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# Remote Waste Handling and Feed Preparation For Mixed Waste Management

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## ABSTRACT

The Mixed Waste Management Facility (MWMF) at the Lawrence Livermore National Laboratory (LLNL) will serve as a national testbed to demonstrate mature mixed waste handling and treatment technologies in a complete front-end to back-end facility (1). Remote operations, modular processing units and telerobotics for initial waste characterization, sorting and feed preparation have been demonstrated at the bench scale and have been selected for demonstration in MWMF.

The goal of the Feed Preparation design team was to design and deploy a robust system that meets the initial waste preparation flexibility and productivity needs while providing a smooth upgrade path to incorporate technology advances as they occur. The selection of telerobotics for remote handling in MWMF was made based on a number of factors - personnel protection, waste generation, maturity, cost, flexibility and extendibility.

Modular processing units were selected to enable processing flexibility and facilitate reconfiguration as new treatment processes or waste streams are brought on line for demonstration. Modularity will be achieved through standard interfaces for mechanical attachment as well as process utilities, feeds and effluents. This will facilitate reconfiguration of contaminated systems without drilling, cutting or welding of contaminated materials and with a minimum of operator contact. Modular interfaces also provide a standard connection and disconnection method that can be engineered to allow convenient remote operation.

## INTRODUCTION

Mixed waste is a growing national problem. An estimated 190,700 $m^3$ of low-level mixed waste was in storage at Department of Energy (DOE) sites across the nation in 1993 and another 49,340 $m^3$ is expected to be generated during the period from 1994-1997 (2). In addition, other industrial sectors, including the medical and academic community also continue to store and generate mixed wastes at many sites across the US. Few acceptable treatment and disposal methods for mixed waste are currently available, resulting in increased storage requirements at DOE and other mixed waste generators' facilities (3). It is expected that, without development of credible solutions for the disposal of these wastes, authority to store mixed waste under the Federal Facilities Compliance Act of 1992 (FFCA) will be jeopardized.

The Mixed Waste Management Facility (MWMF) at the Lawrence Livermore National Laboratory (LLNL) will serve as a national testbed to bridge between mature, bench-scale proven technologies and full-scale treatment facilities by integrating pilot scale processes in a complete front-end to back-end facility (1). Consistent with the intent to focus on technologies that are ready for pilot scale deployment, the front-end handling and feed preparation of incoming waste material will demonstrate the application of emerging technologies. These include remotely operated handling systems and modular processing system interfaces. Each is introduced below.

Since waste received into a typical treatment facility may be very heterogeneous and may not yet be fully characterized, the front-end needs to be both flexible and robust. The degree of uncertainty in characterization also drives the need to be conservative in protecting the operator from unanticipated hazards in the incoming waste material. The items may be heavy, awkward and/or physically hazardous to handle and the container opening and emptying operations will likely release hazardous dusts and vapors. A remotely operated telerobotic handling system for preliminary characterization and sorting addresses many of the major uncertainties in the front-end. Most importantly, it removes the operator from the hazardous environment during the important initial characterization process. It also provides the flexibility to accommodate many different incoming materials and a wide range of possible tasks that might have to be performed including sorting, size reduction of large items, gross decontamination and upset recovery.

Once items have been through preliminary size reduction, they are much more amenable to more traditional handling systems - conveyors, feeders and storage hoppers (4,5). However, because of the heterogeneity in the waste material, a high degree of flexibility is still needed in the equipment that prepares the feed for treatment. Careful attention must be paid to control of dusts and vapors between unit processes to avoid unnecessary spread of hazardous and radioactive contamination. Modular processing equipment in feed preparation allows flexibility in the configuration of a limited set of processing equipment and provides a mechanism to alter process flow between them. In addition, it facilitates removal of equipment modules for decontamination and servicing. In MWMF, standard interfaces for utilities and feed input and output form the basis for modular equipment designs and clean interfaces between unit operations.

