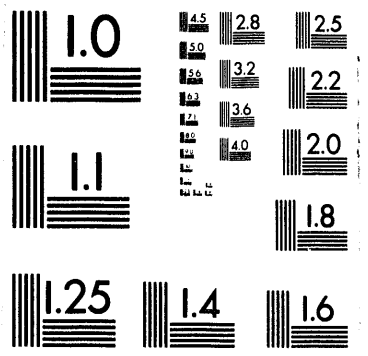
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Environmental Restoration and Waste Management Program

TASK ANALYSIS FOR THE SINGLE-SHELL TANK WASTE RETRIEVAL MANIPULATOR SYSTEM

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ABSTRACT

This document describes a task analysis for the Tank Waste Retrieval Manipulator System. A task analysis is a formal method of examining work that must be done by the operators of human-machine systems. The starting point for a task analysis is the mission that a human-machine system must perform, and the ending point is a list of requirements for human actions and the displays and controls that must be provided to support them.

The task analysis approach started with a top-down definition of the steps in a tank retrieval campaign. It started by dividing a waste retrieval campaign for one single-shell tank into the largest logical components (*mission phases*), then subdivided these into secondary components (*subfunctions*), and then further subdivided the secondary components into tertiary units (*tasks*). Finally, the tertiary units were divided into potentially observable operator behaviors (*task elements*). In the next stage of the task analysis, the task elements were evaluated by completing an electronic task analysis form patterned after one developed by the Nuclear Regulatory Commission for task analysis of nuclear power plant control rooms. In the final stage, the task analysis data base was used in a bottom-up approach to develop clusters of controls and displays called *panel groups* and to prioritize these groups for each subfunction. Panel groups are clusters of functionally related controls and displays. Actual control panels will be designed from panel groups, and panel groups will be organized within workstations to promote efficient operations during retrieval campaigns.

1. INTRODUCTION

This document describes a task analysis for the Tank Waste Retrieval Manipulator System (TWRMS). While the information contained in this document is tentative because the systems are still evolving, it provides a foundation for control room design efforts. These efforts will support the design of a test bed control room in the near future and an operational control room later.

The TWRMS will comprise systems capable of teleoperation and autonomous operations. While operating these systems, the crew will shift from continuous manual control (e.g., using master controllers) to symbolic interaction (e.g., selecting actions from a computer menu), depending on the circumstances. In other words, the human operator's contribution will range from controlling every movement of the machine by directly controlling servomotor operation to entering task-level commands. Specifically, operators will carry out some varying mix of five tasks: (1) programming: storing a behavioral repertoire via symbols, including words; (2) teaching: storing a behavioral repertoire by stepping through examples; (3) controlling: exercising continuous manual control; (4) commanding: control via manipulating symbols to trigger behavioral repertoires; and (5) monitoring: observing the machine perform commands and switching to another task as required. A control room for the TWRMS must include workstations that can support all five user tasks during waste tank remediation campaigns. This document provides supporting information for the design of such workstations. However, because the TWRMS is an emerging system, this analysis must be reviewed prior to developing final control room concepts to ensure that the process model and conclusions contained within it remain applicable.

Control room design must proceed systematically if it is to be effective. One approach is to follow three phases: (1) function analysis, (2) task analysis, and (3) design. A task analysis is a formal method of examining work that must be done by human users. The starting point for a task analysis is the mission that a human-machine system must perform, and the ending point is a list of requirements for human actions and the displays and controls that must be provided to support them. Between the start and the end is a process of dividing and subdividing the work into smaller yet significant components. The TWRMS task analysis began by defining the system mission based on information about the TWRMS mission and system concepts.[1] The second step was listing the system components and user functions needed to operate them.[2] The third step was to develop, based on what was known from the first two steps, a detailed list of tasks that might take place during waste retrieval. Section 2 lists the tasks necessary to complete a waste retrieval campaign for a single storage tank. The final step in the analysis was to use a formal task analysis method to examine the tasks, with the aim of discovering the human actions required to carry out the tasks, and the controls and displays necessary within each task. The task analysis method used was that developed for task analysis of nuclear power plant control rooms,[3] with some modifications to account for the special requirements of remote handling systems. Section 3 describes the outcomes of the task analysis.

The task analysis approach started with a top-down definition of the steps in a tank remediation campaign. It started by dividing a waste retrieval campaign for one single-shell tank into the largest logical components, then subdivided these into secondary components, and then further subdivided the secondary components into tertiary units. Finally, the tertiary units were divided into potentially observable operator behaviors. The highest level components are called *mission phases*, the secondary components are called *subfunctions*, the tertiary units are called *tasks*, and the observable operator behaviors are called *task elements*.

In the next stage of the task analysis, the list of mission phases, subfunctions, tasks, and task elements was evaluated by completing an electronic task analysis form patterned after one developed by the Nuclear Regulatory Commission (NRC) for task analysis of nuclear power plant control rooms. The task analysis form allows determination of the controls and displays necessary for each task element, and the entire set of completed forms provides a task analysis data base for tank remediation.

In the final stage of the task analysis, the task analysis data base was used in a bottom-up approach to develop clusters of controls and displays called *panel groups* and to prioritize these groups for each subfunction. Panel groups are clusters of functionally related controls and displays. Actual control panels will be designed from panel groups, and panel groups will be organized within workstations to promote efficient operations during remediation campaigns.

The task analysis assumes that the TWRMS gantry is in place over the subject tank and that the long reach manipulator (LRM) and auxiliary systems are ready for activation. The mission profile is based on the operating scenario for single-shell tank (SST) remediation described in the retrieval manipulator specification.[1]

2. TASK LIST

This section lists the tasks that must be performed to complete a waste tank retrieval campaign for one tank and defines the starting point, events, and ending point that comprise each task. Because this is a developing system, the information necessary for this evaluation had to be derived from documentation and could not be directly observed. As a consequence, descriptions of the mission phases and tasks must be somewhat speculative and, therefore, the description of the campaign is hypothetical to some degree. In other words, this document describes how tank remediations **might be** carried out, not how they are carried out. However, it is a reasonable approximation of the activities that will take place; the task descriptions contained in this document are best estimates of what an SST remediation campaign will be like and provide a baseline for human-machine interface development. As better information becomes available, it will be incorporated as required.

The retrieval effort for one tank may be called a mission; within the mission there are key milestones that must be accomplished and these milestones delineate mission phases. Within each mission phase there exist functions that must be done to successfully complete the mission phase. For example, in the first mission phase the auxiliary television system (Aux. TV) must be activated, the Aux. TV must be inserted into the tank, the tank interior must be inspected, and a strategy (sequence) for cutting the risers must be developed. These secondary units are the subfunctions. Each subfunction comprises an *initiator*, the event or condition that requires or allows the subfunction; a *task sequence*, the sequential list of tasks that operators must complete; and a *sequence terminator*, the event or condition that is the goal of the subfunction. The tertiary units are tasks. A task is a set of human behaviors executed to fulfill a goal-directed strategy. The task sequence is a set of tasks carried out to fulfill the goal of the subfunction. Tasks are composed of task elements, which are human behaviors required to complete the task.

The following sections list the mission phases and the subfunctions within mission phases. Within each subfunction, the initiator at the start is listed, followed by a sequential list of tasks required and the terminator for the subfunction. The initiator is the status of the system at the start of the subfunction, and the terminator is the goal status of the system for the subfunction. The emphasis in this list is on user tasks, so certain aspects of system functioning are not present. For example, during waste removal the operation of the waste conveyance system is not mentioned. Even though this is an important part of system functioning, it does not require any user behavior beyond manual control of the TWRMS and monitoring system status. Therefore, it is not explicitly listed although it must be running for the waste retrieval end effector to function properly.

Perhaps a better way to understand the retrieval campaign is through examining a task network model, which provides a flow chart for the campaign. A task network model was developed using the MicroSAINT software package and is presented in all figures. Each mission phase, subfunction, and task element is clearly represented; however, the tasks in some subfunctions are not well defined. In all of the figures, task elements are represented by ovals, subfunctions and mission phases by boxes, multiple path events by diamonds labeled with an

"M," tactical decisions (operator choices) by diamonds labeled with a "T," and the conclusion of a subfunction with a circle. The flow of work through the model is represented by arrows.

2.1 MISSION PHASES

As Fig. 1 illustrates, there are three mission phases during a TWRMS campaign: (1) Insert TWRMS equipment into the tank. (2) Remove waste layers. (3) Remove TWRMS equipment from the tank. The first mission phase starts with the TWRMS in place above a tank and ready for activation and ends when the TWRMS is in place in the tank and ready to begin waste retrieval. The second mission phase starts at the end of the first phase and ends when all retrievable waste has been removed from the tank. The third and final mission phase starts at the end of the second phase and ends when the TWRMS has been removed from the tank.

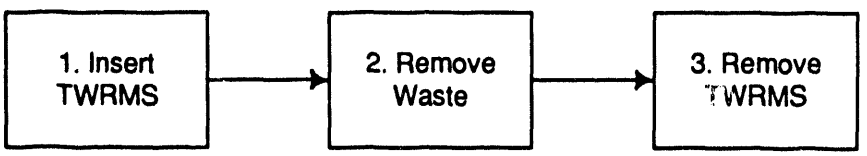

Fig. 1. Mission phases during a tank remediation campaign.

2.2 FIRST MISSION PHASE: INSERT TWRMS EQUIPMENT

During this phase of the mission, the crew takes the auxiliary closed-circuit television (Aux. CCTV) system from an inactive (cold) state to operational readiness within an SST. At the start of the mission phase the TWRMS gantry is in place over the tank and an access port has been prepared. At the end of the mission phase the Aux. CCTV is in the tank, the interior of the tank has been inspected, and a strategy for the first series of cutting operations (if necessary) has been prepared. Figure 2 illustrates the subfunctions within the first mission phase.

2.2.1 Activate Aux. CCTV System

The goal of this subfunction is to safely turn on the power to the Aux. CCTV system and verify that it is operational and ready for insertion. Figure 3 illustrates the task elements in this subfunction.

2.2.1.1 Initiator

TWRMS is in place over SST access port.

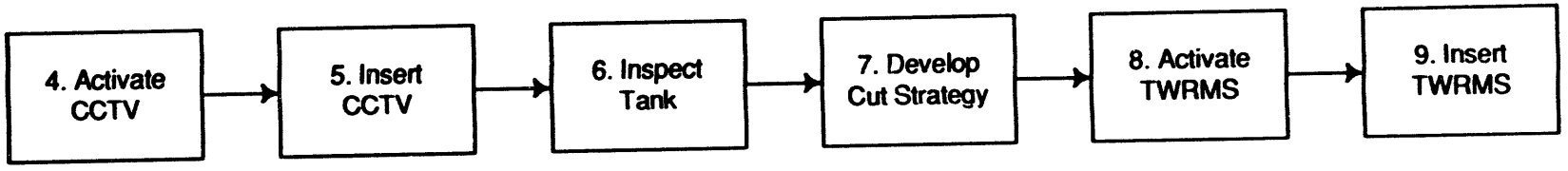

Fig. 2. Subfunctions during the first mission phase.

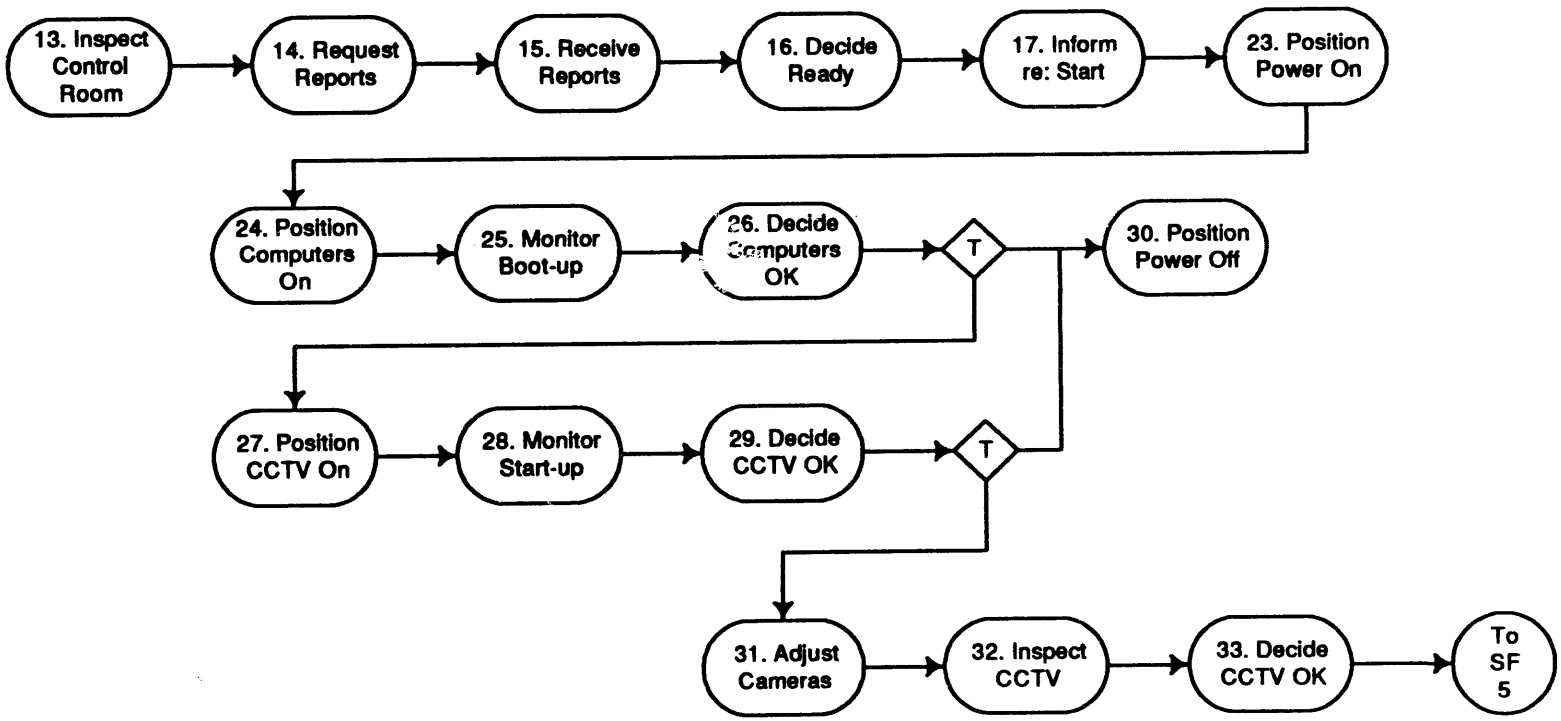

Fig. 3. Task elements during the subfunction "Activate Aux. CCTV System."

2.2.1.2 Task sequence

1. Prepare for Aux. CCTV system activation.
2. Activate Aux. CCTV system.
3. Verify that Aux. CCTV system is functioning properly.

2.2.1.3 Terminator

Aux. TV system is ready for insertion.

2.2.2 Insert Aux. CCTV System into SST

During this subfunction, the crew inserts the Aux. CCTV system into the tank and then verifies that it is in place and functioning properly. The insertion may be teleoperated, using continuous manual control, or it may be automated, in which case the crew would initiate a robotic routine and monitor the progress of the insertion. The best approach to the insertion should be determined on a tank-by-tank basis, depending upon the amount of pre-insertion inspection that has been done and the amount of clutter present around the tank entrance. Figure 4 illustrates the task elements in this subfunction.

2.2.2.1 Initiator

Aux. CCTV system is ready for insertion.

2.2.2.2 Task sequence

1. Choose insertion mode (manual or robotic).
2. Manually insert Aux. CCTV into tank.
3. Initiate robotic Aux. CCTV insertion.
4. Monitor robotic Aux. CCTV insertion.
5. Confirm that Aux. TV system is in place and functioning.

2.2.2.3 Terminator

Aux. TV system is in place and functioning.

2.2.3 Inspect Tank Interior

During this subfunction, the crew inspects the interior of the tank and records the location and description of visible in-tank hardware (ITH) and risers with the ultimate purpose of developing a sequence or strategy for cutting these pieces into removable shapes. Figure 5 illustrates this subfunction.

2.2.3.1 Initiator

Aux. TV system is in place and functioning.

2.2.3.2 Task sequence

1. Inspect tank interior using Aux. TV.
2. Record riser and ITH locations and descriptions.

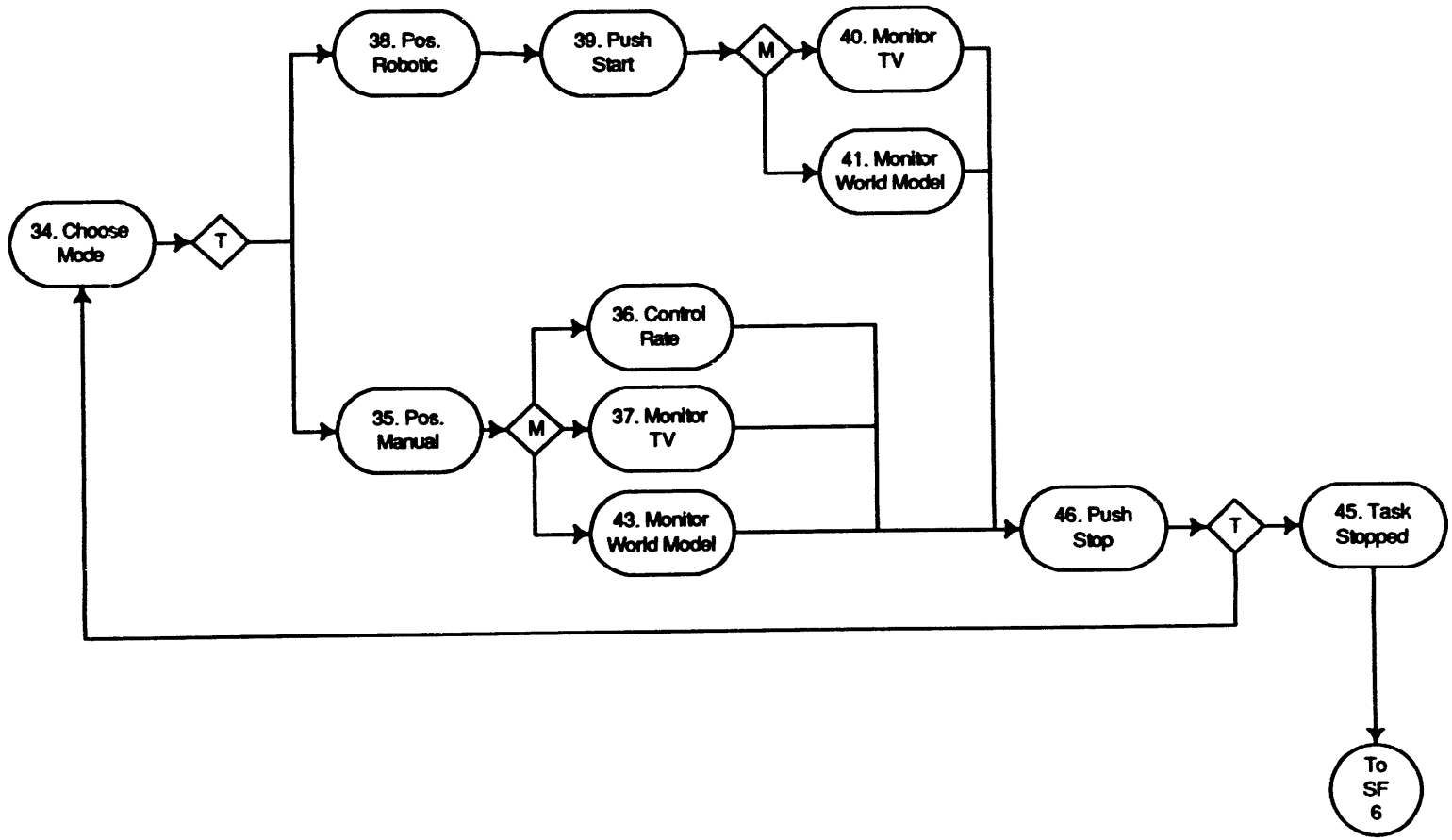

Fig. 4. Task elements during the subfunction "Insert Aux. CCTV System into SST."

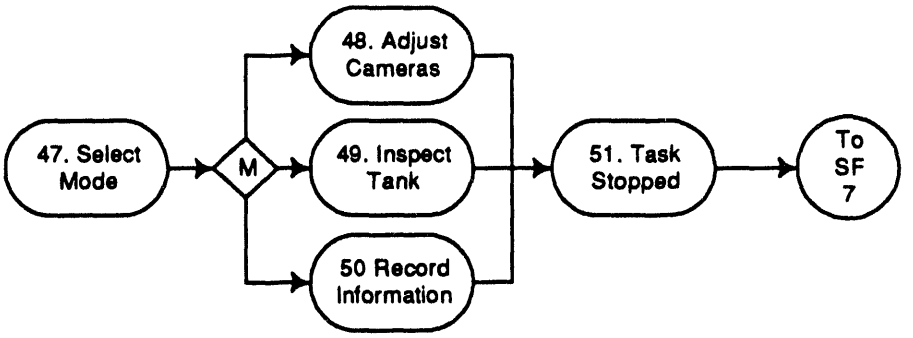

Fig. 5. Task elements during the subfunction "Inspect Tank Interior."

