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PROCEEDINGS OF THE WORKSHOP ON REQUIREMENTS OF MOBILE TELEOPERATORS FOR RADIOLOGICAL EMERGENCY RESPONSE AND RECOVERY

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edited by

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WORKSHOP OVERVIEW

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The rapid development of robotics and teleoperators in recent years has led the Department of Energy to investigate the potential usefulness of these technologies to radiological emergencies. As part of that investigation, the Office of Nuclear Safety, Radiological Controls Division, sponsored a workshop involving government, industry, and research organizations to assess the state of the art of these new technologies as applied to such emergencies. The workshop was held in Dallas, Texas, on June 23-25, 1985. See the Appendix for a list of attendees and speakers.

This proceedings volume encompasses the papers presented at the meeting and the major conclusions of the workshops.

WORKSHOP OBJECTIVES

The objectives of the workshop were to bring together people from organizations that must cope with the possibility of radiological emergencies in their facilities as well as manufacturers of robotic equipment and researchers in the field in order to acquaint them with each other's perspectives. More specifically the workshop was to:

- Describe and characterize the scope and magnitude of a radiological emergency,
- Characterize the features needed in mobile teleoperators used in radiological emergencies,
- Describe currently available mobile teleoperated systems usable for radiological emergencies, and
- Itemize and describe currently available or near-available teleoperations technology.

The workshop was structured in three parts. The first part dealt with a characterization of the radiological emergency environment itself, followed by specific discussions of three significant radiological emergencies: the Three Mile Island accident, the Y-12 criticality accident, and the SL-1 accident. The second part of the workshop focused on current mobile teleoperators and their applicability to radiological emergencies. Specific examples were provided: Three Mile Island; the Oak Ridge National Laboratory device, HERMAN; and ordnance disposal. Future directions in mobile teleoperators were also discussed. The third and last part of the workshop was devoted to the specifics of the current technology and addressed mobility, sensing, mechanical accessories, the human/machine interface, and power and signal transmission.

WORKSHOP SUMMARY

Radiological Emergencies: Environment and Operations

Three papers in the first part of the workshop described the actual situation, environment, and tasks encountered in three significant radiological accidents: the Three Mile Island reactor accident, the Y-12 criticality accident, and the SL-1 reactor accident. A fourth paper presented a generic characterization of radiological emergency environments and needed operations.

The paper on the well-known accident at Three Mile Island (TMI) Unit 2, which resulted in severe radiological accident conditions, describes what could be expected in any serious accident. There was a great deal of highly contaminated water in the reactor building basement as well as several inches of contaminated water in the auxiliary building basement. Radiation levels in the reactor building basement ranged from 20 to 40 rem/hr while the temperature was around 90°F and the humidity was 100%. Moreover, there was some unknown physical damage due to a hydrogen gas ignition. Many other areas of the plant, some of which had to be entered by plant personnel to stabilize the plant, also had high radiation levels.

There was no manned entry for over a year. Mobile teleoperators were not used during that time because none were available with the required versatility and sophistication. Had they been, personnel exposures might have been significantly reduced. Once entry was gained, a number of tasks became necessary: sampling the reactor coolant system, processing liquid radioactive waste, maintaining plant status, and radiation monitoring and sampling.

On the basis of TMI conditions and experience, the paper listed some important functional requirements for mobile teleoperators:

- Ability to access obstructed and constrained areas,
- Manual dexterity with force feedback for valve and switch manipulation,
- Communications to allow control of the teleoperator and to return data to operators, and
- Robust and hardened construction to withstand conditions and decontamination.

The TMI paper also points out a very important consideration for use of remote mobile teleoperators: they must be readily available early in any accident situation. The paper noted that "the highest dose rates and some of the highest individual exposures at TMI occurred within the first few days of the accident." Thus availability and prompt delivery of suitable machines is essential to derive maximum benefit. The cost of designing and constructing such machines and training operators for them will probably need to be borne by a larger group rather than a single potential user. An industry group or DOE sponsorship or both will be needed to ensure the development and availability of such a specialized resource.

The paper on the Y-12 criticality accident of 1958 described that incident and the potential applicability of mobile teleoperators had they been available then. Unlike the TMI accident, there was no widespread contamination. But there was an ongoing and unknown potential for subsequent critical excursions which limited the accessibility to the "impromptu barrel reactor." Access was also severely limited by the complicated physical layout. Therefore the primary tasks in this accident were initial surveillance of the scene, stabilization of the impromptu reactor, and subsequent cleanup and removal.

Surveillance was necessary in the first hours to determine the situation. A remote mobile teleoperator would have been invaluable during this period. Similarly, stabilization of the accident, which required poisoning the solution with a cadmium strip and possibly closing some valves, would have been much simpler and safer had appropriate teleoperators been readily available. And again, sampling of the barrel contents some days later could have been expedited with such technology.

Thus, as in the TMI accident, we see that the necessary tasks were access, surveillance, and manipulation. There are four major operational phases of an accident:

- Initial reconnaissance to gather data on the accident scene,
- Stabilization of the accident by removing those elements that are causing or aggravating the situation,
- Preparation for recovery by clearing rubble and gaining access, and
- Final cleanup and recovery.

Reconnaissance is needed in the first hours and continuing on through the recovery phase. Stabilization is also needed in the first hours or days. Preparation for and actual recovery could start in days and extend to years as in TMI.

Similar problems and tasks were discussed in the third paper on the SL-1 accident of 1961. In this reactor accident, debris in the reactor area restricted access and the dose rate was in excess of 1,000 rem/hr. Temperatures outdoors, where much of the support activity had to be staged, were -20°F.

Two of the three men in the reactor were killed but a third was still alive when the first emergency workers arrived. He was removed by volunteers but later died. It is unlikely that mobile teleoperators would be useful in lifesaving operations, but recovery of bodies from extremely hostile environments would likely be an important consideration for their use.

A major task in this accident was determining the state of the reactor, which required almost a week. Obviously, a readily available teleoperator would have been very valuable.

These three papers begin to reveal the common threads of needs and functional requirements of a mobile teleoperator in any radiological emergency. In the last paper some other incidents are briefly discussed to further define the threads. That paper then gives a general characterization of such emergencies and the functional needs of teleoperators.

In the fourth paper five general classes of radiological emergencies are proposed in which mobile teleoperators would be useful:

- Criticality or potential criticality accidents,
- Misplaced gamma source,
- Atmospheric release of radioactive gas in a confined area,
- Release and subsequent surface contamination by radioactive aerosol, and
- High-level liquid leak or spill.

The range of conditions for which a teleoperator might have to be designed include localized radiation fields of up to 10,000 rem/hr and general fields of several hundred rem/hr. Contamination may be present and criticality a possibility as well. Humidity might range from low to saturation and temperatures from -20°F to 120°F. Atmospheres may be inert.

Moreover, the floor or terrain may be cluttered and obstructed, and doors, stairs, and airlocks may further restrict movement. Electrical power may be unavailable for lighting or teleoperator use.

The paper goes on to identify some of the major tasks that are necessary during the various operational phases. Surveillance is a common need but is not particularly site-specific in its requirements. Stabilization and recovery needs are quite diverse, depending on the specific site, and include a wide variety of tasks (opening and closing doors and airlocks, operating valves and switches, cutting materials, picking up objects, sampling, and so forth). Thus one type of surveillance vehicle might suffice for most accidents, but a modular type of teleoperator might be necessary for later response to the same accidents.

Currently Available Mobile Teleoperators

The second part of the workshop presented papers on some actual teleoperator responses to radiological and other emergencies. Another paper provided an extensive overview of most of the currently available machines and their applicability to radiological emergencies. The last paper discussed the future directions of mobile teleoperators.

As background, the tasks that mobile teleoperators might be called upon to perform can be thought of as a combination of certain generic activities. That is, they must first transport a payload; second, sense the environment en route and at the work site; and possibly third, perform a work task at the site. The first two activities are required in all operational phases while the third is required only in the stabilization and recovery phases.

Predictably, the design of a mobile teleoperator would differ in each operational phase because of the varied tasks and environments. Therefore a modular approach would probably prove most useful.

The basic module is the transporter, whether it crawls, rolls, walks, or uses some combination of these. The transporter must have a power module, whether an umbilical, on-board generator, or battery. The transporter must also be controlled by operators through some sort of human/machine interface involving control circuits of some kind. These modules enable the teleoperator to transport a payload, the first generic activity.

The teleoperator must also sense its immediate environment, the second activity, to allow it to travel to the work site and relay information. Remote sensing requires various sensors to collect the data and a signal transmission module to return the data to the operators.

The third generic activity, performing a work task, requires all the modules for the first two activities plus an additional module with mechanical accessories or tools designed to perform specific tasks.

The application of these ideas is seen in the recent and extensive use of mobile teleoperators in the recovery of the Three Mile Island plant. Several remote reconnaissance vehicles (RRVs) and remote working vehicles (RWVs) have been designed and constructed in conjunction with several different organizations. These machines have been successfully deployed in the TMI cleanup while providing valuable lessons about their development and use.

The TMI machines emphasize available commercial technology and high reliability. The two RRVs are tethered electric vehicles that carry their own umbilicals and novel umbilical management systems. They use six-wheel, skid-steer transporters with high traction and maneuverability. They carry three television cameras and lighting and have a capability for additional monitoring instrumentation, having a several-hundred-pound payload. The RRVs are modular in design and are readily decontaminated.

In use, the RRVs performed all data acquisition tasks as scheduled with only two significant problems: entanglement of the safety retrieval cable and failure of one of three radiation detectors. Because it is a working machine using on-hand construction equipment, the RWV is larger and more robust than the RRVs. It was designed on the basis of remote undersea robotic experience and consequently is an electrohydraulic machine.

The anticipated tasks for the RWV include transfer of waste materials, cleaning, breaking and cutting masonry and concrete, abrasive cleaning, cutting metal, moving shielding, and monitoring.

In short, the TMI experience has demonstrated that the use of mobile teleoperators based on current technology is achievable and reliable for surveillance and heavy cleanup operations.

Another approach, that of using inexpensive and expendable teleoperators, was addressed in a paper on ordnance disposal experience with mobile teleoperators.

Early systems based on electric wheelchairs provided a camera system, a grapple, and some special tools for a cost of about $5,000. Such an inexpensive reconnaissance vehicle could overcome one development problem noted at TMI, the development of methods to rescue or retrieve a failed teleoperator.

This paper also discussed a heavy equipment remote control kit that can be installed in a large vehicle relatively quickly to allow for its remote use. Such systems could be very useful in transportation accidents or other radiological accidents outdoors.

Just as the TMI designs incorporated undersea robotic experience, the ordnance disposal experience also holds promise for innovative and inexpensive solutions to the problem of radiological emergency response.

The next paper presented a thorough review of available teleoperations technology that can be employed in hazardous environments, including the nuclear industry. Sixty-nine systems were described, demonstrating that the industry already has a great store of developed technology which can be incorporated in development of a series of staff robotic devices for routine power plant uses and emergency uses. Such joint use will optimize development costs and more readily ensure the availability of a useful device in an emergency.

The final paper in this part of the workshop described the likely future directions of mobile teleoperations. Several key areas of research were identified as having impact on future development of teleoperators. These included mobility, manipulation, systems and supporting technologies.

Mobility, a critical aspect of teleoperators for emergency response, is receiving significant attention. A variety of approaches are being investigated. While most current machines use wheeled transporters, some of the most significant research is in the area of legged or walking machines. This research shows great promise for transporting heavy payloads through highly unstructured terrain with many constraints, a condition often found in an accident or emergency situation.

Manipulation is also receiving research attention because of the ultimate need for useful work by teleoperators. A special focus is "force reflection," in which the actual work forces at the manipulator are fed back to the operator. Other work of importance is the design of more-flexible manipulators with greater dexterity.

Several efforts were described to integrate manipulators with mobile platforms. Although these systems have not yet been tested in the field, they may well provide important advancements, such as a greater replication of human capabilities in an unstructured environment.

A related paper was presented at the workshop describing mobile teleoperator research at the Savannah River Laboratory for applications there. Their general goals have been to improve safety, reduce personnel exposures, improve operations and productivity, and reduce operations cost. Systems are also under development for emergency response operations. Two major and significant research areas are the application of artificial intelligence and sophisticated walking machines.

Current Mobile Teleoperator Technology

The third and last part of the workshop was largely a tutorial on the state of the art of important mobile teleoperations technologies from the perspective of their application in radiological emergencies. Several presentations discussed the broad classes of transporter technologies and those applicable in emergencies, remote sensors and their limitations in radiation environments, the human model for optimum design of mechanical accessories, the human-machine interface, and means for furnishing power and command signals to remote mobile teleoperators.

CONCLUSIONS

As a result of this workshop, from both the papers presented and the various discussions that followed, we can draw several conclusions about the use of mobile teleoperators in radiological emergencies. To begin, consider some conclusions about the usefulness of teleoperators for such operations.

- On the basis of prior experience with a wide range of accident severities, mobile teleoperators can be very useful for reconnaissance and recovery.
- They can provide significant dose savings and reduce risk to emergency personnel as well as carry out a wide range of useful tasks.
- Their greatest utility is probably in the late emergency stage (beyond 24 to 48 hours) to the recovery stage.
- To accommodate emergencies in these stages, we need two basic types of readily available teleoperators: a standardized remote reconnaissance vehicle and a medium-duty standardized remote working vehicle.

- The design of a standardized mobile teleoperator for radiological emergency response must accommodate a very wide variety of physical and radiological conditions.

- One or two of each of these machines, along with support and operations staff, should be available at some central location for immediate dispatch to an accident site.

- Severe accidents requiring long-term cleanup operations will provide adequate time to develop any unique survey and heavy-duty working teleoperators needed from available hardware and technology.

The experience at the Three Mile Island cleanup as well as the large number of currently available machines allows some additional conclusions about the types of machines that would be needed.

- While significant advances in teleoperations are being made which will improve performance, the available current technology and experience are adequate to produce reliable, standardized reconnaissance and working vehicles of great usefulness for a wide variety of emergency, recovery, and cleanup tasks.

- Current wheeled skid/steer transporters are reliable, low-cost, moderately mobile, and probably the transporter of choice for the near term.

- Legged walkers are complex, expensive, and show great promise for enhanced mobility but are probably a few years away in terms of actual emergency deployment.

- Undersea robotic experience and ordnance disposal experience can provide significant contributions to the development of low-cost teleoperators for hostile environments.

Finally, the discussion sessions suggest some conclusions about the efficient use of funding in developing mobile teleoperators for radiological emergency response and recovery.

- The development and construction of a specialized response vehicle for very rare use is not economic or efficient if done for a single facility.

- Funding, development, and construction of the necessary reconnaissance and working teleoperators will probably have to be jointly undertaken by a group of organizations or facilities to ensure availability to the individual organization in an emergency.

In summary, mobile teleoperators have a significant role in the response to and recovery from radiological emergencies and accidents. The current state of the art is such that reliable and effective systems can be made available today. Future advances in technology will certainly add more capabilities and mobility and extend the range of possible tasks. However, the funding and development of reconnaissance and working vehicles will probably have to be done by a group of organizations or facilities to ensure the availability of the necessary machines.

POST-ACCIDENT RECOVERY OPERATIONS AT TMI-2

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ABSTRACT

The accident at Three Mile Island Unit 2 resulted in severe radiological conditions in many areas of the station. Personnel entry into some of these areas was required to stabilize the plant. Mobile teleoperators were not utilized at the time due to the lack of availability of machines with the required degree of sophistication and versatility. Personnel radiation exposures may have been significantly reduced had these devices been designed to perform certain tasks and been available for immediate use. This paper reviews the immediate post-accident recovery tasks and provides functional criteria for the development of teleoperators which could perform similar tasks in high-radiation environments in the future.

INTRODUCTION

The Three Mile Island Nuclear Generating Station (TMI) is a two-unit, pressurized light-water reactor facility located 10 miles from Harrisburg, Pennsylvania. On March 28, 1979, Unit 2 experienced a reactor shutdown due to a loss of feedwater to the "B" steam generator and subsequent turbine trip. The resulting series of events culminated in a loss of reactor coolant and a partially uncovered core. The fuel cladding failed, due to the dramatically increased core temperatures, which introduced large amounts of radioactive fission products into the reactor coolant system.

Following the turbine trip, the open pressure-operated relief valve (PORV) on the pressurizer permitted reactor coolant to fill the reactor coolant drain tank. Fifteen minutes after the turbine trip the reactor coolant drain tank rupture disc failed due to overpressurization and primary coolant flowed to the reactor building sump, causing the basement to begin filling with water. The reactor building sump pumps started automatically and transferred approximately 8100 gallons to the auxiliary building sump tank before pumping was secured. Since the available capacity of the auxiliary building sump tank was only 700 gallons and the rupture disc was broken, liquid overflowed to the auxiliary building sump, causing water to back up through the floor drains in both the auxiliary and fuel handling buildings.[1] This resulted in several inches of water on the auxiliary building basement floor and very high radiation fields.

At the same time, very high fission product activity and even fuel debris circulating in the primary coolant were introduced into piping systems in the auxiliary and fuel handling buildings. The systems included makeup and purification, seal injection, reactor coolant liquid radwaste, and radwaste disposal. These piping systems, which were designed to normally contain and process reactor coolant and associated liquid wastes, created radiation fields far in excess of the normal plant operating conditions. Despite the extreme radiological conditions, manned entry into the auxiliary and fuel handling buildings was required for several weeks after the accident in order to maintain the operating status of certain plant systems and to attempt to bring the plant into a stable configuration.

Manned entry into the reactor building was not attempted for over a year following the accident. High radiation fields were caused by the presence of fission products that were dispersed by steam and circulating air currents and by fission gases, notably Kr-85. The reactor building basement contained 600,000 gallons of water with fission product concentrations of 160 microcuries per milliliter and attendant radiation fields of 20 to 40 rem per hour. The radiological conditions were difficult to assess because direct measurements were not possible. The reactor building radiation monitors had failed during the accident and only limited access to the reactor building could be obtained through penetrations. Although entry into the reactor building was not required to maintain the plant status, it was important to try to determine the structural condition of the building and plant. As determined a couple of days later, hydrogen gas was vented to the reactor building through the reactor coolant drain tank rupture disc and was ignited on March 28, 1979, causing a pressure spike of 28 psig. This elevated pressure activated the containment spray system which introduced about 17,500 gallons of borated water and sodium hydroxide solution into the reactor building.[2] The combined effects of the hydrogen burn, alkaline sprays, elevated building temperature, sustained high radiation fields, and prolonged condition of 100% humidity were unknown. Attempts to survey the building for damage could only be attempted through penetrations in the reactor building walls.

At the time of the accident remotely operated equipment was not immediately available that could perform the required tasks in lieu of manned entries. Because of the plant layout, physical constraints, and required versatility, the type of remote equipment needed would have been extremely sophisticated. In fact, attempts were made to find equipment to do this work but none was found that possessed the required level of sophistication or versatility. However, if such equipment had been available it would have certainly been used. This paper describes the tasks which were required to be performed with a perspective on the functional criteria for the development of remotely operated equipment which could be used in similar circumstances in the future. Also, recommendations are made for the possible development of plant installed equipment which could be designed to be compatible with remote equipment operations and thus considerably reduce the degree of sophistication needed.

