DISMANTLING THE DAMAGED THREE MILE ISLAND REACTOR VESSEL BY REMOTE PLASMA ARC CUTTING

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ABSTRACT

The use of remote robotic equipment has proven invaluable in the task of removing the fuel from General Public Utility's damaged Three Mile Island Unit 2 reactor. The March 28, 1979 accident at Three Mile Island redistributed an estimated 300,000 pounds of core debris throughout all regions of the reactor vessel. Portions of the debris accumulated in areas that are inaccessible without major demolition efforts. The final stage of fuel removal requires gaining access to the regions below the lower core support assembly and behind the baffle plates where an estimated 67,000 pounds of fuel debris is trapped [1]. The Automated Cutting Equipment System (ACES), a robotic manipulator-controlled plasma arc cutting system, was developed to cut through the five plates comprising the lower core support assembly as well as the baffle plates, creating a passage to the fuel debris entrapped in these areas. This paper will provide a thorough description of the ACES system and its major components, as well as address the design challenges that had to be met to perform the designated task.

1. Overview of the Reactor Vessel Defueling Effort

To perform the fuel removal process, the reactor head and plenum were removed and a rotating shielded work platform was installed on top of the vessel. This platform provides radiation shielding for personnel as well as a means of safe access for deployment of defueling tools via an open work slot in the top of the platform. Below the platform, the reactor vessel is flooded with water which is borated with boric acid and buffered with sodium hydroxide, a highly conductive solution that acts as a neutron absorber to prevent criticality by the remaining fuel in the vessel. Defueling tools are used to dislodge, flush, vacuum, and transport fuel debris into canisters for shipping and off-site disposition. These activities are observed and supervised from the Coordination Center, a remote station located 700 feet from the reactor vessel, via audio and video equipment . At this stage of the defueling effort, all fuel assemblies have been removed and the remaining fuel in the vessel is inaccessible without severing the lower core support assembly and baffle plates.

1.1 Lower Core Support Assembly and Baffle Plate Description

The lower core support assembly consists of a series of five horizontal stainless steel plates, varying in thickness from 1 inch to 13 inches, which are submerged under 29 to 35 feet of water. Each plate has a unique geometry and hole pattern. The incore guide tubes, which house the incore instrumentation, extend vertically through all five plates in a select pattern of aligned holes.

The baffle plates are located above the lower core support assembly, and are also submerged in water. These .75 inch thick by 13 feet tall stainless steel plates create a continuous vertical wall around the core and seal off an area where fuel debris has accumulated between the plates and the core barrel.

