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MAN-MACHINE INTERFACE AND CONTROL OF THE SHUTTLE DIGITAL FLIGHT SYSTEM

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The challenge in designing the Orbiter displays and controls (D&C) system was to integrate the required aircraft and spacecraft D&C in the space available within the pilot's reach and vision. Some of the basic requirements for the D&C system were as follows:

1. A safe return with a single crewman from either forward crew station

2. Normal operation (exclusive of payload management) of all mission phases using a flightcrew of two

3. Accessibility to the flightcrew from the flight seats of D&C required for vehicle or subsystem management during ascent and entry

4. D&C to provide for crew override of automated critical command functions

5. Crew selection of automatic or manual flight guidance and control

6. The means to annunciate and command safing of hazardous systems

7. Interior and exterior illumination consistent in type and quality for crew operations

In early 1970, the D&C system was evolving into an integrated, multipurpose data bus connected system (fig. 1). Front station concepts were to use five or six cathode-ray tubes (CRT's) for most of the display requirements and reformattable control panels and keyboards for most of the controls. Some dedicated switches were used for system initialization and where immediate crew access was required. Circuit breakers were used for power control. A head-up display (HUD) was used for out-the-window display presentation. The HUD is an electronic/optical device that presents essential flight information in the pilot's head-up field of view. The information is projected from a small CRT onto a combiner glass and collimated at "infinity" to overlay the out-the-window, "real world" scene.

During the phase B contract studies, conventional and integrated avionics systems were compared for weight, power, cost, and technology risk. With involvement of flight crewmen and flight operation engineers, many studies of electronic attitude direction indicators (EADI's) versus conventional attitude direction indicators (ADI's) and multipurpose data bus versus hardwired D&C were conducted. The Orbiter program management then chose a low-risk off-the-shelf technology approach. This choice eliminated the EADI's, the HUD's, and the multipurpose displays and controls. Dedicated D&C components with electromechanical displays and hardwired switches were used, although four multifunction displays with keyboards were retained for the digital system interface.

The Orbiter contract was awarded to Rockwell International and the subsystem engineers at both Rockwell and the NASA Lyndon B. Johnson Space Center (JSC) started working together to complete the detail design of the D&C system. One agreement that proved to be very valuable was to initiate a series of formal D&C reviews at Rockwell chaired by the Rockwell and JSC D&C Work Breakdown Structure (WBS) managers. There were 13 of these major reviews during which representatives from the flightcrew, flight operations, engineering, reliability, safety, program office, payloads, software, NASA John F. Kennedy Space Center, Rockwell, and the U.S. Air Force were present. The reviews averaged 46 people including 4 astronauts. The reviews were 2 to 3 weeks long with the first week consisting of the Rockwell subsystem engineers describing their subsystem and the D&C engineers presenting the D&C concept for the subsystem. This procedure allowed NASA to ask questions of the subsystem engineers to understand the system and the Rockwell concept of the operation. Many times, a subsystem engineer desired more D&C for his subsystem than was required for operational use. This method of review also provided consistency between the different subsystems D&C requirements. Rockwell produced a comprehensive blue book handout for these reviews, and review item dispositions (RID's) could be written for consideration by the formal board chaired by the JSC Orbiter Project Manager a week later.

By the end of the first week, the subsystem information for the review was completed and the RID's were written. A few JSC people would stay for the second week with the flightcrew and determine subsystem by subsystem the D&C required and the appropriate nomenclature. Full-size drawings were used to arrange the D&C panel configuration. A full-size foam core mockup was made of the