POST-ACCIDENT RECOVERY OPERATIONS

Despite the radiological conditions and associated constraints to personnel access, certain tasks were required to be performed for plant stabilization and for the protection of the health and safety of the public. The tasks required plant operations personnel to enter the auxiliary and fuel handling building (AFHB) to manipulate valves and to direct the transfer of liquid and gaseous radiological waste from a master control panel located in the auxiliary building. Chemistry personnel were required for sampling and analysis of the reactor coolant system (RCS) and other plant systems. Radiological controls technicians were needed to obtain information about radiological conditions and maintain the station airborne effluent monitoring system. Each of these tasks involved repeated entries into high radiation areas.

The tasks involving chemistry sampling and operations valve lineups were the most exposure intensive. An RCS sample taken the day after the accident was greater than 1000 rem per hour on contact with the sample container and 400 rem per hour at a distance of one foot. The chemist who obtained that sample received 4.1 rem whole body exposure during sampling operations.[3] Exposures between 0.5 rem and 1.5 rem per entry were frequent. Radiological controls technicians were required to strictly limit the stay times of personnel entering high radiation areas, prescribe pathways to and from the work site, and provide radiation monitoring devices in order to keep exposures as low as reasonably achievable. Communications were essentially limited to the plant paging system. Contamination protection for personnel included cloth and plastic coveralls, boots, gloves, hoods, and respiratory protection devices. One consideration not normally encountered in power plant operations was the incremental reduction of worker mobility with each layer of protective clothing, and the subsequently increased time required to perform a task. Because certain entries could have caused a person to receive his quarterly dose limit in just a few minutes, reduced protective clothing was prescribed in order to reduce radiation exposure.

Sampling the Reactor Coolant System

Reactor coolant samples were required frequently for several weeks after the accident. This operation required access to sampling locations, operation of sample valves, and transporting and handling small sample containers.

Because frequent sampling resulted in such high individual and collective worker doses the NRC regulations for post-accident sampling systems have been upgraded. The "lessons-learned from TMI" plant modifications included a revised system design to allow obtaining the highly radioactive liquid samples more efficiently and with lower doses for personnel.

Processing Liquid Radioactive Waste

Continuous movement and processing of liquid radioactive waste was necessary due to limited tank storage capacity. These operations were conducted from the radioactive waste master control panel in the auxiliary building. The tasks included accessing the control panel; reading gauges, meters, indicator lights and alarms; manipulating switches and push buttons; and maintaining communications with the plant control room.

Initially, the dose rates in front of the master control panel were about 8 rem per hour. Several weeks later they were reduced to 0.05 rem per hour. Although these radiation levels were not high compared to other areas in the plant requiring access, the number of hours spent in this area resulted in high collective personnel doses. Establishing a decontaminated pathway to this area, and lowering the dose rates in the area, became the top priority for the initial recovery of the auxiliary building.

Maintaining the Plant Status

Certain operations were critical to maintaining the plant in cold shutdown condition. Regardless of high radiation levels, operators had to access virtually all areas of the plant to perform valve lineups and verifications. An example of such a critical operation is an entry into the seal injection valve room a week after the accident in order to restore seal water to a reactor coolant pump. Dose rates of 400 rem per hour were measured adjacent to the valve. In this radiation field a person could reach his quarterly dose limit in about thirty seconds. Access to the valve was made difficult by narrow passageways and interferences. The entry team members were also encumbered by protective clothing and by self-contained-breathing-apparatus respiratory equipment. Despite these adverse conditions the job was successfully accomplished within established dose limits.

Radiation Monitoring and Sampling

A large percentage of AFHB entries made by radiological controls personnel during the first week after the accident involved the replacement of the roll-type filter paper on the plant ventilation system monitors. The radioactivity collected on the filter paper very rapidly, requiring frequent filter changes in order to keep the detector and meters within their operating range. In addition, the only available access for obtaining reactor building air samples was located in a high radiation area in the AFHB. These operations required access to most areas of the plant; manipulation of small clips, screws, and switches; retrieval of filters; and the reading of meters and gauges.

The need for radiation surveys in the AFHB was limited for two reasons:

1) installed plant area radiation monitors provided an indication of radiation levels in many areas, and

2) plant operations personnel were allowed to carry their own radiation monitoring devices because this was the most dose effective means of conducting building entries. This is contrary to normal plant operating practices because radiological controls technicians are usually used to perform radiation surveillances. As a rule, radiological controls technicians did not enter the affected areas of the plant for the sole purpose of radiation surveys, rather surveys were performed in conjunction with other tasks.

Initial Reactor Building Entry

The first entry into the reactor containment building occurred on July 23, 1980, sixteen months after the accident. This event marked a milestone in the recovery of the damaged reactor and containment building. Until that point, information about the physical and radiological conditions of the building was sparse as measurements had to be obtained remotely.

The first two entries consisted primarily of visual and radiological surveillance. The initial entry occurred after the venting of about 40,000 curies of Kr-85 from the reactor building. The venting allowed some relief from protective clothing requirements because of the reduced beta radiation dose rates. The general area radiation levels were on the order of 0.7 rem per hour. Lighting was generally good, but not available in all areas. The building did not appear to have suffered significant structural damage. The most extensive damage was apparently due to surface rusting of exposed steel surfaces to moisture. The reactor building temperature was generally around 90°F, and a constant 100% humidity caused condensation in the dome region and a subsequent "rain forest" environment. Some minor damage occurred as a result of the hydrogen burn and there was some evidence of chemical damage due to the sodium hydroxide sprays.[4]

The availability of remotely operated equipment to perform the visual and radiological surveillance much sooner in the program would have considerably eased the concern over the damage to the building. Also, earlier knowledge of the building's radiation levels would have greatly aided in recovery and decontamination planning efforts.

FUNCTIONAL REQUIREMENTS FOR TELEOPERATORS

The operations for which teleoperators would have been useful in the recovery of TMI-2 immediately after the accident are varied and complex. The functional criteria for the design of teleoperators are dictated by the operational needs for plant access, valve and switch manipulation, equipment changeout, sample acquisition, and radiation monitoring.

Access Requirements

Unfortunately, access to most of the areas of the plant was made difficult by obstructions. Ideally, a teleoperators would have to have the flexibility to access the same areas as a man. Such flexibility would require cableless signal/power transmission in order to negotiate airlocks, travel to distant areas of the plant, or negotiating complex routes.

Physical constraints that may restrict the movement of remote vehicles include:

1) doors and gates - unlocking, opening, and closing of doors are necessary.

2) piping obstacles - field run pipe and supports, along with valve reach rods, will hinder the vehicle's path. The ability to negotiate these obstructions requires extreme dexterity because pipe can run along the floor at heights ranging up to 24".

3) corridors and labyrinths - due to the many cubicle access labyrinths designed for radiation shielding purposes, and narrow valve and pipe corridors, the vehicle must be sized small enough to proceed through these to reach its destination. In addition, its turning radius must allow for the difficult maneuvering involved.

4) water - the remote teleoperator must be able not only to move through standing water, but to remain functional after being sprayed or rained on by leaking valves or pipes. Electronic equipment, camera lenses, meter covers, and lighting would need protection.

5) stairways - the ability to climb and descend stairs is essential. Elevators are generally unreliable following an accident due to possible power failures or flooding of the pits, as occurred after the TMI accident.

Manual Dexterity

Many operations involved tasks of varying complexity ranging from simple valve operation to removing small clips or handling glassware. Valve sizes ranged from 1" to 8". Because the requirements are so varied, a teleoperator system must be flexible and versatile. The versatility could be supplied by modular components or by a series of different machines.

Force reflective feedback is essential for most of the described operations because of torque limitations on valves and switches and the delicate nature of sample containers. Precise programming may be a suitable alternative to force reflective feedback for identical and repetitive operations such as RCS sampling. However, consideration must be given to changing differential pressures when turning valves during system operation.

Some operations, such as filter paper changeout, may be so complex and require such a high degree of manual dexterity that it may be more practical to redesign the plant equipment to be more easily serviced by remote teleoperators. In the case of plant ventilation radiation monitors, this could be accomplished by designing a cartridge-type of filter holder as opposed to designed models using small pins, clips, and screws.

Communications

The teleoperator must be able to perform visual surveillance of areas, requiring wide angle viewing, as well as to read dials and gauges, requiring high resolution.

Obviously, the camera equipment must be capable of giving enough of a field-of-view to allow the equipment operator to guide the machine to its destination. Portable illumination is also required since the availability of lighting may be uncertain following an accident.

The remote signal capability must allow two-way communication with the operators. This may be accomplished with an umbilical cord, however this system is limited, as previously discussed. Wireless transmission may be made difficult within the plant, however, because of interference and shielding due to thick, reinforced concrete walls.

Radiation surveillance would require the remote transmission of radiation data. Radiation instrumentation should be capable of monitoring conditions over a wide range of dose rates. Instruments should be capable of detecting gamma (penetrating) and beta (nonpenetrating) radiation separately.

General

In a nuclear plant environment, an instrument must be capable of withstanding assault from radiation fields caused the both gamma and beta radiation. The most sensitive components of a teleoperator would be in the electronics or the camera lenses. However, most radiation environments in nuclear power stations will not be sufficiently high to cause concern for even these components. Also, the decontamination of the equipment will be required. Wherever possible, external surfaces should be made smooth and not subject to damage by water. Internal surfaces should be sealed. The reliability of the equipment must be very high, especially the transporter. A breakdown in a high radiation area would make retrieval difficult and may require a manned entry. In the same light, remote vehicles would require high-capacity batteries to sustain long entries.

A very important consideration for the use of remote teleoperators is their availability. Shortly after an accident, or any event requiring access to high-radiation areas, remote teleoperators can be invaluable dose-saving devices. The highest radiation dose rates and some of the highest individual exposures at TMI occurred within the first few days of the accident. With this constraint there is inadequate time for the development of new equipment. Thus, prompt delivery of appropriate equipment and the availability of trained operators is an essential feature for remote equipment if it is to be used for maximum benefit. Yet the cost of such equipment and operator training would probably be sufficiently large that individual utilities would not consider their purchase during construction or even normal operations simply to have as part of their emergency equipment. A DOE-sponsored activity to develop and provide this type of equipment in the event of a nuclear emergency would be a more feasible option, since the prospects for commercial applications may not be encouraging. If teleoperators meeting the previously described functional requirements had been available to the recovery staff at TMI, collective personnel doses may have been considerably reduced.

Under the current recovery program, teleoperators and remote equipment are being developed to perform specific tasks in some remaining high-radiation areas.

Although these work tasks are different from those described in this paper, the functional requirements are similar in many cases. Thus, the development of teleoperators to aid in TMI-2 recovery may lead to future development of equipment which can be used in the event of nuclear emergencies.

QUESTION AND ANSWER SESSION

Question: After your experience with the clutter of the Auxiliary Building of Unit 2, have you instituted any housekeeping regulations?

Mr. Merchant: Yes. There is now a biweekly housekeeping tour. Unit 1 is currently very clean. Of course, they've had a lot of time to clean up since the accident in Unit 2. But many steps are being taken to maintain the facilities both in the reactor and the auxiliary building. As a matter of fact, a few months ago, they cleaned up a pathway through the Unit 1 reactor building and brought the public in -- hundreds of people toured the reactor building. So Unit 1 is clean right now, and we hope to keep it clean.

Question: How were the initial entries of personnel done and what kind of exposure was involved. Were robots considered for those initial surveys?

Mr. Merchant: There was some thought given to using robots, but in the end personnel were used. Radiation levels inside the reactor building were in the range of 350 to 700 MR per hour, with hot spots in various parts. But general areas were in that range, which is really not bad considering what happened there. Of course nobody went down into the basement. Dose rates increased dramatically as you descended. The problem with using mobile teleoperators was once again the air lock. That precludes the use of an umbilical cord or safety line, and that's still the problem today. We do have fixed cameras, though, in the reactor building. Someone can just go to a coordination center and see a lot of different items in the reactor. The cameras were put in early in the program.

Question: You stated that robotics or teleoperators wouldn't be of great use in the first week. Is that based on what was available at that time, or were there other reasons? I recognize that you've got some very special problems, but if you had units that solved those problems, would they have been useful in the first week?

Mr. Merchant: If we had units on site and people trained to use them, they definitely would have been useful. However, it's very expensive for an individual utility to keep these on site as part of their emergency equipment. If the equipment is at another site, it takes some time for it to be transported and then set up, and more time for people to become familiar with where it has to go and how to operate it. I think it would be difficult to get the equipment on site and ready to go for these types of applications within at least the first week.

Question: We really ought to consider that robots are going to be in the workplace on a day-to-day basis in the next ten years, and we're not going to "go get the robot" who is a thousand miles away and fly him in on an airplane. I don't think you're only going to use robots for emergencies; we can't pay for it on an emergency, one-time use basis.

Comment from Audience: The problem is future plans and future operations. You can plan specialty equipment as you design your plan. But we're in 1985, there are a lot of things that need to be retrofitted, and we're not going to have resident robotics for some time. So the generic responder may be needed in the interim.

Question: In the manufacturing industry, the application of robotics has meant great changes to the factories. Factories where people make things are very different from factories where robots make things. Is there a trend in the power industry to design power stations with possible automatic maintenance for emergency procedures in mind? For example, making doorknobs round instead of square so machines can grab them, or eliminating cables that lie on the floor.

Mr. Merchant: It's hard to tell since all the plants in construction now are fairly old in design. I hope they do make access for teleoperators easier, but I really don't know if they are.

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THE Y-12 CRITICALITY ACCIDENT

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The nuclear accident at Y-12 in June of 1958 taught us a lot about preparing for handling accidents. I'll discuss dosimetry at some length because it has a bearing on the subject of this conference. Because of the nature of the Y-12 accident, the health of the survivors -- and all of those involved did survive -- was of paramount importance from the beginning. Initially, we did not know what the dosages were, to even a crude approximation. It was several days before we had those answers. Until that time, we were reasonably certain that two or three people had lethal doses. As far as we know today, no one has ever survived without heroic medical procedures when their blood count was lower than that of the person who received the highest dose at Y-12.

Figure 1 is a simplified map of the entire Y-12 plant layout. The accident location is indicated by the X near the upper center of the figure. In Fig. 2, we focus on the building in question; you can begin to see that this is a fairly complicated layout, even with only the major items identified. The actual point where the accident occurred is shown as a cross-hatched square near the center of the building. This is what we have referred to over the years as the site of the impromptu barrel reactor.

Moving in even closer, we see in Fig. 3 the actual barrel in which the accident occurred; immediately, it's apparent that this is a complicated spot that has only limited access. The workers themselves could not exit rapidly at the time of the accident. This situation is shown in Fig. 4, which is a reenactment of employee positions at the time of the accident. One employee (A) was quite close to the barrel, while several others (B through E) were at increasingly greater distances. A total of eight people received significant exposures. The tall, slender tanks in the foreground (similar tanks on horizontal racks are nearby, but cannot be seen in the picture) are known as Eversafe containers. Procedurally, there could be no container in this area that was larger in diameter than these, but nonetheless, the barrel was there.

Let's look at the events of the actual accident. The man standing nearest the barrel suddenly became aware of a blue flash in the area of the barrel; another worker also saw the flash. Both said it resembled the flicker of a fluorescent bulb, but with a strong blueish tinge. Everyone immediately evacuated via the paths shown in Fig. 5; while not all these paths appear to be the best routes away from the scene, they did turn out to be the fastest routes and resulted in the lowest exposures.

How did it happen? Investigation revealed that the barrel was used was used to collect drainage from lines above, especially during the regular flushing of these lines. Normally during this flushing, all lines containing enriched uranium were closed off; the line to be drained was then opened and flushed with water. Unfortunately, in this instance a valve in one of the uranium lines had leaked and allowed enriched material to drain into the manifold and, when the manifold valve was opened, the material drained into the barrel. When enough of this material accumulated in the barrel, criticality occurred. Water continued to enter the barrel, and after a few minutes, the system went