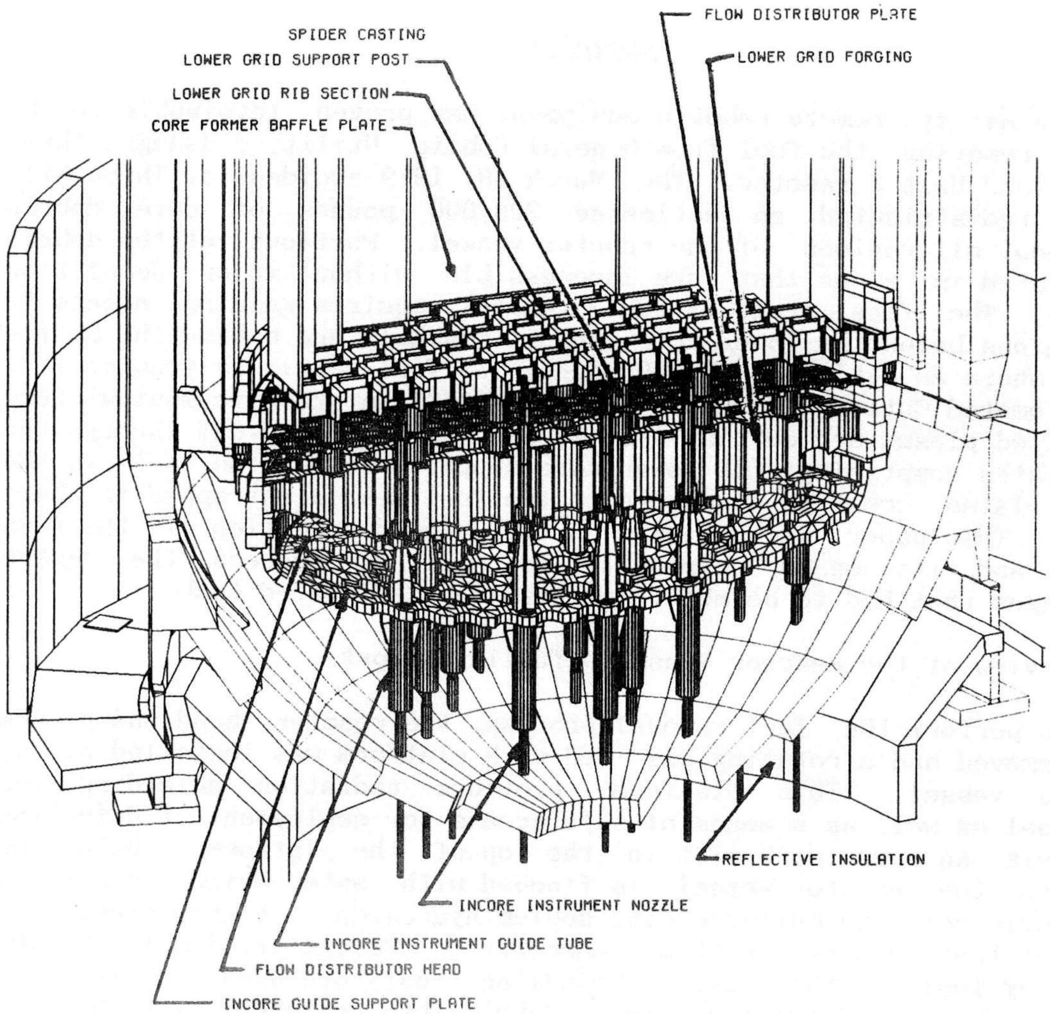

Fig. 1 - Lower Core Support Assembly and Baffle Plate Section View [4]

2. ACES Design Criteria

The complexity of the reactor vessel geometry, coupled with the harsh environment of both the reactor vessel and Reactor Building, create a unique set of design requirements. As a top priority, the system design had to minimize worker exposure to radiation which made complete system control from the Coordination Center essential. Also, the design basis required operation with less than 1 inch of visibility due to the unpredictable effect the cutting process would have on water turbidity. This necessitated an extremely accurate positioning system.

In order to perform underwater cutting, a manipulator system was required which could accurately position the torch head at the required cut trajectories. The manipulator would have to withstand the environment of the reactor vessel, requiring radiation tolerance to a field of 5,000 rad/hr and a cumulative dose of 10 million rad [2]. The system had to be watertight under 35 feet of head pressure, requiring a nitrogen purge system to maintain electrical enclosures at positive pressure. Also, manipulator construction would need to avoid areas where fuel debris could become trapped. Areas where fuel can accumulate become extremely radioactive which complicates contamination control and access by workers.

Furthermore, the system must be deployed through the slot in the work platform and would need to be installed and removed frequently during the cutting process to provide access for the transport of severed pieces and the vacuuming of loose fuel debris. Thus, reliable deployment and cable management systems were required for equipment protection and longevity. System serviceability had to account for limitations in workers' mobility as restricted by protective clothing, a respirator and several pairs of gloves. Torch repairs, a routine maintenance item, would require access to the torch without removing a major portion of the system.

The cutting system would have to be capable of cutting stainless steel slightly over two inches thick under 35 feet of highly conductive water. This presented a research and development challenge since plasma cutting had never been successfully performed at this depth and in such a conductive medium. Extensive testing was required to develop the best torches and cutting parameters.