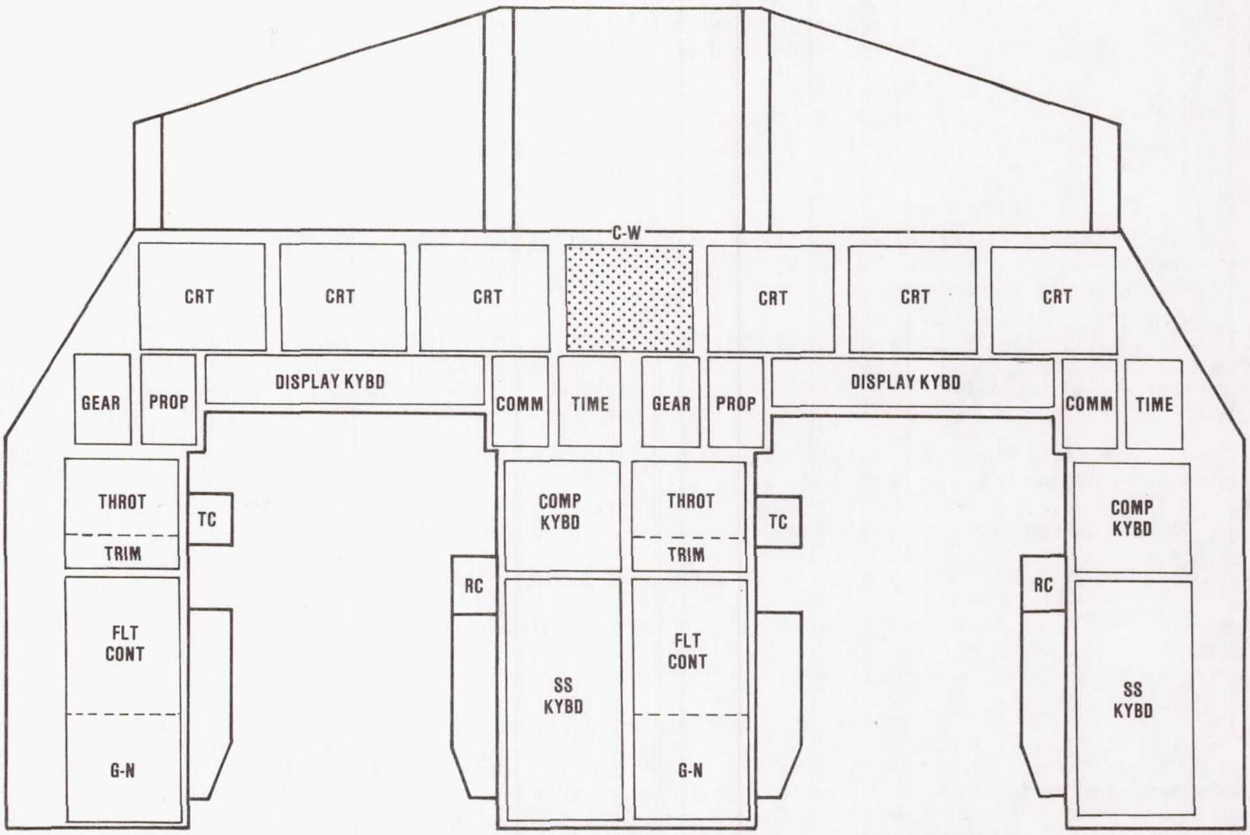


FIGURE 1.- EARLY D&C SYSTEM.

cabin area, and cutouts of the D&C were used to determine the proper location within the reach and visibility requirements derived from other studies. The flightcrew's support was invaluable during these design sessions. At the end of each review, Rockwell produced a D&C configuration drawing and updated the cabin mockup to be ready for the next D&C review, where the process would be repeated. As the subsystems became firm, the D&C panel layout and nomenclature were baselined and put under configuration control. Panel components were selected, meter scaling was chosen, and caution and warning (C&W) parameters were baselined.

The D&C reviews were progressive as a function of Orbiter system maturity, where, in general, D&C reviews 1 through 5 designed the OV-101 system, D&C reviews 5 through 11 designed the OV-102 system, and D&C reviews 12 and 13 completed the OV-099 or operational system. Between the formal reviews, a series of change package teleconferences was held between JSC and Rockwell to get JSC engineering and flightcrew participation in parallel with the Rockwell design process. These teleconferences are continuing much less frequently, to discuss D&C changes required in response to subsystem design changes. These teleconferences greatly reduced the quantity of D&C items that would otherwise go to the JSC Configuration Control Board (CCB). All change package teleconferences were documented with a set of minutes.