## FEED PREPARATION DESIGN GOALS

A primary goal of the feed preparation system is to demonstrate and evaluate remote operations in MWMF that would be required in a typical waste facility to reduce risks to operators from exposure to radioactive or hazardous materials and hazardous or unsafe operations. Because of the nature of many stored wastes and the lack of detailed waste characterization data, operations will have to be performed either remotely, in bubble suits or in other protective clothing (6). Elimination or reduction of tedious or monotonous jobs should also be sought to reduce the potential for operator errors and safety concerns due to inattention. The radioactive component of most LLNL waste does not pose the hazard to operators of mixed waste at some other DOE sites, so personnel access will be provided for maintenance and other hands-on activities given the appropriate personnel protection (7).

Because MWMF will be used to evaluate a variety of treatment processes over a period of years, the initial design must provide sufficient capability to handle and produce varying feed materials for initial operations and flexibility to accommodate future process and statutory requirements.

The following criteria form the basis for design and operation of waste handling systems for MWMF:

- Minimize waste generation in the facility.
- Design in flexibility to reduce future modifications to equipment or facilities that have processed radioactive materials.
- Only open radioactive and mixed waste containers in an alpha containment enclosure.
- Design operator assists to account for waste items that exceed recommended sizes and/or weights for manual handling under OSHA guidelines or DOE glovebox handling guidelines.
- Minimize risks associated with puncture and laceration hazards from handling waste and waste containers.
- Do not preclude the ability to receive and process material in "4x4x7" bins.
- Apply ALARA (as low as reasonably achievable) guidelines to facility and equipment design and operation.

Based on the criteria above, the primary application of remote operations and automation are expected to be in waste sorting and characterization, feed preparation and container decontamination. Depending upon needs and available technology, there may be future opportunities in analysis of treatment residue samples, preparation of final forms, maintenance and correction of upset conditions. This paper will focus on the feed preparation applications.

## FUNCTIONAL REQUIREMENTS

The MWMF front-end will demonstrate technologies for feed characterization and preparation while generating feed for the primary treatment processes. To deploy organic destruction technologies in a typical mixed waste facility, the requirements to prepare feed will include:

- Incoming waste screening to verify it meets acceptance criteria and determine proper routing
- Bulk size reduction to meet feed preparation equipment restrictions
- Preliminary characterization and sorting to remove predominantly inorganic material
- Secondary size reduction (shredding, etc.) to allow further segregation
- Organic/inorganic segregation
- Feed characterization
- Liquid and solid blending to meet treatment process needs.

During initial MWMF operations, incoming waste will be received in 55 gallon drums, so the bulk size reduction step will not be implemented in MWMF initially. A simplified process flow diagram showing the feed prep functions that will be implemented in MWMF is shown in Figure 1.