3. ACES Hardware

The ACES system can be broken down into two primary subsystems, the Manipulator System and the Plasma Cutting System. System hardware is located in three primary areas: 1) in-vessel hardware 2) Work Platform hardware 3) Coordination Center hardware (i.e. remote hardware).

3.1 In-Vessel Hardware - Manipulator and Plasma Systems

To cut the lower core support assembly, a gantry (bridge and trolley), 10 feet square in dimension, is supported horizontally above the lower core support assembly, 28 feet below the surface of the reactor vessel water. The gantry consists of a manipulator saddle positioned on an X and Y servo-driven rack and pinion. The gantry bridge and trolley are driven by permanent magnet DC drive motors which provide horizontal motion control of the manipulator saddle. An 8 inch diameter cylindrical manipulator mast, 12 feet in height, is positioned vertically in the saddle on the X/Y gantry. The mast is a telescoping tube within a tube which includes Z, A, and B axis motion control of a three-point pneumatically-operated gripper. The Z axis drive consists of a three phase AC induction motor, coupled to a lead screw, which drives the inner tube and provides vertical positioning of the torch. A and B axis drives consist of permanent magnet DC motors. The A axis drive provides rotation of the torch while the B axis drive provides translation (i.e. wrist action). In the case of installation of the ninety degree extension on the bottom of the mast, the A axis drive provides rotation of the three-point gripper on the extension while the B axis drive provides rotation of the extension itself. All five drive systems include gear reduction via a harmonic drive package coupled to high resolution optical encoders for position feedback of each drive axis. The manipulator control and power cables are routed from the vessel, vertically, to the Manipulator Control Cabinet on the Work Platform and are purged with nitrogen to prevent water incursion.

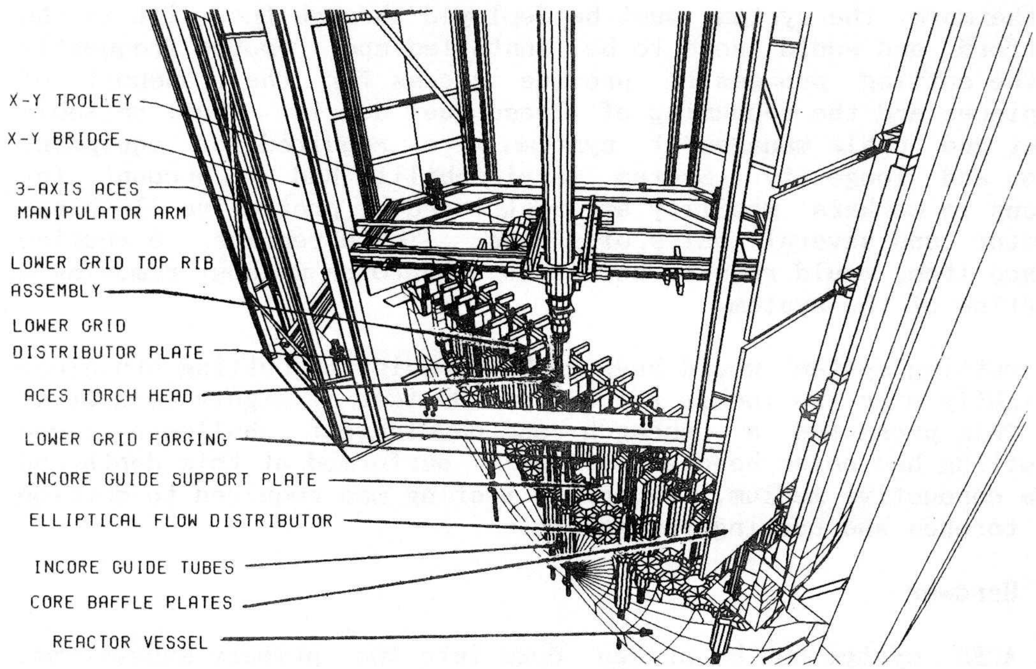

Fig. 2 - In Vessel Elevation View of ACES Gantry and Manipulator [4]