Early in the D&C design process, it was discovered that existing human factors D&C requirements documents should be used as design guides and not firm design requirements. With JSC crew station engineers and flightcrew participation in the design process, many of the human factors requirements were modified to produce a much better D&C system design. One example of this approach was the yellow pointers now used on the flight control electromechanical displays, especially the surface position indicator (SPI). Rockwell made a mockup of an SPI (which contains nine scales) using the standard white pointers. The crew, after determining the pointers were not visible enough, recommended yellow. Another good example was the background lighting specification for the pushbutton switches and the annunciators. Using the recommended specification light levels, the annunciator lighting was satisfactory in the laboratory. To be certain the annunciator lighting was readable in sunlight, sample devices were installed in the JSC one-g trainer and it was towed outside. The trainer was positioned so that the sunrise would shine through the cockpit windows. It was discovered that the annunciator status could not be determined because the resulting Sun shafting washed out the lighted annunciation. The annunciation was changed from lighted background to lighted legend, and optical elements were added to concentrate the light. This change raised the intensity and contrast sufficiently to provide annunciator legibility in full sunlight.

Early in the D&C panel configuration design, it was decided to group subsystem controls by function. However, associated circuit breakers were separated because of a concern that if the higher power circuits behind the circuit breakers did have an electrical fault or mechanical damage in a particular location, the entire subsystem could be affected. To lessen the training impact on the crew, the circuit breakers for each system were positioned at the same relative location on different panels or section of panels.

A numbering system for every panel surface was provided by the crew station engineers. This system is necessary when referring to a control location, especially on test and operational procedures or schematics. The panels are numbered from left to right or front to aft in the cabin. Letters are used for locations such as R for right side, O for overhead, L for left side, C for center console, A for aft, and M for middeck.

The foam core evaluator was a valuable tool for D&C panel component location. The D&C components were located by priority with the systems that need to be reached and viewed during maximum ascent acceleration positioned first. Other controls that require operation during periods in which the crew is strapped in the seats were positioned next, then lower order subsystem D&C components were positioned in the aft flight deck and the middeck. A more advanced analysis capability was used later in the program to assess crew accessibility to various displays and controls. Specifically, a three-dimensional graphics computer-aided design modeling package was used to depict a crewman's access to various D&C components under negative-g conditions during a contingency two-engine-out abort maneuver. The access depicted by the reach modeling program was then verified in a mockup. By increasing use of such modeling and simulation techniques, front-end mockup costs are reduced. Such techniques will not replace mockups, but will permit rapid evaluations of many configuration alternatives during conceptual and preliminary phases before the construction of mockups.

The aft flight deck was divided into three zones designated mission station, on-orbit station, and payload station. The mission station was assigned the D&C to manage flight-critical payload subsystem controls and non-flight-critical Orbiter subsystem controls. A CRT and keyboard is at this station to display subsystem information. The on-orbit station is separated into the on-orbit and the remote manipulator system (RMS) functions. The on-orbit station has an overhead window and a payload bay window; D&C for the functions of rendezvous, docking, TV, lighting, and communications are located here. The RMS station contains D&C for manipulator arm operations and an overhead and aft view. The RMS operator shares D&C for TV, lighting, and communications with the on-orbit station; RMS operations require the simultaneous use of two three-degree-of-freedom hand controllers. The operator also must set up views from as many as seven TV cameras in the payload bay on two monitors, both of which have a split-screen capability. During some payload deployment and retrieval operations, a crewman would be well served to have four arms to accomplish all the required tasks in the necessary timeframe. As it is, the operational configuration of the RMS station contains only about one-third of the D&C originally proposed and evaluated for that function. The payload station was reserved for payload-provided D&C except for an audio and station lighting panel. The middeck panel areas were designated for circuit breakers, housekeeping functions, middeck audio and lighting controls, and airlock controls.

Maintainability of the D&C panels and the line replaceable units (LRU's) was a strong driver in the D&C design. The D&C panels were designed to be small enough to be removed individually. There are more than 80 panels in the Orbiter and many include hinges to allow the panels to be swung out for access behind them. Each LRU is mounted from the front of the panel and can be installed and replaced without removing the panel.