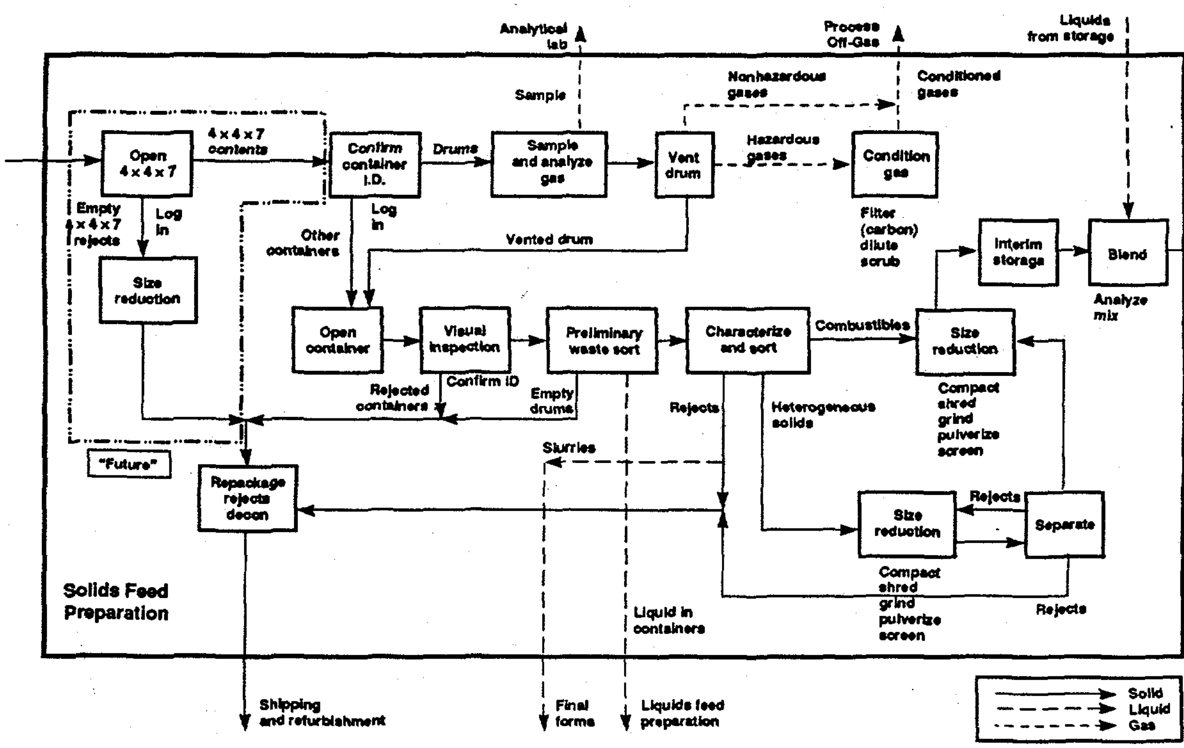


**Figure 1. Functional Flow Diagram for Solids Feed Preparation**

## PROCESS FLOW

The MWMF front-end includes the Receiving and Shipping area, the Feed Preparation area, and the Decontamination area. Each of these areas are shown in Figure 2. The Receiving and Shipping area is a clean area where no containers are opened and no contamination should occur. The liquid and solid feed preparation areas share a common large (room-like) enclosure with some internal enclosures or hoods for airflow control. All materials leaving the facility exit through the decontamination area for cleaning and certification. Each of these areas and operations is described below.