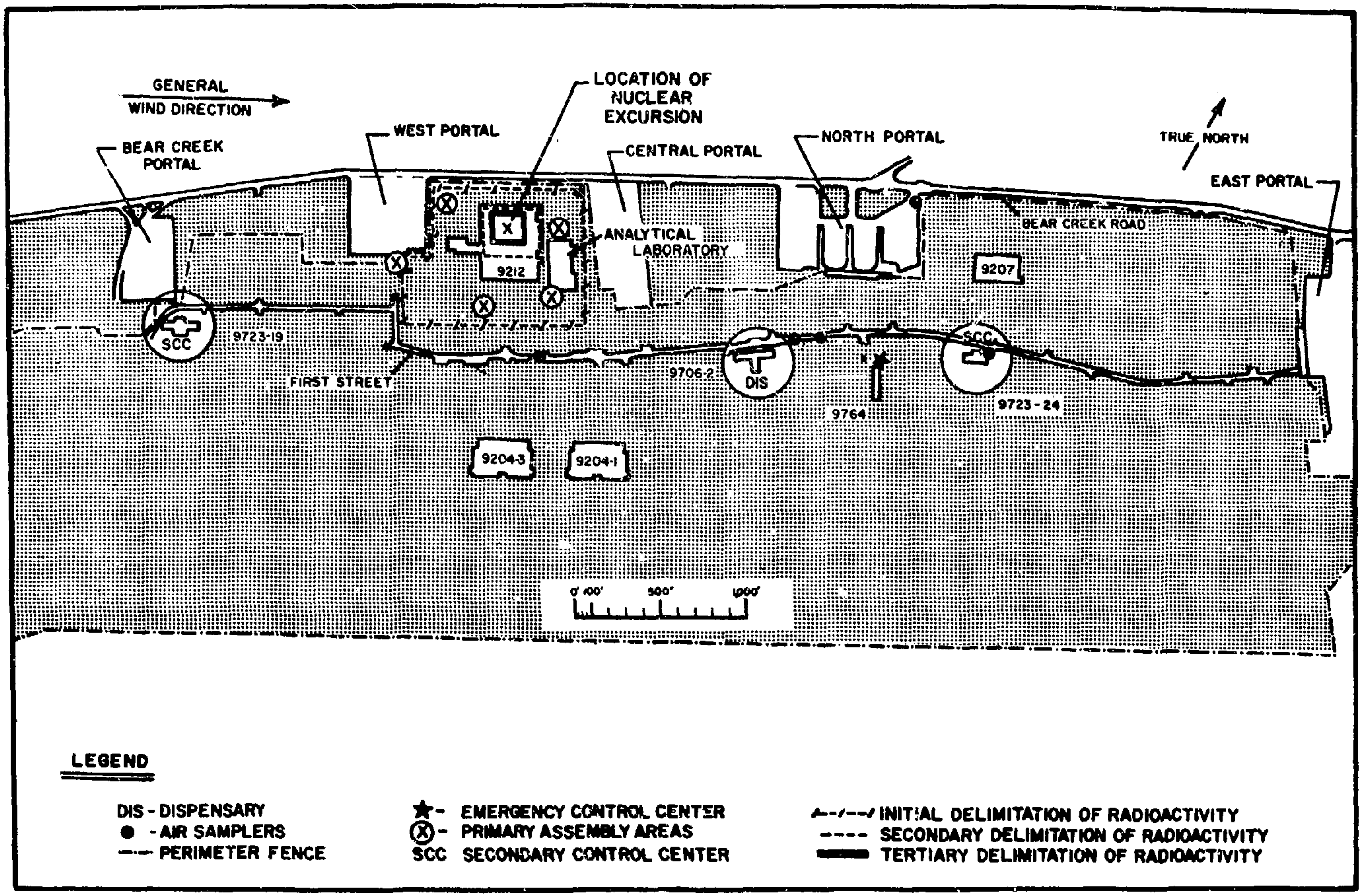

FIGURE 1 Location of Y-12 Buildings Pertinent to Accident

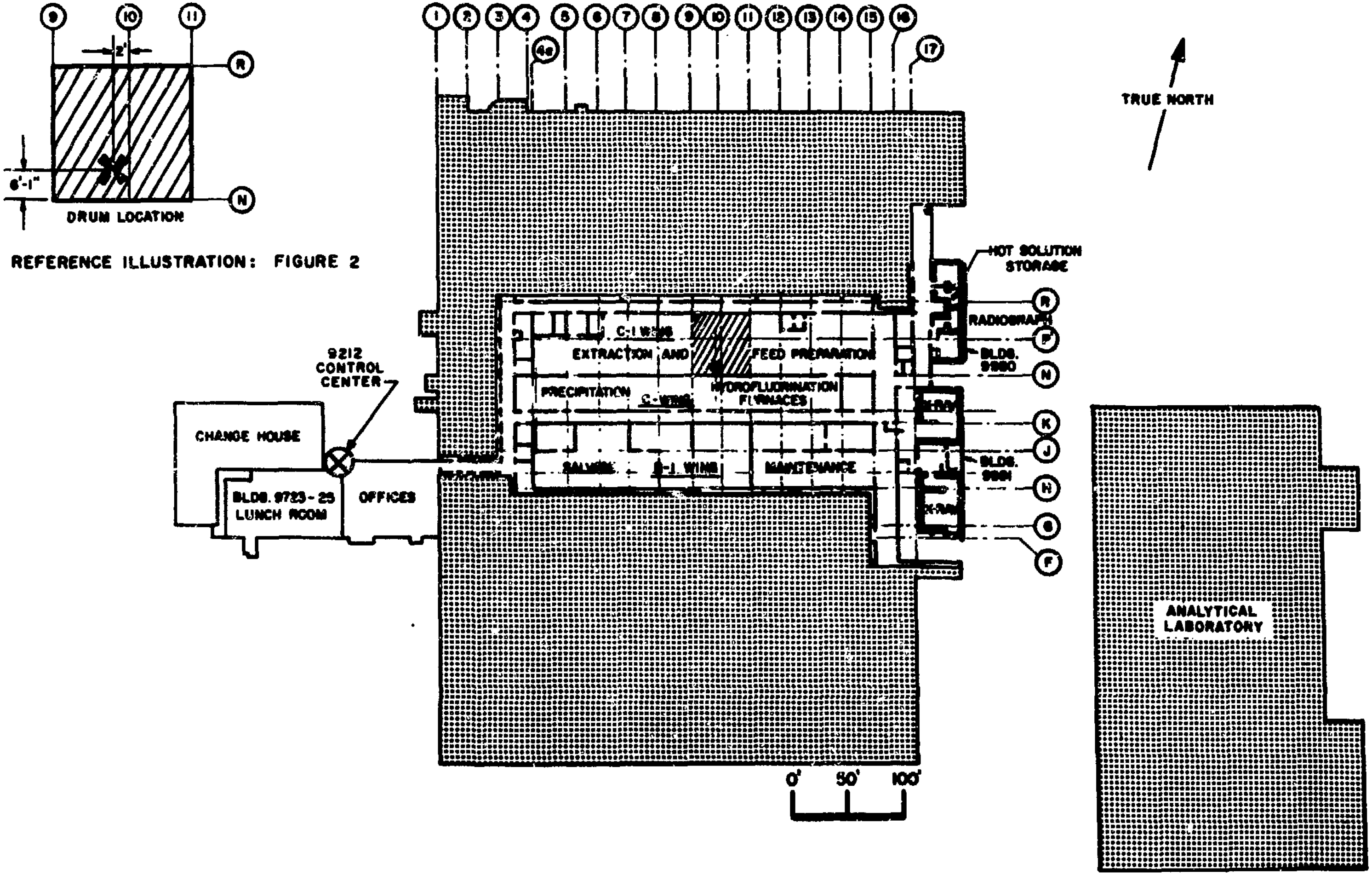

FIGURE 2 Location of Nuclear Explosion

FIGURE 3 Actual 55-Gallon Drum in Which the Accident Occurred

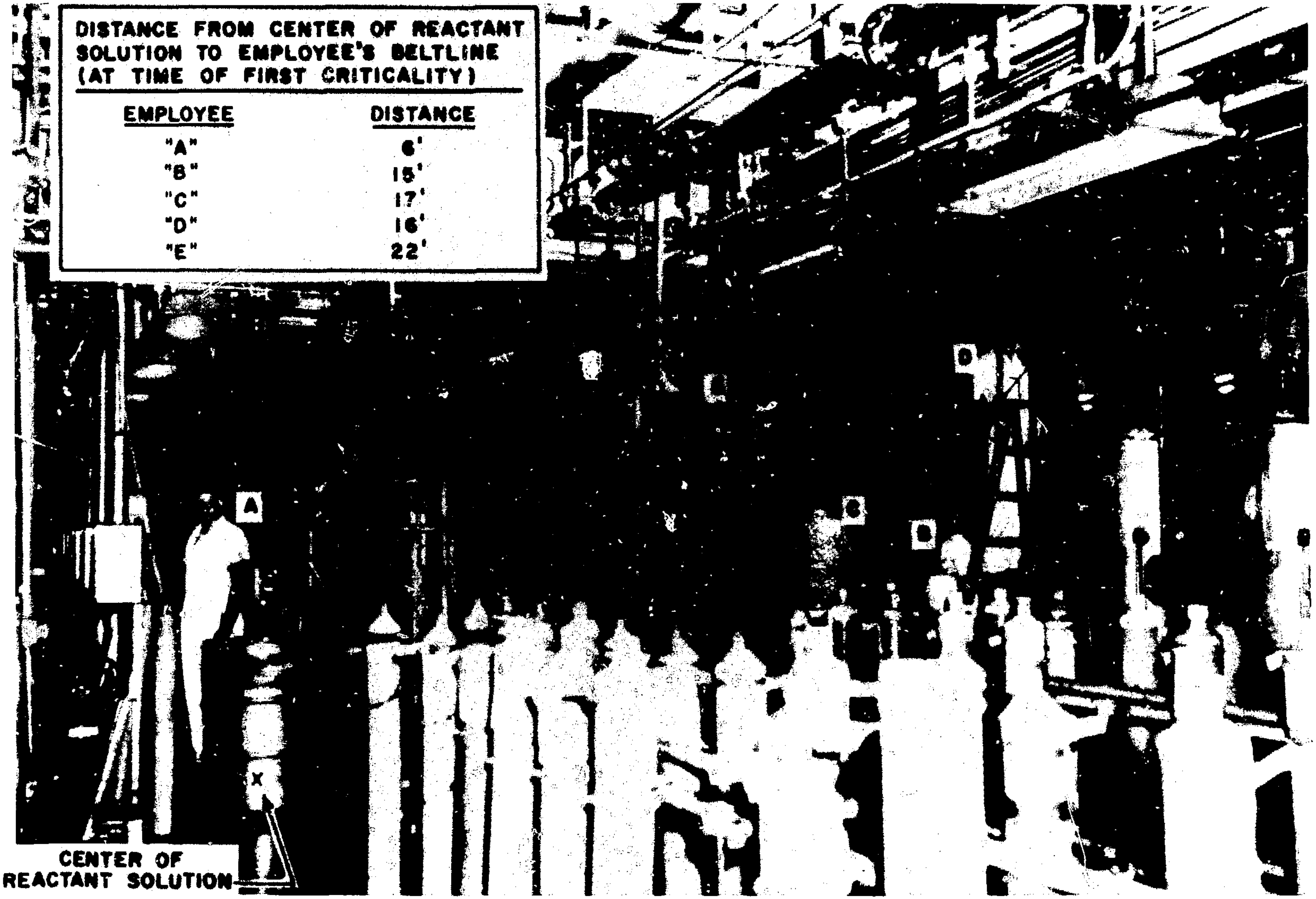

FIGURE 4 Reenactment of Positions of Employee's in Proximity of the Drum at the Time of the Incident

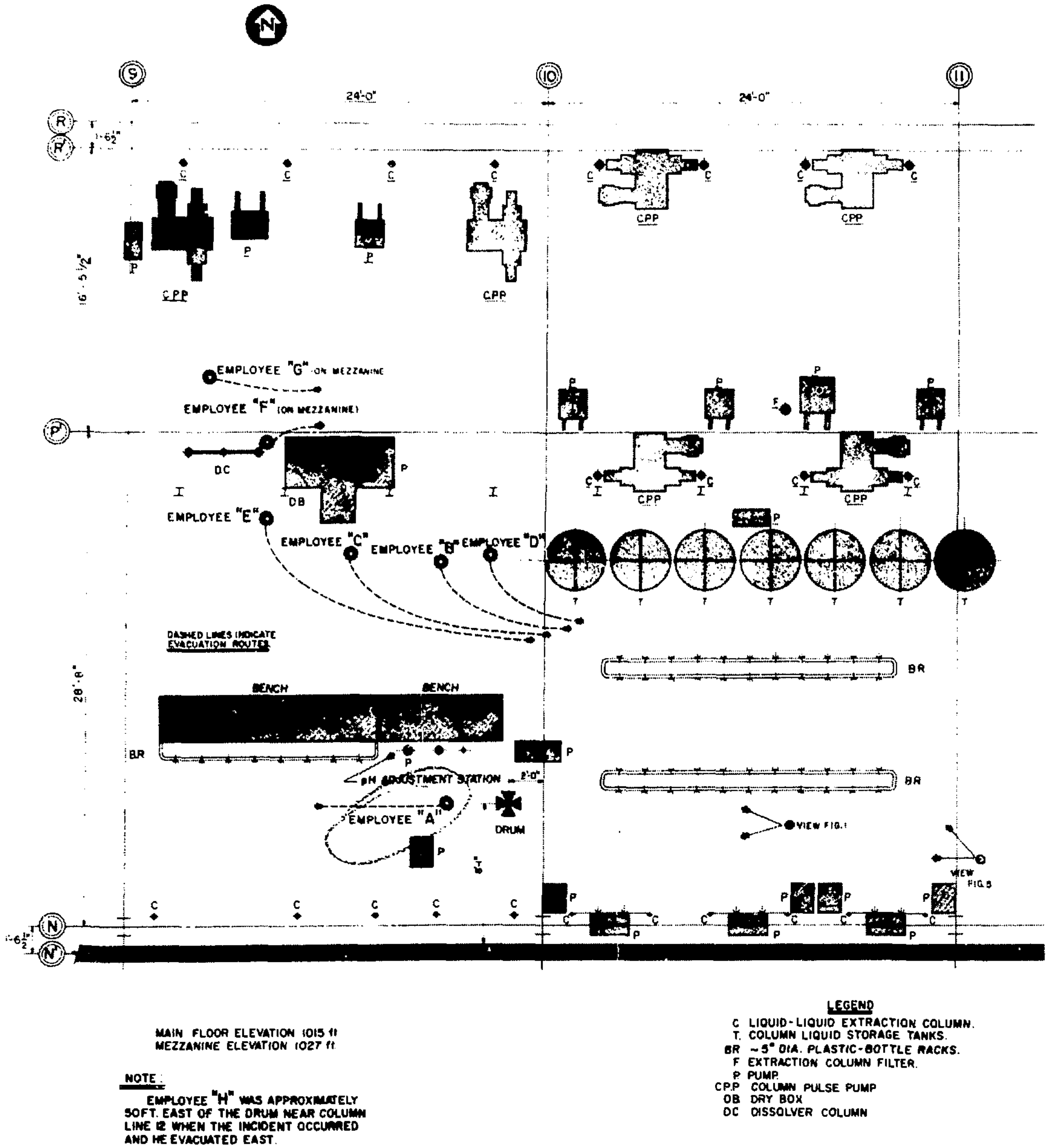

FIGURE 5 Evacuation Paths

subcritical due to the dilution. In the interim, because of thermal expansion and steam bubbles followed by subsidence cooling, two or three more cycles of lower-magnitude criticality occurred; if someone had entered this area during one of these cycles, he could have received a serious exposure.

At this point, it would have been convenient to have a surveillance vehicle that could have entered with dosimeters and other equipment. There being no such vehicle then, people eventually entered the area -- after a few hours -- and saw that the the system was apparently stable. But because they did not know how long it would remain that way, they devised what turned out to be simple robotic equipment. Using a long pole on a dolly rigged with a cross-bar as a fulcrum, they lowered a rolled-up sheet of cadmium into the barrel. To examine and perhaps close the valves, however, was a much more complicated task -- one that would have required much more than just a surveillance machine -- but because the lines finally drained themselves, no further work was actually needed.

After a few days, the system was clearly stable because of the cadmium sheet. The final operation -- removal and draining of the barrel -- would have been carried out easily by a remote device, had one been available. Instead, another dolly was used to remove the barrel to a safe area where its contents were drained into Eversafe containers. By this time, the levels were probably down to about 100 mR or less per hour.

As I noted, we had no idea of the magnitude of the exposures just after the accident. We looked at sodium-24 activation in blood and serum samples, and we also checked activation of sulfur in the air and some similar parameters. What we really needed was a quick way to relate the sodium activation to the radiation dosage, and we did that by putting together a little system that allowed us to measure the activation in the blood of a living system -- in this case, a burro. We irradiated the anesthetized burro and then checked his blood sodium activation against known levels of neutron exposure. We actually duplicated the accident situation in a criticality laboratory within about 24 hours of the accident. As you can see in Table 1, the blood levels of sodium in the burro and in the five workers with the highest exposures were virtually the same. That in the burro told us the sodium activation per unit dose.

TABLE 1 Blood Sodium for Individuals Exposed and for Experimental Burro

Employee	mg/mL Serum
"A"	3.2
"B"	3.2
"C"	3.2
"D"	3.1
"E"	3.2
Experimental Burro	3.1

After measuring neutron-spectrum and gamma ray doses, we then normalized them via the sodium activation in burros, thus obtaining doses. The absorbed doses are shown in Table 2 in the column labeled "First Collision Total Dose." Based on the values here, we were fortunate that the most highly exposed person survived this accident.

TABLE 2 Sodium-24 Activation and Dose Values for Exposed Personnel

Name	Na^{24} (microcuries/cc)	First Collision[b] Neutron Dose (Rad)	First Collision Gamma Dose (Rad)	First Collision Total Dose (Rad)	Estimated RBE Dose (rem)[a]
"A"	5.8×10^{-4}	96	269	365	461
"B"	4.3×10^{-4}	71	199	270	341
"C"	5.4×10^{-4}	89	250	339	428
"D"	5.2×10^{-4}	86	241	327	413
"E"	3.7×10^{-4}	62	174	236	298
"F"	1.1×10^{-4}	18	50.5	68.5	86.5
"G"	1.1×10^{-4}	18	50.5	68.5	86.5
"H	0.36×10^{-4}	6.0	16.8	22.8	28.8
Exptl. Burro	2.9×10^{-4}	48			

[a]With an assumed RBE = 2 for fast neutron dose.

[b]Gold foil measurements indicated that the thermal neutron dose was about 1% of the fast neutron dose and thus can be neglected.

QUESTION AND ANSWER SESSION

Question: How much time was needed for the various operational phases after the accident?

Mr. Auxier: The first two hours were spent in sorting out people and in planning the placement of counters and experiments to follow. The major concern in this sort of accident is in regard to exactly what is happening in there. This is the period in which a surveillance vehicle would have been invaluable. About three hours after the accident, a crew entered the area and, with instruments, determined precisely where the accident occurred. The cadmium sheet was placed in the barrel about six or eight hours after the accident occurred. Finally, the barrel was removed and pumped out after two or three days. The crucial time period, however, was the first few hours, and we were severely limited here.

Question: Would you have sampled the contents of the barrei immediately if you'd had the means to do so?

Mr. Auxier: Yes, if there had been a way to do so easily; that would have very important. We weren't able to get a sample until the following day after the cadmium was in place.

Question: What specifically is being done today with teleoperators to prepare for future accidents such as this? Please comment on the type of work you think will be done in the future to deal with such accidents.

Mr. Auxier: I tend to be rather pessimistic about accidents, assuming that whatever goes wrong will do so in the worst way. Right now, I feel that very little is being done to prepare for future problems such as the Y-12 accident. Obviously, systems such as those being developed to clean up Three Mile Island should be readily adaptable for future accidents elsewhere, but I do not know of any plans to do so. I hope that the recommendations from this meeting will bring about an integrated approach to this problem, because I feel that no single group -- DOE, NRC, the military, etc. -- is doing enough now, in part because of the lack of money. Ideally, all of these groups should work together to develop an integrated system that could at least be applied in the broadest generic sense to a whole range of objectives.

Question: Other than money, what in your opinion are the reasons why so little is being done?

Mr. Auxier: Politically, this is a problem because people tend to become frightened when subjects such as this are addressed. The need to develop equipment to handle these accidents is interpreted as meaning there **will be** accidents in the future, and this is not a good approach to take when attempting to get funding. In my opinion, therefore, if we are eventually able to begin some work, it will be on a different basis than that of preparing for future accidents.

Question: What role can private industry take in promoting the availability and application of technology to solve potential problems?

Mr. Auxier: I'm now in private industry after many years in the DOE laboratory, and I'm surprised at what private industry can do for a given amount of money, relative to what the federal government can do with the same amount. I see a tendency for more and more of this work to be done outside the government. One advantage that we have is the recent application of automated equipment in the automobile industry and in several other areas. Industry can use this experience as a selling point for the development of prototype teleoperators.

Comment from the Audience: There are at least three commercial companies that would be happy to sell you a mobile teleoperator if you had the money. The West German firm of NTG has a mobile unit, with bilateral-force feedback, that sells for $250,000; I have not met anyone in the robotics field, however, who believes that price. Another European company has a vehicle teleoperator system that sells for $800,000. We think that is probably realistic. They have built a prototype, and the machine will likely do what you want it to. There is also HERMAN, built by PAR, which sells for about $1 million. And the work is continuing, mostly in private industry. The problem is that no coordinated effort is being made as far as one can tell.

Question: I'd like to note that, in addition to the three devices just mentioned, we are currently testing a fourth, which will list for under $250,000. This is a rugged surveillance unit that should be very competitive with the other three. Now, my question: is it correct to say that there is no one organization or group that sees itself as the promoter of this technology, that is, no single government agency or nonprofit research institute that anyone knows of? Perhaps we, as a group, should identify an organization whose mission it is to bring everything together for us. This organization could include representatives from industry, government, small businesses, and users.

