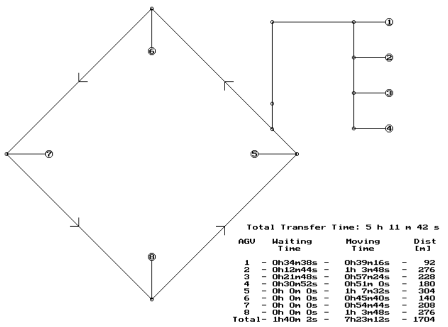


Fig. 9. Simulation results with casks waiting state in the gallery near lift and unidirectional anticlockwise motion in the gallery. Two casks moving simultaneously. Final stage of transfer cycle.

Cask	Direction of motion in the gallery
1	anticlockwise
2	clockwise
3	clockwise
4	anticlockwise
5	clockwise
6	anticlockwise
7	anticlockwise
8	clockwise

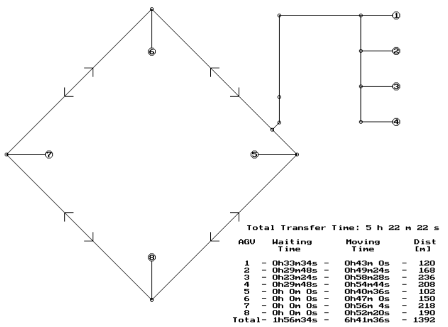


Fig. 10. Simulation results with casks waiting state in the gallery near lift and bidirectional motion in the gallery. Two casks moving simultaneously. Final stage of transfer cycle.

due to the 10 meters path introduced between the gallery and the lift that are not compensated with a length reduction of other paths.

3.2.3. *Cask crossovers between the lift and HCB corridor and casks waiting state in the gallery near lift (B.3).* In this case, a combination of cask crossovers between the lift and the HCB transfer corridor and cask waiting states in the gallery near the lift is used to solve traffic congestions. As such, the first cask to use the lift is not constrained, i.e., for each pair of casks to transfer, both the cask coming from the HCB and the cask coming from a VV port may be the first to use the lift. To optimize lift usage, for every lift trip a cask is carried. Therefore, the first cask to use the lift – the cask coming from the HCB or the one that left a VV port – is the same for all pairs of casks to transfer. The order in which the pairs of casks should be transferred also affects the total transfer time, though in some cases by a very small amount. To optimize lift usage

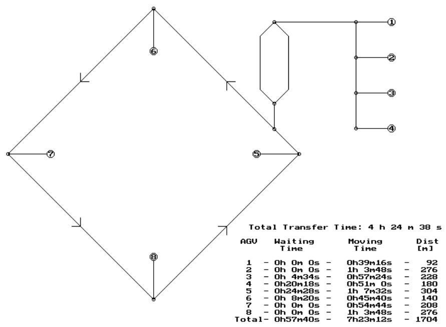


Fig. 11. Simulation results for cask crossovers between the lift and HCB corridor, waiting states in the gallery near lift and unidirectional anticlockwise motion in the gallery. Two casks moving simultaneously.

once again, the first pair to be transferred should be the one with casks initial location closer to the lift. The last pair to transfer should have casks destinations close to the lift to minimize the time consumed with the lift already stopped. Simulations have shown that the shortest time consuming transfer cycle is accomplished when the order to transfer pairs of casks is 1-5, 4-8, 3-7 and finally 2-6.
The results presented in the sequel correspond to the best schedule of cask pairs being transferred with the initial position of each cask shown in Figure 1.

Unidirectional motion in the gallery (B.3.1)
Figure 11 presents the results of the simulation when crossovers are possible in the gallery near the lift and between the lift and the HCB corridor, and only unidirectional motion in the gallery is allowed. Total transfer time is 4h24m38s, total waiting time is 57m50s and total moving time is 7h23m12s. The total travelled distance is 1704 meters.