The Orbiter operates in a zero-g environment while on orbit; therefore, any contaminants or extraneous materials are free to migrate. These materials can be conductive and of sufficient length to bridge terminals on such devices as switches, circuit breakers, and meters. To prevent this eventuality, all exposed electrical terminations on the panels are protected with a conformal coat of resilient insulating material, which also provides a humidity barrier. As with the external terminations on the D&C equipment items, the internal terminations are also treated to eliminate the possibility of floating conductive particles causing failures.

All Orbiter equipment and particularly items in the crew compartment are required to meet very stringent flammability and toxicity requirements. This requirement means that all exposed materials (not contained within at least an environmentally sealed enclosure) must be reviewed by materials and processing specialists for approval before use. In numerous cases in which existing hardware was used, special testing was required to determine the flammability, toxicity, and outgassing characteristics of specific materials for which these data were not available. When an unacceptable material could not be changed, it was overcoated or otherwise protected, and, in some cases, waivers were granted after analysis indicated acceptability because of configuration, quantity, etc.

One early problem was a means of complying with the NASA design standards that included a prohibition on the use of frangible materials. Most of the existing display devices such as CRT's and meters used a glass window as a means of providing visual access and sealing the instrument case. To circumvent this problem, most display devices with glass were provided with a Lexan cover over the window to protect the glass and contain the glass in the eventuality of a fracture. These Lexan covers were easily removable for maintenance. The protective covers were coated with antireflective material for correct optical properties and have proven very practical in actual usage. Other protective devices were designed to protect the D&C from a crewman possibly causing damage to the D&C hardware while floating around the cabin. Wickets were placed around the switches on most of the panels, and on the panels the crew was most likely to step on, the switches were recessed into the panel.

Lighting, both internal and external, would appear to be a straightforward area; however, much design effort went into the Orbiter lighting. Lighting in the cabin consists of fluorescent lights for general area illumination, incandescent floodlights for spot illumination, and integral lighting for meters and panel nomenclature illumination. A good full-size cabin lighting mockup or evaluation would have been desirable. Most of the lighting evaluation was done by area or analysis, and the results were confirmed in the Orbiter cabin built for the Shuttle Avionics Integration Laboratory. The external lighting consists of metal halide lights for the payload bay and incandescent floodlights for overhead and manipulator illumination. One area of design difficulty with the external lights is the rejection of heat from the lights. Conductive cooling and innovative lamp design were required.

As the D&C requirements for the various subsystems continued to grow, the crew workload and knowledge required of each subsystem grew. Much effort went into the nomenclature designation to give the best operational understanding of the use of each control. This task must have crew or operations involvement because subsystem engineers tend to use engineering rather than operational nomenclature.

The flightcrew suggested that schematic layouts on the panels be considered for some of the subsystems to help understand their operation. Schematic panel layouts were done for panel R1 (power distribution and control), panel L1 (environmental control), panel L2 (atmospheric pressure control), panels O7 and O8 (fig. 2) (reaction control and orbital maneuvering systems), panel A1 (communications), panel R12 (supply water), and panel ML31C (wastewater). The use of schematic layouts should be implemented only when the subsystems are mature because once a panel is built, it is very difficult to add a switch in the correct place of the schematic.