2.2.3.3 Terminator

Risers and ITH are noted, located on tank map, and described in operations log.

2.2.4 Develop Riser Cutting Strategy

During this subfunction, the crew decides upon a riser/ITH cutting sequence and records it in the operations log. (The operations log should be an electronic diary of operations and events and should have the capability of translating a cutting sequence into world map coordinates.) Figure 6 illustrates this subfunction.

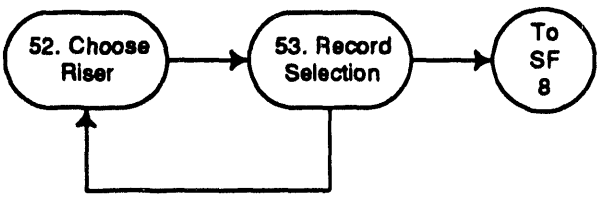

Fig. 6. Task elements during the subfunction "Develop Riser Cutting Strategy."

2.2.4.1 Initiator

Risers and ITH are noted, located on tank map, and described in operations log.

2.2.4.2 Task sequence

1. Develop riser cutting sequence.
2. Record riser cutting sequence in operations log.

2.2.4.3 Terminator

Riser cutting sequence is recorded.

2.2.5 Activate TWRMS

During this subfunction, the crew turns on the power to the TWRMS and prepares it for insertion into the tank. Figure 7 illustrates this subfunction.

2.2.5.1 Initiator

Aux. CCTV is in the tank, and TWRMS is in place over the access port.

2.2.5.2 Task sequence

1. Prepare to activate TWRMS.
2. Activate TWRMS.
3. Verify that TWRMS is functioning properly.

2.2.5.3 Terminator

TWRMS is functioning properly.

2.2.6 Insert TWRMS

During this subfunction, the crew inserts the TWRMS into the tank and then verifies that it is in place and functioning properly. The insertion may be teleoperated, using continuous manual control, or it may be automated, in which case the crew would initiate a robotic routine and monitor the progress of the insertion. The best approach to the insertion should be determined on a tank-by-tank basis, depending upon the amount of pre-insertion inspection and the amount of clutter present around the tank entrance. Figure 8 illustrates the task elements in this subfunction.

2.2.6.1 Initiator

TWRMS is functioning properly.

2.2.6.2 Task sequence

1. Choose TWRMS insertion mode (manual or robotic).
2. Manually insert TWRMS into tank.
3. Initiate robotic TWRMS insertion.
4. Monitor robotic TWRMS insertion.
5. Confirm that TWRMS is in place and functioning.

2.2.6.3 Terminator

TWRMS is in place in tank.

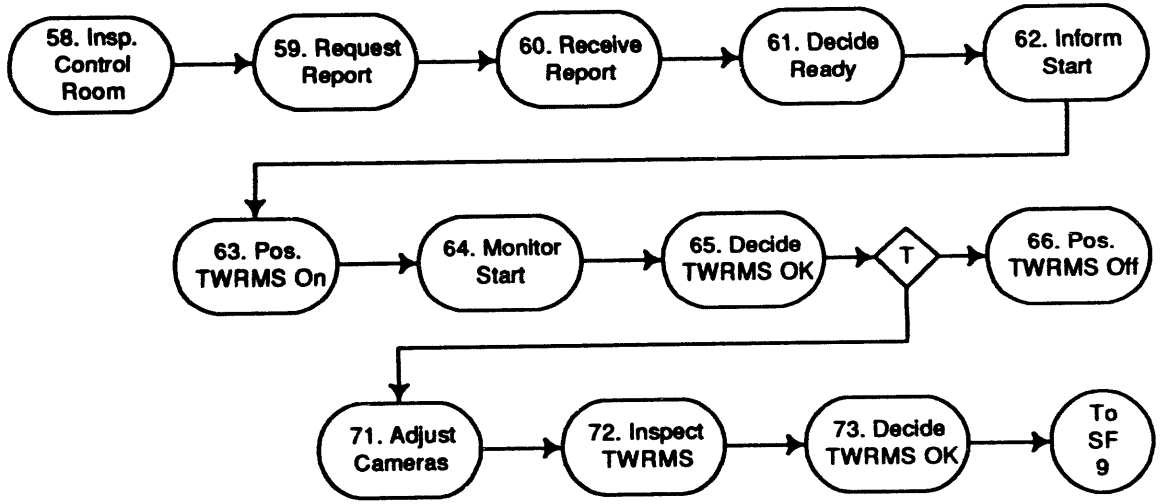

Fig. 7. Task elements during the subfunction "Activate TWRMS."

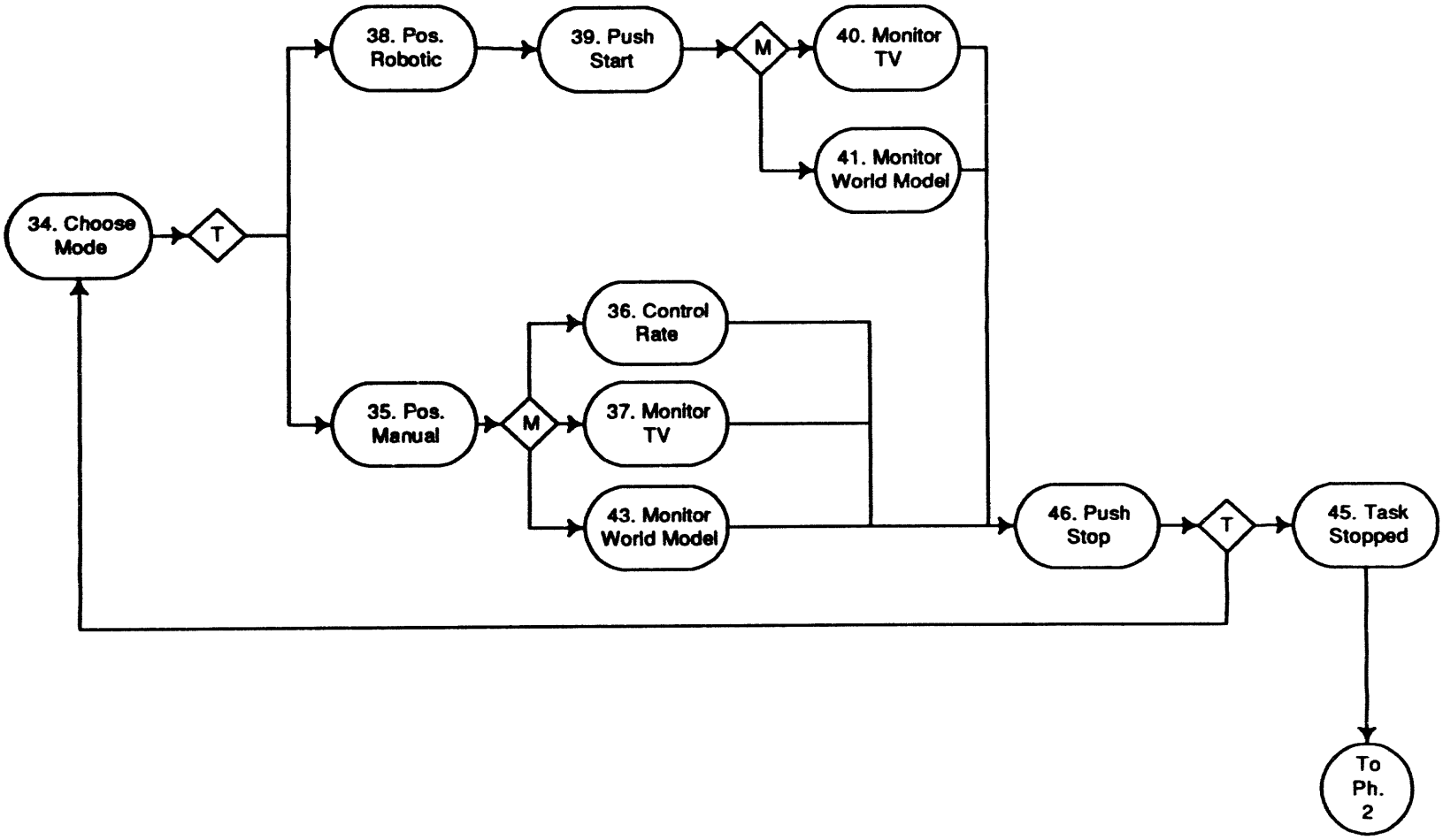

Fig. 8. Task elements during the subfunction "Insert TWRMS."

2.3 SECOND MISSION PHASE: REMOVE WASTE LAYERS

During the second mission phase, risers, ITH, and waste are removed in an iterative process. The mission phase starts with the complete TWRMS operational inside the tank, and it ends with all the risers, ITH, and waste removed from the tank. Figure 9 illustrates the subfunctions in this mission phase; the loop from the end of the fourth subfunction (Remove Waste Layer) to the first subfunction (Cut Risers/ITH) indicates the iterative nature of the process. The iterations could represent the number of layers that must be removed or the number of mines, or pits, dug into the waste by end effectors; the labels used in the current document refer to layers but could just as easily refer to mines or pits.

2.3.1 Cut Risers/ITH

This subfunction is executed repetitively until all risers and ITH are cut into manageable segments, down to the level of the existing waste layer. Figure 10 illustrates the tasks within the subfunction, and Figs. 11–14 illustrate the task elements within each task. Riser/ITH cutting may be teleoperated or automated, depending on the capabilities of the TWRMS. The most efficient scenario may be a combined teleoperated/robotic approach in which the TWRMS moves from workspace to workspace (i.e., from one riser location to the next), approaches to within 3 to 6 in. of the riser, and then requests that the crew intervene to do the actual cutting.

2.3.1.1 Initiator

TWRMS is operational in tank.

2.3.1.2 Task sequence

1. Map waste surface (see Fig. 11).
2. Teach riser cutting sequence (see Fig. 12).
3. Robotically cut risers (see Fig. 13).
4. Manually cut risers (see Fig. 14).

2.3.1.3 Terminator

Risers/ITH cut into manageable sections.

2.3.2 Remove Cut-up Risers/ITH

During this subfunction the sectioned risers and ITH that have fallen onto the waste surface are picked up, placed in the conveyance system, and removed from the tank (these may be removed as they are cut instead). Figure 15 illustrates the tasks in this subfunction, and Figs. 16–20 illustrate the task elements within each task. This operation may be done by teleoperation or robotically, but it is unlikely that robotic operations will be efficient given the high variability likely to occur in the waste surface and section locations; it may be best to do the entire retrieval by teleoperation.

2.3.2.1 Initiator

Risers/ITH are cut into manageable sections.

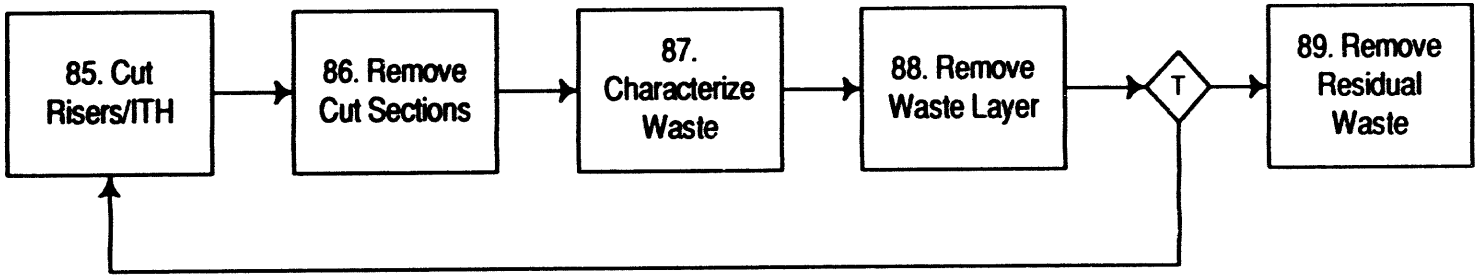

Fig. 9. Subfunctions during the second mission phase.

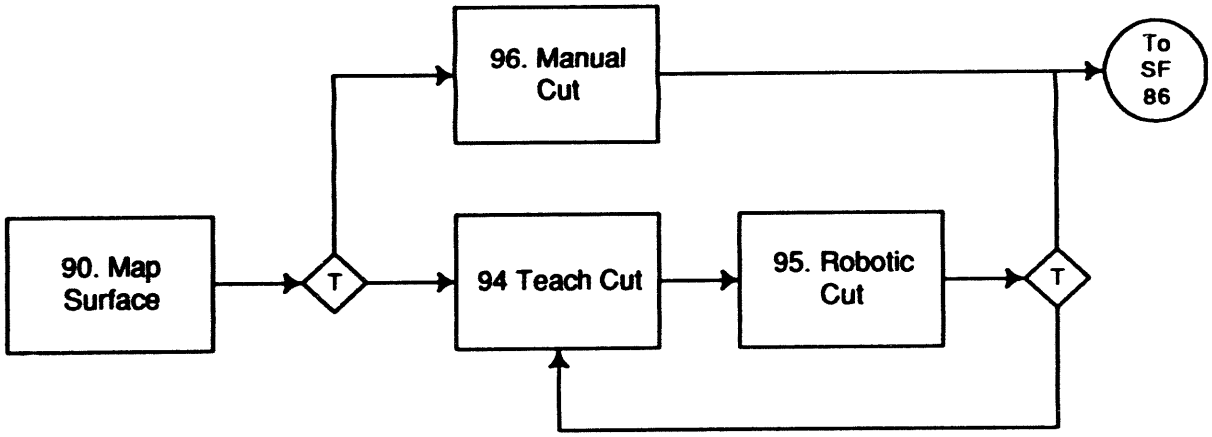

Fig. 10. Tasks during the subfunction "Cut Risers/ITH."

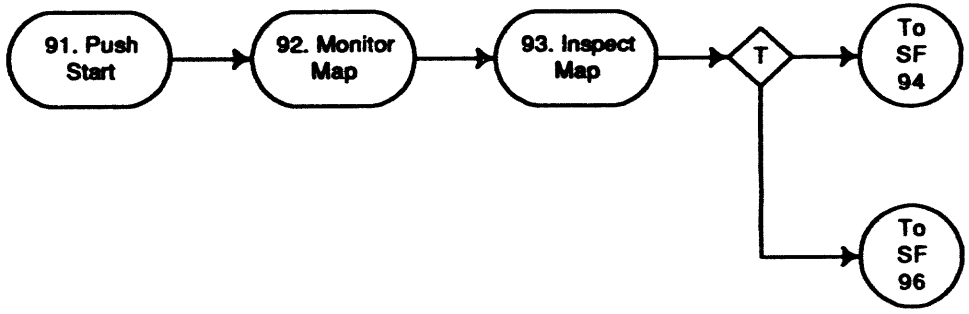

Fig. 11. Task elements during the task "90. Map Surface."

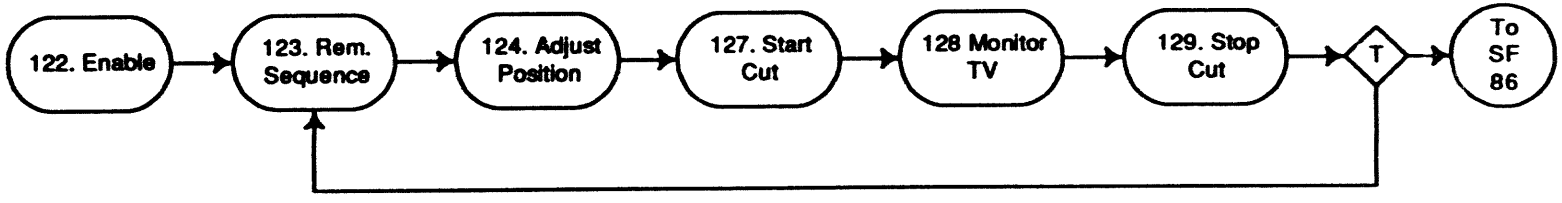

Fig. 12. Task elements during the task "96. Manual Cut."

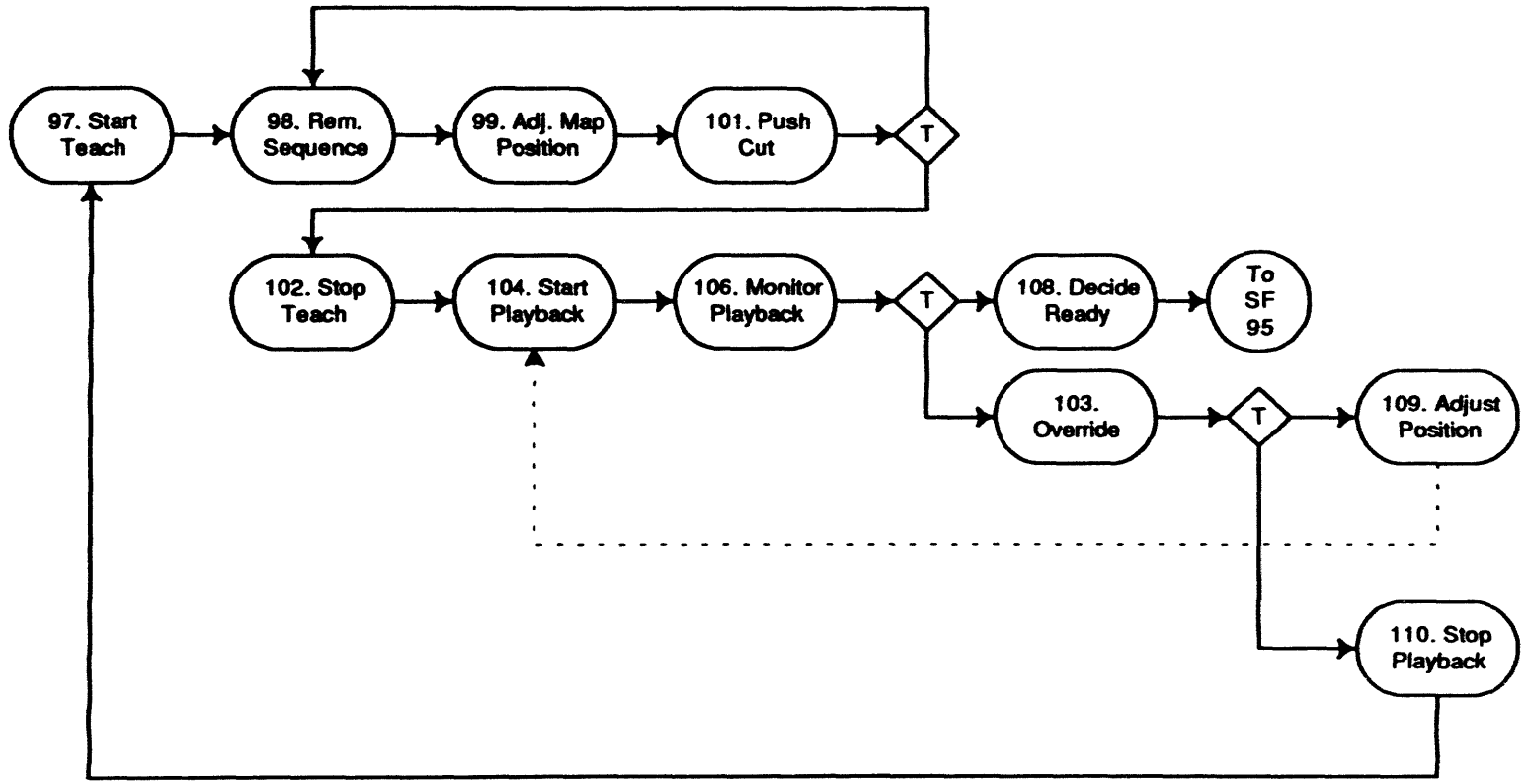

Fig. 13. Task elements during the task "94. Teach Cut."

