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TEST BED CONTROL CENTER DESIGN CONCEPT FOR TANK WASTE RETRIEVAL MANIPULATOR SYSTEMS*

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ABSTRACT

This paper describes the design concept for the control center for the Single Shell Tank Waste Retrieval Manipulator System test bed and the design process behind the concept. The design concept supports all phases of the test bed mission, including technology demonstration, comprehensive system testing, and comparative evaluation for further development and refinement of the TWRMS for field operations.

INTRODUCTION

This paper presents a narrative description and supporting drawings of the Tank Waste Retrieval Manipulator System (TWRMS) test bed control center workstations and facility plan. The scope includes background on the system, the design approach and process that led to the concept, the rationale for design features and supporting research, and discussion of design alternatives. This study was performed by the Oak Ridge National Laboratory in the Robotics & Process Systems Division and Engineering Physics and Mathematics Division. Funding was provided the U.S. Department of Energy's Office of Technology Development, Robotics Technology Development Program.

TWRMS Mission

Because the TWRMS is a developing system, a description of the mission of the operational system is somewhat speculative. However, the following 3-phase mission description provides a reasonable description of the repeated activities that will occur during a tank waste retrieval campaign:[1,2]

1. Using manual control or automated routines, insert the TWRMS and subsidiary equipment into the tank, inspecting the tank and TWRMS as necessary during the process.

2. Remove layers of waste from the tank. This may require cutting and removing risers or other forms of in-tank hardware (ITH).

3. Remove TWRMS equipment from the tank.

Components of the TWRMS that will operate inside the waste tank under remote control include the following: positioning mast, gross positioning manipulator system (GPM), dexterous manipulator (DM), waste retrieval end-effectors, waste conveyance system, viewing system, and other sensor systems.

Test Bed Mission

The TWRMS test bed will support technology development necessary to retrieve hazardous waste from underground storage tanks through use of a remotely operated manipulator.[3] Components of the TWRMS are being developed concurrently with the present control center design concept. A few broad system parameters are known, and other features can be assumed with reasonable certainty; these form a basis for the test bed control center design concept.

The mission of the test bed facility as a whole is to (1) demonstrate the technology under conditions as close as possible in the mockup to those likely to prevail in actual field operations of the TWRMS and (2) support comprehensive system testing and comparative evaluation for further research and development. Research at the test bed facility is expected to guide the continued refinement of hardware and software for the TWRMS design for field operations. This mock-up TWRMS facility will also accommodate personnel dedicated to system performance testing and comparative evaluation.

THE DESIGN PROCESS

Design of the control center involved four phases: (1) task analysis; (2) task function grouping, function allocation, and panel identification; (3) workstation design; and (4) facility layout. This report focuses on the workstation designs and facility layout. The task analysis[1] generated an exhaustive list of tasks required by the TWRMS mission, which were divided into their smallest meaningful components. The tasks provided the basis for a list of required functions and the necessary controls, displays, and interfaces to be incorporated into the control center. The task list also provided the basis for simulation studies of waste retrieval operations, which contributed to an understanding of the requirements for the control center.[4,5] Tasks identified by the analysis were combined into task-functional groupings and then related function groups were combined into control and display panels required to operate each piece of equipment.[6] Workstations were designed to incorporate control and display panels while satisfying ergonomic design guidelines for safe, efficient, system operation and crew interaction. Workstation designs combined some panels where one interface could serve two similar functions. Finally, a facility layout was designed with workstations located to optimize crew interaction, access, and other considerations. This paper provides an overview of the resulting control center design, which is described in more detail in a separate report.[7]

Design Guidelines

In satisfying the design requirements, the following general guidelines applied:

1. *Simplicity.* The design concept is intended to represent the simplest form consistent with functional requirements and expected service conditions while using the minimum number of displays and controls.

2. *Ergonomic design.* Safe, efficient crew functioning and system performance depends on the fit of the design with human physiological and psychological capacities. Workstation dimensions and designs are intended to accommodate the population of likely operators' body dimensions and requirements for visual displays.

3. *Consistency.* Interfaces are designed to be similar, so operators can operate any piece of equipment at either workstation without having to adjust to different movements or different displays.

4. *Flexibility.* Wherever possible, controls and displays allow access to more than one piece of equipment or display more than one kind of information.

5. *Integration.* The design calls for integration of workstations for cooperation and interactive effort, by allowing operators to switch controls, to see each other's camera views, and share control efforts.