Mr. Auxier: There are a few champions around, but most of them simply do not have the influence to make real progress. The people at TMI certainly have more motivation than most because they have some real problems to solve. Some others are here in the audience today; I can mention Conrad Chester and Mel Feldman, among others. Around the country are probably several hundred more people. Our best chance is to have an unbiased group provide some funding to bring together all this knowledge. It is clear that if private industry saw a market, they would soon have the devices available. That's how the marketplace works.

Question: I think the market is already there, otherwise we would not be working so hard in this field. We see it emerging and it's going to be a large market; my role is to educate the industry about what we're doing and what is available. Now, regarding your experience with Y-12: given what you know about today's technology, what would you differently today to prepare for such an accident?

Mr. Auxier: As someone pointed out today -- and as I have said for many years -- it is best not to have a machine that is used only for emergencies, because in many cases such machines don't work when they are most needed. Thus, a machine that you can use every day is the proper approach. The need is to have equipment available that is as useful as possible for ordinary duties. Eventually, prices will drop and we could have equipment with specific applications at many sites. This will not happen in the near future; how long it takes will depend on we bring it all together, as we have been discussing today.

USE OF ACCIDENT EXPERIENCE IN DEVELOPING CRITERIA FOR TELEOPERATOR EQUIPMENT*

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ABSTRACT

The 1961 SL-1 reactor accident in Idaho and the Recuplex accident at Hanford are reviewed to identify problems common to emergency situations, lessons learned from accidents, criteria for emergency equipment, and recommendations for using robotics to solve problems during emergencies. Teleoperator equipment could be used to assess the extent of the damage and the condition of the reactor, retrieve dosimeters, evacuate and treat accident victims, clean up debris and decontaminate accident areas.

INTRODUCTION

The first-hand experience of Mr. Vallario after the SL-1 reactor accident is the basis for most of this information. He developed the Lessons Learned, some of which are included here, many years ago. Unfortunately, if you compare these Lessons Learned to the lessons learned at Three Mile Island (TMI), we really didn't learn these lessons very well the first time.

PROBLEMS COMMON TO EMERGENCIES

Initially, we would like to characterize some of the problems in an emergency situation. Usually you experience a breakdown in the management chain, or perhaps we should say that the normally efficient management chain is compromised. There is often a lack of human resources. The pressure of the situation can be enormous on those individuals who are making important decisions; we have all heard about the problems at TMI where too many people in the control room led to tremendous pressures on the emergency team. Finally, humans may respond inappropriately under the stress of emergencies.

You have absolutely no idea how an individual is going to react in an emergency. No matter how many emergency exercises you have, the real situation may

*This paper is based on a lecture given each year by E.J. Vallario at the Harvard School of Public Health, Boston, Massachusetts, and companion discussions led by J.M. Selby, who is on the faculty of that school. Mr. Vallario led the rescue efforts at SL-1 and received the Carnegie Medal of Bravery for his actions.

show flaws in your emergency plan and in the tempered response. Therefore your exercises need to be as realistic as possible. Everything that even borders on an emergency at a facility should be treated as an emergency. That way you may learn how your people respond.

One example is the accident at Recuplex, a U.S. Department of Energy (DOE) facility. Recuplex had a criticality that occurred in a solvent extraction area, where a rather low neutron spike of approximately 10^{17} fissions occurred. Alarms sounded and people reacted properly. They left quickly and fortunately nobody was injured.

Since Recuplex occurred just a few months after the SL-1 accident, everyone there was aware that data from accident dosimeters were very important in estimating dose received by the exposed workers. So an excellently trained senior staff person at Recuplex decided on his own to retrieve the accident dosimeter. Without being directed, he ran into the building and retrieved it, just barely missing a second neutron spike. That spike was much higher, approximately 10^{19} fissions. Exposure at this level could have been fatal. Here is a case where a senior staff person who was highly trained in routine and emergency operations did not react properly in an actual emergency.

We have reviewed several emergencies and found they have common threads. One common thread is they did not occur during the normal day shift. Whether you're talking about severe accidents and emergencies or just some of the normal operational incidents that we expect during routine operations, you will find that most occur on back shift, graveyard, weekends, or holidays. Seldom do accidents occur on day shift when the full management team and senior union people are present. At several reactors, we found that new or less experienced health physics technicians are assigned to the back shift or graveyard. Thus human resources are compromised or perhaps inadequate. There is another common thread to most accidents, including the accident at SL-1. That is, no matter how well you develop your scenarios and emergency planning exercises, you will find that the accident does not fit any scenario that you actually practiced.

SL-1 REACTOR ACCIDENT

SL-1 was an Army reactor, an experimental reactor used for training cadre. The reactor was designed in pieces so that it could be set up in a reasonable period of time and could then generate power.

The idea was that small reactors could be installed at remote locations, for example, in Alaska. The reactor was contained in a right circular cylinder building somewhat like a big metal grain storage building. The SL-1 site was near Idaho Falls, Idaho.

The control room and support building were located adjacent to the reactor building as shown in Figs. 1 and 2. The access to the reactor was through a door at the end of the hall and up a stairway into the operating level of the reactor, which was 20 feet above the ground (Figs. 3 and 4). The operating level was elevated because, to reduce the construction requirements, the reactor vessel had been moved into place and surrounded by gravel for the biological shield.

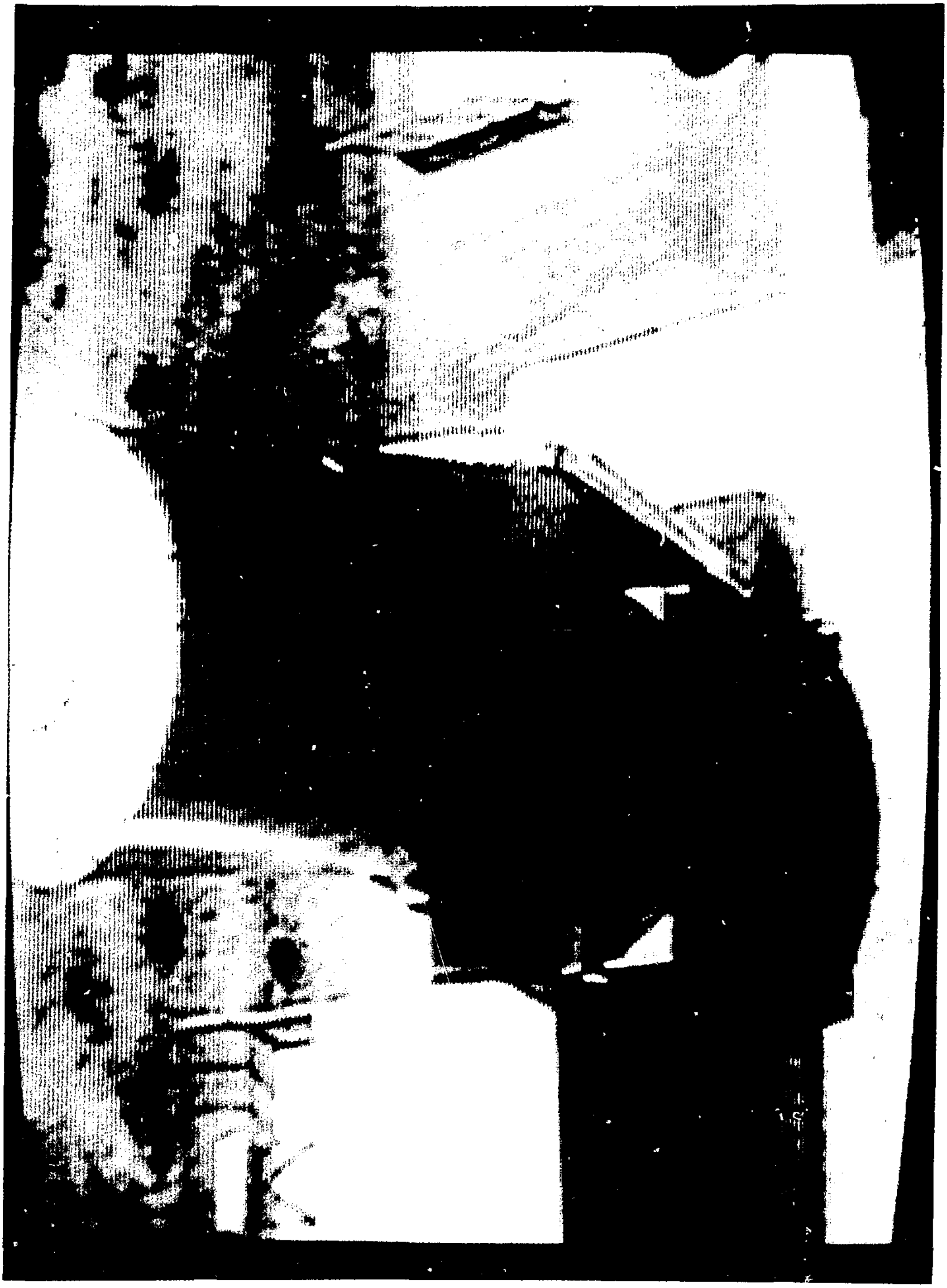


FIGURE 1 SL-1 Reactor

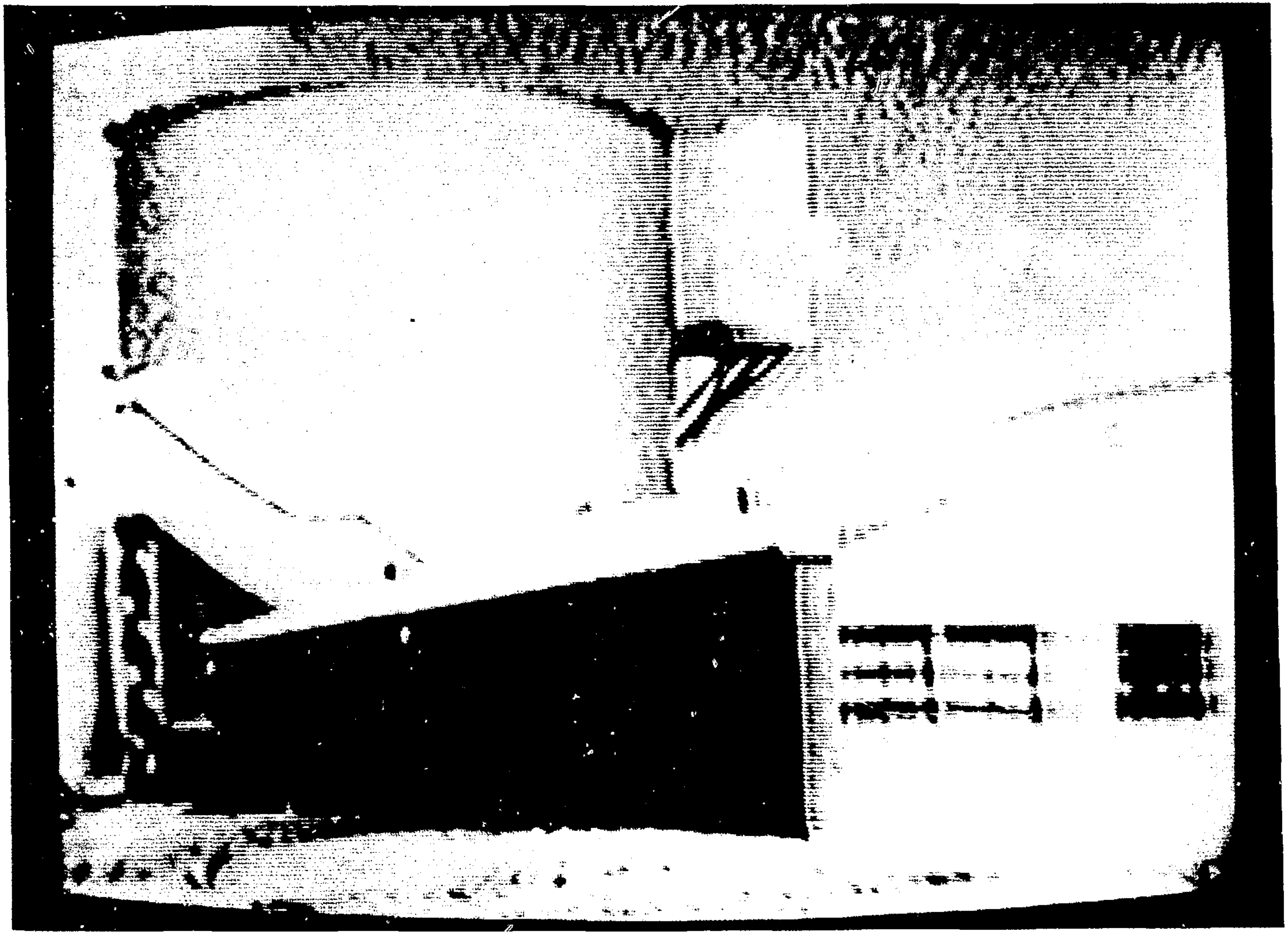


FIGURE 2 SL-1 Reactor and Support Building

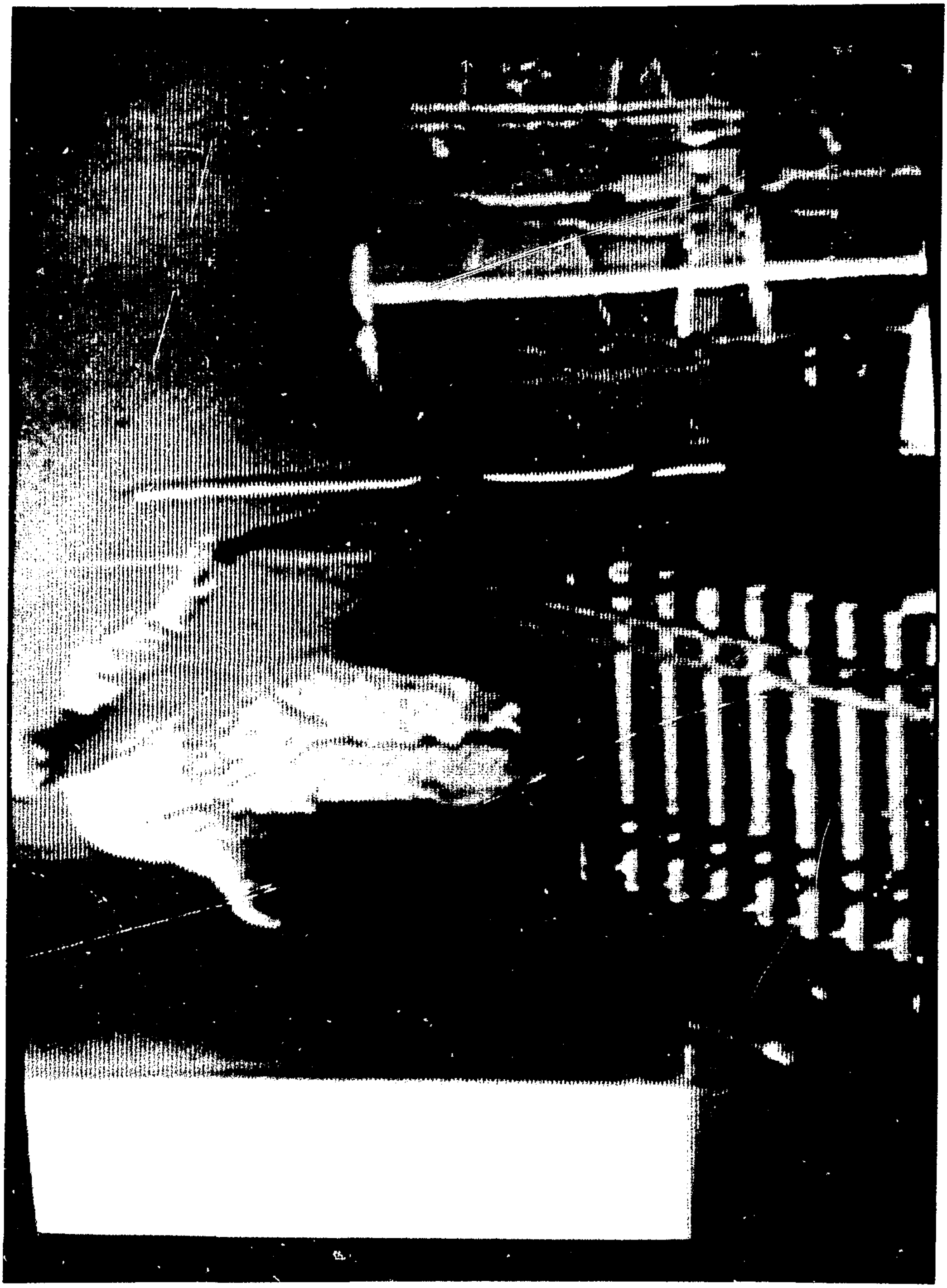


FIGURE 3 Worker Leaving SL-1 Reactor

FIGURE 4 Stairway into SL-1 Reactor

The SL-1 accident occurred on the morning of January 3rd, 1961. Three men were on duty finishing some maintenance work in preparation for starting up the reactor. Alarms went off in the fire station emergency center at Idaho Falls, indicating that an accident had occurred in that building. The first people to arrive were firefighters with radiation-monitoring instruments. They quickly detected high dose rates and had to retreat to a safe distance.

It took approximately one hour for the SL-1 Senior Health Physicist (E.J. Vallario) to establish a team to enter the reactor. Two team members entered the reactor twice, primarily to determine the situation. One of the three men inside the reactor at the time of the accident was still alive; however, he was covered with debris, so the two men could not rescue him. A team returned and evacuated the injured man, but he died on the way to the hospital.

Retrieving the bodies of the other two workers presented some problems that will be discussed later.

Figures 5-8 are copies of the surveys that show some of the dose rates after the accident. The dose rate in the reactor building was more than 1,000 R/hr. The substantial dose rates shown here are characteristic of dose rates experienced at other accidents around the world. These rates suggest that robots and all associated equipment used for accident cleanup must be able to withstand these excessive dose rates.

The SL-1 site was remote and had limited facilities. The existing buildings could not be used for command posts because the dose rates after the accident were too high. Decontamination facilities were brought in. It was winter, and the temperature was minus 20°F. Outdoor command posts, stairs, low temperatures, and high dose rates will make it difficult to use robotics.

One problem at SL-1, common to some similar emergencies, is the need for shielded medical surgery facilities so a highly contaminated person can be medically treated. Without properly shielded facilities, surgeons may receive high radiation exposures while performing life saving efforts or even decontamination.

All three workers in SL-1 at the time of the accident died. However, because the families wanted their bodies buried in a normal cemetery, a shielded facility was necessary so that highly radioactive material that had been embedded in the bodies could be removed before burial.

Since that time, several shielded surgical facilities have been built at DOE sites to deal with problems either at those laboratories or in their region of the country. But these medical facilities are only partially satisfactory because the doctors, using a shadow shield to protect most of their body, must still reach through unshielded glove ports and touch the accident victims. Remote handling techniques, such as those being used by surgeons in some of the knee-joint surgery, etc., should be considered for treating radiation accident victims.