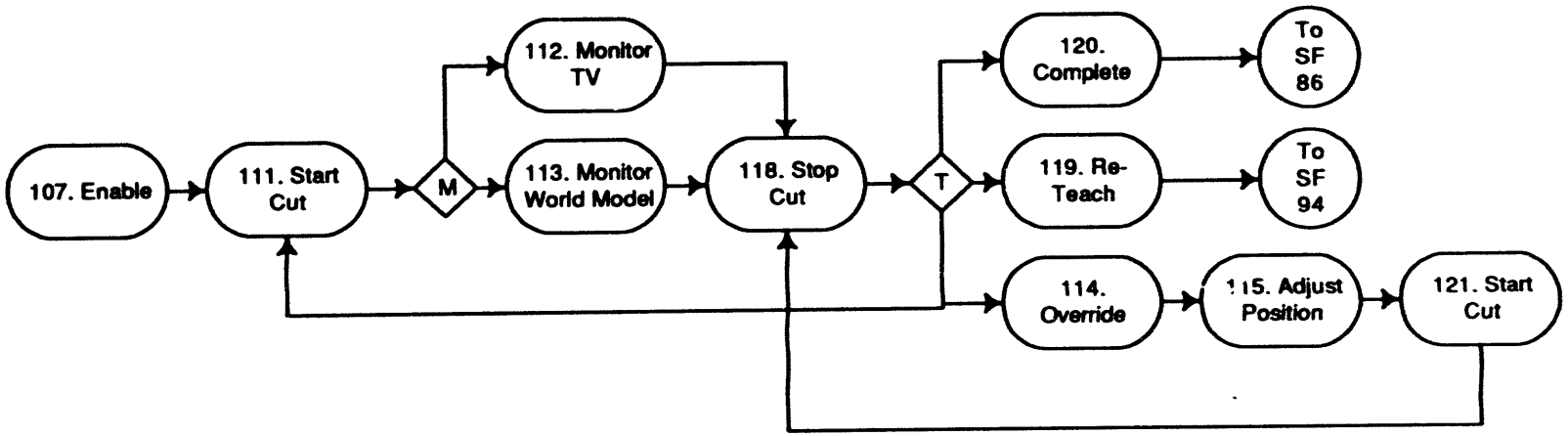

Fig. 14. Task elements during the task "95. Robotic Cut."

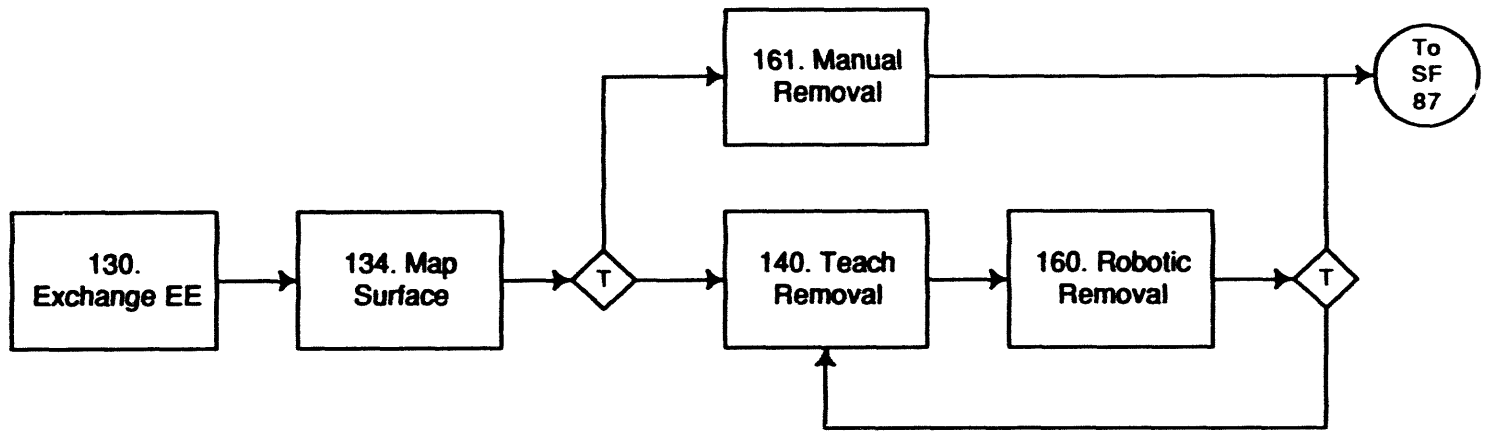

Fig. 15. Tasks during the subfunction "Remove Cut-up Risers/ITH."

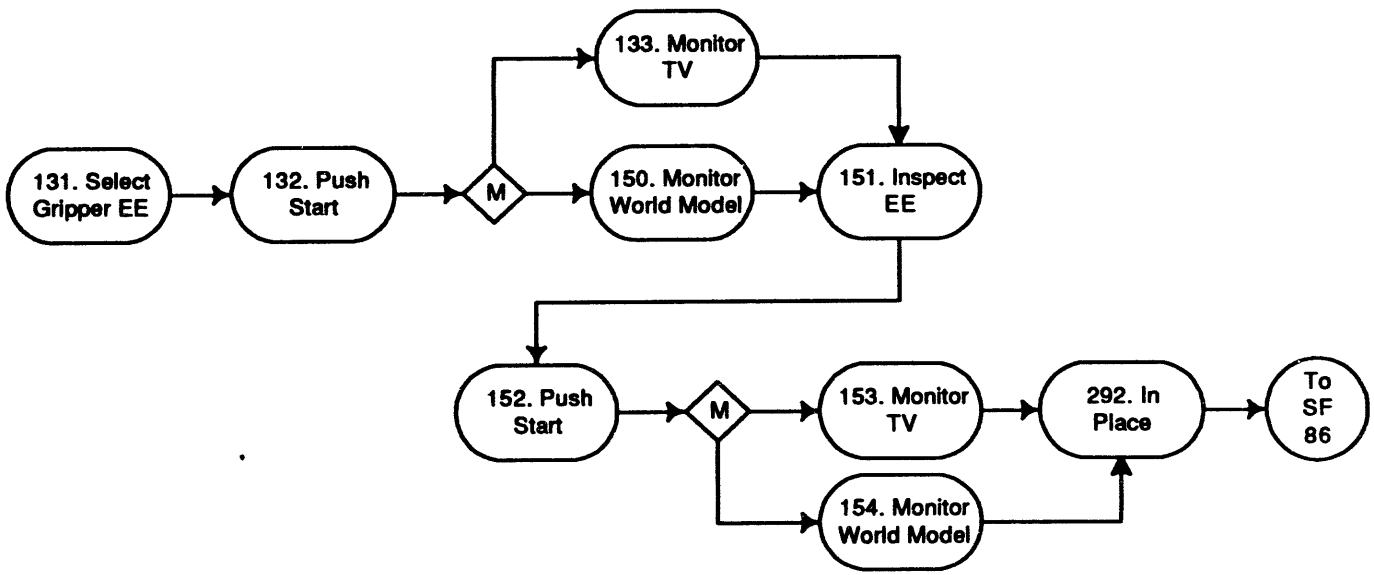

Fig. 16. Task elements during the task "130. Exchange EE."

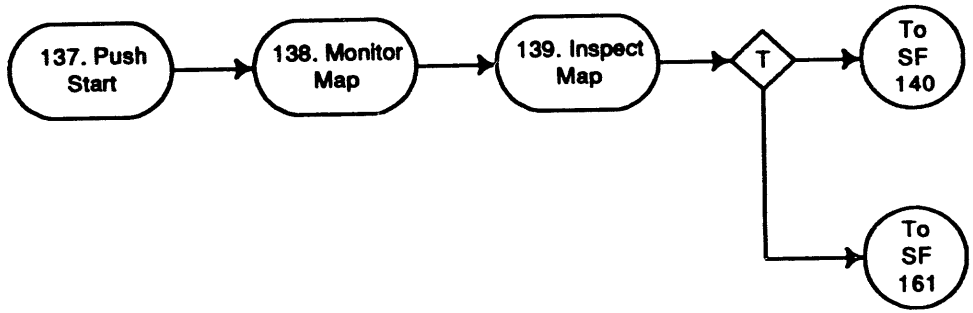

Fig. 17. Task elements during the task "134. Map Surface."

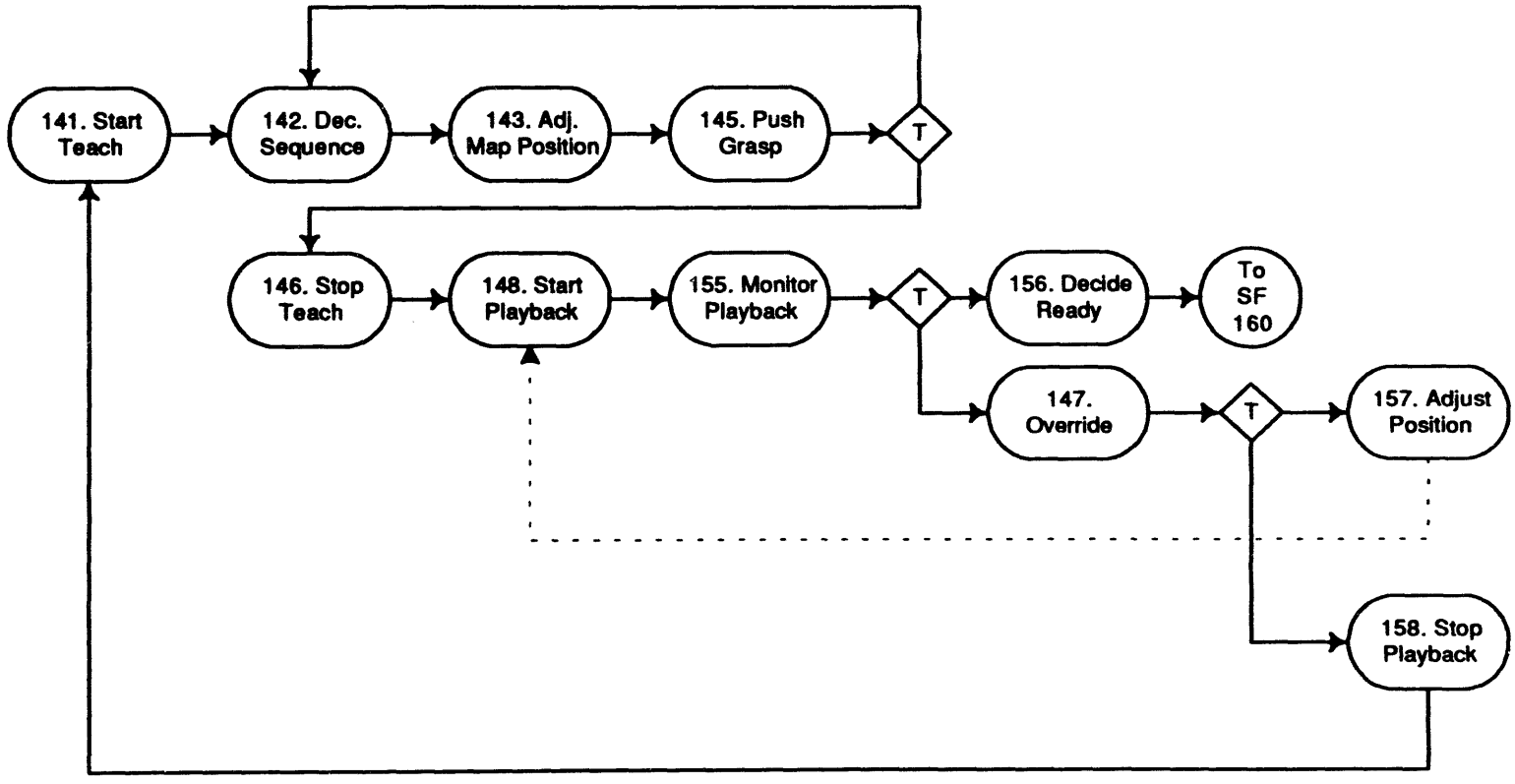

Fig. 18. Task elements during the task "140. Teach Removal."

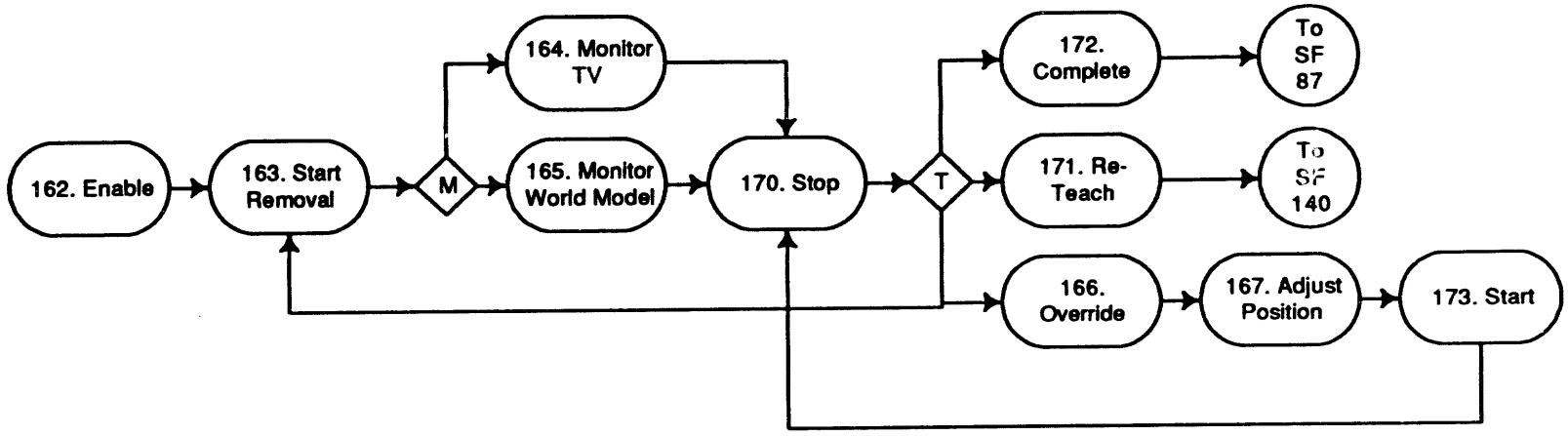

Fig. 19. Task elements during the task "160. Robotic Removal. "

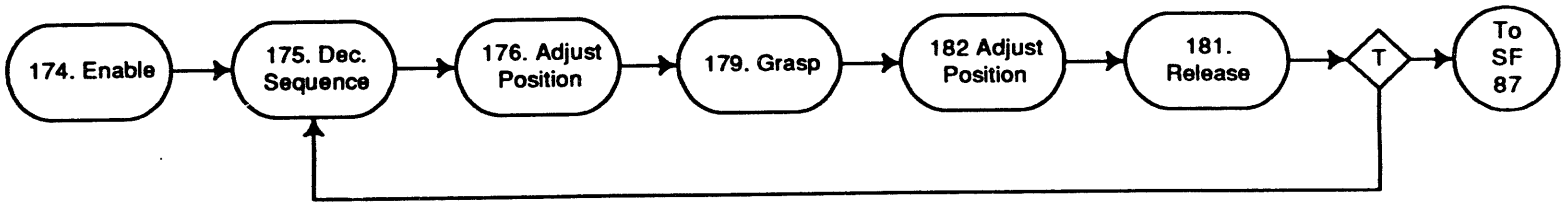

Fig. 20. Task elements during the task "161. Manual Removal."

2.3.2.2 Task sequence

1. Exchange cutting end effector for gripper end effector (Fig. 16).
2. Map waste surface (Fig. 17).
3. Teach riser/ITH removal sequence (Fig. 18).
4. Robotically remove riser/ITH sections (Fig. 19).
5. Manually remove riser/ITH sections (Fig. 20).

2.3.2.3 Terminator

Risers/ITH are removed from the tank.

2.3.3 Characterize Waste

During this subfunction the waste surface and subsurface are mapped and characterized. Figure 21 illustrates the tasks in this subfunction, and Figs. 22–24 illustrate the elements within each task.

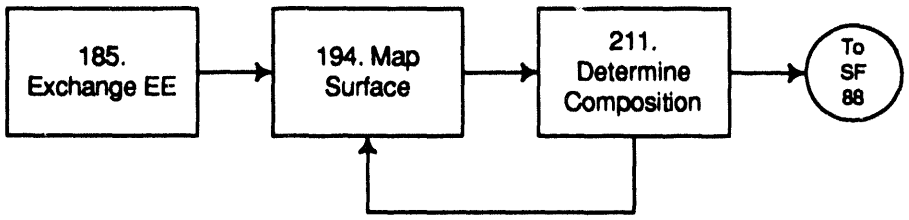

Fig. 21. Tasks during the subfunction "Characterize Waste."

2.3.3.1 Initiator

Risers/ITH are out of the tank.

2.3.3.2 Task sequence

1. Exchange gripper for mapping end effector (Fig. 22).
2. Map waste surface (Fig. 23).
3. Determine waste composition (Fig. 24).

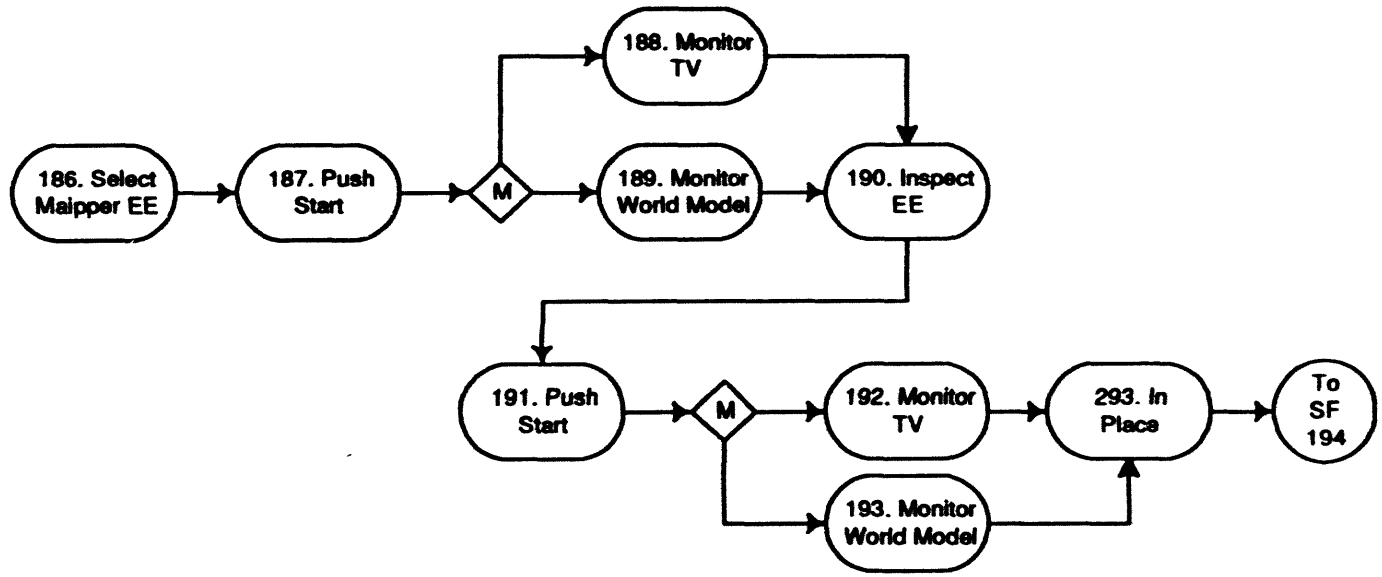

Fig. 22. Task elements during the task "185. Exchange EE."

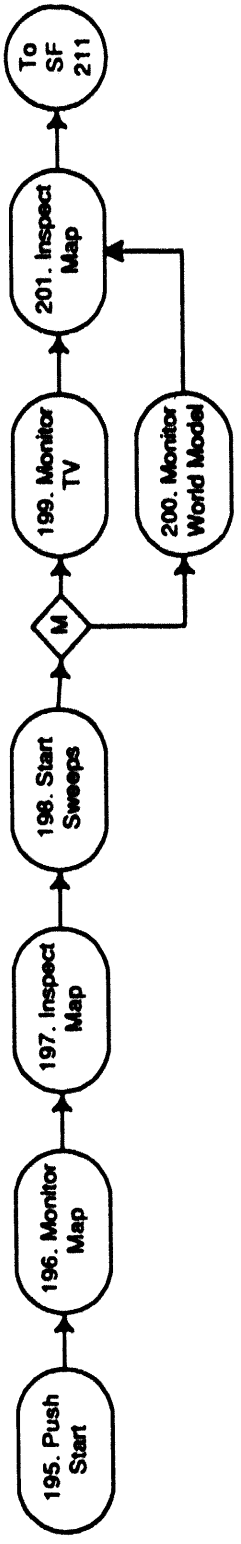

Fig. 23. Task elements during the task "194. Map Surface."

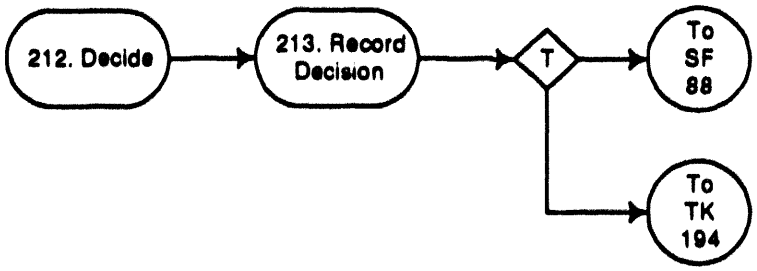

Fig. 24. Task elements during the task "211. Determine Composition."

