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AUTHOR'S ABSTRACT

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PAPER TITLE: Computer Control of a Remote Cell Handling Equipment System for a Thorium Uranium Recycle Facility

Abstract of proposed technical paper—100 words or less (see reverse side).

PLEASE TYPE

The Oak Ridge National Laboratory's Thorium-Uranium Recycle Facility (TURF) has the objective of developing High Temperature Gas-Cooled Reactor (HTGR) fuel recycle technology which can be applied to future HTGR commercial fuel recycling plants.

The TURF facility contains four large hot cells which can be interconnected remotely by lifting shielded doors between cells and extending monorail tracks across the door spans. The monorails then allow cranes, television cameras, and electromechanical manipulators to be transferred to any location within the four cell complex. The above system is referred to as the Remote Cell Handling Equipment System (RCHES).

For optimum use of the RCHES, a computer control system is being designed. This computer control system will ~~The computer will soon~~ execute routine in cell material transfers between conveyor lines, routine between cell monorail equipment transfers, and supervision of collision avoidance during manual operation of equipment for nonroutine maintenance operations.

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A PROPOSED MASTER-SLAVE AND AUTOMATED REMOTE HANDLING SYSTEM FOR HIGH-TEMPERATURE GAS-COOLED REACTOR FUEL REFABRICATION[*]

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ABSTRACT

The Oak Ridge National Laboratory's Thorium-Uranium Recycle Facility (TURF) will be used to develop High-Temperature Gas-Cooled Reactor (HTGR) fuel recycle technology which can be applied to future HTGR commercial fuel recycling plants. To achieve recycle capabilities it is necessary to develop an effective material handling system to remotely transport equipment and materials and to perform maintenance tasks within a hot cell facility.

The TURF facility includes hot cells which contain remote material handling equipment. To extend the capabilities of this equipment, the development of a master-slave manipulator and a 3D-TV system is necessary. Additional work entails the development of computer controls to provide: automatic execution of tasks, automatic traverse of material handling equipment, automatic 3D-TV camera sighting, and computer monitoring of in-cell equipment positions to prevent accidental collisions. A prototype system which will be used in the development of the above capabilities is presented.

INTRODUCTION

The Oak Ridge National Laboratory's Thorium-Uranium Recycle Facility (TURF) will be used to develop High-Temperature Gas-Cooled Reactor (HTGR) fuel recycle technology which can be applied to future HTGR commercial fuel recycling plants.[1] To achieve recycle capabilities it is necessary to develop an effective remote material handling system to periodically transport equipment and materials between in-cell production systems and to perform maintenance tasks on in-cell equipment.

The TURF facility presently includes several hot cells which contain remote material handling equipment such as cranes, electromechanical (E.M.) manipulators, and TV cameras. This existing TURF equipment is described in Section 2.0.

To extend the remote handling capabilities of the above existing equipment, development and installation of a master-slave E.M. manipulator controller and a remote 3D-TV system is necessary. Additional development work entails the installation of a minicomputer support system which provides: automatic "robot" execution of tasks, automatic traverse of material handling equipment, automatic 3D-TV camera sighting and focussing, and computer monitoring of all in-cell equipment positions to allow prediction and prevention of accidental collisions. These extended equipment capabilities are described in Section 3.0.

A prototype system which provides extended capabilities has been proposed. This prototype system is described in Section 4.0.

Conclusions and recommendations regarding the prototype system are presented in Section 5.0.

2.0 The Existing TURF Facility and Equipment[2]

The TURF facility includes a total of seven hot cells. The number of these cells which will actually be used in the development of remote fuel refabrication technology is not defined at this time.

For the purpose of discussion, four of the TURF cells, which possess the complete capability of the TURF material handling equipment, are discussed in this section.

2.1 The Four Interconnected Hot Cells

The most comprehensive material handling capabilities within the TURF facility exist in the four interconnected hot cells whose floor plan is shown in Fig. 1.