Some of the major problems that were encountered as a result of the SL-1 accident may provide insight to where robotics might be applied. As indicated

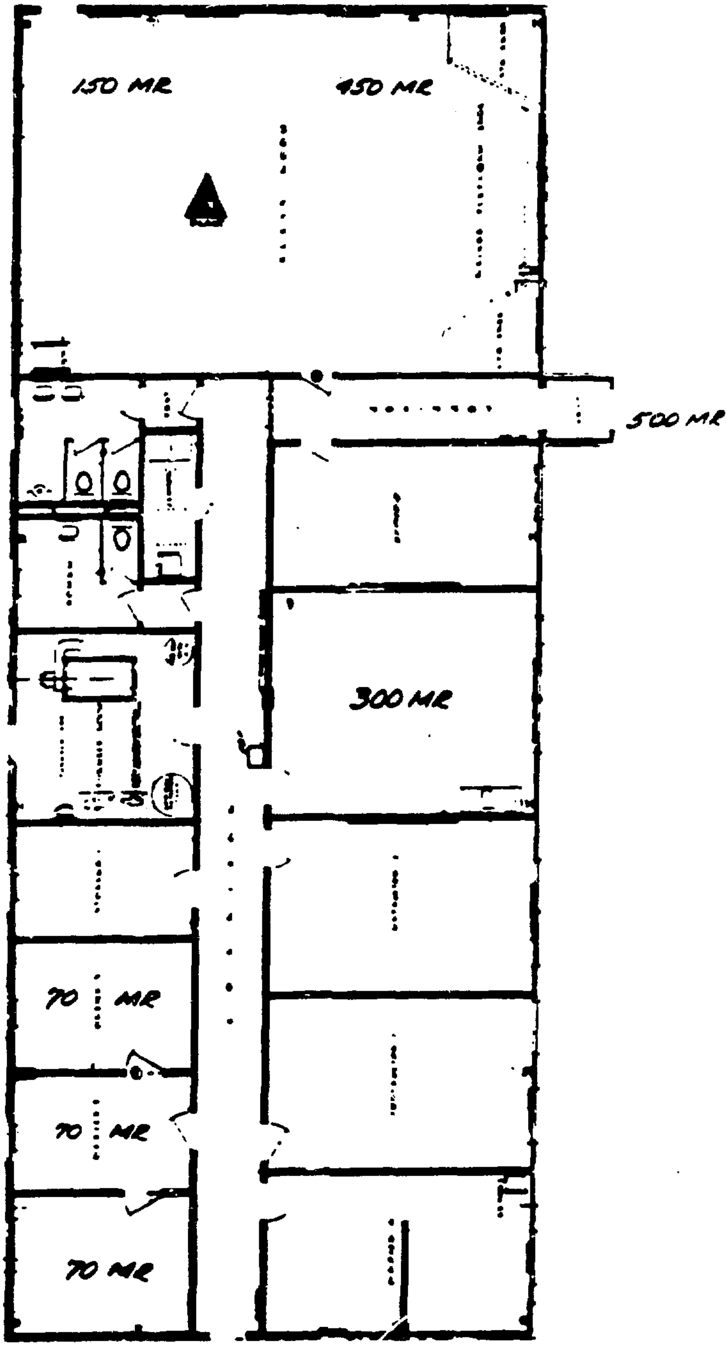
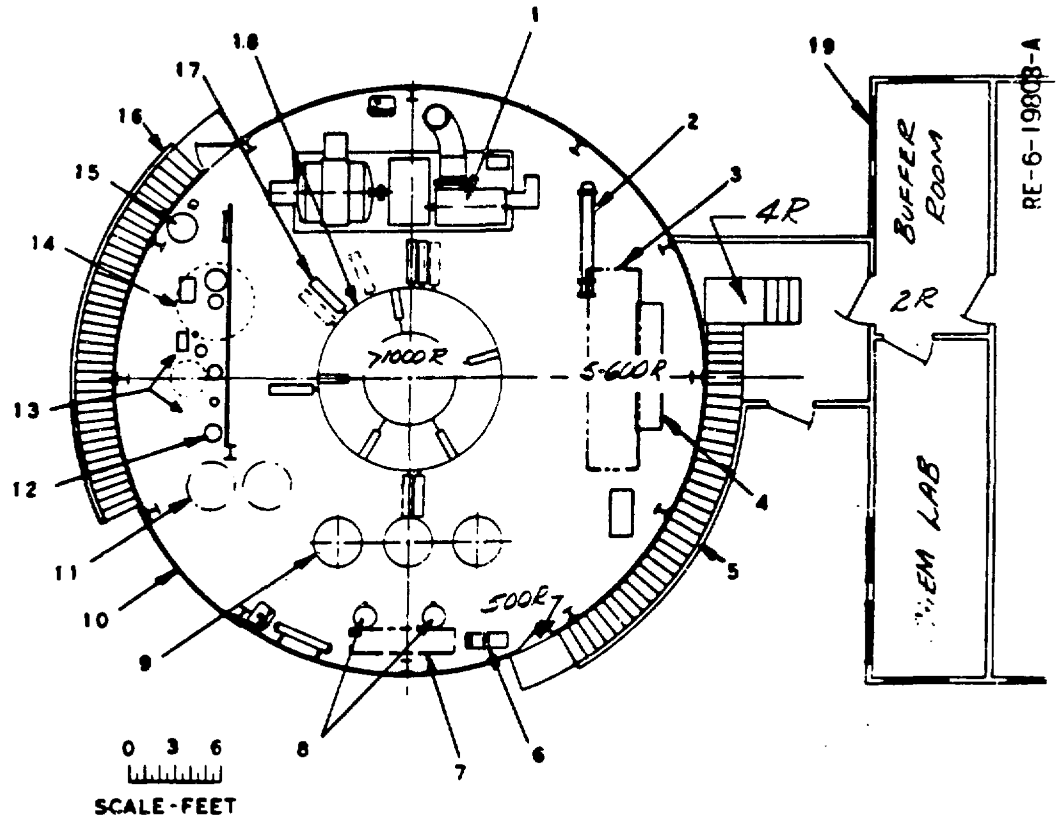


FIGURE 5 Survey of SL-1 Reactor Training Building (1-10-61)



1. TURBINE-GENERATOR
2. HEAT EXCHANGER
3. WATER STORAGE TANK (OVERHEAD)
4. MOTOR CONTROL BOARD
5. COVERED STAIRWAY
6. CONDENSATE CIRCULATING PUMP
7. HOTWELL (OVERHEAD)
8. FEED WATER PUMPS
9. FUEL STORAGE WELLS
10. EQUIPMENT DOORS
11. WASTE STORAGE TANKS
12. FEED WATER LINE FILTER
13. PURIFICATION SYSTEM AREA
14. CONTAMINATED WATER STORAGE TANK
15. BORON STORAGE TANK
16. COVERED EMERGENCY STAIRWAY
17. CONTROL ROD DRIVE MOTORS
18. CONCRETE SHIELD
19. SUPPORT FACILITIES BUILDING (CONTROL ROOM LOCATION)

FIGURE 6 Survey of SL-1 Reactor Operating Floor (1-11-61)

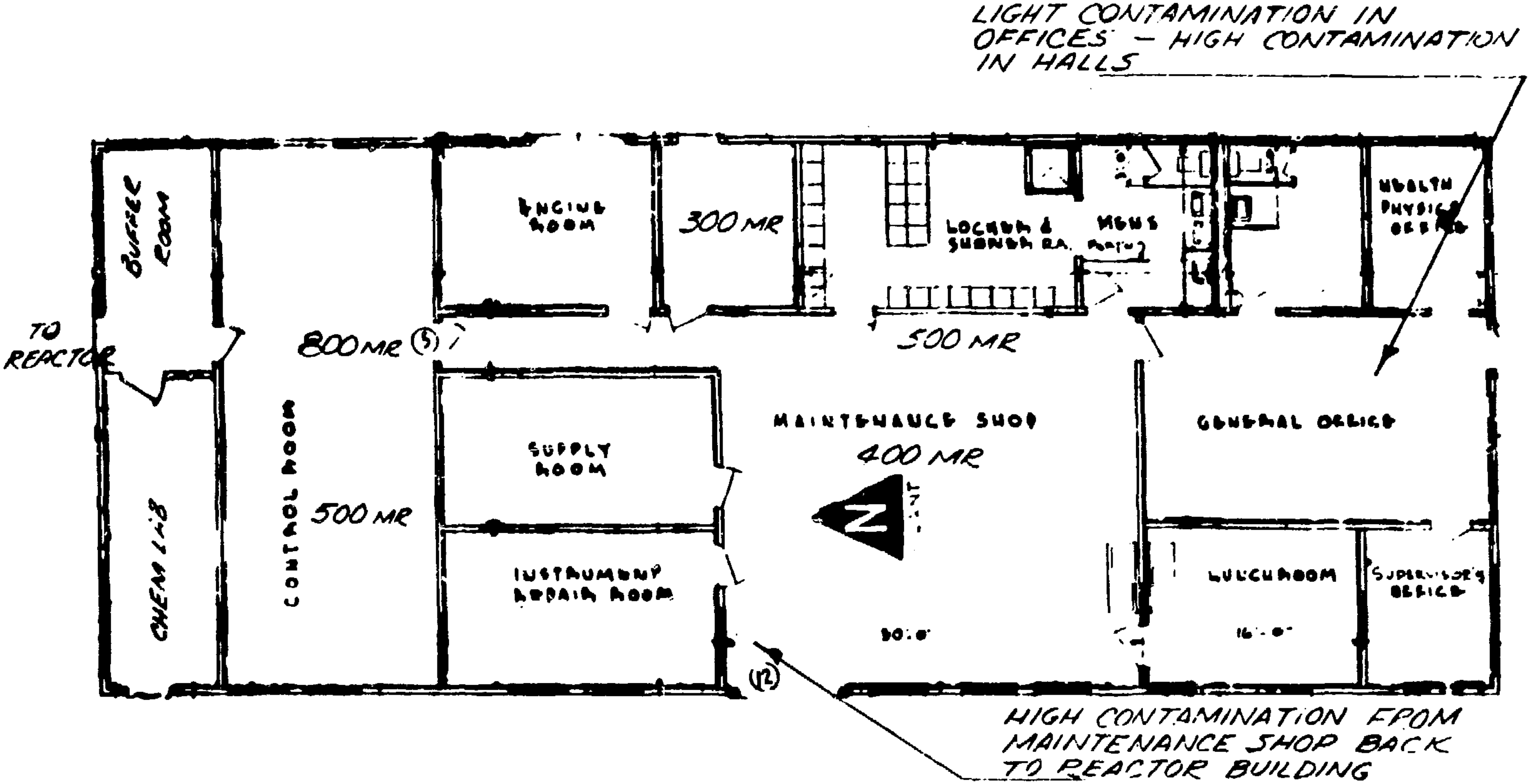


FIGURE 7 Survey of SL-1 Support Building (1-11-61)

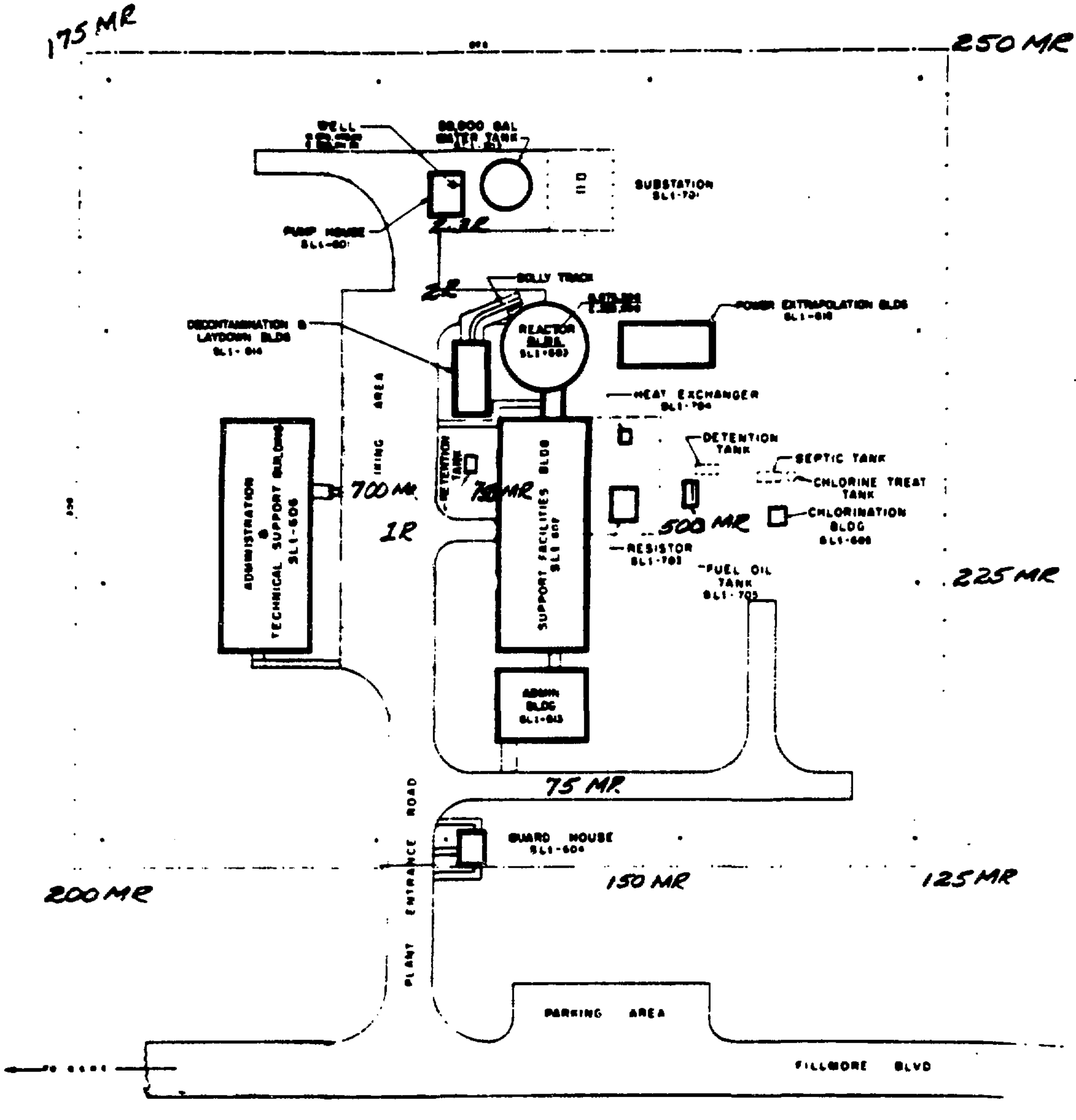


FIGURE 8 Survey of SL-1 Site (1-13-61)

previously, the operating floor was approximately 20 feet above ground. They did not have safety handling equipment, special remote handling systems, remote viewing equipment, remote photographic equipment, camera shields, etc. If there had been remotely operated equipment in place, the cleanup would have been much easier.

As it was, after the survivor was evacuated, extensive planning was necessary to perform later operations with a minimum of exposure to the emergency staff. One of the areas of concern was the condition of the reactor itself. One of the bodies was lodged in the support structure over the reactor some 20 or 30 feet above the reactor.

They didn't want to dislodge it and let it fall onto the reactor, because they were afraid that might start the criticality again.

The first priority then was to remove this body safely. There was an equipment hatch on the side of the metal reactor building. Using a cherry picker, they were able to position a large sling under the body. The body was dislodged, caught in the sling and pulled out.

The problem of determining the condition of the reactor was next. There had been some problems with a sticky control rod, in that it did not move easily. It is postulated that to put the reactor back into service, they needed to move the control rods slightly to attach them to the control mechanisms. It is further postulated that one of the rods momentarily caught, and when it let loose, it moved too far out of the reactor core, which caused a criticality condition. After the accident, they had no idea whether normal controls of the reactor were still in place and whether water was left in the fuel tubes. Many schemes were discussed and/or tried to lower regular or TV cameras into the reactor to take pictures. It took almost a week to determine the reactor condition. Today there still are problems in determining satisfactorily the conditions, such as the water level, of a damaged reactor. Here again is a possible area where robotics could be used.

MAJOR PROBLEMS ENCOUNTERED AT SL-1

The major problems encountered after the SL-1 accident were:

1. high radiation fields;
2. extreme temperatures (-20°F);
3. operating floor 20 feet above ground;
4. lack of safety equipment, such as special remote handling systems, remote viewing equipment, remote photographic equipment, camera shields, monitoring equipment (ranges above 500R), high-intensity lights, antifog breathing equipment with communication system;
5. lack of specialized remote equipment and techniques to determine safety of reactor;
6. need for means to determine core water level;
7. lack of remote retrieval system for the nuclear accident dosimeter;
8. difficulty recovering personnel from the accident area;

9. lack of equipment and procedures for handling highly contaminated victims;

10. control of contamination to minimize movement of hot particles from the reactor building;

11. too much time (1 hr 20 min) before response; and

12. lack of uniform and realistic emergency exposure standards for initial action of the response team.

LESSONS LEARNED

These are some of the Lessons Learned from the SL-1 accident:

1. Several identified problems might be solved through robotics.

   - Specialized remote equipment and techniques could be used to determine the condition of a reactor after an accident.

   - A robot, which could be used for cleanup, could be left in the facility, thus reducing the contamination control problem by reducing the number of workers tracking contamination out of an area during cleanup.

   - A remote retrieval system for the nuclear accident dosimeter could be beneficial.

2. Potential accidents need to be anticipated through safety studies and analyses on a continuing formal basis. The worst case source term estimates should be determined to permit plans for realistic emergency preparedness.

3. Shielded medical facilities are needed for treating accident victims.

4. Serious consideration to emergency preparedness instrumentation is essential and should include number, type, location, ranges, maintenance and testing of instruments. The dose rate at SL-1 was in excess of the top range of the high-range instrument. Since 1961, studies suggest that dose rates in excess of 10^3 R/hr could be traversed by humans safety for life saving purposes. To date, even with the development of ANSI Standard N320 in 1979, we still have no portable instrument that will work properly under adverse accident conditions (temperature, humidity, dose rate, etc.).

CRITERIA FOR EMERGENCY EQUIPMENT

From discussions with others involved in handling accidents, the experiences at SL-1 and Recuplex, and some of the accident analyses that have been performed over the past several years, several characteristics for emergency equipment can be identified.

The equipment needs to be hardened against extreme conditions. Those conditions can be predicted from the nature of a possible accident and where the equipment might be used on the site. Some extreme conditions likely to be encountered are:

- Temperature. Extremes in temperature should be considered. Temperatures at SL-1 were near -10°C; some localities might require capabilities for a temperature range of -20°C to +50°C.

- Humidity. Humidity in many instances may create a problem in the design and operation of equipment. At TMI, intense moisture conditions were experienced within the facility after the accident.

- High dose rates. Most, if not all, nuclear accidents will result in high dose rates. These may adversely affect individual components or the instrument as a whole.