2.3.3.3 Terminator

Waste is mapped and characterized.

2.3.4 Remove Waste Layer

During this subfunction a layer of waste is removed using the appropriate waste dislodging and capture tools. At the end of a repetition, the process is restarted with riser cutting or continues to tank cleaning. Figure 25 illustrates the tasks within this subfunction, and Figs. 26–28 illustrate the task elements within each task. The subfunction may be completed using teleoperation or robotically, but given the low rates (3 in./s) and the positioning tolerances (within 1 in. of the surface for some) required by the end effectors, it will be difficult for the crew to maintain the appropriate pace and position. Therefore, automation is the preferred option; operator aiding though end-effector path restrictions could also be used for these end-effector performance regimes.

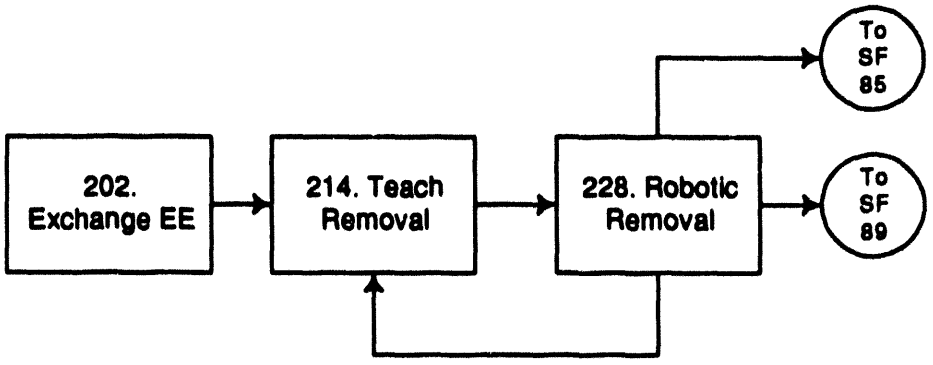

Fig. 25. Tasks during the subfunction "Remove Waste Layer."

2.3.4.1 Initiator

Waste is mapped and characterized.

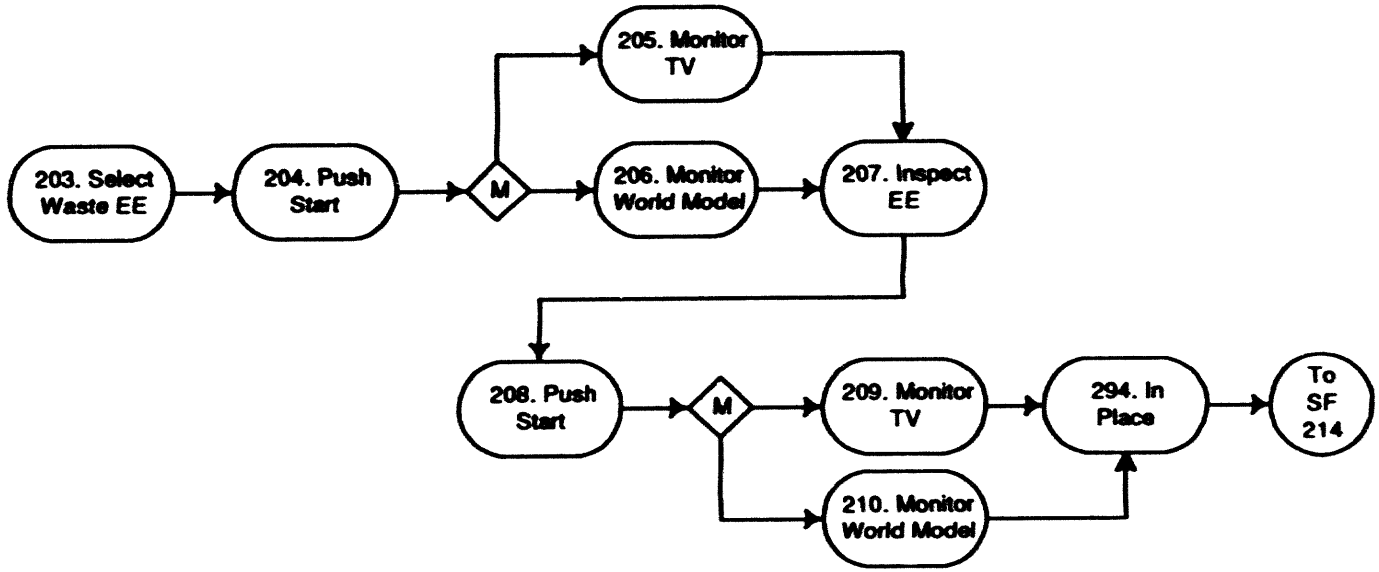

Fig. 26. Task elements during the task "202. Exchange EE."

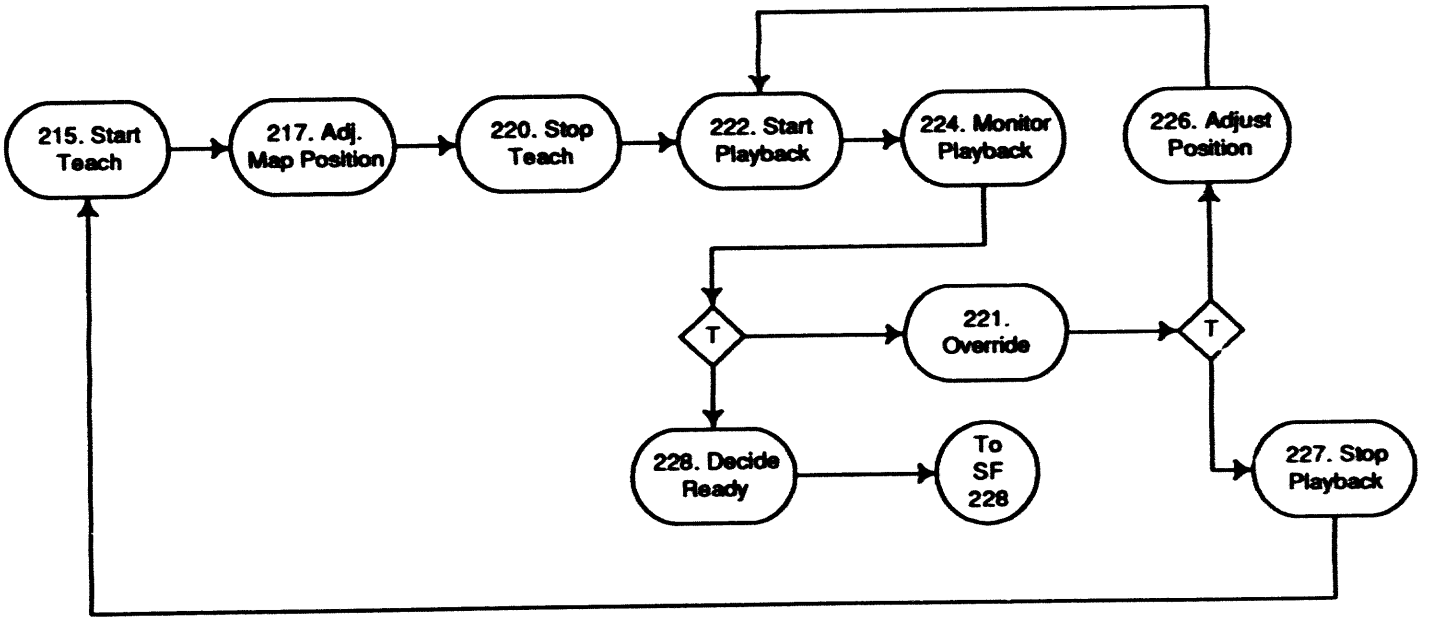

Fig. 27. Task elements during the task "214. Teach Removal."

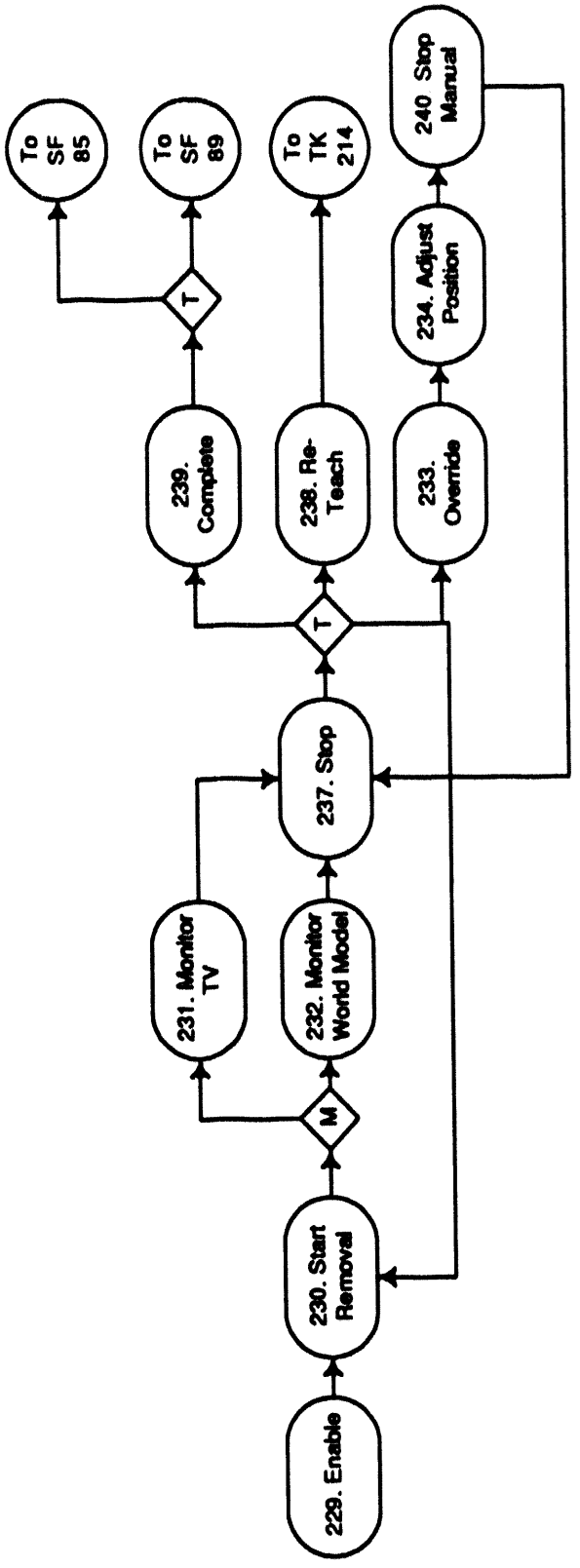

Fig. 28. Task elements during the task "228. Robotic Removal."

2.3.4.2 Task sequence

1. Exchange mapping end effector for waste removal end effector (see Fig. 26).
2. Teach robotic removal sequence (see Fig. 27).
3. Execute robotic removal (see Fig. 28).

2.3.4.3 Terminator

Waste layer is removed.

2.3.5 Remove Residual Waste

During this subfunction, the waste remaining after the last layer has been removed is cleaned from the walls and bottom of the tank. Figure 29 illustrates the tasks in this subfunction, and Figs. 30–33 illustrate the task elements within each task. Once again, automated robotic removal is the preferred option because of the anticipated slow work rate of the end effector.

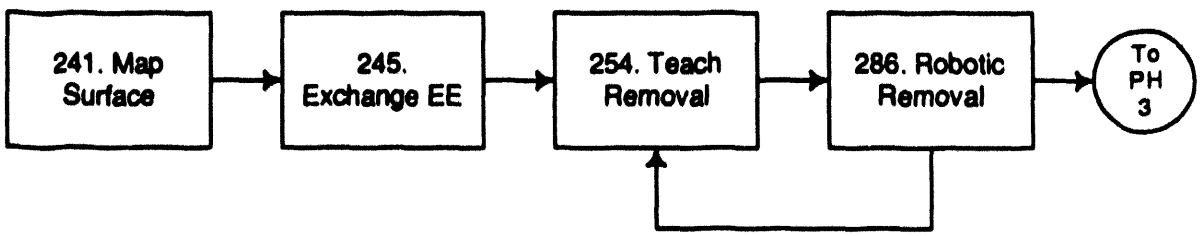

Fig. 29. Tasks during the subfunction "Remove Residual Waste."

2.3.5.1 Initiator

Last layer of waste is removed.

2.3.5.2 Task sequence

1. Map tank surface (see Fig. 30).
2. Exchange waste removal end effector for cleaning end effector (see Fig. 31).
3. Teach robotic removal (see Fig. 32).
4. Execute robotic removal (see Fig 33).

2.3.5.3 Terminator

Residual waste is removed.

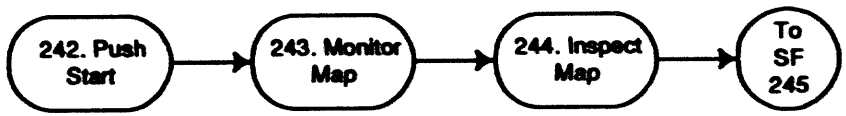

Fig. 30. Task elements during the task "214. Map Surface."

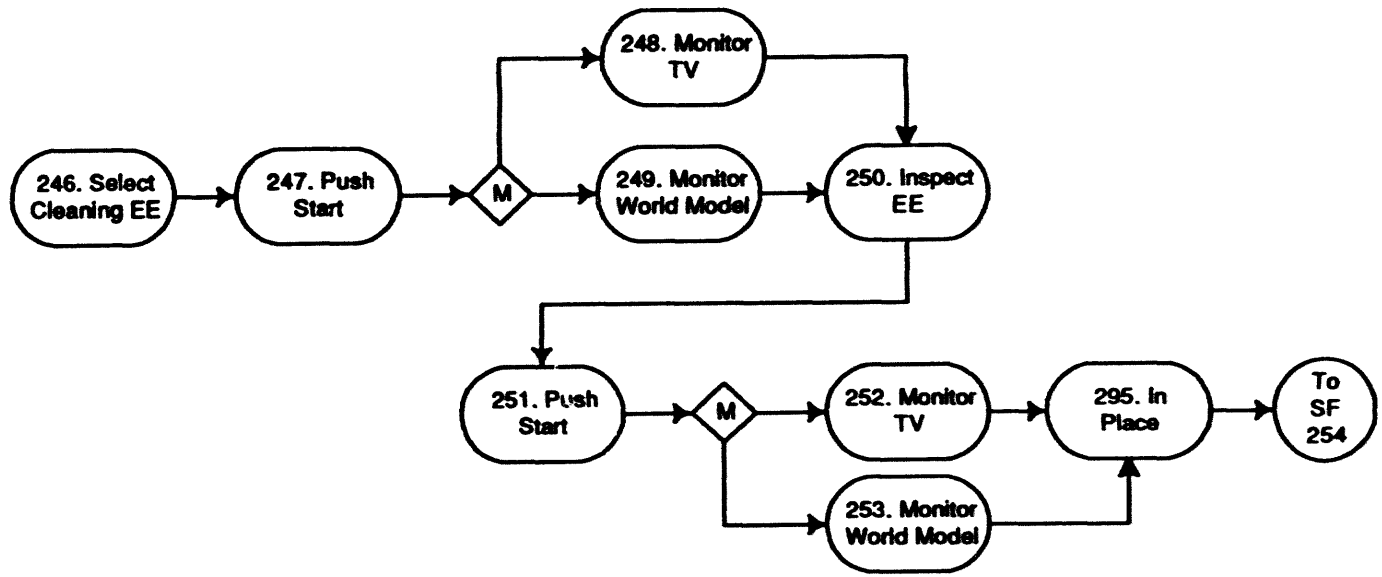

Fig. 31. Task elements during the task "245. Exchange EE."

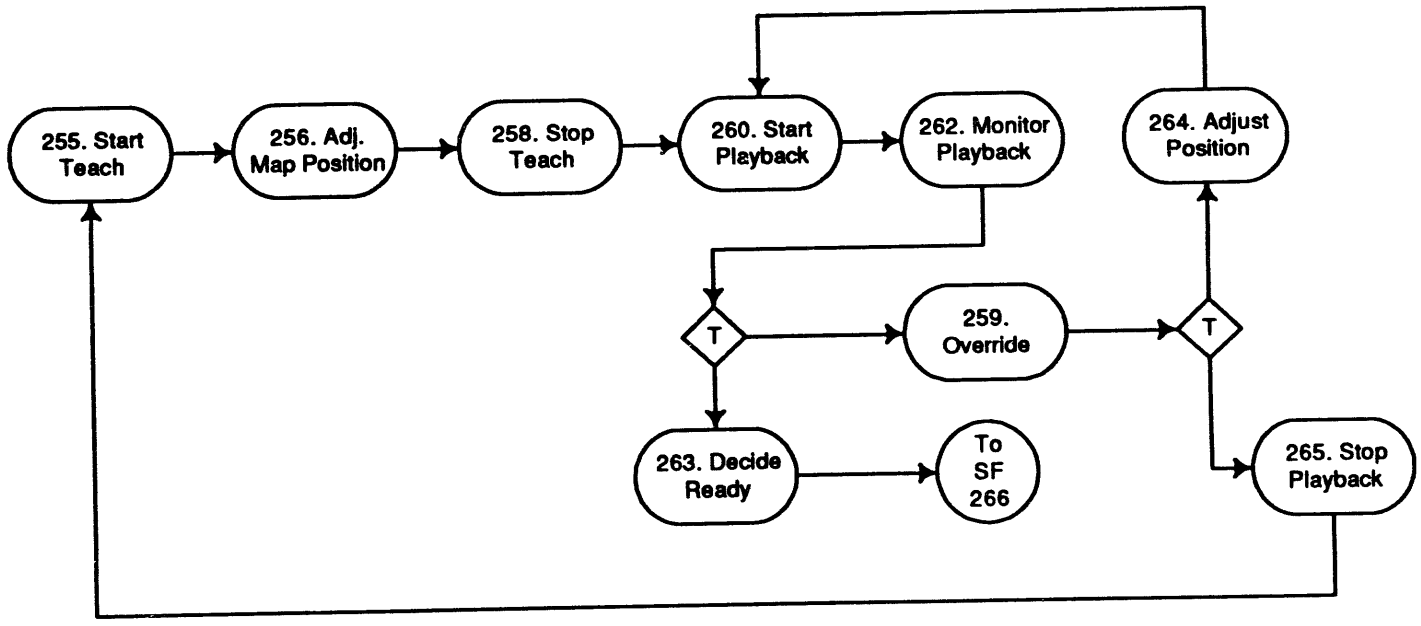

Fig. 32. Task elements during the task "254. Teach Removal."

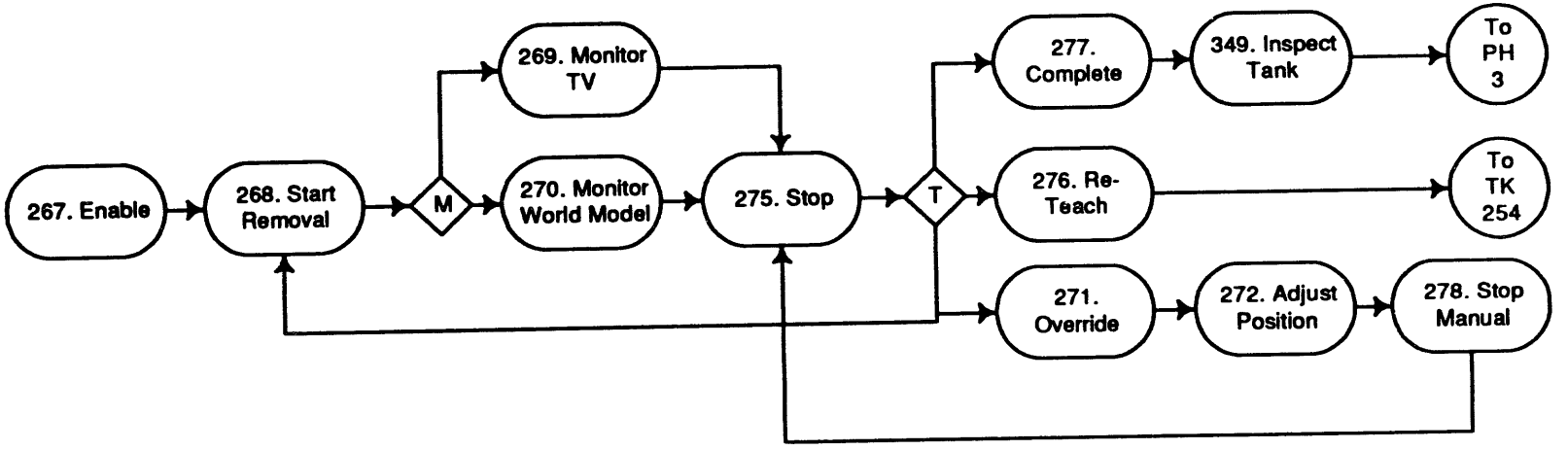

Fig. 33. Task elements during the task "286. Robotic Removal."