The HUD was brought back into the program as an approach and landing aid and flown for the first time on STS-6. From the point of program approval to hardware delivery, a little more than 2 years elapsed, a very tight time frame for hardware development, qualification, and delivery. One area that proved to be a difficult problem was the format development. Simulations are required using both fixed- and motion-base simulators. The simulators had to represent the Orbiter software as closely as possible. One problem area with the HUD display format design effort was that it came in the program with a ground rule to impact the Orbiter general-purpose computers (GPC's) as little as possible. The HUD used the data bus information going to the dedicated electromechanical displays, but the data update rates were too slow. Therefore, data smoothing had to be done in the HUD and, where possible, faster data rates within the GPC were brought to the HUD. The moving-base simulator at the NASA Ames Research Center was not available to evaluate the HUD format, except for a few hours, before the software programable read only memories (PROM's) had to be burned for the hardware. The format that was used at this time had a large amount of information displayed with the capability of decluttering seven levels. The crew was involved during all the format design effort and, as more simulations were conducted, it was obvious the format had too much information. A large effort using fixed- and motion-base simulators and the Shuttle training aircraft (STA) was made and an updated, simpler format was designed for first use on STS-8. Since the hardware PROM's had to be built to deliver hardware on schedule, a retrofit program is now in process to update the HUD. One of the reasons the HUD development went as well as it did was a series of teleconferences held every other week with JSC, Rockwell, Kaiser Electronics (HUD supplier), Sperry (autopilot supplier), and Draper Labs (early systems support). These teleconferences are documented in a comprehensive set of minutes. Astronauts and software, simulator, program, hardware, and flight control engineers attend these teleconferences and help provide integration of the total HUD community.

As the Orbiter became operational, it also became obvious that the cockpit contains the most complicated assortment of D&C ever developed for an aerodynamic vehicle. There is a large variety of D&C devices. For control, there are toggle, pushbutton, thumbwheel, and rotary switches; potentiometers; keyboards; circuit breakers; and hand controllers. Display devices include circular and vertical meters, tape meters, mechanical talkbacks, annunciators, flight control meters, digital readouts, and CRT's. There are more than 2100 D&C devices in the Orbiter cockpit (fig. 3).