Some of the criteria in ANSI N320 (1979) and Regulatory Guide 1.97 (NRC 1980) may apply to the design parameters necessary for teleoperator emergency equipment. One of the problems in developing emergency equipment is the absence of a good testing capability in this country to demonstrate appropriate equipment operation under the extreme conditions expected. DOE is developing that capability now because such testing capabilities are very expensive and not every manufacturer of an instrument or of an intelligent device can afford to establish the necessary test capabilities.

However if you, as the user, are purchasing $250,000 or $1 million worth of emergency equipment, you want assurance the mechanical, electrical, and electronic components of the equipment will operate under extreme conditions. So that's the first point, equipment must be hardened and must be tested.

Emergency devices must be extremely flexible to cope with a wide variety of accidents. Nuclear facilities vary, as do conditions under which accidents occur. Sometimes accidents occur during a maintenance operation. No matter how well a facility is run, an accident during maintenance can result in debris all over the place, which will affect the environmental conditions within the facility.

At SL-1, extreme condensation was experienced when workers entered the building because of a change from minus 20°F to plus 70°F. Workers' masks fogged up to the point where they had to be removed so the workers could see. Later, when they left the building wearing masks, moisture froze in the canisters making it impossible to breathe.

Another problem we discovered in testing high-range instruments is temperature shock; it's one thing to take an instrument and slowly increase it to a very high temperature or slowly decrease it to a very low temperature. It's something else to go through a sudden increase or decrease in temperature; very few instruments will work properly immediately after such a rapid change. They take some time to equilibrate to where they will again operate properly.

Equipment should be simple to operate. During an emergency, human resources are often compromised. A trained operator may not be available to use the equipment, so it may have to be used by someone who is not familiar with it. That individual will be under pressure; people will be pressing for information, "What are you seeing, what's the dose rate, is there anybody in there?" and all that pressure is going to further compromise the smooth operation of emergency instruments.

Equipment should be inexpensive. We feel that the answer is not to develop special equipment or instruments that will be on the shelf or on the floor waiting for a low-probability accident to occur. The equipment and instruments should be used periodically throughout the year, so that several staff will have an opportunity to be well trained in their use. Therefore, instruments should be inexpensive enough to be used for normal and maintenance operations. The maintenance operation may be the closest to what might be experienced during an emergency. Equipment never will be really inexpensive. To be cost effective therefore, equipment must be easily decontaminated so that it can be reused.

There are certainly other factors that must be considered, but it is hoped the ones presented here will stimulate thinking and discussion.

QUESTION AND ANSWER SESSION

Question: One, the issue of money keeps coming up and obviously is important. I personally don't think it's going to take a tremendous amount of money to get done what needs to be done. We've been developing hardware for four years now. Hardware costs are coming down significantly, so I don't think the equipment has to be that expensive. If anything would cost, it would be the software. I think instead of spending the money on hardware, it could be spent coordinating a number of organizations to work together.

My second comment is relative to testing; I think testing is one of the critical barriers right now for the development of this hardware. If you test it in a real environment, it's a one-time shot. The EPRI Nondestructive Evaluation Center has been doing some work with us for a couple of years now; they have been superb in handling the nondestructive testing. So there are testing facilities available; the EPRI Center and of course the military, which I suspect would be available to evaluate such equipment.

Mr. Selby: DOE has spent close to a million dollars for some very sophisticated testing capabilities. The industry is getting there, but it has not been available until the last two or three years. The EPRI Center has some excellent capabilities, but they are lacking some also. So you may need to utilize several testing centers to accomplish all of the tests.

You mentioned the software and intelligence; that, of course, is one of the real problems. We were talking earlier about how videotapes taken during normal maintenance operations could be extremely useful when sending one of these generic intelligence devices to perform an emergency function. Some of that technology might be very helpful at a reactor; for example, using the eyes that are available to us now, ahead of time, might be particularly important since the lenses of the TV camera may fog during emergency operations. If the layout is committed on videotape, then directions can be fed into the device for entry.

During a presentation at the Harvard School of Public Health a few weeks ago, a speaker described a device that used programmed learning in its memory to get through an area. If the entry pathway was programmed into the device, it could enter repeatedly without having to be directed by an operator.

Mr. Silverman (Automation Technology Corp.): I should mention we are working currently with Drexel University, and we hope to have a device that has some of that capability later this year. It is definitely needed, because of the circumstances that you have described here today.

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CHARACTERIZATION OF RADIOLOGICAL EMERGENCIES

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The purpose of this paper is to identify conditions which should be considered by the designers of mobile teleoperator equipment intended for service in radiological emergencies. We will propose a definition of radiological emergency and a taxonomy of emergencies and mention examples of actual emergencies, some of which will be discussed in much more detail by other papers in this workshop. We will attempt to indicate the range of operating conditions that an equipment designer should consider as well as the type of operations that his machine might be expected to perform.

DEFINITION OF RADIOLOGICAL EMERGENCIES

The following definition of radiological emergency is proposed: "A radiological emergency exists when the actuality or potential exists for life or health (including long-term) -threatening amounts of radiation or radioactive material is in an environment where people can be exposed." A shorter way to phrase this might be that a radiological emergency exists when radiation is someplace it shouldn't be. As will be discussed later, not all radiological emergencies require the services of a mobile teleoperator.

TAXONOMY OF RADIOLOGICAL EMERGENCIES

The following taxonomy or classification of radiological emergencies is proposed:

Criticality or potential criticality

Misplaced gamma source

Alpha active aerosol release (weapon accident)

Beta aerosol release (Kyshtym)

Beta-gamma aerosol release

High-level liquid leak or spill

Radioactive gas (Kr, I-Xe, or Rn) in atmosphere

We have not included accelerator accidents among radiological emergencies although they have been an important producer of radiation injuries in the past. The most acute danger from an accelerator can be eliminated by disconnecting its electric power. Any residual radioactivity in the target can be considered like any other gamma source.

Criticality accidents are an important class which have produced a number of fatalities. Very often they present emergency personnel with the possibility of additional critical excursions after the first one. Because of the potential for very large doses from critical accidents, great caution is needed in approaching a configuration of critical material of unknown reactivity. This is a good task for a remote teleoperator.

Misplaced gamma sources are another important producer of radiation injuries and deaths. The source can be radiographic sources, pieces of radioactive waste from a transport shipment, fragments from a reentering reactor-powered earth satellite, or a variety of other radioactive materials and objects if the source is strong enough (e.g., tens of thousands of R/h). Recovery of the source once it is located may be a task for a mobile teleoperator.

The release of an alpha active radioaerosol usually does not generate circumstances where a mobile teleoperator could be profitably applied. Humans with respiratory filters and possibly protective clothing are usually the most economical method of dealing with such an accident. An exception might be routine operations in a highly contaminated enclosure as for example in a plutonium fabricating facility. The time required to suit up men and then decontaminate them might more than offset the slower operation of a mobile teleoperator in such a facility.

A beta aerosol release and subsequent contamination such as occurred at Kyshtym in the Soviet Union about 1958 is very similar to an alpha aerosol release in terms of emergency operations. Workers can be fairly well protected with respirators and protective clothing. Large pure beta releases are very rare, with the Kyshtym incident being essentially unique.

Aerosol releases and subsequent contamination by gamma emitters or beta gamma emitters such as fission products, provide perhaps the major opportunity for application of mobile teleoperators. If the gamma field is high enough, humans cannot work in such an area. The interior of the containment of Unit 2 of Three Mile Island is possibly the outstanding example of such a circumstance.

A leak or spill of a very high level radioactive liquid could provide circumstances when a mobile teleoperator is safer and more economical to use in cleanup. A leak from a large tank of liquid high-level waste might produce such a circumstance. The consequences of such an event presently exist in the basement of the containment of Unit 2 at TMI.

A sealed volume with a large content of radioactive gas (krypton, iodine-xenon, or radon) may provide an environment where it is advantageous to use a mobile teleoperator. Men would have to be suited up and then decontaminated in order to work in such an area. A machine which can remain in the area may be a more economical method of accomplishing tasks.

SOME EXAMPLES (Bertini, 1980; Chester, 1984)

In the past 40 years, there have been a variety of radiological accidents. The required considerable exposure to emergency personnel for rescue, recovery, and decontamination. Some of the more important of these accidents will be covered by individual speakers later in this workshop. We believe that they are highly illustrative of the conditions which would be faced by the users of a mobile teleoperator in future accidents.

Nuclear Incident at the SL-1 Reactor, January 3, 1961

This accident is the most serious in the United States in terms of fatalities (there were three) and may be first or second in terms of personnel exposure during recovery operations.

In January 3, 1961, a group of three reconnecting control rod drives on the SL-1 reactor inadvertently introduced a critical excursion, probably by manually withdrawing a control rod beyond a safe point, The ensuing steam explosion caused fatal mechanical trauma to all three operators. The critical excursion of over 10^{18} fissions produced a very high radiation field in the operating area at the top of the reactor, about ten thousand R/h immediately over the reactor, and several hundred R/h at the periphery of the operating area. The operating area was filled with a radioaerosol which was a severe respiratory hazard and subsequently contaminated adjoining buildings and some of the surrounding area.

Large radiation exposures were absorbed by rescue personnel in their efforts to recover the bodies of the operators. The bodies themselves were reading several hundred R/h. Subsequent efforts at reconnaissance placing television cameras and finally debris removal in recovery entailed further large exposures of recovery personnel.

Because of the maintenance activities on the reactor and removal of movable shielding from the top of the reactor and the steam explosions the operating area was very cluttered. The operating floor was only 6.3 meters (21 ft) above the outside ground level could be entered only by either a crane-bay door at that level or a covered exterior stairway. Most present tracked-vehicle transporters would not have been able to negotiate the stairway and would have been capable only of limited movement on the operating floor due to clutter and debris.

The SL-1 incident can be taken as the archetype of a severe radiological accident. It entailed very high radiation fields, difficult access, cluttered operating areas, severe contamination (including airborne radioaerosols), and time-urgency of the operation of recovering personnel and determining the state of the reactor.

Three Mile Island

The accident at TMI was the result of a long improbable chain of mechanical failures and operator errors that culminated in heavy damage to the reactor core of Unit

2; flooding the basement of that unit with highly radioactive water; general contamination inside the containment; and contamination inside the auxiliary building. In addition, a deflagration of accumulated hydrogen occurred inside the containment producing a pressure spike of about 1.6 atmospheres (25 psi) which caused some mechanical damage to light structures such as sheet metal ducting. Negligible exposure occurred to operating personnel and the general public in the course of the accident. Recovery operations have involved considerable exposures to personnel but generally within Nuclear Regulatory Commission Guidelines.

Three Mile Island certainly must qualify as the most expensive nuclear accident in history and may, before the cleanup is complete, entail cumulative personnel exposures approaching or exceeding those at the SL-1.

No personnel were in the containment at the time of the accident and there was no requirement for rescue. The time-urgent requirement was for information to determine the status inside the containment. Conditions in the containment shortly after the accident were about 50°C, 100% relative humidity, 3.4 kPa (0.5 psi) negative pressure, air atmosphere, some strontium, cesium, and iodine as airborne aerosols, and large amounts of radioactive krypton and xenon. This produced beta doses from the air of 500-600 R/h. Beta doses from surfaces could be as high as several 1000 R/h and were very often the exposure limiting factor.

Here the requirement was for reconnaissance equipment that was capable of television transmission with lights and sensors which could detect gamma and beta radiation over a wide range of dose rates. Mechanically the ability to climb over airlock thresholds was required, as well as to climb stairs and operate on a floor with some clutter on it. Ease of decontamination is an important requirement in this environment, at least initially. The requirement for a manipulator was relatively small and the ability to open and close airlock doors could have been very helpful. Also desirable was the ability to take smear samples and liquid samples.

As time went on the requirement to decontaminate surfaces became paramount. The principal techniques were high-pressure water jet and strippable coatings.

The Y-12 Criticality Incident

In June, 1958, an inadvertent criticality occurred when an operator was draining a critically safe tank into a 200 liter (55 gal.) drum. The water had been used to leak test other critically safe tanks, and was being drained through one that unexpectedly contained some fully enriched uranyl nitrate solution. When about 58 liters of the solution had been run into the drum, the operators observed a bright blue light flash in the areas as though someone had struck a welding arc. Radiation alarms went off and the operators left the area. The operator standing closest to the tank received something over 400 rem and the other four operators in the area received lesser amounts. The reaction was not as violent as the SL-1 incident. The excursion, which may have lasted as long as 20 minutes, produced something of the order of 10^{17} fissions. Very little of the fission products became airborne and got outside the tank.

The big problem in recovery was the unknown nuclear reactivity of the 200 liter (55 gal.) drum after an unknown amount of additional uranyl nitrate and water had flowed into it. A concern was the possible effect on reactivity of the system due to the neutron reflecting characteristics of the water in a man's body as he approached the tank. The required task was to poison the tank. This was finally accomplished by dropping a scroll of cadmium metal into the tank using a long pole. A remote manipulator would have been quite useful for this job in order to reduce the risk to the person who ultimately carried out the task. Additional capabilities of a teleoperator which would have been useful in this incident were radiation detection (particularly a neutron detector) a television camera to determine the level of liquid in the drum and liquid sample-taking capability.

A Stuck Cesium Source at the Armed Forces Radiological Institute, Bethesda, Maryland, February, 1982

In early 1982, a cesium irradiation source became stuck in the raised position at the Armed Forces Radiological Institute in Bethesda, Maryland. The source was normally kept in a water-filled well. It was raised after a specimen, in this case a printed circuit board, was placed in the chamber for irradiation. The source was much too hot (10,000 R/h) to be approached even by a man moving very rapidly. The original design procedure for dealing with a stuck source was to flood the entire room and then manipulate the source with long-handled tools working from a boat floating above it. Flooding the room would have produced tens of thousands of liters of slightly contaminated water which would have presented a very difficult disposal problem in the Washington, D.C. area, not to mention the adverse publicity in today's political climate. The problem was finally solved by the PaR manipulator HERMAN which was able to successfully enter the area by way of an elevator and cut the cable supporting the source using a specially fabricated tool. A few weeks were involved in the operation while the special tooling was fabricated and the operation was practiced on a mock-up.

The NRX Reactor Accident — Chalk River, Canada, December 12, 1952

The NRX Reactor was a 30-megawatt heavy-water-moderated, light-water-cooled experimental reactor installed at the Canadian Chalk River facility. On December 12, 1952, a combination of operator errors, design errors, and equipment failures resulted in coolant loss followed by an overheated and severely damaged core. Following failure of the integrity of the cooling system and contamination of the cooling water, approximately one million gallons of cooling water containing 10,000 curies of fission products were dumped into the basement of the building.

This produced radiation levels of 10 R/h in the basement with hot spots as high as 200 R/h and 100 mr/h in the control room. Cleanup required 1100 people with an aggregate exposure of 2,000 man rem. The maximum exposure to any one individual was 15 rem.

The NRU Reactor Accident, Chalk River, Canada, May 23, 1958

The NRU is a 200 megawatt thermal research reactor which was installed in the Chalk River facility in Canada. On May 23, 1958, the operators observed reactor trips and high fission product levels in the coolant. One fuel rod suffered moderate damage and one fuel rod was severely damaged, possibly due to a faulty rate of rise control switch. In an attempt to remove the severely damaged fuel rod from the reactor to a transfer flask, the rod became jammed in the flask in such a way that it could not be cooled. The rod caught fire and disintegrated with a large piece falling on the top of the reactor and a larger (3-ft) piece falling in the maintenance pit adjacent to the reactor. The operating crew managed to cover the burning pieces with sand to stop the fire.

Radiation levels were 50,000 R/h in the pit and from 10 to 1000 R/h on the top of the reactor. Subsequently, vertical surfaces in the building were measured as reading 0.5 R/h.

The sand and large pieces of fuel were pulled onto pallets with long-handled rakes and removed and eventually the interior of the building decontaminated. Six hundred to eight hundred men participated in the cleanup. Seven hundred man-rem of total exposure was accumulated. The maximum dose to any one individual was 19 rem.

Reactor Accidents at Lucens, Switzerland, January 21, 1969

The Lucens reactor was a 30 megawatt thermal experimental reactor sited in a rock cavern. It was heavy-water-moderated and carbon dioxide cooled. A breach in the seal of the carbon dioxide cooling system led to overheating of the fuel and melting of a fuel element. Fission products escaped from the cooling loop into the cavern raising the radiation level to a few hundred R/h. This decayed to a few hundred mr/h after 44 hours. After several days, the atmosphere in the cavern was vented through filters to the exterior. No radiation above permissible levels was released to the environment from this accident.

FUTURE TRENDS

Many of the radiological emergencies in the past have resulted in large part from the inexperience of the people and institutions involved. In many cases, the accidents occurred at facilities where the main activity was development of nuclear power. As the technology matures, accidents of this type appear to be becoming less frequent. A good example is criticality accidents. There was a hiatus of almost 20 years in these accidents until the one in Argentina last year. As the technology has matured in the industrialized nations, the need for development and exploratory activities has decreased and with it the likelihood of accidents caused by inexperience.

Commercial nuclear power plants are a likely source of radiological emergencies with the possibility for sizable exposures, both in level of dose rate or the number of people potentially at risk. If reprocessing and waste disposal resume in the United States, they will become potential sources of radiological emergencies.

It is much more likely that those parts of the developing world which are developing nuclear power will have radiological accidents. A major source of concern is the potential for political unrest in these areas and the consequent possibility of military or terrorist attacks on nuclear power reactors. These could result in emergencies involving very high radiation levels and over considerable areas.

OPERATING CONDITIONS

From the accidents just described and others which have occurred, it is possible to specify the range of operating conditions that could be encountered by emergency response and recovery forces in future accidents (these are listed in Table 1).

A high level of gamma radiation is the definitive condition of an accident where a mobile teleoperator can be used to great advantage. Radiation levels up to 1000 R/h have been encountered (SL-1, Bethesda) over small areas in some accidents. High radiation levels are theoretically possible in accidents involving irradiation facilities, and in acts of war against large commercial power reactors. Doses of a few hundred R/h are encountered over larger areas.

TABLE 1 Operating Conditions

Radiation:	Up to 10^4 R/h (SL-1, Bethesda) in small areas; few hundred R/h over larger areas
Contamination:	SL-1, TMI
Possible Criticality:	Y-12, SL-1
Inert Atmosphere:	Rocky Flats Dry Room
Temperature Extremes:	50°C at TMI; -20°C at SL-1
Humidity:	100% at TMI
Cluttered Floor: (or outdoor terrain)	SL-1
Stairs and Airlock Threshold:	SL-1
Closed Airlock Door (umbilical):	TMI
No electricity	
Darkness:	TMI

Radiation accidents frequently involve high levels of contamination. Ease of decontamination is a very important property for any machine intended to serve in radiological emergencies.

Criticality accidents, particularly those involving solutions of fissionable material, always involve the potential for additional critical excursions as the systems cool or mechanical disturbances change the geometry of the fissionable material or reflectors around the critical assembly. A critical excursion can produce several hundred to tens of thousands of roentgens in its vicinity, including a lot of high-energy neutrons which can introduce transient effects in solid-state electronics. Control systems, in addition to being hardened against radiation, should be designed to handle transient radiation effects gracefully.