2.4 THIRD MISSION PHASE: REMOVE TWRMS EQUIPMENT

During the third mission phase, the TWRMS equipment is removed from the inside of the storage tank. Figure 34 illustrates the subfunctions in this mission phase, and Figs. 35 and 36 illustrate the task elements in each subfunction.

2.4.1 Remove TWRMS Package

The first step in this phase is to remove the TWRMS from the tank.

2.4.1.1 Initiator

Residual waste is removed.

2.4.1.2 Task sequence

1. Prepare for TWRMS removal.
2. Remove TWRMS from tank.

2.4.1.3 Terminator

TWRMS is out of the tank.

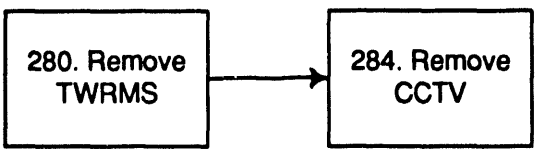

Fig. 34. Subfunctions during the third mission phase.

2.4.2 Remove Aux. CCTV System

During the final subfunction of the campaign, the crew removes the Aux. CCTV system from the tank.

2.4.2.1 Initiator

TWRMS is out of the tank.

2.4.2.2 Task sequence

1. Prepare for Aux. CCTV removal.
2. Remove Aux. CCTV from the tank.

2.4.2.3 Terminator

Aux. CCTV system is out of the tank.

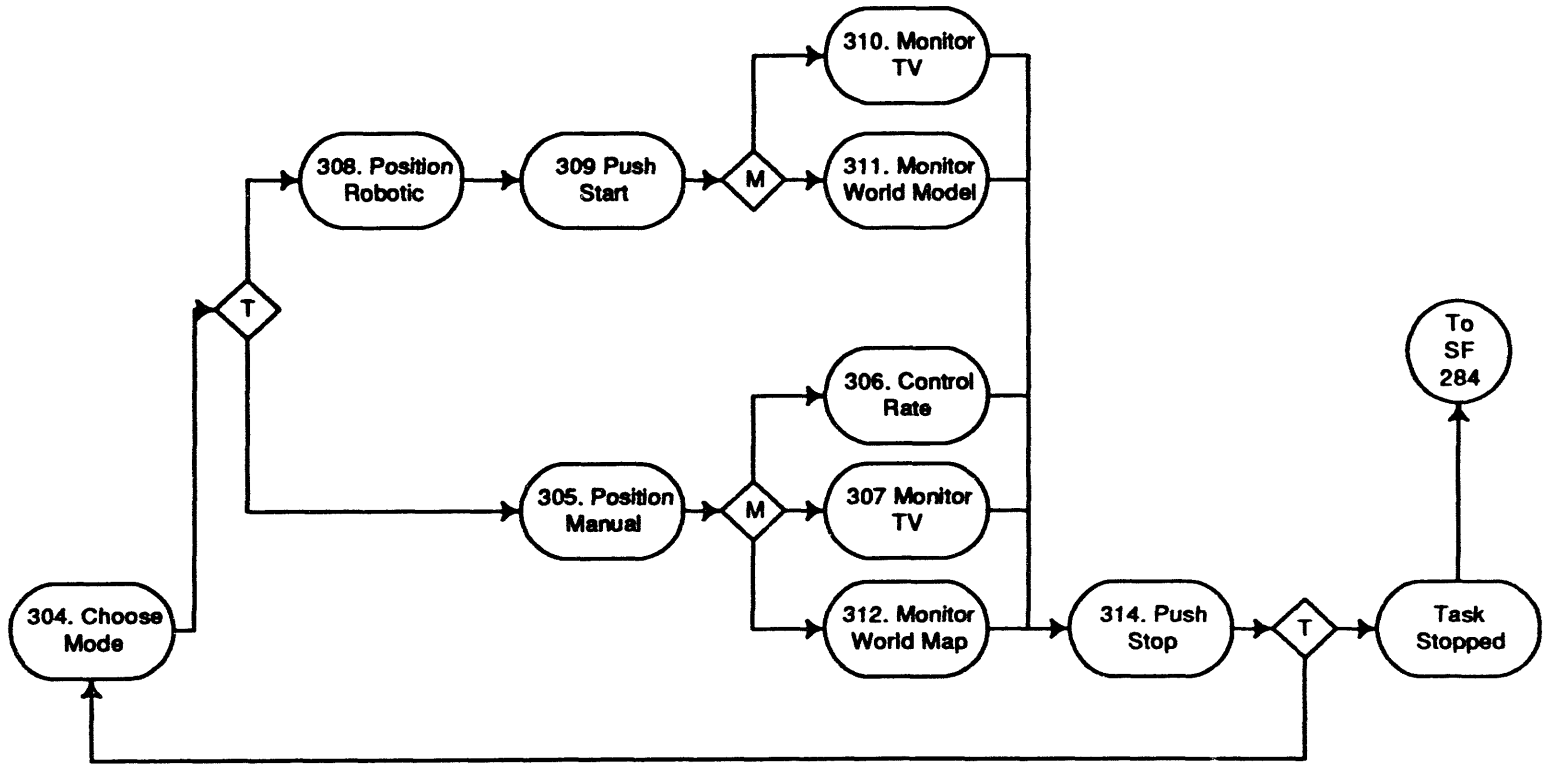

Fig. 35. Task elements during the subfunction "280. Remove TWRMS."

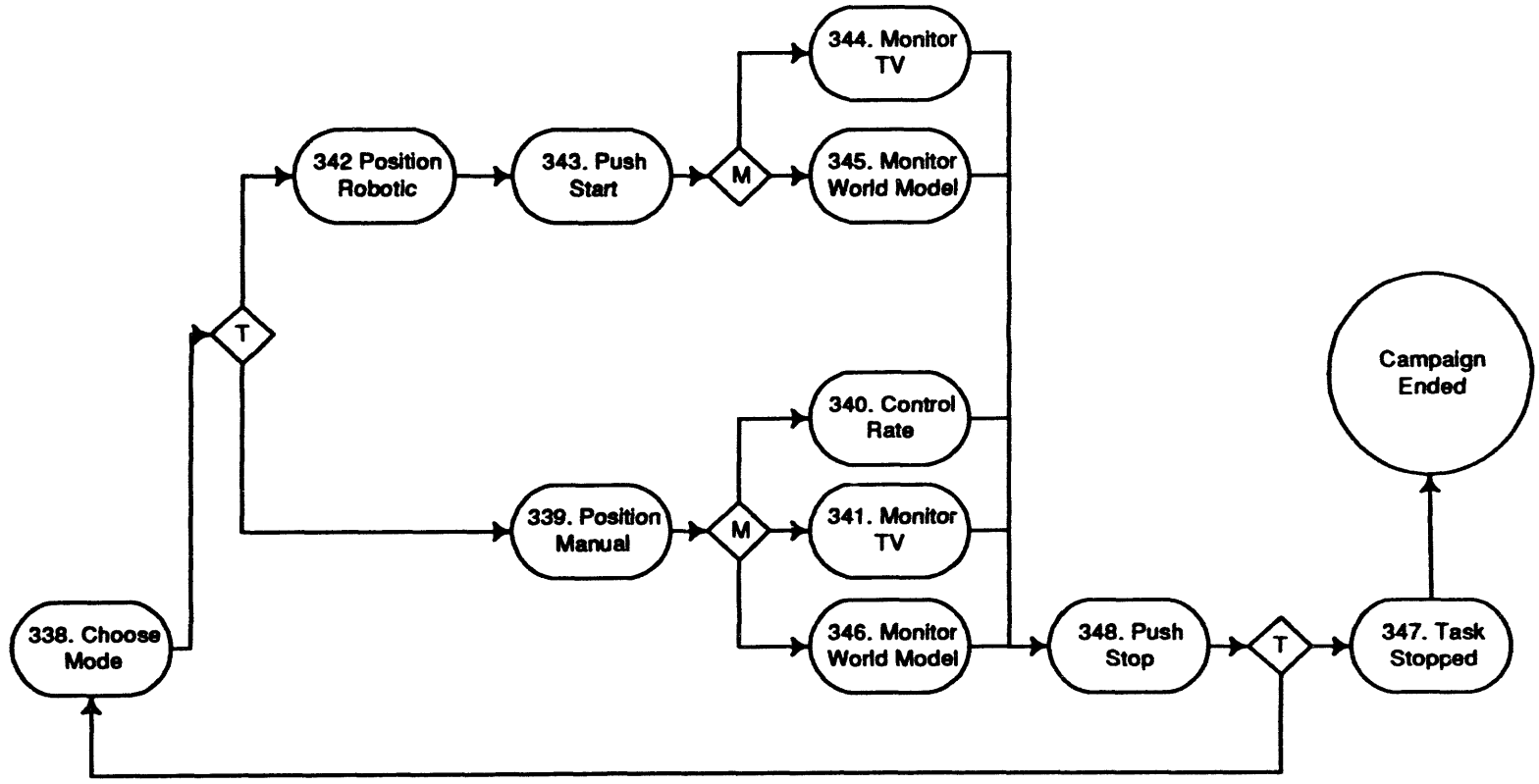

Fig. 36. Task elements during the subfunction "284. Remove CCTV."

3. TASK ANALYSIS RESULTS

3.1 METHODS

The steps in the task analysis thus far have defined a likely sequence for tasks and task elements during a waste retrieval campaign. The next step was to formally examine the task elements and (1) categorize the operator behavior according to a standard behavioral taxonomy,[3] (2) determine what system or system component is being controlled or observed, and (3) determine what means (i.e., controls, displays, log books, etc.) are necessary. This was done by filling out an electronic task analysis form for each task. Figure 37 shows a typical, completed task analysis form. The full set of task analysis forms is provided in the Appendix. The task analysis form was designed and completed using the Microsoft Access data base management program, so the completed task analysis forms are a task analysis data base for waste retrieval system operations. This method follows that developed by the NRC for nuclear power plant control rooms[3] with some modifications to the task analysis vocabulary necessary to fit the unique needs of the waste retrieval application.

3.2 RESULTS

3.2.1 User Actions, Displays, and Controls

The information provided by the task analysis is a list of the user functions, displays, and controls necessary to operate the system. The task analysis data base makes it possible to identify the user actions, displays, and controls necessary during each subfunction by sorting and reorganizing the information in the data base. Tables 1–3 provide such a list.

3.2.2 Crew Size and Function Allocation

An earlier study[2] made a preliminary crew size decision and listed the functions that users must perform. From the task analysis, the preliminary decision to specify a two-person crew appears to be correct. Integrating the function analysis with the task analysis by determining which functions operators perform during each task verifies the crew size decision made in ref. 2 and provides a detailed function allocation for each crew member. Table 4 is a list of tasks and the functions users perform within each task and subfunction.

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.2.2 Insert Aux. CCTV System into SST

Task: Robotically insert aux. CCTV into tank **Sequence:** 2

Purpose: Carry out robotic insertion **Duration:** 0

Cue: Insertion mode selected

Description: After selecting robotic insertion mode, initiate and monitor the insertion process

Comments: Branch 2

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	robotic		aux. CCTV		discrete control		
2	0	Pushes	Motor	mode	start	robotic routine	aux. CCTV		discrete control		
3	0	Monitors	Perceptual	position	in-band	CCTV platform	aux. CCTV		TV		
4	0	Monitors	Perceptual	position	in-band	CCTV platform	aux. CCTV		world map		
5	0	Detects	Perceptual	position	out-of-band	CCTV platform	aux. CCTV				
6	0	Pushes	Motor	mode	stop	CCTV platform	aux. CCTV		discrete control		
7	0	Chooses	Cognitive	mode	robotic or manual	CCTV platform	aux. CCTV				

Fig. 37. Typical completed task analysis form.

Table 1. User actions, displays, and controls during each subfunction of the first mission phase

Subfunction	System/verb	Component/ parameter	State	Means of action
1.1 Activate Aux. CCTV System				
	Inspects		Readiness	Visual
	Requests		Readiness	Verbal communication
	Decides	Readiness	Full	
	Inspects	Computer		
	Decides	Mode	Operable	Computer
	Informs	Mode	Start	Verbal communication
	Receives	Readiness		Verbal communication
	Aux. CCTV	**Aux. CCTV remotes**		
	Monitors	Output signal	In-band	CRT
	Positions	Power	On	Discrete control
	Aux. CCTV	**Cameras**		
	Adjusts	Position	Continuous control	
	Aux. CCTV	**Control computers**		
	Decides	Mode	Operable	
	Decides	Mode	Operable	
	Monitors	Output signal	In-band	CRT
	Positions	Power	On	Discrete control
	Aux. CCTV	**Electrical power**		
	Positions	Power	On	Discrete control
1.2 Insert Aux. CCTV System into SST				
	Aux. CCTV			
	Chooses	Mode	Robotic or manual	
1.2.1 Insert Aux. CCTV System into SST				
	Aux. CCTV			
	Positions	Mode	Manual	Discrete control
	Monitors	Position		TV
	Adjusts	Rate		Continuous control
1.2.2 Insert Aux. CCTV System into SST				
	Aux. CCTV			
	Pushes	Mode	Robotic	Discrete control
	Aux. CCTV	**CCTV platform**		

Table 1. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	Chooses	Mode	Robotic or manual	
	Pushes	Mode	Stop	Discrete control
	Monitors	Position in-band		TV
	Monitors	Position in-band		World map
	Detects	Position out-of-band		
	Aux. CCTV	**Robotic routine**		
	Pushes	Mode	Start	Discrete control
1.3 Inspect Tank Interior				
	Aux. CCTV			
	Pushes	Mode	Robotic or manual	Discrete control
	Tank	Risers/ITH		
	Inspects	TV		
	Records	Position and status		Operations Log
	Aux. CCTV	**TV camera**		
	Adjusts	Position		Continuous control
1.4 Develop Riser Cutting Strategy				
	Risers/ITH			
	Chooses cut order			Operations Log
	Records	Cut order		Operations Log
1.5 Activate TWRMS				
	Inspects	Readiness		Visual
	Inspects			TV
	Informs	Mode	Activation	Verbal communication
	Decides	Mode	Operable	Computer
	Receives	Readiness	Verbal communication	
	Requests	Readiness	Verbal communication	
	Decides		Readiness full	
	TWRMS	**Control computers**		
	Decides		Mode	Operable
	Monitors	Output signal	In-band	CRT
	Positions	Power	On	Discrete control
	TWRMS	**Electrical power**		

Table 1. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	Positions	Power	On	Discrete control
	TWRMS	**TWRMS remotes**		
	Monitors	Output signal	In-band	CRT
	Positions	Power	On	Discrete control
	TWRMS	**Manipulator**		
	Adjusts	Position		Continuous control
1.6 Insert TWRMS into SST				
	TWRMS			
	Chooses	Mode		
1.6.1 Insert TWRMS into SST				
	TWRMS			
	Positions	Mode	Manual	Discrete control
	Monitors	Position		TV
	Adjusts	Rate		Continuous control
1.6.2 Insert TWRMS into SST				
	TWRMS			
	Decides	Mode	Operable or inoperable	
	Chooses	Mode	Playback	Discrete control
	Pushes	Mode	Playback	Discrete control
	Pushes	Mode	Robotic	Discrete control
	Chooses	Mode	Robotic or manual	
	TWRMS	**TWRMS platform**		
	Pushes	Mode	Stop	Discrete control
	Monitors	Position in-band	World map	
	Monitors	Position in-band	TV	
	Monitors	Position in-band	World map	
	Decides	Position out-of-band		
	TWRMS	**Robotic routine**		
	Decides		Mode	Operable
	Pushes	Mode	Start	Discrete control

Table 2. User actions, displays, and controls during the second mission phase

Subfunction	System/verb	Component/ parameter	State	Means of action
2.1 Cut Risers/ITH				
	Computer map			
	Remembers	Sequence		Operations Log
	Remembers	Sequence		Operations Log
	Inspects			CRT
	Pushes	Mode	Enable	Discrete control
	Pushes	Mode	Enable	Discrete control
	World map	**Cutting EE**		
	Monitors	Cutting	In-band	TV
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
	Monitors	Position		TV
	Adjusts	Position		Continuous control
	Monitors	Position		World map
	Monitors	Position		CRT
	Adjusts	Position		Continuous control
	Pushes	Mode	Start	Discrete control
	Computer map	**Data collection**		
	Monitors	Mode	Operable	CRT
	Pushes	Mode	Start	Discrete control
	World map	**TWRMS**		
	Monitors	Position		CRT
	Monitors	Position		CRT
	Adjusts	Position		Continuous control
	Adjusts	Position		Continuous control
	World map	Playback		
	Decides	Mode	Operable	
	Pushes	Mode	Enable	Discrete control
	Monitors	Mode	Operable	TV
	Pushes	Mode	Override	Discrete control
	Decides	Mode	Override	
	Pushes	Mode	Start	Discrete control
	Monitors	Mode	Operable	CRT

Table 2. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	Monitors	Mode	Operable	CRT
	Pushes	Mode	Override	Discrete control
	Decides	Mode	Override	
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Start	Discrete control
	World map	**Teach**		
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
2.2 Remove Cut-up Riser/ITH Sections				
	TWRMS			
	Remembers	Sequence		Operations Log
	Remembers	Sequence		Operations Log
	Inspects			CRT
	Pushes	Mode	Enable	Discrete control
	Pushes	Mode	Enable	Discrete control
	Monitors	Position	In-band	TV
	Computer map	**Data collection**		
	Monitors	Mode	Operable	CRT
	Pushes	Mode	Start	Discrete control
	TWRMS	**End effector**		
	Inspects	TV		
	Pushes	Gripper	Discrete control	
	Pushes	Mode	Start	Discrete control
	World map	**Gripper EE**		
	Monitors	Gripper EE	In-band	TV
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
	Monitors	Position		TV
	Monitors	Position		World map
	Adjusts	Position		Continuous control
	Adjusts	Position		Continuous control
	Monitors	Position		CRT
	Pushes	Mode	Start	Discrete control

Table 2. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	World map	**TWRMS**		
	Adjusts	Position		Continuous control
	Adjusts	Position		Continuous control
	Monitors	Position		CRT
	Monitors	Position		CRT
	Monitors	Position in-band		CRT
	World map	Playback	Playback	Playback
	Decides		Mode	Operable
	Pushes	Mode	Enable	Discrete control
	Monitors	Mode	Operable	TV
	Pushes	Mode	Override	Discrete control
	Decides		Mode	Override
	Pushes	Mode	Start	Discrete control
	Monitors	Mode	Operable	CRT
	Monitors	Mode	Operable	CRT
	Pushes	Mode	Override	Discrete control
	Decides		Mode	Override
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Start	Discrete control
	World map	Teach	Teach	Teach
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
2.3 Characterize Waste				
	TWRMS			
	Inspects	CRT		
	Monitors	Position in-band	TV	
	Computer map	Data collection		
	Monitors	Mode	Operable	CRT
	Pushes	Mode	Start	Discrete control
	TWRMS	**End effector**		
	Inspects	TV		
	Pushes	Subsurface mapping		Discrete control
	Pushes	Mode	Start	Discrete control

Table 2. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	World map	**TWRMS**		
	Monitors	Position	In-band	CRT
	Decides	Composition etc.		
	Records	Composition etc.		Operations Log
2.4 Remove Waste Layer				
	TWRMS			
	Remembers	Sequence		Operations Log
	Remembers	Sequence		Operations Log
	Pushes	Mode	Enable	Discrete control
	Pushes	Mode	Enable	Discrete control
	Monitors	Position	In-band	TV
	TWRMS	**End-effector**		
	Decides			
	Inspects			TV
	Pushes	Subsurface mapping	Discrete control	
	Pushes	Mode	Start	Discrete control
	World map	**TWRMS**		
	Adjusts	Position		Continuous control
	Adjusts	Position		Continuous control
	Monitors	Position		CRT
	Monitors	Position		CRT
	Monitors	Position in-band		CRT
	World map	Playback	Playback	Playback
	Decides		Mode	Operable
	Pushes	Mode	Enable	Discrete control
	Monitors	Mode	Operable	TV
	Pushes	Mode	Override	Discrete control
	Decides		Mode	Override
	Pushes	Mode	Start	Discrete control
	Monitors	Mode	Operable	CRT
	Monitors	Mode	Operable	CRT
	Pushes	Mode	Override	Discrete control
	Decides		Mode	Override