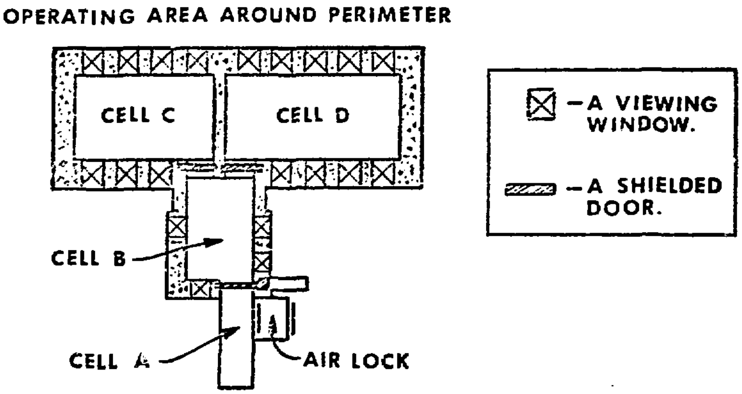

Figure 1
The four interconnected TURF hot cells.

There are two heavily shielded process cells (C and D), a shielded service cell (B), and an unshielded glass-walled maintenance cell (A). Cell A connects to the perimeter area through an airlock. Cells B, C, and D are provided with numerous viewing windows and the operation of in-cell equipment, such as cranes and manipulators, is possible through visual feedback from these windows.

The facility shielding allows Cells C and D to be used to refabricate highly radioactive recycle fuels with chemical and mechanical fuel refabrication equipment. These two cells will become contaminated with high-level radioactivity which will require remote operation and remote maintenance of all in-cell process equipment. The material handling equipment (cranes, manipulators, etc.) must be reliable and they also must be repairable or removable from any location within the hot cells C and D. If process or material handling equipment requires removal, it will be transferred to Cell B for decontamination. After decontamination, equipment will be transferred to Cell A where glove contact maintenance and/or repair can be performed. The airlock connected to Cell A may be used for direct contact maintenance or the removal of decontaminated equipment from the hot cells.

2.2 The Monorail, Crane, and TV Systems

The ability to remotely move equipment from Cells C and D to Cell A is provided by a two-level monorail system which runs through Cells A, B, C, and D (see Fig. 2). The heart of this system is the transfer monorail unit in Cell B. This unit consists of a north-south transfer monorail (1), an east-west double girder bridge (2), and an up-down elevating bridge (3). When the elevating bridge (3) is at its low level, the transfer monorail can be moved north-south to align with the crane bridges (7 in Cell C or 8 in Cell D) or with the monorail (6) in Cell A. At this time the door opening can be spanned by the double girder bridge (2). Such monorail transfer

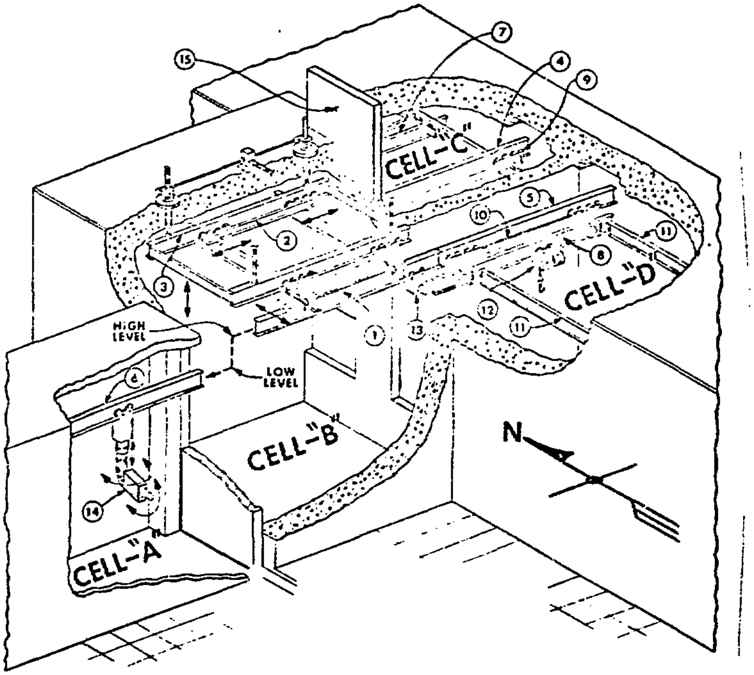

Figure 2

The monorail, crane, and TV system.

unit movements allow crane hoists (12 in Fig. 2; also see Fig. 3) and remote TV cameras (14 in Fig. 2; also see Fig. 4) to move to any of the four hot cells.