One application for a mobile teleoperator would be routine maintenance operations in rooms filled with inert atmosphere as in certain types of fabrication and storage facilities for fissionable materials.

Temperature extremes may range from 50°C inside the containment at Three Mile Island to lower than -20°C encountered outside the SL-1 under normal conditions for January in Idaho.

High humidity coupled with high temperature can be expected inside the containment in a variety of accident scenarios involving light water reactors. Poor footing due to mechanical debris scattered on a floor or poor soil conditions outdoors, are very common in emergencies of all sorts. Any mobile system must be able to negotiate debris and difficult terrain.

A related problem is stairs. Most radiological operations are conducted in buildings with more than one story very often with the floor connected by stairways. The mobile system must be able to manage stairs. A related problem is that many airlocks have thresholds which must also be climbed over.

Many radiological operations are conducted inside some type of containment and the principal access through an airlock. In most emergencies an effort would be made to arrange some type of containment for the affected area of contamination. If the containment included an airlock for access, the machine must be capable of traversing the airlock and closing the door behind it. This would preclude the exclusive use of an umbilical cable for power and/or signal. If a machine is to be able to to enter an area and close a metal door behind it, it must have some form of onboard power and some system for getting command and sensor signals in and out of the containment area.

Loss of electric power and darkness have been experienced in radiological accidents and can be expected in the future. While a machine ought to be able to take advantage of electrical power if it exists in the area, it must also be capable of providing for own light and motive power.

REQUIRED OPERATIONS

A mobile teleoperator must be able to gain access to the area, conduct reconnaissance, carry out such operations as necessary to stabilize the system, and possibly begin the recovery. In order to do this it must have the requisite mobility to handle irregular terrain, climb stairs and traverse cluttered areas. To conduct reconnaissance, it must be able as a minimum to transmit television pictures and measure and transmit radiation levels.

A wide variety of tasks may be required to effect stabilization of the accident and begin the recovery operation. These are listed in Table 2 as possible manipulator tasks. These tasks were compiled from conversations with people who have conducted operations in radiological emergencies.

TABLE 2 Stabilization and Recovery Manipulator Tasks

- Open and close airlocks
- Throw switches
- Turn valves, hand wheels and door knobs
- Insert electric plugs
- Break or cut hasps and padlocks
- Pick up objects off the floor or from elevated surfaces
- Pick up samples
- Take surface smears
- Take liquid samples
- Stack lead bricks (26 lb)
- Cut and seal pipes
- Open junction boxes
- Operate a screwdriver and socket wrench
- Operate an abrasive saw
- Pry with a pry bar
- Pick up floor plates

Rescue

Rescue capability in a mobile teleoperator is likely to be of little value in a radiological emergency. Getting a teleoperator into operation would be a task taking from hours, if the machine is available locally, to days if the machine has to be brought in from another facility. Human response in an emergency is likely to take several minutes to an hour. If any casualties are savable, the radiation levels cannot be too high. If the dose to the casualties is to be under 500 R, the dose to human rescuers will be tolerable. Fast-moving volunteers can extricate casualties an order of magnitude more quickly than any machine, reducing the dose to the casualties by a corresponding amount.

However, the recovery of bodies is likely to be a high priority task as it was at the SL-1 incident.

CONCLUSIONS

We have attempted to characterize some of the conditions which might be encountered by a mobile teleoperator intended for service in radiological emergencies. These conditions are based on experience with actual emergencies over the past 40 years. The most severe circumstances have been very high radiation fields and difficulty of access to the area of the emergency, coupled with complete ignorance of the conditions existing in the emergency area. The fundamental requirement for the machines are mobility in difficult terrain, tolerance for radiation, tolerance for up to the 10^6 R of gamma radiation, and the ability to communicate to the emergency personnel the conditions existing in the emergency area. Only then can the tasks of mobile teleoperation begin.

QUESTION AND ANSWER SESSION

Question: I disagree with your last point that fast-moving volunteers can extricate casualties faster than any machine and thus reduce their dose by an order of magnitude or more. If the casualty is directly in line with the radioactive source, then that statement is correct. But in many instances the area may be cluttered and the casualty may be in the shadow of the source. People going in to rescue a casualty may very well have to pass through a radiation field of 1,000 to 10,000 R per hour.

Mr. Chester: You may be right, but I think that would be a relatively unusual circumstance. Looking back at the SL-1 incident, I think the recovery of bodies will be a very high priority task that a machine would be very useful for, at least where time is not a critical concern. Accidents in the future might be different -- one of the things that struck me is how many of the really severe accidents occurred quite some time ago, when we were first developing nuclear power.

Comment from the audience: I think the most likely threat we face is from terrorists who either get or pretend to have nuclear devices or toxic substances.

Mr. Chester: Yes, if terrorists succeed in acquiring nuclear material they would certainly use it as a threat. It's spectacular and it goes bang and it gets a lot of television publicity. Given the publicity that Three Mile Island got, I would not be surprised to see terrorists take over a reactor and attempt to hold it hostage.

Question: Would you comment on the Rocky Flats plutonium fire?

Mr. Chester: It was a very expensive accident, but it was not one where I thought a mobile teleoperator would have been particularly helpful.

Question: In a fire at a nuclear installation, would there be any interaction between radiological safety people and fire-fighters? Would they be able to use teleoperators for fire-fighting?

Mr. Chester: Fire fighting has to be done very quickly, and mobile teleoperators with our present and foreseeable technology are relatively slow. When you have a fire in a plutonium facility, your principal problem is inhalation of plutonium, and you can adequately protect humans with respirators and protective clothing. Of course, there is also the possibility of a critical configuration, and sending men in there to even approach the assemblies is dangerous, But again, if there's a fire, you don't have time to fool around with a teleoperator.

Question: Could you comment on the operational phases that we might encounter in terms of time -- immediate responses versus long-term responses. We identified four general phases, and I'd be interested to see if the group felt that was a valid characterization. The initial operational phase would include a lot of reconnaissance tasks and not so much of the mechanical tasks you discussed. The basic purpose of this phase would be gathering information and data. Subsequently -- these phases would all overlap, of course -- the second phase would be a review and stabilization of the accident. For example, you might want a machine that could close a valve or perhaps partially shield a source. Phase three is the preparation for a long-term recovery. For example, you might remove clutter from the area, open doors, or gain access to a certain box. The final operational phase is the actual recovery and repair of the facility. The initial reconnaissance phase may take only hours or days, whereas the final recovery phase could obviously extend into years.

Chester: Reconnaissance is the first thing that has to be done. You don't need a teleoperator for reconnaissance. I think there's a consensus growing in the nuclear energy community that reconnaissance at reactors should be handled by installing remote TV cameras or cameras on tracks that can get in and out. But you might want to develop a different machine for reconnaissance, something with just a TV camera and a light on it. You would like to have high mobility, of course, but you don't need to do any manipulating in this step. One other thing you need on your machine is a radiation detector, because finding out what the radiation levels are is a critical and difficult problem.

Comment from the audience: These problems all occur after the accident and have nothing to do with the accident itself. The remote devices we're talking about today are probably of no use in controlling the accident, which would hopefully take place in the first 20 minutes or so. You don't have time to get them in place. You've got to rely instead on good in-place systems like the TV cameras and high dose rate instruments.

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THE TMI-2 REMOTE TECHNOLOGY PROGRAM

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SUMMARY

The TMI-2 Remote Equipment Program provides a unique opportunity to observe and participate in the development of valuable tools for responding to severe radiological situations.

Since the accident at Three Mile Island Unit 2 (TMI-2), an aggressive approach has been pursued in developing the tools needed for the recovery of the plant. The plant's owner, General Public Utilities (GPU) Nuclear Corporation, in conjunction with the Electric Power Research Institute (EPRI), Carnegie-Mellon University (CMU), and the Commonwealth of Pennsylvania has embarked on a systematic program to develop remote equipment. After some initial experiences, the program expanded rapidly to develop conceptual and then physical equipment. In the course of developing the program, an experienced technical team has been assembled.

The remote reconnaissance vehicles (RRVs) and the remote working vehicle (RWV) span the requirements of the recovery program from the ability to perform radiological and video surveys to heavy-duty decontamination and demolition work. The practical experience gained during the first mission into the reactor building basement has already been fed into the program, and has resulted in further improvements in equipment and technique and better definition of the recovery tasks to be performed.

The Remote Equipment Program at TMI-2 is pragmatic. The requirements of the program are constantly being refined in the light of experience and there are many unique opportunities for development. Outside participation in this program has proven beneficial to the nuclear industry and further participation is invited. The lessons to be learned involve all phases of equipment design and use and can provide a rapid, inexpensive, and reliable means of radiological emergency response.

INTRODUCTION

The TMI-2 Remote Technology Program has been developed for the inspection and recovery of contaminated areas at Three Mile Island Unit 2. The participants in the program are General Public Utilities Nuclear Corporation, the Electric Power Research Institute, Carnegie-Mellon University, and the Commonwealth of Pennsylvania.

GPU Nuclear, EPRI, and CMU have objectives that, although not the same, are complementary. The GPU Nuclear objectives include performing necessary TMI-2 inspection and cleanup work without suffering adverse personnel radiation exposure in high-radiation zones. The fundamental EPRI objective is to demonstrate the practical utility of a remote system and to transfer the technology learned at TMI-2 to the electric power industry. The CMU objective is to further the state of knowledge in robotic and remote technology.

In line with these objectives, the program objective is to design and fabricate the basic equipment, and then perform decontamination tasks in the highly contaminated reactor building basement (El. 282' 6"). As GPU Nuclear uses the first-generation equipment, improvements and future needs are communicated to EPRI and CMU for second-generation expansion.

Currently, two types of remote vehicles have been identified for this program: remote reconnaissance vehicles Nos. 1 and 2 (RRV-1 and RRV-2), and remote working vehicle No. 1 (RWV-1). RRV-1 was successfully deployed in the reactor building basement in November 1984, RRV-2 will support core boring in the basement and the removal of sludge samples during the summer of 1985, and RWV-1 should be ready to perform substantial cleanup tasks in early 1986.

Available commercial technology exists to fabricate the vehicles. The most challenging technical task is the development and integration of available equipment into functioning machines that can meet the mission criteria and functional requirements. Earlier experience with robotics in 1982 provided GPU Nuclear with valuable lessons in preparing functional criteria for this program. The resulting experience in developing and operating these vehicles has provided a valuable resource to the TMI-2 cleanup and, correspondingly, the nuclear industry.

REMOTE RECONNAISSANCE VEHICLES

RRV General System Description

The hardware for both RRVs is essentially the same. They differ only in the equipment they carry to perform specialized tasks. The RRV, also known as Rover, is a tethered electric remote vehicle that carries its own umbilical and umbilical management system (Fig. 1). Three cameras perform visual surveillance and monitor on-board functions; a lighting system provides illumination for the video system. All RRV power and control signals are transmitted to the vehicle from the control console through the umbilical cable. A lift cage is supplied to deploy and retrieve the RRV and as a mount for on-board equipment such as the electrical junction box and the TV cameras and lights. An unused area is available on the front of the RRV so that additional data acquisition equipment such as radiation scanners or other small equipment core boring units can be added.

The RRV was designed to deal with a wide range of conditions in the basement, including a floor covered with water and some sludge deposits. An assortment of construction equipment and obstructions are also known to be present in the basement. Because of the variety of possible debris, the RRV was designed to operate in several inches of water and have high climbing traction. The vehicle can also maneuver in the walkways of the basement. The rigid frame skid-steer six-wheel drive transporter was chosen because of its stability, traction, maneuverability, and ease of decontamination. Tracked locomotion was rejected, despite its superior climbing capabilities, because of the problems associated with track derailment and with decontaminating the track drive systems.

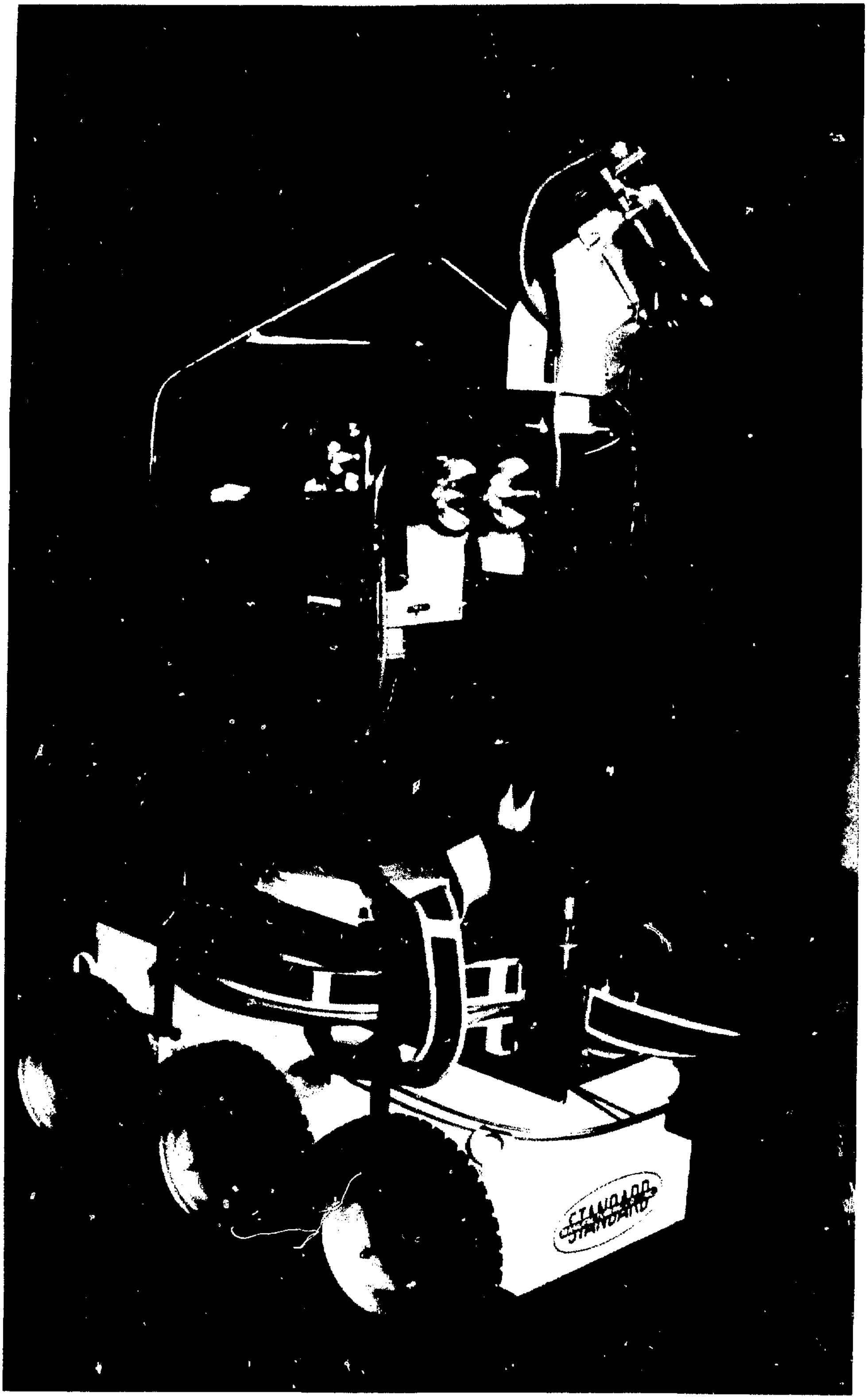

FIGURE 1 RRV Back View

The RRV base is capable of supporting several hundred pounds of payload, climbing 35° inclines, traversing obstacles, and pushing or pulling heavy objects. Additionally, the fully configured RRV-1 is stable, with over 800 of its 1090 lb within 24 in. of the floor. The base is capable of very precise speed and maneuvering control and is capable of turning about its center.

A hard-wired umbilical system was selected to provide control and power for the RRV and its subsystems. Radio control was rejected for the first vehicle because of the questions of signal interference and reliability in the enclosed, heavily shielded environment that exists in the TMI-2 basement, and because a wireless vehicle would require on-board batteries and some type of off-board battery recharging requirement. Simple hard-wire control through the umbilical is used for the drive motors, capstan motor, and lights, thus eliminating the need for on-board electronics. Camera system controls are multiplexed over the coaxial cables that carry video signals from the RRV-1 to the control console.

Power and control signals are transmitted from the command console to the RRV via a multiconductor ribbon cable. To avoid the problems that occur when a mobile vehicle drags its umbilical, an on-board umbilical management system was used. Because of the problems involved with standard drum cable reels (high center of gravity, large diameter reel and cable, and the requirement for slip rings), a unique reel was invented. The reel is a flat, large-diameter disc that rotates about a vertical axis, and uses a counter-winding technique for the umbilical cable at its core to compensate for reel motion, thus eliminating the need for slip rings. By eliminating the slip ring, signal transmission reliability was increased, especially for the video signals that are sent via coaxial cable. Because the reel is flat and rests directly atop the transporter, the center of gravity of the vehicle remains low. The cable is payed out and reeled in by activating a motorized capstan and pinch roller assembly mounted on the vehicle behind the reel. The cable is kept taut on the reel by a spring motor mounted above it. The spring motor prevents the cable from loosening on the reel, and rewinds the cable tightly onto the reel. The cable exits the center of the reel and is connected to an on-board junction box that houses the camera system receivers and transformers and is used for power and signal distribution to the drive motors and subsystems of the RRV.

The main camera system consists of two low-light-level cameras and lighting mounted on a single pan-and-tilt mechanism, which is centrally located. The use of different types of cameras reduces the chance of simultaneous failures. Zoom lenses are used on both cameras to enable wide-angle views for navigation and close-up views for inspection.

A third camera with a fixed-focal-length wide-angle lens mounted high and to the rear is primarily used to monitor umbilical cable operations to prevent damaging the cable. The rear camera is mounted on a pan-and-tilt, thus enabling it to monitor the lift hook during deployment and retrieval activities. Both the main and rear camera systems on the RRV have pan-and-tilt capabilities to provide vision backup. If one of the vision systems fails, the other system is capable of viewing the umbilical for exit navigation.

A lift cage provides protection for certain on-board systems during remote operations, and provides a means to support the subsystems and hoist the vehicle.

The decontamination considerations incorporated into the RRV design greatly aid in the recovery and reusability of the RRV equipment. Permitting decontamination of the majority of the RRV effectively increases vehicle life and reduces costs during its use. To enhance decontamination of the vehicle, the umbilical reel and capstan assembly, camera enclosures, junction box, and lift cage are made of highly polished stainless steel. The vehicle base, junction box, and camera enclosures are sealed to prevent internal components from becoming contaminated or damaged by the high-pressure water spray used for decontamination.

Although not made of stainless steel, the base is painted with an epoxy paint that is easily washable and allows the application of strippable coatings.