Table 2. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Start	Discrete control
	World map	Teach	Teach	Teach
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
	World map	**Waste removal EE**		
	Monitors	Gripper EE in-band	TV	
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
	Adjusts	Position		Continuous control
	Monitors	Position		CRT
	Monitors	Position		TV
	Adjusts	Position		Continuous control
	Monitors	Position		World map
	Pushes	Mode	Start	Discrete control
2.5 Remove Residual Waste				
	TWRMS			
	Records	Operations Log		
	Inspects	TV		
	Remembers	Sequence		Operations Log
	Remembers	Sequence		Operations Log
	Pushes	Mode	Enable	Discrete control
	Pushes	Mode	Enable	Discrete control
	Monitors	Position in-band	TV	
	TWRMS	**End effector**		
	Inspects	TV		
	Pushes	Subsurface mapping	Discrete control	
	Pushes	Mode	Start	Discrete control
	World map	**TWRMS**		
	Adjusts	Position		Continuous control
	Monitors	Position		CRT
	Adjusts	Position		Continuous control
	Monitors	Position		CRT

Table 2. (continued)

Subfunction	System/verb	Component/ parameter	State	Means of action
	Monitors	Position	In-band	CRT
	World map	Playback	Playback	Playback
	Decides		Mode	Operable
	Pushes	Mode	Enable	Discrete control
	Monitors	Mode	Operable	TV
	Decides		Mode	Override
	Pushes	Mode	Override	Discrete control
	Pushes	Mode	Start	Discrete control
	Monitors	Mode	Operable	CRT
	Monitors	Mode	Operable	CRT
	Decides		Mode	Override
	Pushes	Mode	Override	Discrete control
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Start	Discrete control
	World map	**Tank cleaning EE**		
	Monitors	Cleaning EE	In-band	TV
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control
	Adjusts	Position		Continuous control
	Monitors	Position		TV
	Monitors	Position		World map
	Adjusts	Position		Continuous control
	Monitors	Position		CRT
	Pushes	Mode	Start	Discrete control
	World map	Teach	Teach	Teach
	Pushes	Mode	Start	Discrete control
	Pushes	Mode	Stop	Discrete control

Table 3. User actions, controls, and displays during the third mission phase

Subfunction	System/verb	Component/ parameter	State	Means of action
3.1 Remove TWRMS from SST				
	TWRMS			
	Chooses	Mode		
3.1.1 Remove TWRMS from SST				
	TWRMS			
	Positions	Mode	Manual	Discrete control
	Monitors	Position		TV
	Adjusts	Rate		Continuous control
3.1.2 Remove TWRMS from SST				
	TWRMS			
	Pushes	Mode	Robotic	Discrete control
	Chooses	Mode	Robotic or manual	
	TWRMS	**TWRMS platform**		
	Pushes	Mode	Stop	Discrete control
	Monitors	Position in-band		World map
	Monitors	Position in-band		TV
	Decides	Position out-of-band		
	TWRMS	Robotic routine		
	Pushes	Mode	Start	Discrete control
3.2 Remove Aux. CCTV System from SST				
	Aux. CCTV			
	Chooses	Mode		
	Positions	Mode	Manual	Discrete control
	Pushes	Mode	Robotic	Discrete control
	Chooses	Mode	Robotic or manual	
	Monitors	Position		TV
	Adjusts	Rate		Continuous control
	Aux. CCTV	**CCTV platform**		
	Pushes	Mode	Stop	Discrete control
	Monitors	Position in-band		World map
	Monitors	Position in-band		TV
	Decides	Position out-of-band		
	Aux. CCTV	Robotic routine		
	Pushes	Mode	Start	Discrete control

Table 4. User functions for each crew member

1. Insert WaRMS Equipment into SST	
1.1 Activate Aux. CCTV system	
Prepare for Aux. CCTV activation	
Chief	Monitor system status
	Restart system
Monitor	Monitor system status
	Communicate with outside
Activate Aux. CCTV system	
Chief	Monitor system status
	Restart system
Monitor	Monitor system status
Verify Aux. CCTV functioning	
Chief	Visually monitor end-effector operations
	Converge stereo cameras
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Visually monitor end-effector operations
1.2.1 Insert Aux. CCTV System into SST	
Manually insert Aux. CCTV into tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
	Manually maneuver aux.
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
Robotically insert Aux. CCTV into tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Initiate robotic deployment sequence
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
1.3. Inspect Tank Interior	
Inspect tank interior using Aux. CCTV	
Chief	Visually monitor end-effector operations
	Converge stereo cameras
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera

Table 4. (continued)

	Zoom camera
Monitor	Visually monitor end-effector operations
	Monitor system status
	Maintain operations log
1.4. Develop Riser Cutting Strategy	
Develop and record riser cutting sequence	
Monitor	Maintain operations log
1.5. Activate TWRMS	
Prepare for TWRMS activation	
Monitor	Monitor system status
Activate TWRMS	
Chief	Monitor system status
	Restart system
Monitor	Maintain operations log
Verify TWRMS functioning	
Chief	Aurally monitor remote sounds
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector trajectories
	Manually control end effector using position control
	Manually control end effector using rate control
Monitor	Aurally monitor remote sounds
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector trajectories
	Monitor system status
	Maintain operations log
1.6.1 Insert TWRMS into SST	
Manually insert TWRMS into tank	
Chief	Monitor functions
	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
	Manually maneuver aux.
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
1.6.2 Insert TWRMS into SST	
Robotically insert TWRMS into tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Initiate robotic deployment sequence
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status

Table 4. (continued)

2. Remove Waste Layers	
2.1. Cut Risers/ITH	
Map waste surface	
Chief	Monitor system status
	Engage acoustic proximity sensor-based surface mapping
	Engage laser range finder-based surface mapping
	Engage optical proximity sensor-based surface mapping
	Engage structured light-based surface mapping
Monitor	Monitor system status
	Maintain operations log
Teach riser cutting sequence	
Chief	Visually monitor manipulator position
	Visually monitor playback on world model
	Engage automatic playback
	Engage semiautomatic playback
	Engage step-through playback
	Engage teaching
	Manually control end effector using position control
	Manually control end effector using rate control
	Manually make teaching inputs
Monitor	Maintain operations log
Robotically cut risers/ITH	
Chief	Aurally monitor remote sounds
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage automatic playback
	Engage semiautomatic playback
	Engage sensor-based obstacle avoidance
	Engage step-through playback
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data

Table 4. (continued)

	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Manually cut risers	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage sensor-based obstacle avoidance
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
2.2 Remove Cut-up Riser/ITH Sections	
Exchange cutting end effector for gripper	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Detect watchdog action
	Monitor system status
	Initiate automated end-effector changeout
	Manually control end effector using position control
	Manually control end effector using rate control
	Converge stereo cameras
	Disengage end-effector tracking

Table 4. (continued)

	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Map waste surface	
Chief	Monitor system status
	Engage acoustic proximity sensor-based surface mapping
	Engage laser range finder-based surface mapping
	Engage optical proximity sensor-based surface mapping
	Engage structured light-based surface mapping
Monitor	Monitor system status
	Maintain operations log
Teach riser removal sequence	
Chief	Visually monitor manipulator position on world model
	Visually monitor playback on world model
	Engage automatic playback
	Engage semiautomatic playback
	Engage step-through playback
	Engage teaching
	Manually control end effector using position control
	Manually control end effector using rate control
	Manually make teaching inputs
Monitor	Maintain operations log
Robotically remove risers/ITH	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage automatic playback
	Engage semiautomatic playback
	Engage sensor-based obstacle avoidance

Table 4. (continued)

	Engage step-through playback
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Manually remove risers	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage sensor-based obstacle avoidance
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model

Table 4. (continued)

	Maintain operations log
2.3 Characterize Waste	
Exchange gripper for mapping end effector	
Chief	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Detect watchdog action
	Monitor system status
	Initiate automated end-effector changeout
	Manually control end effector using position control
	Manually control end effector using rate control
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Map waste surface	
Chief	Monitor system status
	Engage acoustic proximity sensor-based surface mapping
	Engage laser range finder-based surface mapping
	Engage optical proximity sensor-based surface mapping
	Engage structured light-based surface mapping
Monitor	Monitor system status
	Maintain operations log
2.4. Remove Waste Layer	
Exchange mapping EE for waste removal EE	
Chief	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Detect watchdog action
	Monitor system status
	Initiate automated end-effector changeout

Table 4. (continued)

	Manually control end effector using position control
	Manually control end effector using rate control
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Teach waste removal sequence	
Chief	Visually monitor manipulator position on world model
	Visually monitor playback on world model
	Engage automatic playback
	Engage semiautomatic playback
	Engage step-through playback
	Engage teaching
	Manually control end effector using position control
	Manually control end effector using rate control
	Manually make teaching inputs
Monitor	Maintain operations log
Robotically remove waste	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage automatic playback
	Engage semiautomatic playback
	Engage sensor-based obstacle avoidance
	Engage step-through playback
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking

Table 4. (continued)

	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Manually remove waste	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage sensor-based obstacle avoidance
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
2.5. Remove Residual Waste	
Exchange waste removal EE for cleaning EE	

Table 4. (continued)

Chief	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Detect watchdog action
	Monitor system status
	Initiate automated end-effector changeout
	Manually control end-effector using position control
	Manually control end-effector using rate control
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor automated end effector
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Teach tank cleaning sequence	
Chief	Visually monitor manipulator position on world model
	Visually monitor playback on world model
	Engage automatic playback
	Engage semiautomatic playback
	Engage step-through playback
	Engage teaching
	Manually control end effector using position control
	Manually control end effector using rate control
	Manually make teaching inputs
Monitor	Maintain operations log
Robotically remove residual waste	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action

Table 4. (continued)

	Monitor system status
	Engage automatic playback
	Engage semiautomatic playback
	Engage sensor-based obstacle avoidance
	Engage step-through playback
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Manually remove residual waste	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor end-effector sensor data
	Monitor manipulator forces
	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Detect watchdog action
	Monitor system status
	Engage sensor-based obstacle avoidance
	Engage end effector
	Converge stereo cameras
	Disengage end-effector tracking
	Engage end-effector tracking
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Monitor manipulator forces
	Monitor end-effector sensor data

Table 4. (continued)

	Monitor manipulator sensor data
	Visually monitor end-effector operations on video
	Visually monitor end-effector trajectories on video
	Visually monitor manipulator position on world model
	Maintain operations log
Inspect tank interior	
Chief	Visually monitor end-effector operations
	Converge stereo cameras
	Iris camera
	Pan camera
	Roll camera
	Select camera
	Tilt camera
	Zoom camera
Monitor	Visually monitor end-effector operations
	Monitor system status
	Maintain operations log
3. Remove WaRMS Equipment from SST	
3.1.1. Remove TWRMS from SST	
Manually remove TWRMS from tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
	Manually maneuver aux.
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
3.1.2. Remove TWRMS from SST	
Robotically remove TWRMS from tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Initiate robotic deployment sequence
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
3.2. Remove Aux. CCTV System from SST	
Manually remove Aux. CCTV from tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status
	Manually maneuver aux.
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status

Table 4. (continued)

3.2. Remove Aux. CCTV System from SST	
Robotically remove Aux. CCTV from tank	
Chief	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Initiate robotic deployment sequence
Monitor	Aurally monitor remote sounds
	Monitor collision avoidance system
	Visually monitor deployment
	Monitor system status

3.2.3 Panel Groups

A panel group, the fundamental building block of a control room concept, is a set of displays or controls that must be simultaneously available for an operator to successfully complete a task. Panel groups should not be confused with control/display panels; the panel group is an organizational concept that specifies what must be available within the control/display panel that is its physical manifestation. In a systematic design approach, panel groups define what control/display panels must include; control/display panels are then designed to meet these requirements efficiently and integrated into workstations that meet the operator's needs during the campaign.

Panel groups for the TWRMS were identified by examining the task analysis forms for each subfunction and the user functions table (i.e., by combining, for each operator, Tables 1–3 and Table 4). This allows identification of controls and displays that must be available at the same time.

3.2.3.1 TWRMS chief

Table 5 lists 16 panel groups that may be identified from the task and function analyses for the TWRMS chief.

Table 5. Panel groups for the TWRMS chief

Panel type	Panel description
Display groups	1. System status monitors
	2. Remote viewing
	3. Remote sound
	4. Collision avoidance
	5. Manipulator outputs
	6. World map
	7. End-effector outputs
Control groups	1. Power (startup)
	2. Camera controls
	3. Auxiliary CCTV system maneuvering
	4. Manipulator inputs
	5. TWRMS platform maneuvering
	6. Remote mapping
	7. Virtual maneuvering
	8. End-effector inputs
	9. Robotic operations

Some of these panel groups are similar functions or may include a small number of functions. For example, auxiliary CCTV system maneuvering and LRM platform maneuvering will likely require some identical controls and may be combined into one panel, which may be called the platform maneuvering panel. For another example, end-effector inputs will likely be limited to turning the end effector on or off. This control may be integrated into another panel, perhaps manipulator inputs. There are also natural couplings between some displays and controls: (1) The remote viewing display panel will be manipulated by the camera control panel. (2) The power control panel will have an impact on system status monitors. (3) The remote mapping control panel will have an impact on the world map display panel. These natural similarities and relationships allow a smaller set of panel groups to be specified for the TWRMS chief. Table 6 lists a revised set of panel groups for the TWRMS chief.

Table 6. Revised/control display panel groups for the TWRMS chief

Panel type	Panel description
Display groups	1. System status
	2. Remote viewing
	3. Remote sound
	4. Collision avoidance
	5. Manipulator outputs
	6. World map
	7. End-effector outputs
Control groups	1. Power (startup)
	2. Camera controls
	3. Platform maneuvering
	4. Manipulator and end-effector inputs
	5. Remote mapping
	6. Virtual maneuvering
	7. Robotic operations

Returning to the task analysis, we can identify for each task the display and control panels that are required and, furthermore, rank the criticality of each panel for that task. By understanding the work flow (via the task analysis) and integrating the criticality rankings for each panel during each task, it will be possible to configure the workstation to optimize efficiency throughout the process. Tables 7–9 show a prioritized list of TWRMS chief panels required during each task.

3.2.3.2 TWRMS monitor

A similar process can be used to identify panels for the TWRMS monitor. From the task and function analyses, 16 panel groups may be identified for the TWRMS monitor (see Table 10).

Table 7. Panel groups for the TWRMS chief during each task in the first mission phase

Mission Phase 1	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
1. Insert WaRMS equipment into SST	1.1 Activate Aux. CCTV system	Prepare for Aux. CCTV activation	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.1 Activate Aux. CCTV system	Activate Aux. CCTV system	System status panel	Power panel	None	None	None	None
1. Insert WaRMS equipment into SST	1.1 Activate Aux. CCTV system	Verify Aux. CCTV functioning	Remote viewing panel	Camera control panel	System status panel	Power panel	None	None
1. Insert WaRMS equipment into SST	1.2 Insert Aux. CCTV system into SST	Choose insertion mode (manual or robotic)	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.2.1 Insert Aux. CCTV system into SST	Manually insert Aux. CCTV into tank	Remote viewing panel	Platform maneuvering panel	System status panel	Power panel	Remote sound panel	None
1. Insert WaRMS equipment into SST	1.2.2 Insert Aux. CCTV system into SST	Robotically insert Aux. CCTV into tank	Remote viewing panel	Robotic operations panel	System status panel	Power panel	Remote sound panel	Platform maneuvering panel
1. Insert WaRMS equipment into SST	1.3 Inspect tank interior	Inspect tank interior using Aux. CCTV	Remote viewing panel	Camera control panel	System status panel	Platform maneuvering panel	Remote sound panel	Robotic operations panel
1. Insert WaRMS equipment into SST	1.4 Develop riser cutting strategy	Develop and record riser cutting sequence	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.5 Activate LRM system	Prepare for LRM activation	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.5 Activate LRM system	Activate LRM system	System status panel	Power panel	None	None	None	None
1. Insert WaRMS equipment into SST	1.5 Activate LRM system	Verify LRM functioning	Remote viewing panel	Manipulator and end-effector inputs panel	Manipulator outputs panel	Platform maneuvering panel	System status panel	Power panel
1. Insert WaRMS equipment into SST	1.6 Insert LRM system into SST	Choose insertion mode (manual or robotic)	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.6.1 Insert LRM system into SST	Manually insert LRM into tank	Remote viewing panel	Platform maneuvering panel	System status panel	Power panel	Remote sound panel	None
1. Insert WaRMS equipment into SST	1.6.2 Insert LRM system into SST	Robotically insert LRM into tank	Remote viewing panel	Robotic operations panel	System status panel	Power panel	Remote sound panel	Platform maneuvering panel

Table 8. Panel groups for the TWRMS chief during each task in the second mission phase

Mission Phase 2	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
2. Remove waste layers	2.1 Cut risers/ITH	Map waste surface	World map panel	Remote mapping panel	System status panel	Camera control panel	Remote viewing panel	None
2. Remove waste layers	2.1 Cut risers/ITH	Teach riser cutting sequence	World map panel	Virtual maneuvering panel	Remote viewing panel	Camera control panel	None	Manipulator and end-effector inputs panel
2. Remove waste layers	2.1 Cut risers/ITH	Robotically cut risers/ITH	Remote viewing	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	Remote sound panel	Manipulator outputs panel
2. Remove waste layers	2.1 Cut risers/ITH	Manually cut risers	Remote viewing panel	Manipulator and end-effector inputs panel	Manipulator outputs panel	Camera controls panel	Remote sound panel	None
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Exchange cutting end-effector for gripper	Remote viewing panel	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	End-effector outputs panel	None
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Map waste surface	World map panel	Remote mapping panel	System status panel	Camera control panel	Remote viewing panel	None
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Teach riser removal sequence	World map panel	Virtual maneuvering panel	Remote viewing panel	Camera control panel	None	Manipulator and end-effector inputs panel
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Robotcally remove risers/ITH	Remote viewing	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	Remote sound panel	Manipulator outputs panel
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Manually remove risers	Remote viewing panel	Manipulator and end-effector inputs panel	Manipulator outputs panel	Camera controls panel	Remote sound panel	None
2. Remove waste layers	2.3 Characterize waste	Exchange gripper for mapping end effector	Remote viewing panel	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	End-effector outputs panel	None
2. Remove waste layers	2.3 Characterize waste	Map waste surface	World map panel	Remote mapping panel	System status panel	Camera control panel	Remote viewing panel	None
2. Remove waste layers	2.3 Characterize waste	Determine waste composition	End-effector outputs panel	Remote mapping panel	Remote viewing panel	Camera control panel	System status panel	None
2. Remove waste layers	2.4 Remove waste layer	Exchange mapping EE for waste removal EE	Remote viewing panel	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	End-effector outputs panel	None
2. Remove waste layers	2.4 Remove waste layer	Teach waste removal sequence	World map panel	Virtual maneuvering panel	Remote viewing panel	Camera control panel	None	Manipulator and end-effector inputs panel
2. Remove waste layers	2.4 Remove waste layer	Robotically remove waste	Remote viewing	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	Remote sound panel	Manipulator outputs panel
2. Remove waste layers	2.4 Remove waste layer	Manually remove waste	Remote viewing panel	Manipulator and end-effector inputs panel	Manipulator outputs panel	Camera controls panel	Remote sound panel	None
2. Remove waste layers	2.5 Remove residual waste	Exchange waste removal EE for cleaning EE	Remote viewing panel	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	End-effector outputs panel	None
2. Remove waste layers	2.5 Remove residual waste	Teach tank cleaning sequence	World map panel	Virtual maneuvering panel	Remote viewing panel	Camera control panel	None	Manipulator and end-effector inputs panel

Table 8. (continued)

Mission Phase 2	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
2. Remove waste layers	2.5 Remove residual waste	Robotically remove residual waste	Remote viewing	Robotic operations panel	World map panel	Manipulator and end-effector inputs panel	Remote sound panel	Manipulator outputs panel
2. Remove waste layers	2.5 Remove residual waste	Manually remove residual waste	Remote viewing panel	Manipulator and end-effector inputs panel	Manipulator outputs panel	Camera controls panel	Remote sound panel	None
2. Remove waste layers	2.5 Remove residual waste	Inspect tank interior	Remote viewing panel	Camera control panel	System status panel	Platform maneuvering panel	Remote sound panel	Robotic operations panel

Table 9. Panel groups for the TWRMS chief during each task in the third mission phase

Mission Phase 3	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
3. Remove WaRMS equipment from SST	3.1 Remove LRM system from SST	Choose removal mode (manual or robotic)	None	None	None	None	None	None
3. Remove WaRMS equipment from SST	3.1.1 Remove LRM system from SST	Manually remove LRM from tank	Remote viewing panel	Platform maneuvering panel	System status panel	Power panel	Remote sound panel	None
3. Remove WaRMS equipment from SST	3.1.2 Remove LRM system from SST	Robotically remove LRM from tank	Remote viewing panel	Robotic operations panel	System status panel	Power panel	Remote sound panel	Platform maneuvering panel
3. Remove WaRMS equipment from SST	3.2 Remove Aux. CCTV system from SST	Choose removal mode (manual or robotic)	None	None	None	None	None	None
3. Remove WaRMS equipment from SST	3.2 Remove Aux CCTV system from SST	Manually remove Aux CCTV from tank	Remote viewing panel	Platform maneuvering panel	System status panel	Power panel	Remote sound panel	None
3. Remove WaRMS equipment from SST	3.2 Remove Aux CCTV system from SST	Robotically remove Aux CCTV from tank	Remote viewing panel	Robotic operations panel	System status panel	Power panel	Remote sound panel	Platform maneuvering panel

Table 10. Panel groups for the TWRMS monitor

Panel type	Panel description
Display groups	1. System status monitors
	2. Remote viewing
	3. Remote sound
	4. Collision avoidance
	5. Manipulator outputs
	6. World map
	7. End-effector outputs
Control groups	1. Power (startup)
	2. Communications
	3. Operations log

In addition to these functions required by the assignment of responsibilities in the task analysis, other control functions could be added so that the TWRMS monitor can assist the TWRMS chief during periods of high workload. These functions are camera controls, remote mapping, virtual maneuvering, and robotic operations. Table 11 lists the complete set of panel groups for the TWRMS monitor. Tables 12–14 provide a prioritized list of the panel groups for the TWRMS monitor during each mission phase, subfunction, and task.