6. *Existing components.* Wherever possible, the TWRMS control center concept uses standard, off-the-shelf components that meet or exceed all human factors standards and have demonstrated reliability.

CONTROL CENTER CONCEPT

Crew Size

TWRMS is designed for operation by a 2-person crew comprised of qualified dexterous manipulator operators capable of operating all TWRMS subsystems.

Chief Operator. The chief operator will be the mission commander, with primary reporting responsibility for safe and efficient execution of the waste removal process. The chief will have responsibility for controlling the GPM and DM during waste removal. The chief operator will also have camera controls and a station for data entry/retrieval and teleconferencing.

Monitor. The monitor serves in a support capacity to the chief operator, and is expected to relieve the chief operator as necessary and cooperate in positioning GPM, cameras, and other tasks. The monitor is also expected to take control, when necessary, of all TWRMS subsystems, including GPM and DM.

Mission Specialists. Mission specialists will be charged with system performance testing. During system trials, they will conduct research on the operation and effectiveness of individual controls and displays. They will monitor crew performance under varying conditions and

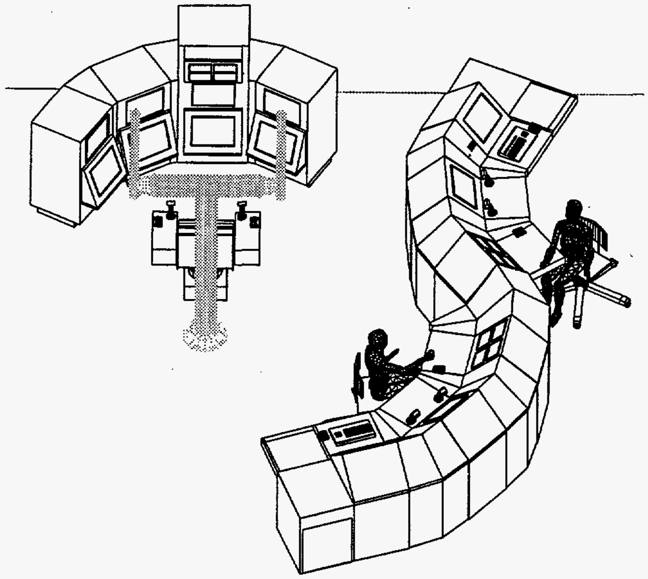

Figure 1. chief operator's, monitor's, and de x-
terous manipulator workstations.

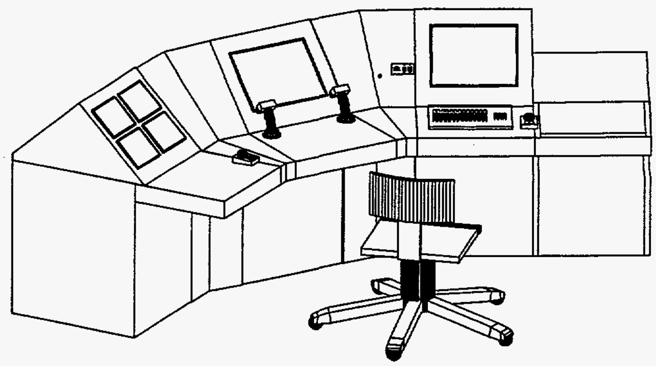

Figure 2. chief operator's workstation.

conduct comparative evaluations of controls and displays in different modes.

Workstations

The design concept calls for 3 workstations for the TWRMS crew, plus 2 additional workstations for personnel assigned to the test bed. Figure 1 illustrates the arrangement of the TWRMS crew workstations.

Chief Operator's Workstation. This workstation, shown in Figure 2, was designed primarily for turning system power on and off, entering and retrieving data, communicating by telephone and teleconference, and camera control. It will also serve as a secondary position for controlling the manipulators and end-effector systems. It is located adjacent to and facing the monitor's station. The chief operator's workstation has a display console with 6 monitors, including a 48-cm (19-in.) graphics monitor, a 48-cm (19-in.) video monitor, and four 25-cm (10-in.) monitors, one of which is a graphics monitor and 3 are video monitors capable of displaying camera views and teleconference views. Displays are mounted behind a horizontal work-surface fitted with a track ball cursor control and 2 variable-rate hand controllers with multiple function switches to control graphics screens, GPM, and cameras. The console has emergency disengage/shut-down controls. A keyboard in a drawer in the front edge of the work-surface allows data entry and other tasks requiring text handling. The station has an ergonomically designed, manually adjustable, office chair.