The crane bridges (7 and 8) operate north-south. The crane bridge (8) normally operates on fixed rails (11) in Cell D and the crane bridge (7) normally operates in Cell C, but it is possible to move either crane bridge to any other hot cell. Such crane bridge transfers are executed by driving a crane bridge (7 or 8) onto a transfer trolley (9 in Cell C, or 10 in Cell D). The transfer trolley and crane bridge are then towed by a traction unit (13) from either of fixed monorails (4 or 5) onto the Cell B transfer monorail (1). This transfer is only possible after the transfer monorail (1) has been raised to the high level by the Cell B elevating bridge (3) and the double girder bridge (2) has moved east across the door span. With the elevating bridge (3) high, a crane bridge and transfer trolley can be returned from the Cell B transfer monorail (1) to fixed monorails (4 or 5) in either of Cells C or D. When the elevating bridge (3) is low, a crane bridge and transfer trolley can be towed from the Cell B transfer monorail (1) onto the fixed monorail (6) in Cell A.

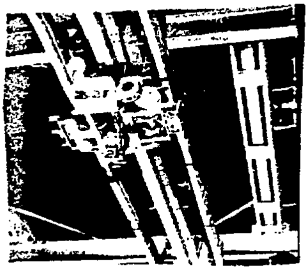

Figure 3

A typical crane hoist.

Figure 4

A typical remote TV camera.

2.3 The E.M. Manipulator System

In addition to the monorail and crane system, up to four E.M. manipulators may be operated within the four hot cells (see Fig. 5, also Fig. 6). Each E.M. manipulator (1) rolls east-west on an E.M. carriage (2).

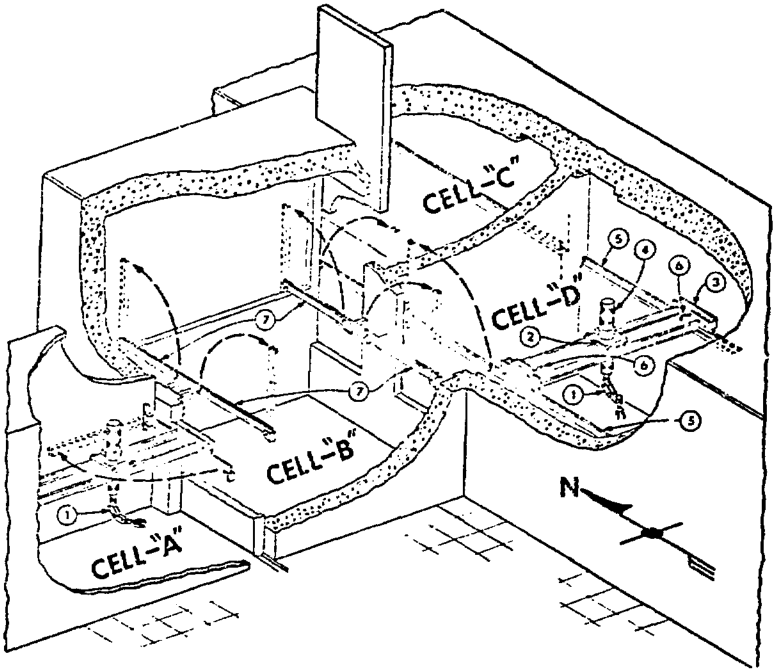

Figure 5

The E.M. manipulator system.

The carriage rides on an E.M. bridge (3) which rolls north-south. Up and down movement is supplied with a telescoping tube hoist (4). Thus, the E.M. manipulator can be positioned at any location inside a hot cell.

The stationary E.M. manipulator tracks (5 in Fig. 5) are located below the monorail tracks and crane hoists. This permits two cranes to lift an entire E.M. manipulator and bridge. This is accomplished by hooking the crane hoists onto the manipulator lifting hooks (6 in Fig. 5). After an E.M. manipulator and bridge have been hoisted off their stationary rails, they may be carried by the crane hoists along the monorail tracks to any hot cell. Clearance for movement through doorways is provided by activating D.C. motors which swing sections of the E.M. manipulator rails (7 in Fig. 5) up out of the way.

Each E.M. manipulator utilizes D.C. electric motors to power its joints. Each motor in turn is controlled by a bidirectional variable rate slide switch. The farther each slide switch is moved from the center position, the faster the joint moves. This bidirectional variable rate control allows precise arm positioning for delicate operations.

A variable rate slide switch box used with the TURF E.M. manipulators is shown in Fig. 7.