Table 11. Revised set of control/display panel groups for the TWRMS monitor

Panel type	Panel description
Display groups	1. System status
	2. Remote viewing
	3. Remote sound
	4. Collision avoidance
	5. Manipulator outputs
	6. World map
	7. End-effector outputs
Control groups	1. Power (startup)
	2. Camera controls
	3. Remote mapping
	4. Virtual maneuvering
	5. Robotic operations
	6. Communications
	7. Operations log

Table 12. Panel groups for the TWRMS monitor during each task in the first mission phase

Mission phase	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
1. Insert WaRMS equipment into SST	1.1 Activate Aux. CCTV system	Prepare for Aux. CCTV activation	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.1 Activate Aux. CCTV system	Activate Aux. CCTV system	System status panel	Communication panel	None	Operations log	None	None
1. Insert WaRMS equipment into SST	1.1 Activate Aux. CCTV system	Verify Aux. CCTV functioning	Remote viewing panel	Power panel	System status panel	Operations log	None	None
1. Insert WaRMS equipment into SST	1.2 Insert Aux. CCTV system into SST	Choose insertion mode (manual or robotic)	None	Operations log	None	None	None	None
1. Insert WaRMS equipment into SST	1.2.1 Insert Aux. CCTV system into SST	Manually insert Aux. CCTV into tank	Remote viewing panel	Camera control panel	System status panel	None	None	None
1. Insert WaRMS equipment into SST	1.2.2 Insert Aux. CCTV system into SST	Robotically insert Aux. CCTV into tank	Remote viewing panel	Camera control panel	System status panel	None	None	None
1. Insert WaRMS equipment into SST	1.3 Inspect tank interior	Inspect tank interior using Aux. CCTV	Remote viewing panel	Camera control panel	System status panel	None	None	None
1. Insert WaRMS equipment into SST	1.4 Develop riser cutting strategy	Develop and record riser cutting sequence	Remote viewing panel	Operations log	None	None	None	None
1. Insert WaRMS equipment into SST	1.5 Activate LRM system	Prepare for LRM activation	None	None	None	None	None	None
1. Insert WaRMS equipment into SST	1.5 Activate LRM system	Activate LRM system	System status panel	Communication panel	None	Operations log	None	None
1. Insert WaRMS equipment into SST	1.5 Activate LRM system	Verify LRM functioning	Remote viewing panel	Power panel	System status panel	Operations log	None	None
1. Insert WaRMS equipment into SST	1.6 Insert LRM system into SST	Choose insertion mode (manual or robotic)	None	Operations log	None	None	None	None
1. Insert WaRMS equipment into SST	1.6.1 Insert LRM system into SST	Manually insert LRM into tank	Remote viewing panel	Camera control panel	System status panel	None	None	None
1. Insert WaRMS equipment into SST	1.6.2 Insert LRM system into SST	Robotically insert LRM into tank	Remote viewing panel	Camera control panel	System status panel	None	None	None

Table 13. Panel groups for the TWRMS monitor during each task in the second mission phase

Mission phase	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
2. Remove waste layers	2.1 Cut risers/ITH	Map waste surface	World map	Remote mapping panel	System status panel	Operations log	None	None
2. Remove waste layers	2.1 Cut risers/ITH	Teach riser cutting sequence	World map	Remote mapping panel	None	Operations log	None	None
2. Remove waste layers	2.1 Cut risers/ITH	Robotically cut risers/ITH	Remote viewing panel	Robotic operations panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.1 Cut risers/ITH	Manually cut risers	Remote viewing panel	Camera control panel	System status panel	Operations log	None	None
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Exchange cutting end effector for gripper	Remote viewing panel	Camera control panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Map waste surface	World map	Remote mapping panel	System status panel	Operations log	None	None
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Teach riser removal sequence	World map	Remote mapping panel	None	Operations log	None	None
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Robotically remove risers/ITH	Remote viewing panel	Robotic operations panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.2 Remove cut-up riser/ITH sections	Manually remove risers	Remote viewing panel	Camera control panel	System status panel	Operations log	None	None
2. Remove waste layers	2.3 Characterize waste	Exchange gripper for mapping end effector	Remote viewing panel	Camera control panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.3 Characterize waste	Map waste surface	World map	Remote mapping panel	System status panel	Operations log	None	None
2. Remove waste layers	2.3 Characterize waste	Determine waste composition	World map	Remote mapping panel	System status panel	Operations log	None	None
2. Remove waste layers	2.4 Remove waste layer	Exchange mapping EE for waste removal EE	Remote viewing panel	Camera control panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.4 Remove waste layer	Teach waste removal sequence	World map	Remote mapping panel	None	Operations log	None	None
2. Remove waste layers	2.4 Remove waste layer	Robotically remove waste	Remote viewing panel	Robotic operations panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.4 Remove waste layer	Manually remove waste	Remote viewing panel	Camera control panel	System status panel	Operations log	None	None
2. Remove waste layers	2.5 Remove residual waste	Exchange waste removal EE for cleaning EE	Remote viewing panel	Camera control panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.5 Remove residual waste	Teach tank cleaning sequence	World map	Remote mapping panel	None	Operations log	None	None
2. Remove waste layers	2.5 Remove residual waste	Robotically remove residual waste	Remote viewing panel	Robotic operations panel	World model	Virtual maneuvering panel	System status panel	Operations log
2. Remove waste layers	2.5 Remove residual waste	Manually remove residual waste	Remote viewing panel	Camera control panel	System status panel	Operations log	None	None
2. Remove waste layers	2.5 Remove residual waste	Inspect tank interior	Remote viewing panel	Camera control panel	System status panel	Operations log	None	None

Table 14. Panel groups for the TWRMS monitor during each task in the second mission phase

Mission phase	Subfunction	Task	Primary display panel	Primary control panel	Secondary display panel	Secondary control panel	Tertiary display panel	Tertiary control panel
3. Remove WaRMS equipment from SST	3.1 Remove LRM system from SST	Choose removal mode (manual or robotic)	None	None	None	None	None	None
3. Remove WaRMS equipment from SST	3.1.1 Remove LRM system from SST	Manually remove LRM from tank	Remote viewing panel	Camera control panel	World map	Virtual maneuvering panel	System status panel	Operations log
3. Remove WaRMS equipment from SST	3.1.2 Remove LRM system from SST	Robotically remove LRM from tank	Remote viewing panel	Camera control panel	World map	Virtual maneuvering panel	System status panel	Operations log
3. Remove WaRMS equipment from SST	3.2 Remove Aux. CCTV system from SST	Choose removal mode (manual or robotic)	None	None	None	None	None	None
3. Remove WaRMS equipment from SST	3.2 Remove Aux. CCTV system from SST	Manually remove Aux. CCTV from tank	Remote viewing panel	Camera control panel	World map	Virtual maneuvering panel	System status panel	Operations log
3. Remove WaRMS equipment from SST	3.2 Remove Aux. CCTV system from SST	Robotically remove Aux. CCTV from tank	Remote viewing panel	Camera control panel	World map	Virtual maneuvering panel	System status panel	Operations log

4. REMAINING STEPS IN THE PROJECT

The third phase of the task (after function analysis and task analysis) will be to develop conceptual designs of control panels, workstations, and the control room layout. In this phase the panel group organization developed in the first phase will be translated into recommendations for arranging physical components in the control room. The outcome of this phase will be a set of conceptual design drawings describing workstation and control room layout concepts.

4.1 CONTROL PANEL DESIGN

Control panels are the building blocks of workstation design and include all displays and controls necessary for one operator to perform an activity for which he is responsible. The outcome of this part of the task will be conceptual designs for all of the control panels required by each member of the crew. This step will use the panel groups identified in the task analysis and the flow charts (at the task element level) to optimize the arrangement of displays and controls within panels.

4.2 WORKSTATION DESIGN

Workstations include control panels and supporting equipment. Some crew members may require multiple panels (e.g., a control panel to turn on and initialize the equipment and a control panel to conduct manipulator operations); workstations will be designed to integrate or separate multiple control panels as necessary to optimize user efficiency. Workstations will also support the users by providing room for manuals, storage, etc. The outcome of this part of the task will be conceptual design drawings for workstations, including recommendations for displays, controls, cabinets, and seating. This step will use the panel groups and task analysis flowcharts (at the task and subfunction levels) to optimize the arrangement of control/display panels within workstations.

4.3 CONTROL ROOM LAYOUT

The final stage of the design phase will be to integrate workstations into a control room. The control room layout will optimize cooperation and communication among users of separate workstations. The outcome of this part of the task will be a conceptual design drawing for a recommended layout of workstations within the control room. This stage will use task analysis flowcharts at the mission phase and subfunction level to optimize the arrangement of workstations within the control room.

5. SUMMARY

A task analysis was conducted to support control room conceptual design work for the TWRMS. Initially, the control room will be deployed for an integrated demonstration of retrieval technology, but it will also serve as a prototype for a deployable control room for waste retrieval operations.

The study used existing TWRMS concepts to generate a campaign scenario; a formal task analysis, using methods developed for nuclear power plant control rooms, was conducted in this scenario. The task analysis (1) verified preliminary crew size decisions, (2) allowed detailed allocation of functions between members of a two-person crew, (3) allowed organization of control/display requirements for each crew member into related groups, and (4) allowed prioritization of panel groups based on mission stages. The resulting panel groups and prioritization will guide future control/display panel conceptual design work. A task network model developed alongside the task analysis will also guide future control/display panel, workstation, and control room layout conceptual design work.

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APPENDIX
TASK ANALYSIS FORMS

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.1. Activate Aux. CCTV System

Task: Prepare for aux. CCTV activation **Sequence:** 1

Purpose: Get crew and equipment ready for start-up. **Duration:** 0

Cue: Receive instructions to proceed

Description: After receiving instructions to proceed, prepare the crew and equipment for aux. CCTV system activation.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Inspects	Perceptual	readiness				control room	visual		
2	0	Requests	Communication	readiness					verbal communication	crew	readiness report
3		Receives	Communication	readiness			aux. CCTV		verbal communication		
4	0	Decides	Cognitive	readiness	full						
5	0	Informs	Communication	mode	start		aux. CCTV		verbal communication	crew	warning

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.1. Activate Aux. CCTV System

Task: Activate aux. CCTV system **Sequence:** 2

Purpose: Turn on the aux. CCTV system **Duration:** 0

Cue: Crew and equipment prepared to activate system

Description: After preparing the crew and equipment for activation, turn on the aux. CCTV system

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Positions	Motor	power	on	electrical power	aux. CCTV		discrete control		
2	0	Positions	Motor	power	on	control computers	aux. CCTV		discrete control		
3	0	Monitors	Perceptual	output signal	in-band	control computers	aux. CCTV		CRT		
4	0	Decides	Cognitive	mode	operable	control computers	aux. CCTV				
5	0	Positions	Motor	power	on	aux. CCTV remotes	aux. CCTV		discrete control		
6	0	Monitors	Perceptual	output signal	in-band	aux. CCTV remotes	aux. CCTV		CRT		
7	0	Decides	Cognitive	mode	operable	control computers	aux. CCTV				

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.1. Activate Aux. CCTV System

Task: Verify aux. CCTV functioning **Sequence:** 3

Purpose: Make sure that the CCTV systems are functioning properly and are **Duration:** 0

Cue: Aux. CCTV activated

Description: After turning on the aux. CCTV, make sure that it is functioning properly.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Adjusts	Motor	position		cameras	aux. CCTV		continuous control		
2	0	Inspect					aux. CCTV		computer		
3	0	Decides	Cognitive	mode	operable		aux. CCTV		computer		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.2. Insert Aux. CCTV System into SST

Task: Choose insertion mode (manual or robotic) **Sequence:** 1

Purpose: Select an insertion mode **Duration:** 0

Cue: Aux. CCTV is ready for insertion

Description: After deciding that the aux. CCTV is ready for insertion, decide whether to use manual or robotic insertion mode.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Chooses	Cognitive	mode	robotic or manual		aux. CCTV				

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.2.1 Insert Aux. CCTV System into SST

Task: Manually insert aux. CCTV into tank **Sequence:** 2

Purpose: Carry out manual insertion **Duration:** 0

Cue: Insertion mode selected

Description: After selecting manual insertion mode, manually control the insertion process

Comments: Branch 1

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Positions	Motor	mode	manual		aux. CCTV		discrete control		
2	0	Adjusts	Motor	rate			aux. CCTV		continuous control		
3	0	Monitors	Perceptual	position			aux. CCTV		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.2.2 Insert Aux. CCTV System into SST

Task: Robotically insert aux. CCTV into tank **Sequence:** 2

Purpose: Carry out robotic insertion **Duration:** 0

Cue: Insertion mode selected

Description: After selecting robotic insertion mode, initiate and monitor the insertion process

Comments: Branch 2

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	robotic		aux. CCTV		discrete control		
2	0	Pushes	Motor	mode	start	robotic routine	aux. CCTV		discrete control		
3	0	Monitors	Perceptual	position	in-band	CCTV platform	aux. CCTV		TV		
4	0	Monitors	Perceptual	position	in-band	CCTV platform	aux. CCTV		world map		
5	0	Detects	Perceptual	position	out-of-band	CCTV platform	aux. CCTV				
6	0	Pushes	Motor	mode	stop	CCTV platform	aux. CCTV		discrete control		
7	0	Chooses	Cognitive	mode	robotic or manual	CCTV platform	aux. CCTV				

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.3. Inspect Tank Interior

Task: Inspect tank interior using aux. CCTV **Sequence:** 1

Purpose: Use the aux. CCTV to examine the tank interior **Duration:** 0

Cue: Aux. CCTV system in place and functioning

Description: After inserting the aux. CCTV, use it to inspect the tank interior.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	robotic or manual		aux. CCTV		discrete control		
2	0	Adjusts	Motor	position		TV camera	aux. CCTV		continuous control		
3	0	Inspects	Perceptual			risers/ITH	tank		TV		
4	0	Records	Communication	position and status		risers/ITH	tank		Operations Log		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.4. Develop Riser Cutting Strategy

Task: Develop and record riser cutting sequence **Sequence:** 1

Purpose: Determine the order for cutting risers and ITH and record the seq **Duration:** 0

Cue: Risers/ITH noted and described

Description: After inspect the tank and recording the position and status of risers/ITH, develop a cutting strategy and record it in the Operations Log

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Chooses	Cognitive	cut order		risers/ITH			Operations Log		
2	0	Records	Communication	cut order		risers/ITH			Operations Log		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.5. Activate LRM System

Task: Prepare for LRM activation **Sequence:** 1

Purpose: Get crew and equipment ready for start-up. **Duration:** 0

Cue: Aux. CCTV in tank

Description: After receiving instructions to proceed, prepare the crew and equipment for LRM system activation.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Inspects	Perceptual	readiness				control room	visual		
2	0	Requests	Communication	readiness			LRM		verbal communication	crew	readiness report
3	0	Receives	Communication	readiness			LRM		verbal communication		
4	0	Decides	Cognitive	readiness	full		LRM				
5	0	Informs	Communication	mode	activation		LRM		verbal communication	crew	warning

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.5. Activate LRM System

Task: Activate LRM system **Sequence:** 2

Purpose: Turn on the LRM system **Duration:** 0

Cue: Crew and equipment prepared to activate system

Description: After preparing the crew and equipment for activation, turn on the LRM system

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Positions	Motor	power	on	electrical power	LRM		discrete control		
2	0	Positions	Motor	power	on	control computers	LRM		discrete control		
3	0	Monitors	Perceptual	output signal	in-band	control computers	LRM		CRT		
4	0	Decides	Cognitive	mode	operable	control computers	LRM				
5	0	Positions	Motor	power	on	LRM remotes	LRM		discrete control		
6	0	Monitors	Perceptual	output signal	in-band	LRM remotes	LRM		CRT		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.5. Activate LRM System

Task: Verify LRM functioning **Sequence:** 3

Purpose: Make sure that the LRM systems are functioning properly and are r **Duration:** 0

Cue: LRM activated

Description: After turning on the LRM, make sure that it is functioning properly.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Inspects	Perceptual				LRM		TV		
2	0	adjusts	Motor	position		manipulator	LRM		continuous control		
3	0	Decides	Cognitive	mode	operable		LRM		computer		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.6. Insert LRM System into SST

Task: Choose insertion mode (manual or robotic) **Sequence:** 1

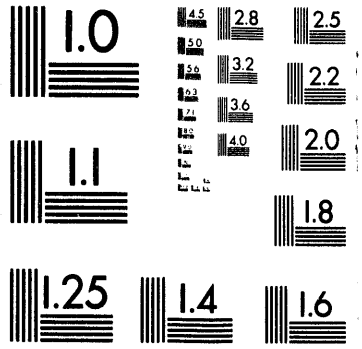
Purpose: Select an insertion mode **Duration:** 0

Cue: LRM is ready for insertion

Description: After deciding that the LRM is ready for insertion, decide whether to use manual or robotic insertion mode.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication	
										Respondent	Content
1	0	Chooses	Cognitive	mode			LRM				


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

2 of 2

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.6.1. Insert LRM System into SST

Task: Manually insert LRM into tank **Sequence:** 2

Purpose: Carry out manual insertion **Duration:** 0

Cue: Insertion mode selected

Description: After selecting manual insertion mode, manually control the insertion process

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Positions	Motor	mode	manual		LRM		discrete control		
2	0	Adjusts	Motor	rate			LRM		continuous control		
3	0	Monitors	Perceptual	position			LRM		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 1. Insert TWRMS Equipment into SST

Sub-Function: 1.6.2. Insert LRM System into SST

Task: Robotically insert LRM into tank **Sequence:** 2

Purpose: Carry out robotic insertion **Duration:** 0

Cue: Insertion mode selected

Description: After selecting robotic insertion mode, initiate and monitor the insertion process

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	robotic		LRM		discrete control		
2	0	Chooses	Cognitive	mode	playback		LRM		discrete control		
3	0	Pushes	Motor	mode	playback		LRM		discrete control		
4	0	Monitors	Perceptual	position	in-band	LRM platform	LRM		world map		
5	0	Decides	Cognitive	mode	operable	robotic routine	LRM				
6	0	Pushes	Motor	mode	start	robotic routine	LRM		discrete control		
7	0	Monitors	Perceptual	position	in-band	LRM platform	LRM		TV		
8	0	Monitors	Perceptual	position	in-band	LRM platform	LRM		world map		
9	0	Decides	Cognitive	position	out-of-band	LRM platform	LRM				
10	0	Pushes	Motor	mode	stop	LRM platform	LRM		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Decides	Cognitive	mode	operable or inoperable	LRM
12	0 Chooses	Cognitive	mode	robotic or manual	LRM

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.1. Cut Risers/ITH

Task: Map waste surface **Sequence:** 1

Purpose: Create a computerized map of the waste surface and the risers/ITH **Duration:** 0

Cue: LRM operational in tank

Description: After the LRM is operational inside the tank, create a computerized map of the waste surface including the positions of any risers or ITH present.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	start	data collection	computer map		discrete control		
2	0	Monitors	Perceptual	mode	operable	data collection	computer map		CRT		
3	0	Inspects	Perceptual				computer map		CRT		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.1. Cut Risers/ITH

Task: Teach riser cutting sequence **Sequence:** 2

Purpose: Teach the system to do riser/ITH cutting **Duration:** 0

Cue: Map completed

Description: After mapping the waste surface, teach the system to cut the risers/ITH into pieces manageable by the removal system.