The console has three facets, with the right and left facets angled 15° inward toward the operator for optimal viewing. This arrangement places the screens approximately equidistant from the operator's eyes, allowing the operator to look quickly from one screen to another without refocusing his eyes. The top of the display console is horizontal and 93 cm (37-in.) from the floor, to provide an open line of sight to the monitor's workstation. Screen faces are all angled at 45° from vertical, to optimize viewing angles under conditions of prolonged viewing. (Research shows that operators tend to -in.droop-in. after awhile and look downward at an angle of about 30°.[8]) The displays are located behind a work-surface large enough to accommodate papers and files, though the design concept assumes the crew will exchange most information electronically, and will use very few printed documents.

Chief Station's Hand Controllers. The chief's station has two aircraft-style, variable-rate hand controllers with symmetrical right-hand and left-hand contours. (The same controller handles are used for the hand controllers in the monitor's workstation and the Dexterous Master station.) Each handle has 4 dof; it moves in 3 axes (right-left, forward-backward, and upward-downward) and rotates clockwise and counterclockwise, with spring-loaded return to center. For all hand controller functions involving handle movement, the design concept calls for the graphics menu system to allow a choice of at least three different rate control ratios (high, medium, or low). For example, when the operator inserts the GPM into a well-mapped tank interior, he or she may choose a high ratio of slave system to handle movement, or relatively fast speed at maximum handle displacement. For more delicate operations, such as moving the GPM into its final position at the waste removal site, the operator may select the low ratio, like low gear in an autom obile.

Besides choices of ratio of slave system speed to handle displacement, the menu system will give the chief operator the choice of *constant-speed directional control,* in which the speed of slave system movement is the same for any displacement of the handle. Under this control option, no matter how far the operator displaces the handle, the slave system moves at the same constant speed. (This is the default for camera control.) The operating system will offer a choice of at least 4 constant rate control speeds, with a very slow speed for the most delicate positioning maneuvers.

Each hand controller has 4 switches: a trigger switch activated by the operator's index finger and 3 switches on the top face of the handle within convenient reach of the operator's thumb. All of the switches give tactile (detent) and auditory feedback (clicks) when activated and deactivated. The trigger is a momentary (spring-loaded) on-off switch. The top inboard push-button switch is also a spring-loaded momentary on-off switch. In the center is a 4-position, two-axis joystick momentary switch (right-left and up-down movement with spring-loaded return to center). The top outboard switch is a 4-position selector that moves in one axis from side to side into one of four detents to select one of the four hand controller modes:

1. Screen mode: Cursor and selector controls for graphics menu screen
2. Camera mode: Pan, tilt, zoom, focus, iris and lights for selected camera
3. Gross position manipulator mode (one hand controller)
4. Dexterous manipulator mode (involves both hand controllers)

Emergency Power-Off Controls. Two push buttons located on the front of the chief's display console provide different levels of emergency power off. The buttons are above the right hand controller, in a location that requires the operator to reach outside the normal working envelope by leaning forward and fully extending his or her right hand. (This design makes the emergency power-off switches unlikely to be activated unintentionally while remaining easily accessible at all times.) The one at the left is a rounded, triangular, bright yellow button with black lettering (REMOTE POWER OFF) and two spring-loaded detents. This button provides a system disengage function that cuts all power to remote effector systems—the Gross Positioning Manipulator, Dexterous Manipulator, and end-effector—and cuts power to the force-reflecting DM controller handles. Pushing the button to its first detent activates a yellow console light below the button and causes a distinctive 80 db repeating buzzer to sound. Pushing to the second detent cuts the remote power. It is anticipated that the chief operator will use this button when the end-effector runs into an unexpected hazard, such as a hard rock, and expects damage if the system keeps operating. Similarly, if a force-reflecting controller handle malfunctions, the chief might use the yellow disengage button to deactivate the force-reflecting controls. When this button is activated, the TWRMS remote moving components are frozen in place without power, and the force-reflecting controls free wheel without power, but all other TWRMS systems continue to have power: controls, displays, cameras, and lights.