Bidirectional motion in the gallery (B.3.2)
Allowing bidirectional motion in the gallery, two simulations were done with two and four as the maximum number of casks moving simultaneously.
With two casks moving simultaneously, total transfer time is 4h16m44s, total waiting time is 1h26m56s and total moving time is 6h36m48s. The total travelled distance is 1356 meters (see Figure 12).
Under this simulation scenario, the possibility of simultaneously moving four casks was also tested, in order to check whether it was advantageous to reduce total transfer time. With four casks moving simultaneously, total transfer time is 4h16m44s, total waiting time is 7h36m28s and total moving time is 6h36m48s. The total travelled distance is 1356 meters (see Figure 13).

Discussion
In this case, bidirectional motion in the gallery brings major reductions to the total transfer time and to the total travelled distance.
With bidirectional motion in the gallery, the increase from two to four, on the number of casks moving simultaneously, leads to no advantage: the

Cask	Direction of motion in the gallery
1	anticlockwise
2	clockwise
3	clockwise
4	anticlockwise
5	clockwise
6	anticlockwise
7	anticlockwise
8	clockwise

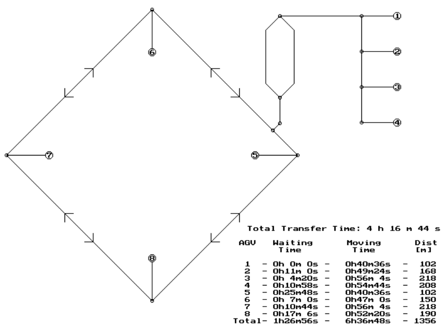


Fig. 12. Simulation results for cask crossovers between the lift and HCB corridor, waiting states in the gallery near lift and bidirectional motion in the gallery. Two casks moving simultaneously.

Cask	Direction of motion in the gallery
1	anticlockwise
2	clockwise
3	clockwise
4	anticlockwise
5	clockwise
6	anticlockwise
7	anticlockwise
8	clockwise

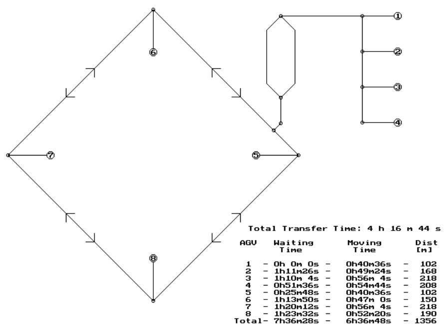


Fig. 13. Simulation results for cask crossovers between the lift and HCB corridor and in the gallery near lift and bidirectional motion in the gallery. Four casks moving simultaneously.

total transfer time, the total moving time and total travelled distance remain the same. However, the total waiting time changes (from 1h26m for two casks to 7h36m for four casks). This is due to the fact that with two casks moving simultaneously, the lift is already continuously used. The main conclusion is that the lift, namely the total time spent on lift related operations, is the major bottleneck of the whole system.

4. CONCLUSIONS

If neither cask crossovers between the lift and the HCB transfer corridor nor cask waiting states in the gallery are allowed, it is not possible to have more than one cask moving at a time. In this case (simulations **A.1** and **A.2**), the total moving time equals total transfer time and no waiting time exists. When more than one cask is allowed to move simultaneously, only four ports are needed in the HCB. In this case, total transfer time is smaller than total moving time because there are simultaneous movements. With bidirectional motion in the gallery, total travelled distance is significantly reduced because each vehicle uses the shortest path between the lift and the VV port. Generally, bidirectional motion also reduces total transfer time.
The smallest transfer time occurs when cask crossovers and waiting states are allowed (simulation **B.3.2**). With two casks moving simultaneously, the lift is optimally used. Therefore, allowing more casks to move simultaneously does not improve transfer time. Reducing the total travelled distance is an important achievement because it leads to higher power autonomy of the casks and/or lower capacity (thus lighter) batteries. It also decreases fault probability of vehicles increasing their reliability.
The gallery lift is the major bottleneck of the whole system. The smaller transfer time is obtained when the lift is optimally used. This occurs when it is always occupied, i.e., when a cask leaving it immediately gives room for another cask already waiting. Should lift performance be improved, or the installation of another lift considered, transfer times would decrease in all studied cases.

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