Comments: This is a teaching, not programming task. Elements 2-6 and 7-13 could occur repetitively.

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1		Pushes	Motor	mode	start	teach	world map		discrete control		
2		Remembers	Cognitive	sequence				risers/ITH	Operations Log		
3	0	Adjusts	Motor	position		LRM	world map		continuous control		
4	0	Monitors	Perceptual	position		LRM	world map		CRT		
5	0	Pushes	Motor	mode	start	cutting EE	world map		discrete control		
6	0	Pushes	Motor	mode	stop	teach	world map		discrete control		
7	0	Pushes	Motor	mode	start	playback	world map		discrete control		
8	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
9	0	Decides	Cognitive	mode	override	playback	world map				
10	0	Pushes	Motor	mode	override	playback	world map		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Adjusts	Motor	position		LRM	world map	continuous control
12	0 Monitors	Perceptual	position		LRM	world map	CRT
13	0 Pushes	Motor	mode	start	playback	world map	discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.1. Cut Risers/ITH

Task: Robotically cut risers/ITH **Sequence:** 3

Purpose: Cut risers/ITH robotically **Duration:** 0

Cue: Cutting program taught

Description: After the cutting program is taught, execute and monitor the program, intervening manually as necessary.

Comments: Elements 4-11 would occur repetitively

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Decides	Cognitive	mode	operable	playback					
2	0	Pushes	Motor	mode	enable		LRM		discrete control		
3	0	Pushes	Motor	mode	start	playback	LRM		discrete control		
4	0	Monitors	Perceptual	mode	operable	playback	LRM		TV		
5	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
6	0	Decides	Cognitive	mode	override	playback	LRM				
7	0	Pushes	Motor	mode	override	playback	LRM		discrete control		
8	0	Adjusts	Motor	position		cutting EE	LRM		continuous control		
9	0	Monitors	Perceptual	position		cutting EE	LRM		TV		
10	0	Monitors	Perceptual	position		cutting EE	LRM		world map		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Pushes	Motor	mode	enable	playback	LRM		discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.1. Cut Risers/ITH

Task: Manually cut risers **Sequence:** 4

Purpose: Cut risers under manual control **Duration:** 0

Cue: Map completed

Description: After the map is completed, cut the risers/ITH into manageable sections using manual control.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	enable		LRM		discrete control		
2	0	Remembers	Cognitive	sequence				risers/ITH	Operations Log		
3	0	Adjusts	Motor	position		cutting EE	LRM		continuous control		
4	0	Monitors	Perceptual	position		cutting EE	LRM		CRT		
5	0	Pushes	Motor	mode	start	cutting EE	LRM		discrete control		
6	0	Monitors	Perceptual	cutting	in-band	cutting EE	LRM		TV		
7	0	Pushes	Motor	mode	stop	cutting EE	LRM		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.2. Remove Cut-up Riser/ITH Sections

Task: Exchange cutting end-effector for gripper **Sequence:** 1

Purpose: Discard the cutting end-effector and attach the gripper so that s **Duration:** 0

Cue: Risers/ITH cut into sections

Description: After completing cutting, exchange the cutting end-effector for the gripper end-effector.

Comments: This should be done automatically.

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1		Pushes	Motor		gripper	end-effector	LRM		discrete control		
2	0	Pushes	Motor	mode	start	end-effector	LRM	change program	discrete control		
3	0	Monitors	Perceptual	position	in-band		LRM		TV		
4	0	Monitors	Perceptual	position	in-band	LRM	world map		CRT		
5	0	Inspects	Perceptual			end-effector	LRM		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.2. Remove Cut-up Riser/ITH Sections

Task: Map waste surface **Sequence:** 2

Purpose: Create a computerized map of the waste surface and the risers/ITH **Duration:** 0

Cue: Gripper end-effector installed

Description: After the gripper end-effector is installed, create a computerized map of the waste surface including the positions of any risers or ITH present.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	start	data collection	computer map		discrete control		
2	0	Monitors	Perceptual	mode	operable	data collection	computer map		CRT		
3	0	Inspects	Perceptual				computer map		CRT		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.2. Remove Cut-up Riser/ITH Sections

Task: Teach riser removal sequence **Sequence:** 3

Purpose: Teach the system to do riser/ITH cutting **Duration:** 0

Cue: Map completed

Description: After mapping the waste surface, teach the system to pick up riser/ITH sections.

Comments: This is a teaching, not programming task. Elements 2-6 and 7-13 could occur repetitively.

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1		Pushes	Motor	mode	start	teach	world map		discrete control		
2		Remembers	Cognitive	sequence				risers/ITH	Operations Log		
3	0	Adjusts	Motor	position		LRM	world map		continuous control		
4	0	Monitors	Perceptual	position		LRM	world map		CRT		
5	0	Pushes	Motor	mode	start	gripper EE	world map		discrete control		
6	0	Pushes	Motor	mode	stop	teach	world map		discrete control		
7	0	Pushes	Motor	mode	start	playback	world map		discrete control		
8	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
9	0	Decides	Cognitive	mode	override	playback	world map				
10	0	Pushes	Motor	mode	override	playback	world map		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Adjusts	Motor	position		LRM	world map	continuous control
12	0 Monitors	Perceptual	position		LRM	world map	CRT
13	0 Pushes	Motor	mode	start	playback	world map	discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.2. Remove Cut-up Riser/ITH Sections

Task: Robotically remove risers/ITH **Sequence:** 4

Purpose: Remove riser/ITH sections robotically. **Duration:** 0

Cue: removeting program taught

Description: After the removeting program is taught, exeremovee and monitor the program, intervening manually as necessary.

Comments: Elements 4-11 would occur repetitively

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Decides	Cognitive	mode	operable	playback					
2	0	Pushes	Motor	mode	enable		LRM		discrete control		
3	0	Pushes	Motor	mode	start	playback	LRM		discrete control		
4	0	Monitors	Perceptual	mode	operable	playback	LRM		TV		
5	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
6	0	Decides	Cognitive	mode	override	playback	LRM				
7	0	Pushes	Motor	mode	override	playback	LRM		discrete control		
8	0	Adjusts	Motor	position		gripper EE	LRM		continuous control		
9	0	Monitors	Perceptual	position		gripper EE	LRM		TV		
10	0	Monitors	Perceptual	position		gripper EE	LRM		world map		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Pushes	Motor	mode	enable	playback	LRM	discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.2. Remove Cut-up Riser/ITH Sections

Task: Manually remove risers **Sequence:** 5

Purpose: Remove riser/ITH sections manually. **Duration:** 0

Cue: Map completed

Description: After the map is completed, remove the risers/ITH into manageable sections using manual control.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	enable		LRM		discrete control		
2	0	Remembers	Cognitive	sequence				risers/ITH	Operations Log		
3	0	Adjusts	Motor	position		gripper EE	LRM		continuous control		
4	0	Monitors	Perceptual	position		gripper EE	LRM		CRT		
5	0	Pushes	Motor	mode	start	gripper EE	LRM		discrete control		
6	0	Monitors	Perceptual	gripper EE	in-band	gripper EE	LRM		TV		
7	0	Pushes	Motor	mode	stop	gripper EE	LRM		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.3 Characterize Waste

Task: Exchange gripper for mapping end-effector **Sequence:** 1

Purpose: Discard the gripper and attach the sub-surface mapping end-effect **Duration:** 0

Cue: Risers/ITH sections removed

Description: After completing riser/ITH removal, exchange the gripper for the sub-surface mapping end-effector.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1		Pushes	Motor		sub-surface mapping	end-effector	LRM		discrete control		
2	0	Pushes	Motor	mode	start	end-effector	LRM	change program	discrete control		
3	0	Monitors	Perceptual	position	in-band		LRM		TV		
4	0	Monitors	Perceptual	position	in-band	LRM	world map		CRT		
5	0	Inspects	Perceptual			end-effector	LRM		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.3 Characterize Waste

Task: Map waste surface **Sequence:** 2

Purpose: Create a computerized map of the waste surface and the risers/ITH **Duration:** 0

Cue: Sub-surface mapping end-effector in place

Description: After the sub-surface mapping end-effector is installed, create a computerized map of the waste surface including the positions of any risers or ITH present.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	start	data collection	computer map		discrete control		
2	0	Monitors	Perceptual	mode	operable	data collection	computer map		CRT		
3	0	Inspects	Perceptual				computer map		CRT		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.3. Characterize waste

Task: Determine waste composition **Sequence:** 3

Purpose: Decide what the waste is like, that is, its consistency, composit **Duration:** 0

Cue: Map completed

Description: After completing the surface map, determine and record the characteristics of the waste layer.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Decides	Cognitive	compositio n etc.				waste layer			
2	0	Records	Communicati on	compositio n etc.				waste layer	Operations Log		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.4. Remove Waste Layer

Task: Exchange mapping EE for waste removal EE **Sequence:** 1

Purpose: Discard the sub-surface mapping EE and attach the waste removal e **Duration:** 0

Cue: Waste layer mapped and characterized

Description: After the waste has been described and the description recorded, change the mapping end-effector for the appropriate waste removal end-effector

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Decides	Cognitive			end-effector	LRM				
2	0	Pushes	Motor		sub-surface mapping	end-effector	LRM		discrete control		
3	0	Pushes	Motor	mode	start	end-effector	LRM	change program	discrete control		
4	0	Monitors	Perceptual	position	in-band		LRM		TV		
5	0	Monitors	Perceptual	position	in-band	LRM	world map		CRT		
6	0	Inspects	Perceptual			end-effector	LRM		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.4. Remove Waste Layer

Task: Teach waste removal sequence **Sequence:** 2

Purpose: Teach the system to do waste removal **Duration:** 0

Cue: Waste removal end-effector in place

Description: After change end-effectors, teach the system to remove the waste layer.

Comments: This is a teaching, not programming task. Elements 2-6 and 7-13 could occur repetitively.

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1		Pushes	Motor	mode	start	teach	world map		discrete control		
2		Remembers	Cognitive	sequence				waste	Operations Log		
3	0	Adjusts	Motor	position		LRM	world map		continuous control		
4	0	Monitors	Perceptual	position		LRM	world map		CRT		
5	0	Pushes	Motor	mode	start	waste removal EE	world map		discrete control		
6	0	Pushes	Motor	mode	stop	teach	world map		discrete control		
7	0	Pushes	Motor	mode	start	playback	world map		discrete control		
8	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
9	0	Decides	Cognitive	mode	override	playback	world map				
10	0	Pushes	Motor	mode	override	playback	world map		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Adjusts	Motor	position		LRM	world map	continuous control
12	0 Monitors	Perceptual	position		LRM	world map	CRT
13	0 Pushes	Motor	mode	start	playback	world map	discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.4. Remove Waste Layer

Task: Robotically remove waste **Sequence:** 3

Purpose: Remove waste layer robotically. **Duration:** 0

Cue: Waste removal program taught

Description: After the waste removal program is taught, execute and monitor the program, intervening manually as necessary.

Comments: Elements 4-11 would occur repetitively

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Decides	Cognitive	mode	operable	playback					
2	0	Pushes	Motor	mode	enable		LRM		discrete control		
3	0	Pushes	Motor	mode	start	playback	LRM		discrete control		
4	0	Monitors	Perceptual	mode	operable	playback	LRM		TV		
5	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
6	0	Decides	Cognitive	mode	override	playback	LRM				
7	0	Pushes	Motor	mode	override	playback	LRM		discrete control		
8	0	Adjusts	Motor	position		waste removal EE	LRM		continuous control		
9	0	Monitors	Perceptual	position		waste removal EE	LRM		TV		
10	0	Monitors	Perceptual	position		waste removal EE	LRM		world map		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Pushes	Motor	mode	enable	playback	LRM	discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.4. Remove Waste Layer

Task: Manually remove waste **Sequence:** 4

Purpose: Remove waste layer manually. **Duration:** 0

Cue: Waste layer mapped and characterized

Description: After the map is completed, remove the waste using manual control.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	enable		LRM		discrete control		
2	0	Remembers	Cognitive	sequence				waste	Operations Log		
3	0	Adjusts	Motor	position		waste removal EE	LRM		continuous control		
4	0	Monitors	Perceptual	position		waste removal EE	LRM		CRT		
5	0	Pushes	Motor	mode	start	waste removal EE	LRM		discrete control		
6	0	Monitors	Perceptual	gripper EE	in-band	waste removal EE	LRM		TV		
7	0	Pushes	Motor	mode	stop	waste removal EE	LRM		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.5. Remove Residual Waste

Task: Exchange waste removal EE for cleaning EE **Sequence:** 1

Purpose: Discard the waste removal end-effector and attach the cleaning EE **Duration:** 0

Cue: Last waste layer removed

Description: After the last layer of waste is removed, exchange the waste removal EE for the cleaning EE.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor		sub-surface mapping	end-effector	LRM		discrete control		
2	0	Pushes	Motor	mode	start	end-effector	LRM	change program	discrete control		
3	0	Monitors	Perceptual	position	in-band		LRM		TV		
4	0	Monitors	Perceptual	position	in-band	LRM	world map		CRT		
5	0	Inspects	Perceptual			end-effector	LRM		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.5. Remove Residual Waste

Task: Teach tank cleaning sequence **Sequence:** 2

Purpose: Teach the system to do tank cleaning **Duration:** 0

Cue: Tank cleaning end-effector in place

Description: After changing end-effectors, teach the system to remove the residual waste.

Comments: This is a teaching, not programming task. Elements 2-6 and 7-13 could occur repetitively.

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1		Pushes	Motor	mode	start	teach	world map		discrete control		
2		Remembers	Cognitive	sequence				waste	Operations Log		
3	0	Adjusts	Motor	position		LRM	world map		continuous control		
4	0	Monitors	Perceptual	position		LRM	world map		CRT		
5	0	Pushes	Motor	mode	start	tank cleaning EE	world map		discrete control		
6	0	Pushes	Motor	mode	stop	teach	world map		discrete control		
7	0	Pushes	Motor	mode	start	playback	world map		discrete control		
8	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
9	0	Decides	Cognitive	mode	override	playback	world map				
10	0	Pushes	Motor	mode	override	playback	world map		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Adjusts	Motor	position		LRM	world map	continuous control
12	0 Monitors	Perceptual	position		LRM	world map	CRT
13	0 Pushes	Motor	mode	start	playback	world map	discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.5. Remove Residual Waste

Task: Robotically remove residual waste **Sequence:** 3

Purpose: Remove waste layer robotically. **Duration:** 0

Cue: Tank cleaning program taught

Description: After the tank cleaning program is taught, execute and monitor the program, intervening manually as necessary.

Comments: Elements 4-11 would occur repetitively

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Decides	Cognitive	mode	operable	playback					
2	0	Pushes	Motor	mode	enable		LRM		discrete control		
3	0	Pushes	Motor	mode	start	playback	LRM		discrete control		
4	0	Monitors	Perceptual	mode	operable	playback	LRM		TV		
5	0	Monitors	Perceptual	mode	operable	playback	world map		CRT		
6	0	Decides	Cognitive	mode	override	playback	LRM				
7	0	Pushes	Motor	mode	override	playback	LRM		discrete control		
8	0	Adjusts	Motor	position		tank cleaning EE	LRM		continuous control		
9	0	Monitors	Perceptual	position		tank cleaning EE	LRM		TV		
10	0	Monitors	Perceptual	position		tank cleaning EE	LRM		world map		

Modified Task Analysis Form for Waste Retrieval Manipulator System

11	0 Pushes	Motor	mode	enable	playback	LRM		discrete control

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.5. Remove Residual Waste

Task: Manually remove residual waste **Sequence:** 4

Purpose: Remove waste layer manually. **Duration:** 0

Cue: Waste layer mapped and characterized

Description: After the map is completed, remove the residual waste using manual control.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	enable		LRM		discrete control		
2	0	Remembers	Cognitive	sequence				waste	Operations Log		
3	0	Adjusts	Motor	position		tank cleaning EE	LRM		continuous control		
4	0	Monitors	Perceptual	position		tank cleaning EE	LRM		CRT		
5	0	Pushes	Motor	mode	start	tank cleaning EE	LRM		discrete control		
6	0	Monitors	Perceptual	cleaning EE	in-band	tank cleaning EE	LRM		TV		
7	0	Pushes	Motor	mode	stop	tank cleaning EE	LRM		discrete control		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 2. Remove Waste Layers

Sub-Function: 2.5. Remove Residual Waste

Task: Inspect tank interior **Sequence:** 5

Purpose: Inspect the interior of the tank after cleaning and record the st **Duration:** 0

Cue: Waste cleaning completed

Description: After cleaning the tank, inspect the tank and make a record of its status.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Inspect						tank interior	TV		
2	0	Record						tank interior	Operations Log		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 3. Remove TWRMS Equipment from SST

Sub-Function: 3.1. Remove LRM System from SST

Task: Choose removal mode (manual or robotic) **Sequence:** 1

Purpose: Select a removal mode **Duration:** 0

Cue: Tank inspection completed

Description: After deciding that the LRM is ready for removal, decide whether to use manual or robotic removal mode.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication	
										Respondent	Content
1	0	Chooses	Cognitive	mode			LRM				

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 3. Remove TWRMS Equipment from SST

Sub-Function: 3.1.1. Remove LRM System from SST

Task: Manually remove LRM from tank **Sequence:** 2

Purpose: Carry out manual removal **Duration:** 0

Cue: Removal mode selected

Description: After selecting manual removal mode, manually control the removal process

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Positions	Motor	mode	manual		LRM		discrete control		
2	0	Adjusts	Motor	rate			LRM		continuous control		
3	0	Monitors	Perceptual	position			LRM		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 3. Remove TWRMS Equipment from SST

Sub-Function: 3.1.2. Remove LRM System from SST

Task: Robotically remove LRM from tank **Sequence:** 2

Purpose: Carry out robotic removal **Duration:** 0

Cue: Removal mode selected

Description: After selecting robotic removal mode, initiate and monitor the removal process

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	robotic		LRM		discrete control		
2	0	Pushes	Motor	mode	start	robotic routine	LRM		discrete control		
3	0	Monitors	Perceptual	position	in-band	LRM platform	LRM		TV		
4	0	Monitors	Perceptual	position	in-band	LRM platform	LRM		world map		
5	0	Decides	Cognitive	position	out-of-band	LRM platform	LRM				
6	0	Pushes	Motor	mode	stop	LRM platform	LRM		discrete control		
7	0	Chooses	Cognitive	mode	robotic or manual		LRM				

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 3. Remove TWRMS Equipment from SST

Sub-Function: 3.2. Remove Aux. CCTV System from SST

Task: Choose removal mode (manual or robotic) **Sequence:** 1

Purpose: Select a removal mode **Duration:** 0

Cue: LRM removed

Description: After deciding that the aux. CCTV is ready for removal, decide whether to use manual or robotic removal mode.

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication	
										Respondent	Content
1	0	Chooses	Cognitive	mode			aux. CCTV				

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 3. Remove TWRMS Equipment from SST

Sub-Function: 3.2. Remove Aux. CCTV System from SST

Task: Manually remove aux. CCTV from tank **Sequence:** 2

Purpose: Carry out manual removal **Duration:** 0

Cue: Removal mode selected

Description: After selecting manual removal mode, manually control the removal process

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Means of Action	Communication: Respondent	Communication: Content
1	0	Positions	Motor	mode	manual		aux. CCTV		discrete control		
2	0	Adjusts	Motor	rate			aux. CCTV		continuous control		
3	0	Monitors	Perceptual	position			aux. CCTV		TV		

Modified Task Analysis Form for Waste Retrieval Manipulator System

Mission Phase: 3. Remove TWRMS Equipment from SST

Sub-Function: 3.2. Remove Aux. CCTV System from SST

Task: Robotically remove aux. CCTV from tank **Sequence:** 3

Purpose: Carry out robotic removal **Duration:** 0

Cue: Removal mode selected

Description: After selecting robotic removal mode, initiate and monitor the removal process

Comments:

El. No.	Time	Verb	Group	Parameter	State	Component	System	Other Obj.	Communication: Means of Action	Communication: Respondent	Communication: Content
1	0	Pushes	Motor	mode	robotic		aux. CCTV		discrete control		
2	0	Pushes	Motor	mode	start	robotic routine	aux. CCTV		discrete control		
3	0	Monitors	Perceptual	position	in-band	CCTV platform	aux. CCTV		TV		
4	0	Monitors	Perceptual	position	in-band	CCTV platform	aux. CCTV		world map		
5	0	Decides	Cognitive	position	out-of-band	CCTV platform	aux. CCTV				
6	0	Pushes	Motor	mode	stop	CCTV platform	aux. CCTV		discrete control		
7	0	Chooses	Cognitive	mode	robotic or manual		aux. CCTV				

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