A second level of power off is provided by a bright red button 7.6 cm (3-in.) in diameter with white lettering (ALL POWER OFF), located to the right of the yellow disengage button, also with 2 detents. This button shuts down all power to the TWRMS system, including cameras and lights and the operating system. When it is activated, the first detent causes red lights to show on all control panels and an 80 db buzzer to sound. When pushed to the second detent, the system instantly shuts down, with remote systems frozen in place and control systems free-wheeling. It is expected that the crew will only use this button to prevent a catastrophic malfunction of the TWRMS.

Dexterous Master Control Workstation*:* As shown in Figure 3, the dexterous master workstation is designed for comfortable, long-term operation of the system's end-effectors, such as a remote grasping manipulator or suction tool. The workstation has controls and displays for every TWRMS subsystem, if needed, except system power. (For operator safety, the force-reflecting controls should not be powered up from the DM master station nor while the chair's sensor indicates that a person is in the DM master station.) This workstation has a powered, adjustable cockpit chair where the operator will sit while using the primary DM control (likely to be a force-reflecting hand controller attached to a floor-mounted, elbow-up arm extending in front of the chair with its base behind the chair). The hand controllers have molded aircraft-style hand-grips, with multiple function switches. While the controller details are to be developed by the manipulator vendor, the workstation is compatible with a

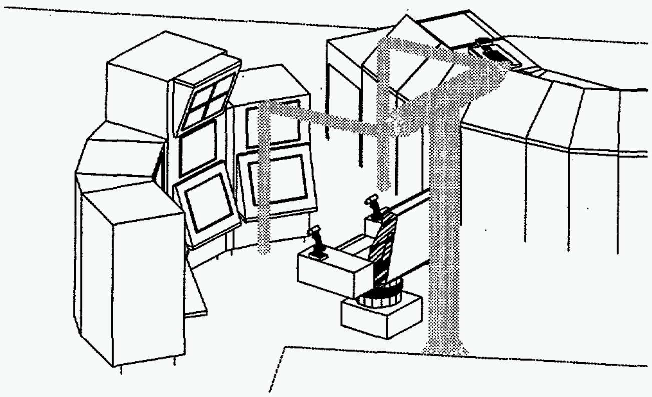

Figure 3. Dexterous manipulator workstation.

pair of force-reflecting master controllers. Arm rest hand controllers can be used to operate the graphics screens and cameras, and provide resolved rate control of the DM and GPM.

The DM master station's display console has eight large monitor screens (48-cm [19-in.] or 63-cm [25-in.] diagonal) arranged in two rows of four, including 2 graphics monitors capable of displaying system menus and the world model of the entire system and 6 video screens for camera views and tele-conferencing. Four additional 25-cm (10-in.) monitors display other camera views.

The displays for the DM master station were designed to support an operator during complex remote manipulation tasks requiring high-fidelity views of the working area from multiple cameras. Remote manipulation requires a focal screen plus one or two additional side or oblique views (for depth perception) and a top view for details not visible from front or sides. The operator is expected to rely heavily on 4 video screens during remote manipulation tasks. In addition, he or she will require a graphics screen for menu control and another graphics screen for the animated world map that displays the TWRMS system and its status. To these 6 screens the design concept adds 2 more for teleconferencing and a series of smaller camera view screens.

The design of the DM master station is limited by the requirement that no equipment occupy the space envelope defined by the range of motion of the force-reflecting controllers. This is a precaution against the unlikely event that the controls malfunction and collide with something in their range of motion. As a consequence, the design incorporates a display console with a 1.5-m buffer zone between the screen faces and the cockpit chair; the full mechanical range of motion of the force-reflecting controllers is required to fall at least 5 cm (2-in.) within this zone when the controllers are active. Because the operator sits about 2 m from the screens, they are larger than those in the chief operator's console. The DM master station has no horizontal work su rface.

The console has four facets, each angled 15° inward from the adjacent facet, so that the screens are equidistant from the operator's eyes when in normal working position (approximately 2-ms from the screens), and the screens on the bottom row are angled 20° upward to optimize the operator's viewing angles. The top row of large screen faces is vertical, and the four 25-cm (10-in.) monitors, mounted on top of the second facet from the right, have their faces angled 20° toward the operator to equate the eye-to-screen distance and optimize visual angles. Having the centers of the screens equidistant from the operator's eyes allows the operator to look quickly from one screen to another without re-focusing his or her eyes. The top of the main console is 183 cm (72 in.) from the floor, and 33 cm (13 in.) higher where the 25-cm (10-in.) video screens are mounted; the bottom edge of the bottom row of screens is 61 cm (24in.) from the floor for all but the focal screen.