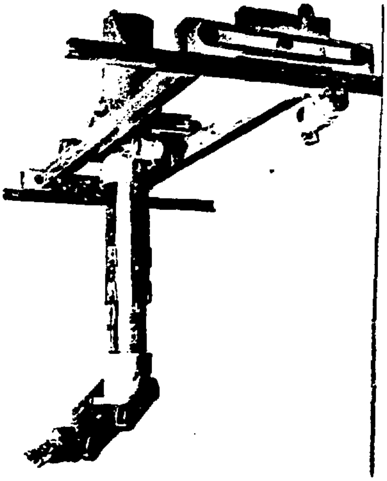

Figure 6

The E.M. manipulator, carriage, bridge, and tube hoist.

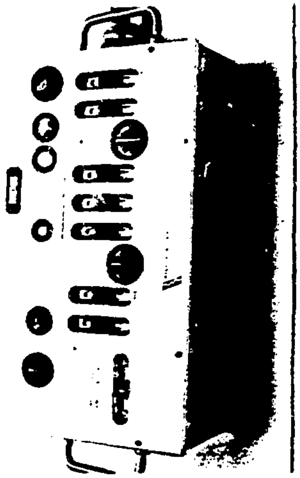

Figure 7

A variable rate slide switch box for E.M. manipulators.

3.0 Future TURF Equipment Capabilities

The TURF material handling system will be used to service HTGR fuel refabrication equipment. The refabrication equipment, which is currently under development, is extremely complex and will require a remote handling capability with a much higher level of control and automation than the existing handling system can deliver. To provide these required future high level handling capabilities, development of additional remote handling equipment is necessary.

There are presently three areas in which remote material handling equipment development is planned. These areas are:

1. The development of master-slave control of the E.M. manipulators.
2. The development of a 3D-TV viewing system.
3. The development of a minicomputer support system for the material handling equipment.

Each item above will be briefly described in the following sections.

3.1 Master-Slave Control of the TURF E.M. Manipulators

While the variable rate slide switch box (Fig. 7) provides precise positioning capability, the speed at which any position can be achieved is limited. There are ten joints on the TURF E.M. manipulator and ten corresponding variable rate slide switches. This large number of switches is cumbersome to operate. Even experienced operators cannot simultaneously coordinate more than two or three joints safely. When tasks require many joint movements, as would be expected in servicing complex refabrication equipment, the operator must first move a few selected joints, then a few more, iterating until he zigzags the manipulator to a new position. Obviously this procedure is very slow. Futhermore, it requires intense concentration and is highly fatiguing.

To increase the speed and ease with which E.M. manipulators can be positioned, a master-slave controller is required. Such a master-slave arrangement has two basic parts: an out-of-cell E.M. master arm (Fig. 8), and an in-cell slave arm (see 1, Fig. 6). These two arms are of similar geometry and they are electrically coupled so that the motions of the out-of-cell master are mimicked by the in-cell slave. This mimic capability allows the operator to concentrate his natural sense of coordination on the movements of the master arm. The slave arm automatically follows along and performs a remote task in-cell. Even inexperienced operators can quickly learn to do simple remote tasks with this type of control. Time study comparisons between a variable rate slide switch box and a master-slave controller indicate speed increases of five to ten times with the master-slave.[3] In addition, operator fatigue is greatly reduced.

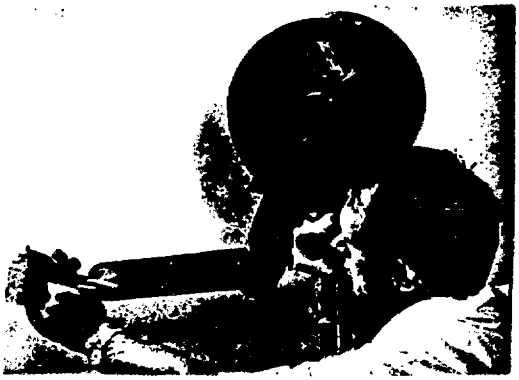

Figure 8

An out-of-cell E.M. master arm.

3.2 3D-TV Viewing for the TURF Facility

The only feedback for manual operation of remote material handling equipment is visual. Whether or not a task can be executed manually depends largely on an adequate view of the task area. Tests have indicated that a master-slave manipulator can do very delicate operations. Even threading a needle is possible if close-up vision is available. In past hot cell work, tasks with tolerances closer than 1/8 inch have been very difficult to perform largely because of limited vision.[5] Visual limitations through hot cell shielded windows are largely due to the distance from the master to the work area.