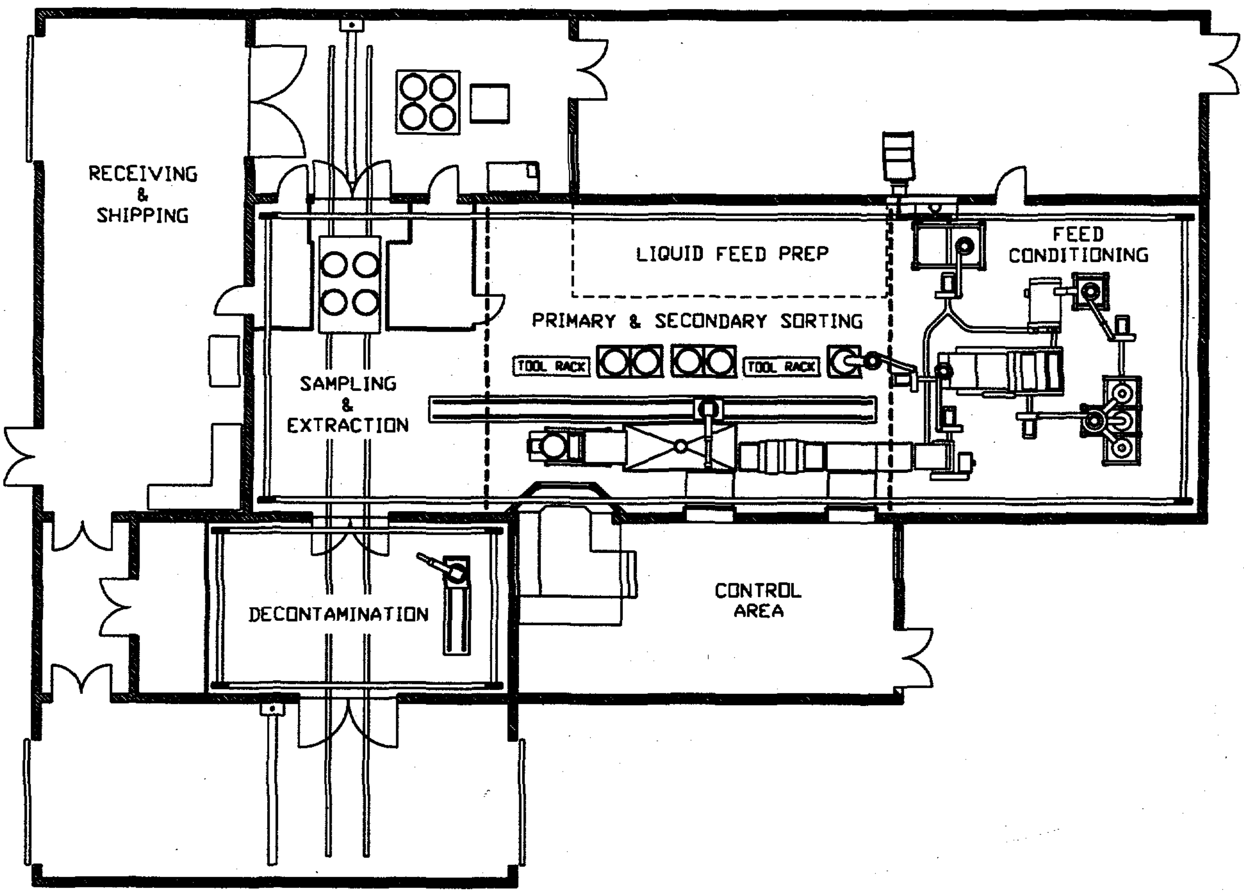


**Figure 2. General Equipment Arrangement for MWMF Front-end**

Initial screening of waste to determine proper routing occurs in the Receiving and Shipping area and will be accomplished using generator knowledge recorded on the waste requisition, confirmed by real-time-radiography (RTR). RTR is expected to provide the qualitative and gross quantitative information needed for container receipt and characterization during initial MWMF operations. RTR can be used to determine if liquids exist within a container that is mostly solid waste and will also be used to determine the approximate organic content of a solid waste container. Additional information that can be provided by active and passive computer aided tomography (A&PCT) scan would be extremely useful in a facility accepting waste with questionable traceability and may be appropriate for evaluation as the technology is further developed. A&PCT is not required in MWMF because LLNL wastes are generally well characterized and the container contents are represented on the waste requisition.

The Feed Preparation area consists of a variety of size reduction, separation, homogenization, sampling and conditioning steps that all occur within a large enclosure. A large enclosure was chosen because initial size reduction, characterization and segregation equipment will be difficult to enclose in a glovebox with adequate external access for manual handling and maintenance. An overhead crane will provide access to most areas of the feed preparation enclosure for handling heavy items, equipment modules and waste containers. The crane will primarily be used as an alternative to floor mounted conveyors for moving drums between process lines.

Containers accepted following the receiving and screening operation are passed through the receiving vestibule for container sampling and venting. This is accomplished at a station that provides for operator access through gloves, shown at the right in Figure 3. Head space sampling is used primarily to determine what volatile materials are present in the container.