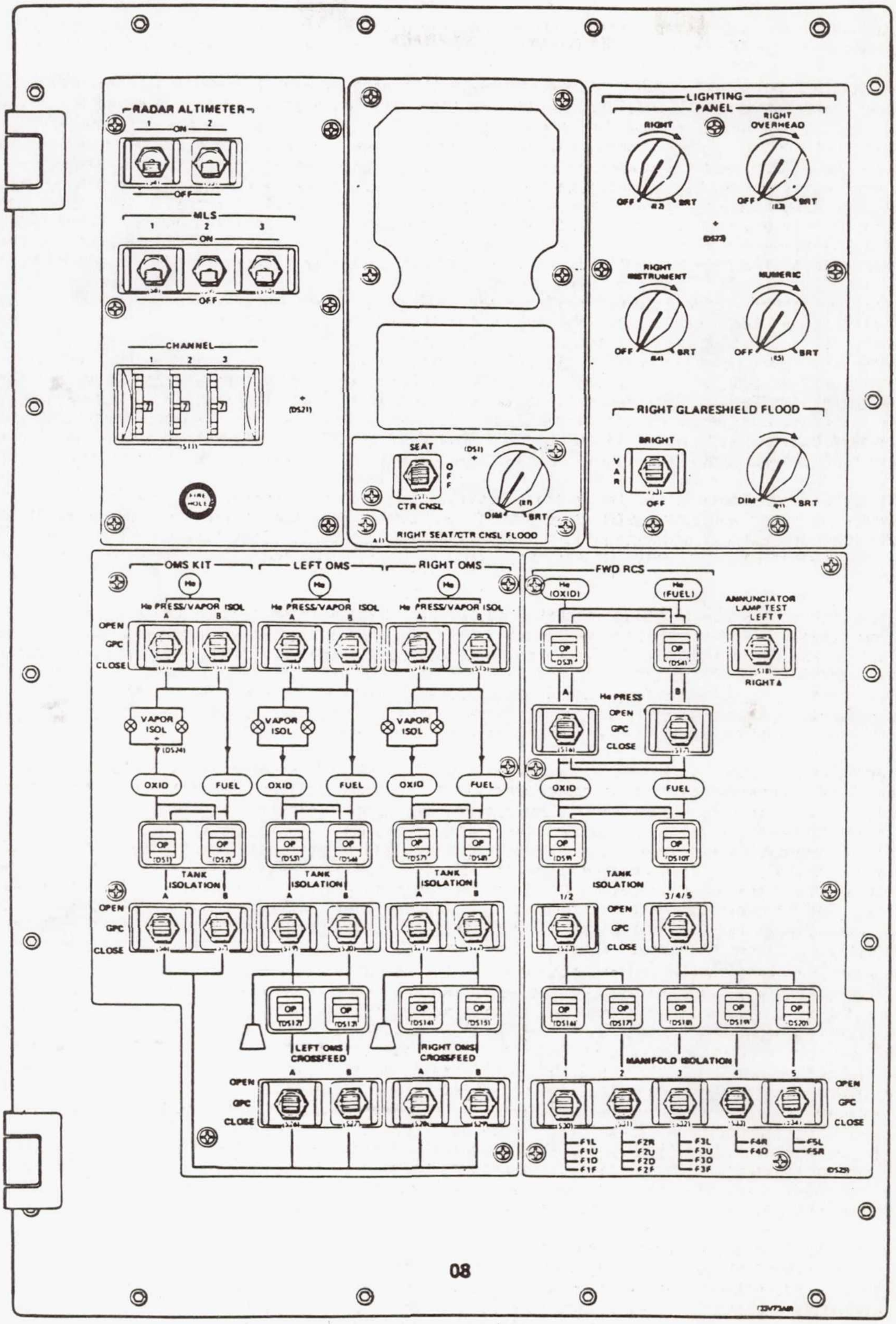
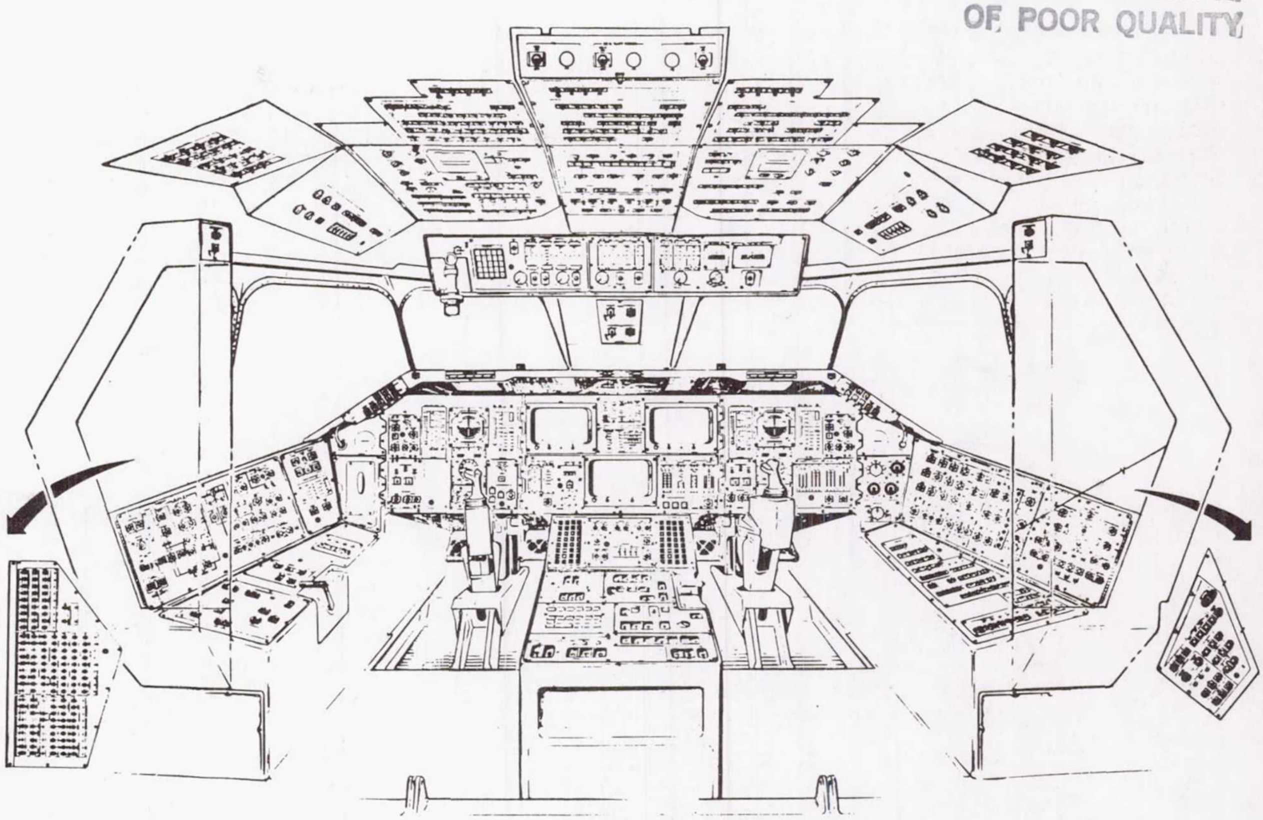