To cut the baffle plates, the ACES manipulator mast is installed in a saddle mounted on the Manual Tool Positioner. The Manual Tool Positioner, a vertical post indexed from the rotating work platform, provides a means of positioning the mast at various elevations since the Z axis is limited to 44 inches of travel. To perform a baffle plate cut, the work platform is rotated to position the torch in the desired radial cut location. Next, the Z, A, and B axes drives are utilized to control motion of the torch over the range of a 40 inch long vertical cut. Then, the platform is rotated to each cut at this elevation and the Manual Tool Positioner is repositioned to locate the mast at the next elevation for another set of 40 inch vertical cuts.

An underwater camera viewing system with pan and tilt control is utilized by the operators in the Coordination Center to ensure accurate positioning of the manipulator. One camera is mounted on the X/Y gantry and the other is mounted on a long-handled pole. Each camera is equipped with a flip-down welding shield to prevent the cutting arc from damaging the camera iris.

The plasma arc torch, when positioned in the manipulator gripper, obtains power, control, nitrogen gas and coolant via a service umbilical, 100 feet in length. The umbilical is routed through the platform work slot to the Plasma Junction Box on the work platform above the vessel. A junction canister is included on the end of the umbilical near the torch to shorten the length of the torch whip that must be handled each time a torch is removed and repaired. There are four different torch configurations utilized: 1) 180 degree, 2) large 90 degree, 3) small 90 degree, and 4) dog leg 180 degree. Each torch is designed to access a specific geometry of the reactor vessel and includes a small servo motor which controls the standoff distance from torch to work piece. Standoff is utilized to control cutting voltage.

3.2 Work Platform Hardware - Plasma Cutting System

The torch umbilical connects to the Plasma Junction Box, the central point for distribution of torch power, nitrogen gas, and coolant from the plasma system. Power to the torch is derived from an insulated power bus in the Plasma Junction Box which is paralleled to the output of two Thermal Dynamics PAK-45 plasma arc power supplies, also located on the platform. Each power supply develops up to 450 amperes at a nominal 180 volts DC straight polarity for a total combined torch output of 900 amperes. The torch power lead is a #2 AWG copper conductor inside a plastic Synflex hose which carries a closed loop demineralized water coolant from a Thermal Dynamics HE-200 heat exchanger located on the platform. The heat exchanger provides coolant for both the torch power conductor as well as the torch.

Nitrogen gas is also provided to the torch from the Plasma Junction Box on two separate gas headers, primary (plasma) and secondary (shield). The primary gas is applied to a fixed orifice in the torch, which creates a swirling gas stream as it exits the tip in front of the electrode. To initialize a cut, a capacitive discharge arc starter pulses high voltage across the electrode to the tip at a frequency of 15 hertz. These rapid voltage pulses create an arc that extends as much as 1 inch from the end of the torch and ionize the primary gas stream. Eventually, the arc is transferred to the work piece (main arc transfer) and full power supply current is conducted through the ionized plasma gas stream. This heats the plasma at 20,000 to 50,000 degrees fahrenheit and forms a focused beam capable of cutting stainless steel, in this application, as thick as 2 inches. The secondary gas surrounds the swirling primary gas as it exits the tip and acts as a thermal insulator between the plasma stream and the copper tip of the torch. Thus, the secondary gas protects the tip from absolute destruction by the plasma stream, but also provides a means of blowing away the dross from the kerf to clear the path to new material and prevent resolidification of molten material back into the cut path.