The console is designed around a primary or focal video screen, which is the lower screen in the second facet from the right side of the console from the operator's perspective. The lower screen is preferred as a focal screen because operators are more comfortable when looking slightly downward during prolonged visual tasks. This screen is larger than all others in the console (63 cm or 25-in. diagonal), so it will show greater detail than the others. The graphics screen immediately above the focal video screen is also a 63 cm (25-in.) monitor, and is expected to be used mainly for the world map, though it can serve as a menu screen. The monitor at the operator's upper right is the other graphics screen. These graphics screens are controlled by arm rest track ball cursor controls, with the left arm track ball dedicated to the left screen and the right arm track ball to the right screen. Additional screen control is available from any of the workstation's four hand controllers.

The video screens at the operator's left are designed to serve as a teleconferencing center. The two 48-cm (19-in.) video monitors are visible not only to the DM master operator, but to the monitor and to the chief operator while occupying the chief's station. Above the monitor are mounted two console teleconferencing cameras, one of which can show a wide-angle, remote view of all three workstations at once.

DM master cockpit chair. The DM master station uses a power-operated cockpit chair, for three reasons. First, a powered chair provides a stable base from which to operate force-reflecting controls, requiring no effort by the operator to keep the chair in position. Second, a powered chair requires less effort by the operator for adjustment, which may encourage adjustment for greatest efficiency. Third, a powered chair allows a wide range of adjustment in back and seat tilt, which are important for operator comfort in prolonged work. It is anticipated that in field operations the DM master station might be operated for relatively long periods of time, perhaps as long as 4 hours for a single operator, so the chair is ergonomically designed to maximize the amount of time an operator can operate the controls at peak efficiency. Therefore the cockpit chair is designed for comfort under conditions of prolonged use.

DM master arm rest hand controllers. Mounted at the ends of both the right and left arm rests of the cockpit chairs are hand controllers of the same type as those in the chief's workstation. They are identical to those in the chief's station in both their operation and default control configurations.

DM emergency power-off. Two push buttons identical to the ones on the chief's workstation are mounted on the outside of the right-hand arm rest of the cockpit chair to allow the operator to disengage the TWRMS system or shut it down completely.

Monitor's Workstation. Because the monitor serves as the chief operator's backup during waste retrieval operations, he or she may potentially be required to perform any function that the chief performs. Therefore the monitor's workstation exactly duplicates the chief's station. It allows control over system power, cameras, GPM, DM, and all other TWRMS subsystems It has primary power on/off controls, a display console with 6 screens, a horizontal work-surface with keyboard and two track balls, and right- and left-hand multi-function hand controllers. This workstation has an adjustable chair on wheels.

Mission Specialist Workstation. Two identical workstations for mission specialists have work surfaces with 5-screen display consoles and desk-mounted trackball cursor control. These workstations have read-only access to the TWRMS operating system, and no controls for TWRMS equipment systems.

Test Bed Control Center Floor Plan.

Figure 4 shows the floor plan for the control center, which occupies a floor area of 40 by 40 feet, or 1,600 square feet (including space for high bay Waste Dislodging & Conveyance project observers, labeled "WD&C Area" in Figure 4). The plan is organized around the process area, which is adjacent to the test bed support staff area and visitor observation area. Both are elevated 3' above the process area to give an unobstructed view, and they are separated by glass partitions to isolate the process area. On the same level with the process area is an enclosed room for computer racks that serve the TWRMS operating system and crew workstations.

Process Area Layout. As shown in Figure 4, the layout of the process area is designed to promote face-to-face communication between the chief operator and monitor while they operate the 3 crew stations of the TWRMS. The chief's station and monitor's station face toward one another and are adjacent to one another, placing them within comfortable conversation distance. The monitor's station has an open line of sight within the acceptable visual zone to the working positions at both the DM Master station and the chief's station, at distances appropriate for face-to-face conversation with the other operator in either position. Similarly, the chief's station and the DM master station allow conversation, but both people must turn their heads to converse. This layout optimizes the line of sight between monitor and DM master workstations, which are expected to be the most common seating positions for the chief operator and monitor, respectively.

Test Bed Support Staff Area Layout. The mission specialists are located in an area that overlooks the process area. The mission specialists' L-shaped workstations have flat work surfaces oriented toward the window overlooking the process area. Their consoles face toward one another, giving an open line of sight at comfortable conversation distance, which allows face-to-face conversation during their work.