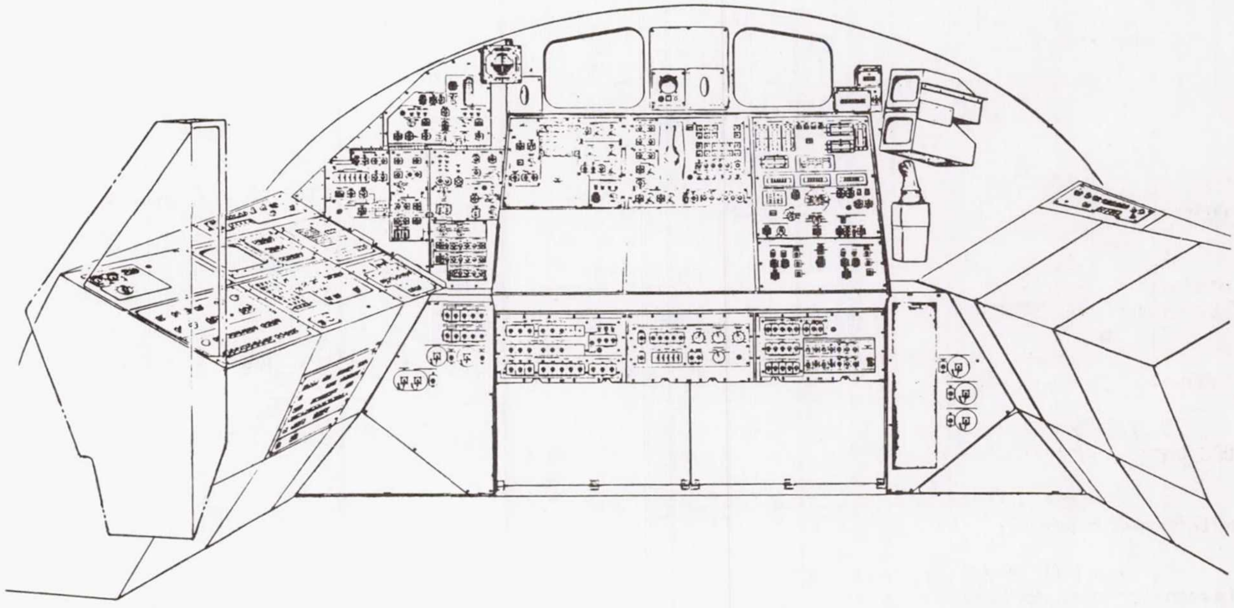