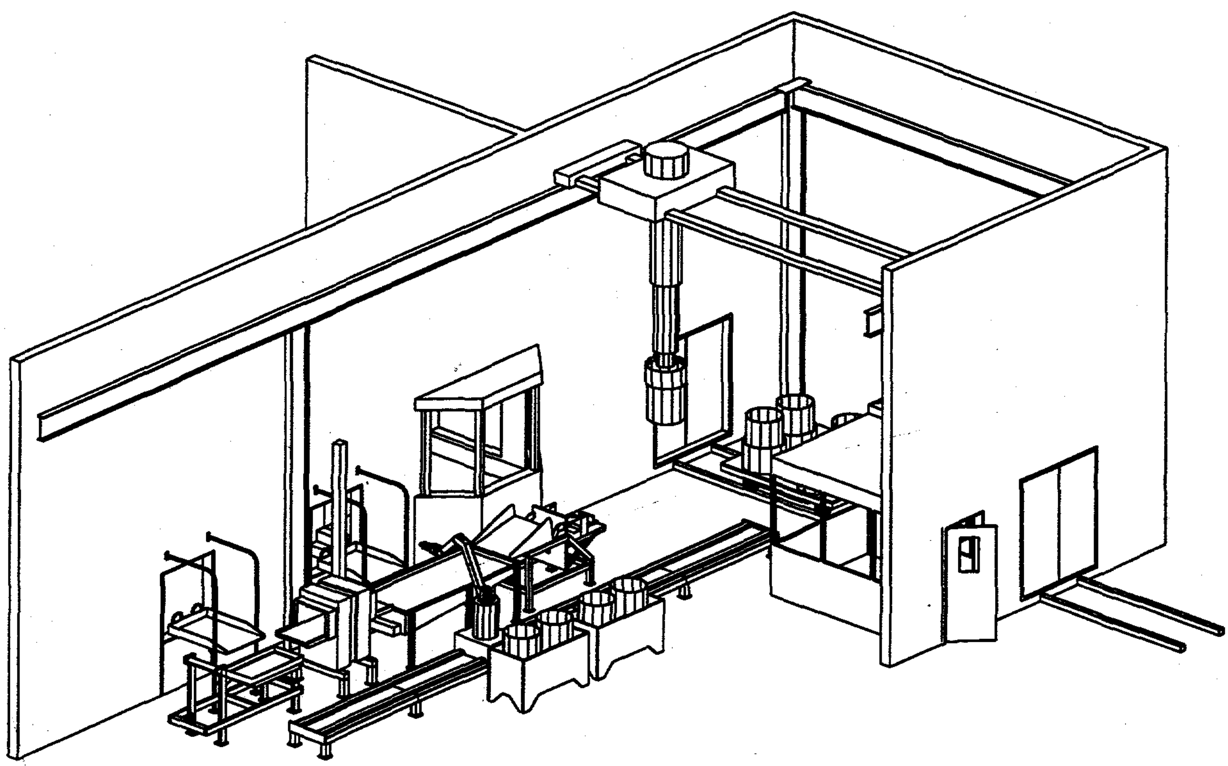

**Figure 3. 3D Representation of Receiving, Extraction and Sorting Area**

Once it has been determined that the container is safe to open, lids of solid containers are removed and the containers are transported to the drum dump station using the overhead crane. The bungs of liquid containers are removed and are replaced with an in-drum strainer and pumping adapter to facilitate downstream operations. Then they are transported to the liquid container emptying area where the free liquids are removed and centrifuged to remove any remaining solids that do not meet process feed criteria.

Solid containers are dumped into a sorting tray where small particulates are screened out and larger objects are sorted with the assistance of various cameras, sensors, and an on-line radiograph. This initial sorting operation segregates individual items, generally in bags, into waste stream categories, including inorganics (glass, ceramics and adsorbents), metals, cellulosics (paper and wood), and plastics. Items that are determined to be above radiation thresholds will be segregated for repackaging at this point as well. Remote handling technology will be used because received waste will not yet be fully characterized; items may be heavy, awkward and/or physically hazardous to handle; and, the container opening, emptying and size reduction operations will likely release hazardous dusts and vapors. Since there is limited external access for manual maintenance, if remote waste handling equipment can also be used for simple remote maintenance, associated waste clothing, wipes, and other secondary waste streams can be reduced. Several alternative technologies were evaluated for remote handling during preliminary sorting, including teleoperators, telemanipulators and telerobots. A telerobotic approach was chosen and will be described in more detail below.

Following preliminary sorting, items that are heterogeneous and require further segregation are de-bagged and the contents sorted. Initially, since the items will be small and easily handleable, this operation may be performed manually through glove ports. Material acceptable to primary treatment is then queued up for feed conditioning.