SUMMARY

This paper described a new, ergonomically designed control center for the TWRMS test bed. The control center was designed to promote the technology development and demonstration mission of the test bed, while providing a human-machine interface also applicable to future tank waste retrieval operations. Experience gained using this control center in the future will guide human-machine interface development for remotely controlled

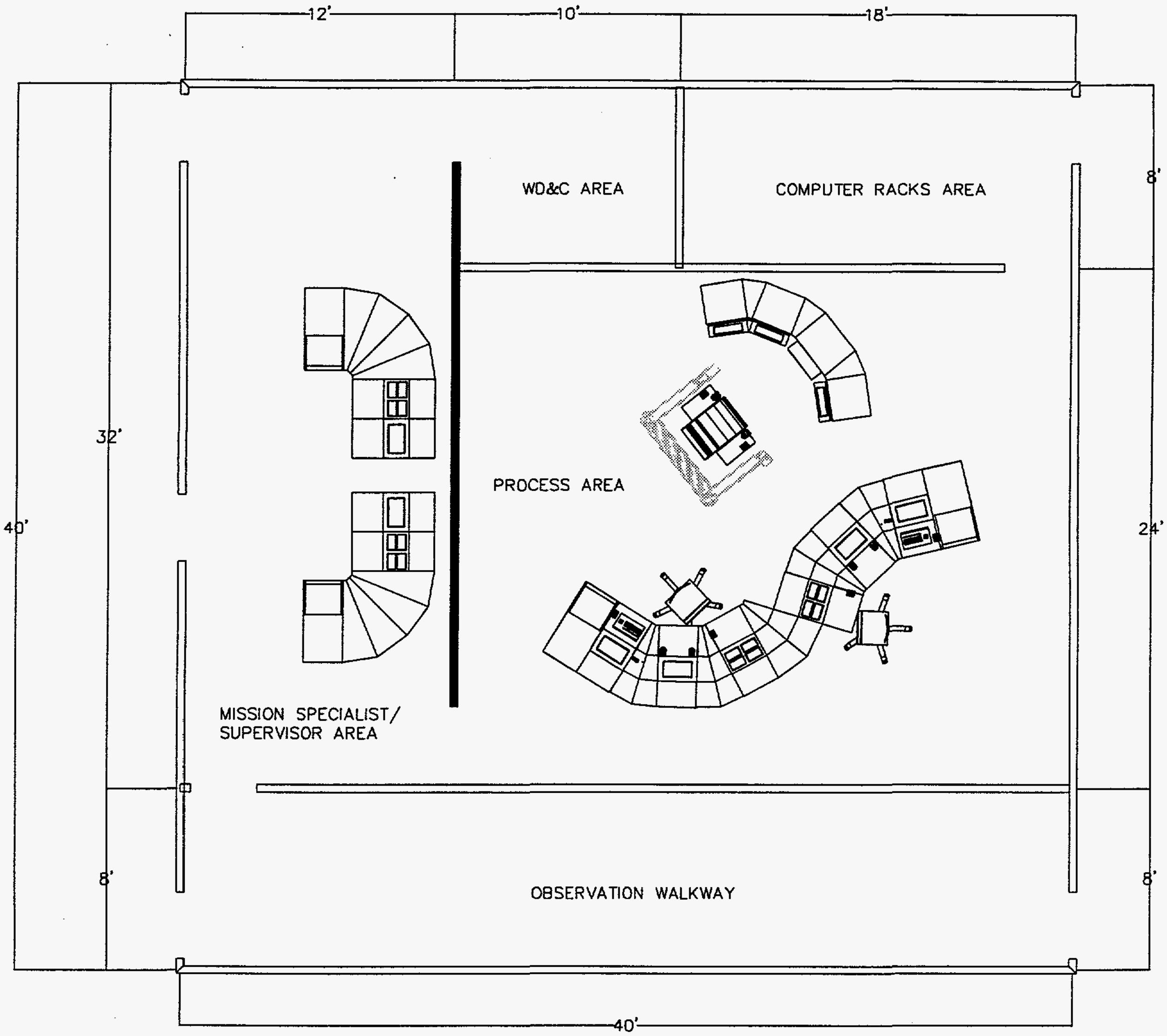

Figure 4. Control center floor plan.

manipulators generally and for tank waste retrieval operations specifically. Eventually, this experience will promote the design of optimally safe and efficient human-machine interfaces for remote waste retrieval.

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