Inside the Plasma Junction Box, primary and secondary gas flows are controlled by pressure regulators and a fixed orifice that is in line with the torch umbilical. Each gas has three flow levels: 1) purge - a low flow utilized only to keep the torch dry during nonproduction periods; 2) start - a reduced flow necessary for arc starting; and 3) run - utilized during cutting after main arc transfer.

These flow levels are activated by solenoid valves which are tied to the plasma control electronics in the Plasma Distribution Box. Transducers are also included for monitoring flow and pressure of primary and secondary gas as well as flow, temperature, pressure, and conductivity of torch coolant.

The PAK-45 power supplies are configured as a master and slave unit each with its own independent closed loop current control system. A current command signal is generated at the Plasma Control Console in the Coordination Center and each PAK-45 maintains a constant current output at this level. In the master unit, a Thermal Dynamics SC-504 Standoff Control Unit monitors cutting voltage which is proportional to the torch standoff distance from the work piece (i.e. arc length). The SC-504 drives the servo motor on the torch up and down to adjust the arc length and thus regulate voltage of the cut. The master unit has complete control over cutting voltage and arc starting.

All transducer outputs and solenoid valve controls in the Plasma Junction Box, all HE-200 controls, and all PAK-45 controls are routed to the Plasma Distribution Box, an interface enclosure comprised of prototype circuit boards for transmission and distribution of control signals to and from the Plasma Control Console in the Coordination Center. Feedback signals from the Reactor Building and command signals from the Coordination Center are converted from analog to digital and are transmitted via a half duplex data transmitter and receiver. This method of data transmission reduces the number of twisted wire pairs required to be routed through the Reactor Building penetrations and is necessary to achieve complete system control from the Coordination Center with available penetration conductors.

Strip chart recorders were added to the system during operation to monitor cutting voltage and current. These parameters provide visual indication of system cutting stability as it is affected by torch feed rates, response of the standoff control system, stability of current control, rigidity of the torch end effecter, and accuracy of gas flow.

3.3 Coordination Center Hardware - Plasma Control System

The Plasma Control Console contains all of the Coordination Center remote plasma control circuitry and operator's controls. This panel is comprised of two prototype circuit boards and an operator's control panel. Signals to and from the Reactor Building Plasma Distribution Box are sent and received via the data multiplexing system. Data signals are latched on the Plasma Control Interface Board where digital to analog conversion and signal conditioning is performed for display on the operator's front panel analog meters and status indicating lights. The Fault Logic Board receives process status parameters from the Plasma Control Interface Board and stops the cutting process when the following system parameters are out of a specified range: 1) HE-200 coolant water flow, pressure, and temperature; 2) primary gas flow and pressure; 3) secondary gas flow and pressure; 4) torch overcurrent; and 5) standoff control servo drive overtravel. This panel provides complete operator control of the plasma cutting process remotely from the Coordination Center.

3.4 Work Platform Hardware - Manipulator System

All manipulator control cables to the in-vessel hardware and the Coordination Center Manipulator Operator's Console connect at the Manipulator Control Cabinet on the work platform. This cabinet houses all interfacing controls for the manipulator system, the heart of which is a General Numerics Fanuc five axes numerical controller. This numerical controller is designed specifically for computer-aided machine tool control but is extremely well suited for this application due to its flexible programming ability and its ability to perform accurate simultaneous control of up to five axes of motion in four degrees of freedom. The microprocessor cards and input/output unit for the Fanuc are installed in the Manipulator Control Cabinet and control the direction and speed of each axis via pulse width modulated variable speed servo drives also located in the Manipulator Control Cabinet. The numerical controller uses advanced bubble memory technology to store program parameters for trajectory control in increments as small as one ten-thousandth of an inch [3].