Feed conditioning is the final step in feed preparation. It involves "final sorting" of materials that make up waste items to generate acceptable process feed. "Final sorting" involves shredding bags of organics that may contain small amounts of metals or other inorganics, removing metals using a magnetic and paramagnetic separation system, passing the material through a screening operation to sort it into a few particle size ranges and then using a density separator to separate each stream into paper, plastic and inorganic streams. The different particle size streams are then recombined by material type. The particle size screening and separation process is necessary to allow the density separator to more effectively separate organics and light inorganics. The different solid and liquid streams are then blended and characterized to meet the treatment demonstration needs of the primary processes. Each of these processing unit operations is a module with standard interfaces to facilitate reconfiguration, reuse, and removal for decontamination and maintenance. Additional information is provided below.

All reject material is repackaged and sent with empty containers to the decontamination area for clean-up and certification prior to release to the Shipping area for return to LLNL's Hazardous Waste Management organization.

## DESIGN DESCRIPTION

### TELEROBOTICS

There are three pieces of equipment that are used in conjunction to perform most of the discrete item and container handling in the feed preparation area - a floor mounted linear rail in the preliminary and secondary sorting area, an overhead gantry with a telescoping mast and a remotely operated manipulator. During routine operations, the manipulator is mounted on the linear rail to easily access the preliminary sorting tray, characterization equipment, tool racks, and waste stream output drums. Standard interfaces on the manipulator, crane and rail allow the manipulator to be picked up by the crane for non-routine operations, including reaching into containers and areas that cannot be accessed using the rail mounted configuration, or decontamination and clean-up operations after a spill or other material release. In the future, studies may be performed to determine the effectiveness of the manipulator for limited remote maintenance - primarily removal of entire modules from the feed prep area.

Research and trade-off studies were performed to determine whether to deploy teleoperator, telemanipulator or telerobot technology in MWMF (8,9,10). Teleoperators provide replication of operator motions (and forces) in a remote environment for the performance of a task. Telemanipulators are also operator controlled but have electronic or computer augmentation to provide position and force offsets, scaling, or other operator enhancements. Telerobots provide more sophisticated computer control, allowing some operations to be performed under operator control and others (tool changing and other repetitive tasks) under computer control. As one moves from teleoperators to telerobots, the ability to control the system in an autonomous manner increases. The ability of telerobots to perform routine operations autonomously is what gives them their potential for improved productivity over a strictly teleoperated system (11).

The selection of telerobotics for deployment in MWMF was made based on a number of factors - personnel protection, waste generation, technology maturity, cost, flexibility and extendibility. The goal was to design and deploy a robust system that meets the initial waste preparation flexibility and productivity needs while providing a smooth upgrade path to incorporate technology advances. The key issues that lead to the selection of telerobotics were:

- the potential to increase productivity through the use of preprogrammed tasks
- the need to coordinate manipulator motion with that of other devices including drum dumpers, the linear rail and overhead crane
- the need to provide input/output device correspondence by compensating for camera viewpoint
- the need to provide workspace collision avoidance
- the need to provide complex paths for some operations
- the desire to minimize the cost to incorporate new technology as it matures

The limited record and playback capabilities of teleoperators and telemanipulators was the primary drawback to their use. A telerobotic approach also appeared the best long term approach since it provided the only clean upgrade path toward more autonomous systems.

Although the maturity of fully automated sorting technology is at the proof-of-principal level now, many of the improvements necessary to make it more robust are in soft technologies. A telerobotic system can be "software-upgraded" as technology matures to take advantage of these advances and without large system cost increases.

In summary, telerobotics was chosen for deployment in MWMF because it is low risk, provides the flexibility needed to increase or decrease the amount of automation or operator intervention according to task complexity and provides an inherent backup in that it can be operated in a teleoperated mode as required. Primary components of the telerobotic system include the manipulator and standard modular interface, a sufficiently rich telepresence system and the control system. Each will be discussed briefly below.

**Manipulator/Interface**

The manipulator provides the dexterity, reach and motive force required to handle items at the speed and acceleration needed for teleoperation. For dexterous tasks, the manipulator must respond and travel fast enough to avoid delaying the operator. Studies have shown that manipulator must be capable of operating at speeds close to 1 m/sec and the system bandwidth needs to be in the range of 9 to 25 Hz (10). The standard interface at the manipulator base, along with mating interfaces on the linear rail and overhead crane, provide the flexibility needed to locate the manipulator in the proper orientation relative to the task space.