To eliminate the distance problem, TV systems have been used to view objects from inside of hot cells at close range. While conventional TV (Fig. 4) gives a close view of tasks in cell, it provides very limited depth perception and this destroys the effectiveness of the technique. For example, tests have shown it is very difficult to estimate depth accurately enough to do a simple task such as pouring liquid into a beaker (even when the TV camera is only a few feet from the task). Fortunately, 3D-TV viewing systems are now commercially available which provide excellent depth perception. The operating principle of commercial 3D-TV is shown in Fig. 9.[4]

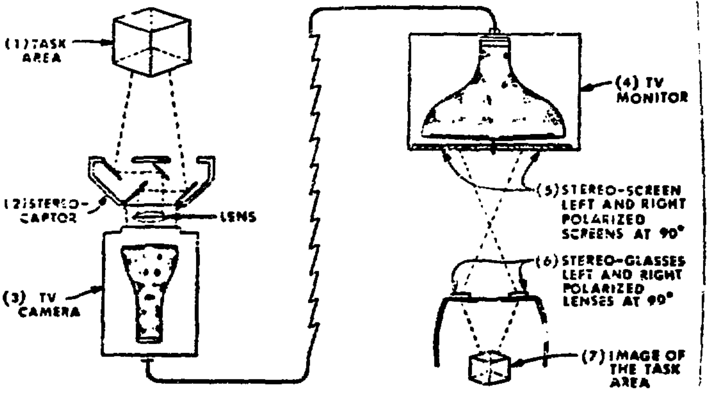

Figure 9

Operating principle of a commercial 3D-TV viewing system.

Operation is as follows, a stereo captor (2) utilizes mirrors 4 inches apart to relay "left eye" and "right eye" views of the task area (1) to a standard TV camera (3). The "left eye" view is relayed through the right side of the camera lens and the "right eye" view through the left side. The two (left and right) images are transmitted by standard TV methods to a TV monitor (4). There, the right eye view appears on the left side of the monitor and the left eye view on the right. In front of the right and left side of the monitor screen are stereo screens (5) which are polarized filters at right angles to each other. The TV viewer then wears stereo glasses (6) which consist of similar polarized filters which allow the viewer's right eye to see the TV monitor left view and allows the left eye to see the TV monitor right view. Both pictures are optically superimposed, and as a result, the viewer's mind fuses the left and right images into one 3D-TV image (7). A typical 3D-TV system has been operated by the author and the system works well. The image is clear and the depth dimension is excellent. This enhances the remote performance of delicate tasks such as placement of a small socket wrench on a bolt. The 3D-TV visual feedback is so accurate that a magnified 3D-TV picture is presently being used to perform eye surgery at a San Francisco Hospital.[5]

The 3D-TV has been installed for visual feedback in a typical heavily shielded hot cell. Its advantages for this application are presently being demonstrated. In the case of very large hot cells (such as will be required in future commercial fuel recycling plants), the use of 3D-TV will be a necessity, not an option. Without 3D-TV's visual feedback from those locations far inside large hot cells, it would be impossible to see adequately to execute maintenance operations with remote handling equipment.

3.3 Minicomputer Support for the Material Handling Equipment

Minicomputer support for the material hardling equipment will be necessary for an effective demonstration of the fabrication of HTGR recycle fuels. To appreciate this necessity, the refabrication system and its interface to the material handling system must be understood. These topics are briefly described below.

The processes associated with fuel refabrication are, in general, quite complex and have high unit throughput rates. The refabrication process is sequential in nature and each of the processing stages will be designed to operate independently for short periods of time by providing product buffer capacity at the outlets of each stage and a completely stand-alone local instrumentation and control system (LICS) for each stage. It is envisioned that each of the processing stages will require the full-time availability of a remote material handling system which includes at least one E.M. manipulator. The control hierarchy of each stage will be such that the LICS for each specific stage will perform all of that stage's process control and data acquisition functions. One LICS process control responsibility is to interface the refabrication stage to the material handling system through operating personnel. This interface is shown schematically in Fig. 10 which shows a hypothetical refabrication stage and the functional interface between the stage LICS and the operating personnel which is necessary for the refabrication stage operation.

Basically, the material handling system's E.M. manipulator will be called by the LICS to perform routine production tasks symbolized by items (3), (6), and (13) in Fig. 10 and maintenance support tasks shown in (10) and (11). Consequently, each material handling system is an integral part of a processing stage and its functional capabilities must be consistent with the support requirements of that stage.