FIGURE 2.- PANEL 08.



(a) VIEW LOOKING FORWARD.



(b) VIEW LOOKING AFT.

FIGURE 3.- ORBITER COCKPIT.

Orbiter enhancement D&C studies conducted recently have all gone back to the multifunctional cockpit (fig. 4). To get the systems operations to a more automated and simpler level will greatly reduce crew workload. Multifunction CRT's and flat panel displays could replace the electromechanical displays and annunciators. Programable keyboards or CRT overlays could replace most of the 1300 control devices. Remote power switching could eliminate many of the 400 circuit breakers. Voice control and synthesis could be used as an added input/output channel to more efficiently use the crew during peak workload periods. A study was conducted in the Manipulator Development Facility (MDF) to assess the feasibility of using voice control of the many switching functions associated with the closed-circuit television system supporting the RMS. It was found that identical tasks (berthing and deployment) were completed in virtually identical times using manual switching (standard Orbiter operation) as a comparison for voice-controlled switching having a recognition accuracy between 85 and 95 percent. Using state-of-the-art voice recognition equipment should allow a marked improvement in the overall RMS operations.

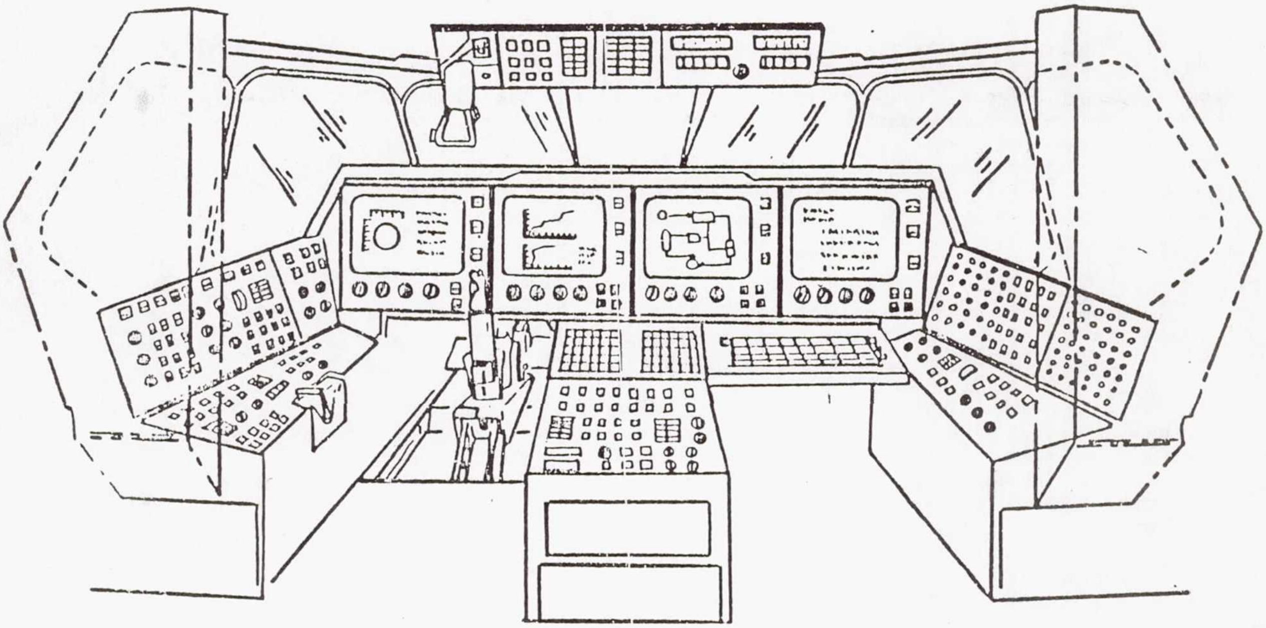


FIGURE 4.- MULTIFUNCTIONAL COCKPIT.

In summary, some of the most important lessons learned during the Orbiter D&C program are repeated here.

1. The formal D&C reviews held at Rockwell were necessary. The total Orbiter systems community needs to be involved; participation by the flightcrew and engineering personnel is very important. The reviews should be well documented.

2. The change package teleconferences are valuable to provide continuous JSC input into the Rockwell D&C design effort.

3. D&C engineers with crew and human factors engineering support should provide a consistent D&C panel layout and nomenclature configuration.

4. The early availability of the foam core cabin mockup was very important for D&C placement within reach and visibility constraints.

5. The HUD integration teleconferences were necessary, and comprehensive documentation of these teleconferences is important. Formal simulations should be done early in the program using high-fidelity simulators.

6. With large numbers of redundant subsystems, the use of dedicated D&C devices can rapidly grow into a large, complex system. Multipurpose D&C should be encouraged with local processing to help offload the central computer system and to improve crew efficiency.