### Telepresence

The telepresence system provides remote viewing, tactile and audio feedback to the operator. For most routine operations, direct viewing of the preliminary sorting and decontamination areas is planned. However, remote viewing will be needed for many situations, including removal of delicate items from waste drums prior to dumping. The current design includes a number of 2D as well as stereographic cameras. The cameras will be represented in the computer model so the transformation matrix representing their viewpoints of the manipulator arm may be used to correct the input/output relationship between the control command and the manipulator arm (e.g. when an operator selects a view and wants to move the manipulator to the left in the camera view, they can move the control arm to the left and the manipulator will move to the left.)

There are a large number of hand and master arm controllers on the market and their capabilities vary widely. They can be classified as passive or active. Passive controllers accept operator input as position or force commands but have no capability to reflect position or force of the manipulator back to the operator. Active, force reflecting hand controllers, are actively driven to provide operator force feedback cues on the state of the manipulator arm. In addition, through the use of virtual forces, the robot force information can be augmented with additional information representing impending collisions to cue the operator to stay away from a particular area. Hand controllers are typically end-point control devices while master arms are usually full size kinematically similar manipulator arms akin to traditional master arms in master-slave manipulators.

LLNL performed surveys of the industry, has acquired and evaluated a number of active and passive systems, and has received a number of studies on other hand controller performance evaluations (12,13). Since most dexterous tasks (grasping, fine manipulation, etc.) take place in relatively small volumes (.75m x .75m x 1m) a hand controller based system with position scaling was selected for initial deployment in MWMF (9). A force-reflecting system will be implemented in order to provide actual and virtual force telepresence.

Audio feedback is very important when operating mechanical equipment and is an essential part of a telepresence system. Stereo audio provides a sense for where action is taking place and the sound can indicate the amount of load on a motor, bearing failures and other indicators of the system performance or impending failures. A number of audio channels will be available for operator selection. Again, by representing the microphones and cameras in the computer model, appropriate, rather than confusing, information can be sent to the operator.

## Control System

The control system is the heart of a telerobotics system. Since telerobotics involves both teleoperation and robotics, a shared control scheme is used during normal operations. Shared control refers to the "seamless" transfer of control from a human operator to a computer control algorithm during different portions of a task. For example, in MWMF the operator will control the manipulator during complex, unstructured tasks such as sorting through and grasping waste items. For routine tasks, such as placing waste in a barrel, the operator can select the destination for the object off a preprogrammed menu of options and relinquish control. The computer algorithm will then assume control and execute the task. Shared control provides a mechanism for improving productivity by performing routine tasks with a minimum of operator intervention. The shared control system must provide robust, dexterous manipulation; reliable, graphics model based, programmed operation; and, seamless transfer between teleoperated and programmed operation. The control architecture being used in MWMF to accomplish this is a hierarchical structure with two primary levels - the graphical model based planning and high level control system and a high speed low-level manipulator control loop (14).

A graphics based world model provides the mechanism for implementing low-level control including manipulator control, input/output device correspondence, and virtual forces for collision avoidance. At a high level, it is used for off-line, model-based path programming and simulation; collision free path planning; device coordination; displaying sensor data gathered as material advances through processing steps; and preplanning, previewing and monitoring system operation. The three dimensional world model representation provides the geometric relationships for many of the transformations and calculations required to implement both the low-level and high level control systems.

There are currently several vendors who provide graphical modeling environments that can be integrated with the required subsystems. A review of the leading systems was conducted during FY92/93 and again in October, 1994 to evaluate the simulation and control capability of various systems (15,16). The results of the controller review indicate that graphical simulation and control of the various devices in a uniform and coherent fashion is achievable and advantageous during operation of remote processing systems. In addition to the required computational support the model provides, it also serves as a useful interface for displaying material transport and container flow through the facility and allows remote "viewing" from arbitrary workcell locations. The latter can be especially valuable during decontamination operations and other complex operations where clearances with the workcell need to be checked. An integral object-oriented CAD database is well suited for updating properties of objects as they are characterized and transformed by the system, providing a suitable mechanism for tracking materials through the feed preparation area (17).