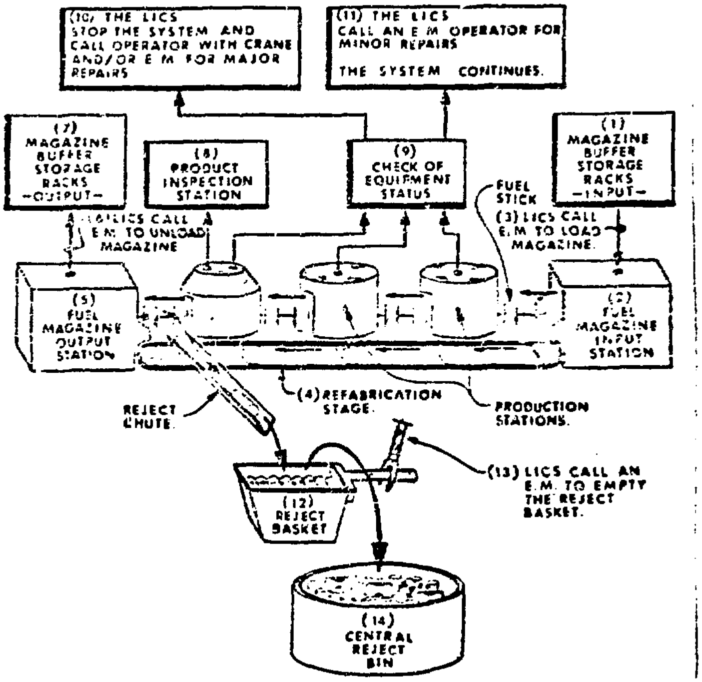

Figure 10

A hypothetical refabrication stage and the functional interface between the stage LICS and the operating personnel.

To perform the production and maintenance support tasks described above, the following four basic functional capabilities are envisioned for the remote material handling system:

1. Automatic "robot" execution of routine in-cell production tasks with an E.M. manipulator.
2. Automatic traverse of all remote handling equipment between selected in-cell operating locations.
3. Automatic 3D-TV camera sighting and focussing on any in-cell coordinate, especially the operating area of the E.M. manipulator hand.
4. Continuous monitoring of the relative positions of in-cell process and material handling equipment when manual or master-slave remote handling equipment is activated.

All of these capabilities require either a substantial computational capability (for performing coordinate transformation) or data storage and readout capabilities. For these reasons, a dedicated minicomputer to support control of remote handling equipment associated with each process stage will be required. The details concerning the computer requirements for each of the basic functional capabilities are discussed in Section 4.0.

4.0 A Prototype Remote Material Handling System

To develop the remote material handling technology necessary for the demonstration of HTGR fuel refabrication, a prototype remote material handling system will be constructed and evaluated. A description of this prototype system interfaced with a refabrication stage follows (see Fig. 11). Section 4.1 provides a description of the major prototype system components. Section 4.2 describes the operational capabilities of the prototype system including the interface from the refabrication stage LICS to the operating personnel. Finally, Section 4.3 provides a description of the control logic necessary to achieve the remote material handling system operating capabilities.

4.1 The Components of the Prototype System

Each TURF hot cell will contain one or more refabrication stages. One such refabrication stage is represented schematically by the in-cell conveyor in Fig. 11. In addition to refabrication stages, there are in general several remote handling devices in-cell. These devices include: automatic sighting and focussing 3D-TV cameras for accurate close-up visual feedback; a remote in-cell crane for automatic intra- and inter-cell transfer of heavy objects between work stations; and a remote E.M. manipulator (slave) which can perform automatic "robot" production tasks or manual maintenance tasks (by master-slave control).

An operator station will be located out-of-cell at the cell front and includes: 3D-TV receivers which deliver close-up views from the in-cell cameras; an E.M. master, which is articulated by operator personnel to accomplish in-cell manual E.M. manipulator tasks; an operator control panel, which the operators read to determine remote handling actions required and on which the operator sets switches to actuate the requested mode of control (see Section 4.2); and a set of manual variable-rate slide-switch control boxes for the E.M. manipulators, cranes, and TV cameras.

Additional out-of-cell equipment includes: D.C. servos to drive the remote handling devices; a minicomputer with analog and digital interfaces. This minicomputer is of the process control class and provides the computational capability and memory storage necessary to implement the desired system functions; and a local instrumentation and control system (LICS) for control of the production processes of each refabrication stage. The LICS interfaces with the remote material handling system through the operating personnel. This interface will be described in Section 4.2.