Feedback pulses from each axis encoder as well as axis limit switch outputs are connected to prototype circuit boards in the Manipulator Control Cabinet where they are optically isolated from their connection to the numerical controller input/output unit. Optical isolation is utilized in all interfacing logic to reduce the potential for ground loops and thus enhance system noise immunity. To provide additional noise immunity, an isolated ground bus in the Manipulator Control Cabinet connects to a ground rod in the plant yard and provides a stable ground plane for shield reference ground. Also located in the Manipulator Control Cabinet is a half duplex data transmitter and receiver for communications with the Manipulator Operator's Console. The numerical controller and servo drives provide complete status of each axis to the Manipulator Operator's Console in the Coordination Center via the data multiplexing system.

3.5 Coordination Center Hardware - Manipulator System

The remote manipulator hardware consists of a Manipulator Operator's Console, an off-line system computer, and video monitors to assist in manipulator positioning. The Manipulator Operator's Console contains the General Numerics Fanuc data entry keyboard, panel controls, and graphics monitor. The data entry keyboard is used by the operator to enter all commands into the numerical controller via the data multiplexing system. These commands control manipulator positioning, cut trajectories, feed rates, manipulator start/stop functions, and operating modes. Also, controller diagnostics can be performed with the keyboard to determine transmission errors, system fault status, and proper program parameters.

The off-line system computer is a Sperry PC/IT - IBM AT compatible with a 44 megabyte hard drive on which the lower core support assembly is modeled in AutoCad. Also included on the off-line computer is the AutoCad Numerical Control (NC) Programmer and Complete Postprocessor software packages. This software enables the operator to locate desired cut patterns and trajectories on the AutoCad model and have the computer generate the program instruction set to be down-loaded onto the numerical controller bubble memory. This provides a tool for the manipulator operator to determine program parameters to be entered into the numerical controller for the desired cut trajectories. The model is updated as sections of the lower core support assembly are removed.

4. Operational Summary

The manipulator operator in the Coordination Center identifies the area to be cut on the three dimensional AutoCad model and lays out the cut trajectory. From this input, the computer generates the proper numerical control program instructions which the operator down-loads onto the controller bubble memory. The operator positions the manipulator such that the torch is at the edge of the work piece and the plasma operator generates a Find Height command in which the Standoff Control Unit jogs the torch servo motor toward the work piece until the proper voltage is established. Once the torch is properly positioned, the plasma operator initiates the cut by generating an arc start until the arc is transferred to the work piece. The manipulator operator observes cutting voltage and current; he begins manipulator travel once the plasma parameters stabilize. Feed rates may be adjusted during the cut to achieve maximum cutting stability and are reduced at the end of the cut to ensure severance of the final segment.

After completion of the cut, the kerf is inspected with underwater cameras to determine if the cut severance is complete. Recuts are sometimes required to sever tabs at the end or beginning of the cut or in some cases to cut resolidified material. Once all cuts are verified to be complete, the ACES hardware is removed from the vessel and the cut segments are lifted, cleaned, and moved to a storage area external to the reactor vessel for later disposition. The ACES hardware is then reinstalled in the vessel to perform the next evolution of cuts.

ACES demonstrates integration of state of the art hardware in a robotic system designed to perform a defined specialized task. Much has been learned from this process for future applications in remote positioning and plasma arc cutting. In the area of remote positioning, a numerical controller, such as the one used in ACES, is a powerful and flexible means of accurate position control. This technology continues to develop capabilities and diversity; it also provides a very reliable operating system. In the area of plasma cutting, ACES demonstrates the ability to perform this process under 35 feet of water and in a highly conductive solution. System design will be very meaningful in the off-shore industry and in any applications for cutting steel underwater. Clearly, most underwater environments will be simplistic in comparison to that encountered at Three Mile Island.

ACKNOWLEDGMENTS AND REFERENCES

[1] GPUN Document TB-89-03, Estimated Core Material Distribution
[2] ACES Design Specification for the Lower Core Support Assembly
[3] ACES Manual of Operation and Maintenance - Power Cutting Inc.
[4] 3-D Computer Models (Figures 1 and 2) by Construction Systems Associates, Inc. - Marietta, Georgia