MWMF is currently using the Cimetrix ROBLINE package, which provides "symmetrical" graphical simulation and control. "Symmetrical" in this use, means that the same control program drives both the software simulation and the actual workcell hardware. A set of low-level drivers communicates with the simulated sensors and devices when running off-line and the actual hardware when running on-line. The approach allows as much (or as little) sophistication to be built into the simulated environment as needed. The ability to simulate program logic, as well as device motion, is extremely important when controlling tasks involving many different devices and interlocks. The Cimetrix approach performs this function better than many off-line programming packages tailored toward repetitive manufacturing tasks.

The graphical simulation and control package provides a variety of information required for teleoperation and control, including the transformation matrices to describe orientations between the manipulator, hand controller and remote viewing system. These "parameters" are relatively static from a servo-level control system standpoint and are passed down as the operating mode changes. This keeps the simulation package, which is computationally intensive, out of the servo control loop.

At the servo level, a high speed control loop is needed to translate operator commands, force sensor data, and viewpoint information into commands to the manipulator and feedback to the operator. The Sequential Modular Architecture for Robots and Teleoperation (SMART) was developed at Sandia National Laboratories in Albuquerque to address many of these servo-level telerobot control issues (18). SMART is in widespread use across the DOE complex in association with the Office of Technology Development Robotics Technology Development Program and forms the basis for the MWMF servo-level telerobotic control system.

## MODULAR PROCESSING SYSTEM INTERFACES

The primary feed preparation process units will be modular to facilitate reconfiguration and easy disassembly for repair or replacement. Modular processing system interfaces are not uncommon in the nuclear field and have been used in a variety of facilities at the Hanford and Savannah River Sites, as well as Power Reactor and Nuclear Fuels Corporation sites in Japan. Modular interfaces for mechanical attachment as well as process utilities, feeds and effluents facilitate reconfiguration of contaminated systems without drilling, cutting or welding of contaminated materials and with a minimum of operator contact. One of the drivers for facilitating module reconfiguration and replacement in MWMF is the need to accommodate a wide variety of feed materials and some uncertainty in how the equipment will perform on very heterogeneous wastes. A number of processing steps may need to be interchanged for some feeds or a new piece of equipment added.

Modular interfaces also provide a standard connection and disconnection method that can be engineered to allow convenient remote operation. This facilitates removal of modules for decontamination, refurbishment or disassembly in a lower hazard exposure area. Traditionally, these systems have been used for highly radioactive materials, but they provide many of the same risk and waste reduction advantages in hazardous environments or when lower levels of alpha or transuranic contamination exist.

During initial operations, feed preparation processing modules will include a radiography module, a knife shredder capable of shredding material to 1 mm particle size, a magnetic and paramagnetic material separator, a particle size screener, a density separator and a liquid/solid blender. These modules have been selected to meet the feed prep needs of the initial suite of treatment technologies and their effectiveness will be evaluated as part of the demonstration. Others may be added, or these may be reconfigured to meet future treatment demonstration needs.

## SUMMARY AND CONCLUSIONS

The MWMF is being deployed to demonstrate emerging technologies to treat organic mixed waste in an integrated fashion. It fulfills a need to bridge between R&D bench scale experiments and full-scale technology deployment. As such, technologies being demonstrated should already have been shown to work at the bench scale, should be relatively robust, and should show promise for deployment in a full-scale facility. Remote operations, modular processing units and telerobotics for initial waste characterization, sorting and feed preparation meets these criteria and have been selected for demonstration in MWMF as part of an integrated treatment train encompassing everything from waste receipt to final forms. The initial telerobotics configuration will allow robust telerobotics to be demonstrated and evaluated and provide the infrastructure needed to incorporate more advanced technology as it matures. Modular processing units will provide processing flexibility and facilitate reconfiguration as new treatment processes or waste streams are brought on line for demonstration.

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