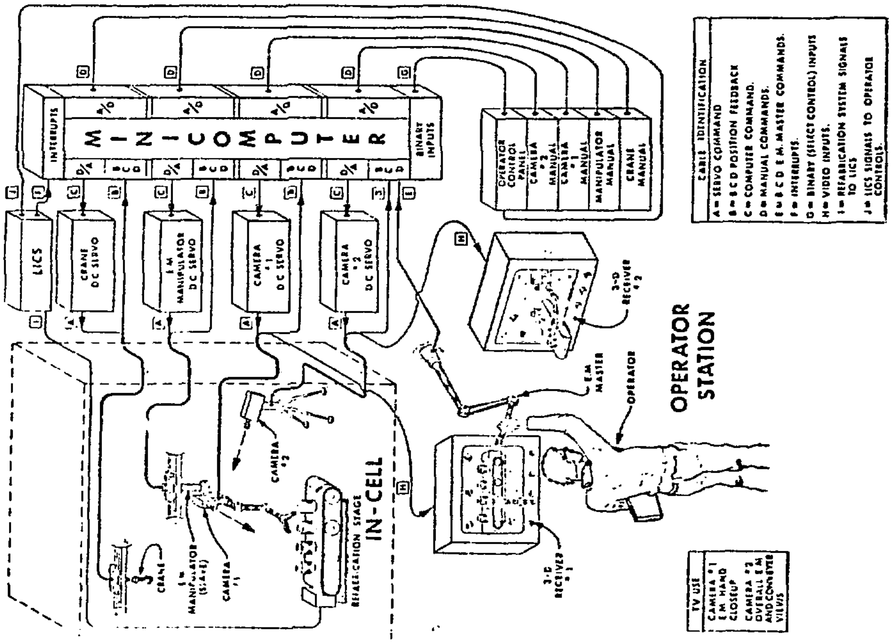

Figure 11

The prototype system interfaced with a refabrication stage.

4.2 Operational Capabilities of the Prototype System

The LICS (Fig. 11)receives status signals (cable I) from the in-cell refabrication stage. Those signals pertaining to the remote material handling system are transmitted by the LICS to the operator control panel (cable J). The operating personnel then read the status signals at the panel and set panel switches to activate the minicomputer (cable G) which provides the computational capability to implement the remote material handling mode requested. In effect the LICS assists the operating personnel by suggesting modes of operation. The operators then interpret this data and make the final operational decision.

There are five basic modes of control the operator may choose:

1. Manual control (all devices)
2. Automatic traverse control (all devices)

3. Automatic "robot" task control (E. M. manipulators)
4. Master-slave control (E. M. manipulators)
5. Automatic sighting and focussing control (3D-TV).

The interactions between Fig. 11 components and the resulting operating capabilities of each of the basic modes are briefly described below.

4.2.1 Manual Control

Manual control will be provided for all in-cell devices. This control mode allows the operator to move any in-cell remote material handling device manually to perform non-routine tasks for which the minicomputer has not been programmed. The minicomputer may remain on line during manual operations and monitor the positions of all in-cell devices (through feedback cables B). The computer periodically utilizes this position data to update device position vectors* and to compute algorithms comparing position vectors with stored in-cell topography to determine if a collision is impending. If a collision is impending, the offending devices are halted and the problem indicated on the operator control panel.

Manual control is also provided as a backup. Should the computer fail, a switch at the operator control panel transfers manual control signals directly to the D.C. servo inputs. This entirely isolates the control system from the minicomputer.

4.2.2 Automatic Traverse Control

Automatic traverse control will be provided for all remote material handling devices. Automatic traverse entails the ability to move a device from a given starting location to a desired end location along a specified trajectory. Typical traverse movement may occur within a single hot cell, or it may occur inter-cell, requiring the use of the transfer monorail tracks (see Section 2.2).

Programming the traverse trajectories will be accomplished utilizing the established industrial robot "teach and playback" technique. This technique simply requires the operator to place the operator control panel into a "teach" mode. He then manually increments the in-cell device point by point along a desired traverse trajectory. At each point the position vector is stored in the minicomputer memory (through cables B). After the entire trajectory is stored, it can be executed (played back) automatically by the operator on request from the refabrication stage LICS.

When a stored traverse trajectory is executed, the measured position vector of the in-cell device (cable B) is subtracted from the stored traverse trajectory vector. This difference is used as the position error which drives the D.C. servos (cable C). In effect the stored traverse trajectory vectors represent time-varying position commands which lead the in-cell device through desired task actions.

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*All device position vectors will be transformed to a common in-cell coordinate system for ease of comparisons.

4.2.3 Automatic "Robot" Task Control

Automatic "robot" task control will be provided for the E.M. manipulator. This mode of operation allows automatic movement of E.M. manipulators through task movements while at a work location in a hot cell. This mode is accomplished by the same "teach and playback" technique described for automatic traverse control (Section 4.2.2). The only distinction is in the actions controlled. The automatic "robot" task mode controls only the E.M. manipulator arm position, whereas the automatic traverse mode controls the carriage, bridge, and telescoping tube (gross movements) of all in-cell devices. The philosophy of operation implied is that the automatic traverse mode is utilized to move equipment to work locations, and the automatic "robot" mode performs tasks with an E.M. manipulator arm once devices are on location.

4.2.4 Master-Slave Control

Master-slave control will be provided to control the E.M. manipulator. The operator will utilize the operator control panel to activate this mode of operation. When the mode is in effect, the E.M. manipulator follows a position vector (through cable E) supplied by position encoders mounted on the E.M. master. This mode is identical to the automatic "robot" task control mode (Section 4.2.3) except here the time varying position vector comes from the E.M. master rather than from minicomputer storage.

For this mode the minicomputer monitors all in-cell devices and checks for impending collisions just as it does in the manual mode (see Section 4.2.1).

4.2.5 Automatic Sighting and Focussing Control

Two 3D-TV cameras can be commanded from the operator control panel to automatically sight and focus on a selected material handling device (target device). The 3D-TV cameras work in a pair (see Fig. 11) to provide two approximately orthogonal views of the work area for excellent operator spatial orientation to accomplish manual tasks.

To achieve this capability, the minicomputer utilizes the camera position vectors and the target device position vectors to calculate a sighting and focussing vector. The sighting and focussing vector then commands the camera D.C. servos (through cables C) and maintains the camera sighted to the target device.

4.3 The Prototype System Control Logic

In previous sections of this paper it has been emphasized that an operator control panel is used by operating personnel to select the mode of operation in which the prototype system operates. To achieve this mode control, preliminary operational logic has been defined. The basic flow diagram describing control logic for the prototype is shown in Fig. 12. A study of this flow diagram will clarify the operating logic for the prototype system. Execution of control modes will be implemented under an interrupt and priority task structure in the minicomputer system.

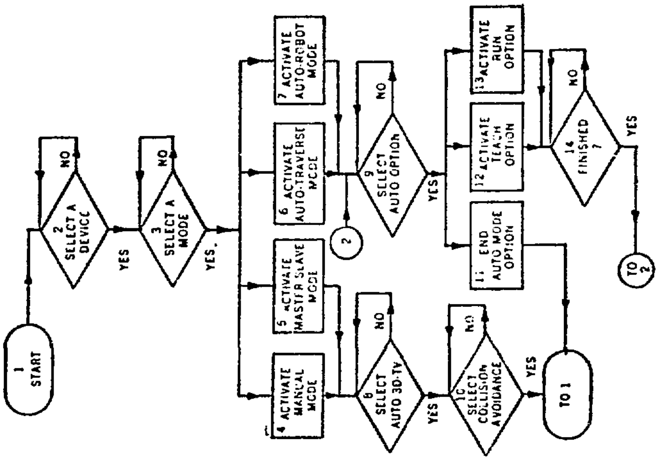

Figure 12

The prototype system control logic

5.0 Conclusions and Recommendations

The prototype described in this paper will be utilized and evaluated to experimentally determine remote material handling procedures and techniques necessary for effective support of the refabrication production stages. Information to be obtained includes:

1. The determination of convenient 3D-TV camera positions for viewing the various in-cell devices at all work stations.
2. Determination of fixtures, tools, process stage interlocks, and operating techniques for efficient utilization of all material handling system devices.
3. Determination of the levels of automation which are necessary for remote material handling system support of the refabrication stages.
4. Determination of the operator control panel layout for maximum convenience of operator personnel.

The remote handling technology established above will support the design of future commercial HTGR fuel recycling plants. In addition, this material handling technology will provide a theoretical framework for design of future remote material handling systems built to service large complex radioactive in-cell systems.

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