The console used to monitor and control the RRV is located in a radiation-free area. Operation of the vehicle requires two operators: one to drive the vehicle and perform inspections, and one to operate the umbilical management system. The drive and capstan motors are controlled using forward/off/reverse toggle switches and speed adjustment rheostats. There is a safety interlock between the drive system and umbilical management system such that the umbilical operator can stop the vehicle if the umbilical is endangered during a mission. Individual television monitors are used for each of the RRV cameras. The pan-and-tilt mechanisms are also operated from the control console.

The modular design of the vehicle and its subsystems enhances maintenance and decontamination work on the vehicle. Each major subsystem can be removed from the vehicle as a unit and can itself be disassembled in a modular fashion. This concept proved very useful during initial testing, debugging, and maintenance practice sessions.

RRV-1

Preparations. A set of RRV-1 functional specifications were developed and published in July 1983. Standard Manufacturing Company (SMCO) of Texas fabricated the transporter at the end of 1983, with some variations on the commercially available vehicle as prescribed by CMU. During this base vehicle production period, CMU detailed and fabricated the control console, umbilical management subsystem, junction box, camera enclosures, and lift cage. The vehicle was delivered to CMU in mid-January 1984, when system integration and testing were performed. RRV-1 was delivered to TMI-2 in February, 1984. GPU Nuclear then used the equipment to train the operators and make modifications to improve its performance and increase its reliability.

Two training programs were pursued in parallel: one program was directed at training operating personnel with the RRV-1 and the other was directed at maintenance and troubleshooting training for the RRV-1 system.

The training program was divided into sessions that addressed different operational aspects of the RRV-1. Two operators are required per team -- one for maneuvering the RRV-1 and the other for umbilical management. The operator sessions addressed: (1) equipment familiarization, (2) turning corners, (3) movement over obstacles, (4) movement under obstructions, (5) identification of dimensions of objects, and (6) area mapping. The maintenance training program involved principles of system operation, troubleshooting/disassembly/repairs, and mockup maintenance training.

An obstacle course was constructed for specific maneuvers. In addition, the video and radiation survey equipment was tested to ensure practical use in the adverse conditions known to exist in the basement. A leak test was also performed to ensure that RRV-1 could function in the anticipated 3 to 10 in. of basement sludge and water.

As a result of the testing and training, modifications were made to: improve reliability and the ease of replacing the motors, improve the defense against leakage, and ease decontamination of the RRV-1. In addition, steps were taken to facilitate removal of the lift cage, protect equipment, and ease hooking the hoist to the RRV-1. The umbilical management system required further refinement to ensure control of the umbilical cable, and the camera system was also refined. Finally, to ensure optimum operator interface, adjustments were made to the control console. The extensive on-site pragmatic testing increased the confidence of the operators and produced a vehicle that could function under real working conditions.

Entry Experience. RRV-1 was lowered from El. 305' into the reactor building basement in November 1984 on its first mission, which entailed two entries. The primary goal of the first mission was data acquisition and equipment proof-of-principle testing. The following types of data were sought: (1) vertical radiation profiles on walls; (2) general area and floor radiation measurements; and (3) video inspections of the floor and equipment.

RRV-1 performed all data acquisition tasks as scheduled. Only two problems of significance were encountered. One, the safety retrieval cable became intertwined with the transporter wheels in the middle of the first entry. A operator had to exercise the vehicle through special freeing maneuvers to disengage the cable. The mission was cut short rather than jeopardize the return of the vehicle; the safety retrieval cable was removed for the second entry. The second problem was that one of the three radiation detectors failed while in service; this detector was not repaired during the two entries.

Figure 2 depicts the general radiation levels on El. 282' 6". The shaded areas show the extent of travel, and the shaded cross-section shows the radiation levels 4 ft off the floor. Figures 3 and 4 show typical vertical radiation profiles for the liner wall, the D-ring and impingement walls, and the enclosed stairwell. A 15-min. videotape was made from the many hours recorded. This videotape shows the distribution of sludge and the general physical conditions in the basement. In summary, the basement equipment is in good shape with expected dirt and water damage, and the area is full of construction debris.

The entry experience revealed that the safety line could be eliminated to ease maneuverability and the remote flushing that took place as the RRV-1 was raised from the basement could be improved. Currently, because no provision exists for free rolling, no means exists to retrieve the RRV-1 if a drive motor should fail. This and the potential browning effect of radiation on camera lenses are two problems that will require eventual resolution.

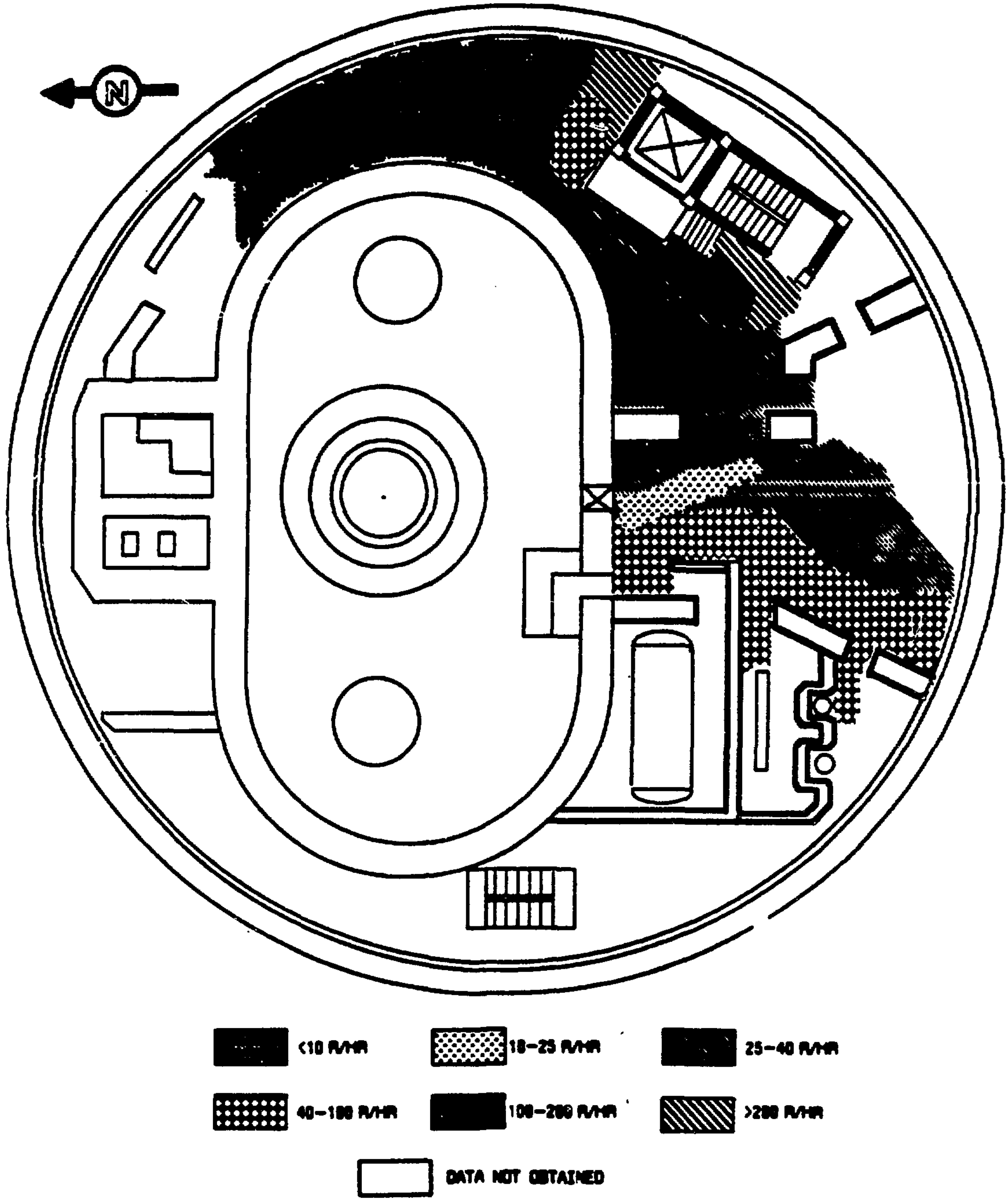

FIGURE 2 Iso-exposure Map of El. 282' 6"

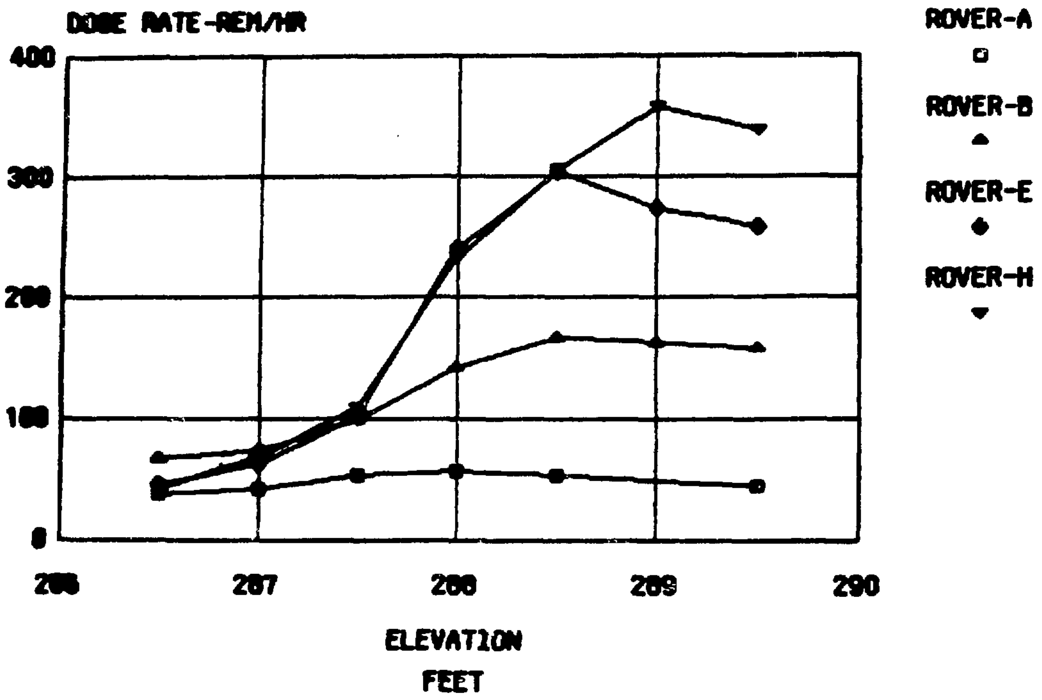

FIGURE 3 Rover Dose Rate Measurements, 3000 psi Concrete

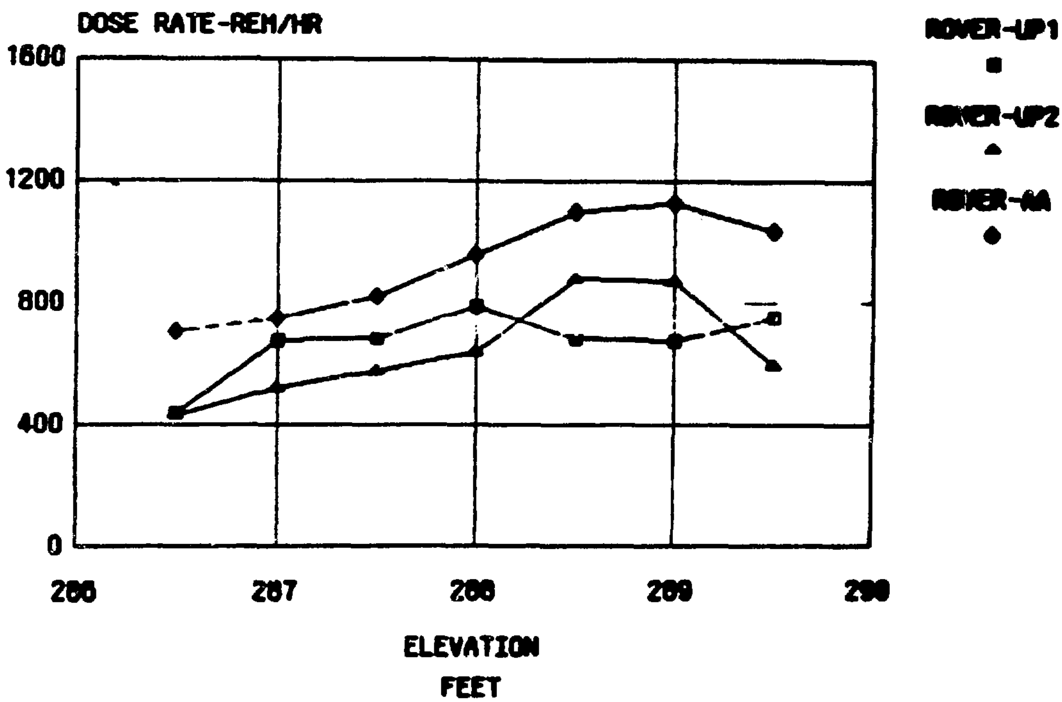

FIGURE 4 Rover Dose Rate Measurements, Enclosed Stairwell

RRV-2

Based on the successful experience with RRV-1, remote core-boring equipment was developed and existing parts from RRV-1 were assembled to provide a second transporter. Functional criteria were agreed to by all parties and a modular core-boring unit was developed and fabricated at CMU in April 1985. GPU Nuclear plans to deploy RRV-2 in the summer of 1985.

RRV-2 is basically identical to RRV-1 and has been developed as a backup for RRV-1. RRV-2 will facilitate training and modifications without distracting from the use of RRV-1. It is also equipped with core-boring hardware that will be transferred to RRV-1 for actual use.

The core-boring equipment thrusts a bit into concrete to cut a cylindrical void. The bit then twists the cylinder to break off a sample, which will be 1.5 in. deep and 1.5 in. dia. Each tubular core-bore module will cut a single core to ensure sample isolation and tagging. The modules are of low cost and reusable. The samples are raised from El. 282' 6" separately from the RRV-1, which is flushed as it is raised from the basement. The handling of the core bores is still under development, but results from analysis should indicate the amount and depth of contamination on the basement concrete.

REMOTE WORKING VEHICLE

Description

In parallel with the development of RRV-2, plans were prepared for the conceptual design of RWV-1. Specific tasks were identified for the decontamination and recovery of El. 282' 6". CMU then prepared conceptual designs and listed commercially available equipment that could be used or modified for these applications. Functional criteria were specified by GPU Nuclear to restrict the size of the equipment and to ensure compatibility with GPU Nuclear facilities and procedures. The delivery of RWV-1 to TMI-2 is scheduled for late 1985 and deployment in the basement should occur early in 1986.

Existing on-hand construction equipment is available to execute most of the decontamination tasks identified in the reactor building basement. Equipment for high-pressure wash-down, sand-blasting, demolition, scabbling, and painting is prevalent in the construction industry. Such construction equipment endurance and ruggedness standards are needed for long-term operation in the TMI-2 basement.

As the power requirement for this type of equipment increases, electro-hydraulic systems begin to have a size and weight advantage over purely electric systems. Electro-hydraulic systems predominate in underwater remotely operated vehicles (ROVs), mining equipment, and aircraft. Much of the recommended approach to developing the RWV-1 has been based on experience gained using undersea robotic equipment; consequently, RWV-1 will be an electro-hydraulic machine.

Large tools will be attached to RWV-1 in the manner of a bucket to a backhoe. Small tooling will carry "T" handles to be gripped by the RWV-1 manipulator. The scoop and other tools will be attached to the RWV with a changeout plate, which will have pin locks that can be remotely actuated.

Because the size of the umbilical cable is of extreme importance for the RWV-1, multiplexing of the many degrees of freedom is absolutely necessary to minimize the number of control conductors. The RWV-1 will manage its umbilical cable from on board in a manner similar to management on the RRV. The reel will be a conventional, spring-loaded cable reel with slip rings to transmit power and control.

Subject to given locomotor constraints, the Sperry-New Holland 250 skid-steer loader has been recommended for the locomotor and primary lift, with some modifications. Some beefing up of the shell will also be required to improve the decontaminability of the equipment. Functional requirements will identify areas of concern that need protection beyond epoxy coatings. A Reliance continuous-duty, explosion-proof, 440-V ac 3-phase motor switched at the console has been recommended. A transformer had also been recommended to derive the voltages from the 110-V ac input.

Three backup pump motors will be configured so that the RWV-1 can move and manage its umbilical cable in the event of any system failure, excluding that of the umbilical. Each of the critical motions (left drive, right drive, and capstan drive) will have a backup pump motor connected directly to the actuator. In normal vehicle operation, the pump motor will not allow fluid to pass from one line to the other. In the event of prime electrical or hydraulic failure, the backup pump motors enable recovery.

The RWV-1 will also carry a single work manipulator, mounted forward and between the locomotor lift arms. The manipulator can be tilted back for storage and forward for working reach. This manipulator is a two-station, electro-hydraulic device consisting of a master control arm and an underwater-grade slave manipulator. Movements introduced at the master control arm by the operator are duplicated by the slave manipulator, producing a spatial correspondence between the master and the slave. Six degrees of freedom motion plus variable grip force provides well-controlled dexterity and is highly adaptable to deploy tooling on the RWV-1.

Tasks

The RWV-1 will contribute to dose reduction and decontamination in the reactor building basement by accomplishing the following tasks: (1) transfer of solid waste and sludge; (2) wash-down cleaning; (3) activating the basement floor drain; (4) radiation monitoring; (5) breaking and cutting concrete/masonry; (6) abrasive cleaning and surface conditioning; (7) metal cutting; (8) core bore plugging/sealing; and (9) emplacement of shielding.

The removal of liquid waste is required at various locations on the basement floor level and where additional water will accumulate from wash-down drainage. The mobility of the RWV-1 allows the emplacement of a free-standing sump pump at desired locations. The pump will be mechanically attached to the vehicle at El. 305' before it is lowered to El. 282' 6".

Sludge, contaminated block, and other debris will be collected and transferred by the vehicle in a boom-mounted bucket or by maneuvering containers to lift points.

The planned use of a fire hose wash-down requires that the hose nozzle be secured to the discharge hose before mounting it on the vehicle. Because of large reaction forces, the hose discharge will be centered and securely fastened to the boom mounting plate.

The tools utilized to activate the floor drain could vary considerably pending the sequence of events at each point and will be determined as the program progresses. A multiscale radiation monitor with an output display available for continuous or selected remote video viewing will also be used.

CONCLUSION

The TMI-2 Remote Technology Program experience can provide extensive benefits to other utilities and the nuclear industry. The TMI-2 program is a case study conducted in a licensed power plant with the most stringent requirements in terms of reliability, remote control, severe radiation environment, and number of uncertainties.

The original functional specification was a basically sound approach that did not restrict GPU Nuclear or the designers to a specific system. Technical flexibility was therefore available to the designers to ensure the generic applicability of the equipment. This approach did cause some difficulties in that several contractors and vendors were involved in equipment development; however, long-term benefits were secured in the form of: (1) a modular design concept; (2) expandability of features; (3) multipurpose use of equipment; (4) improved reliability/maintainability; and (5) lower program costs.

As with any developmental project, technical problems were encountered that remain to be resolved. These include: (1) design and installation of support equipment; (2) methods to rescue or retrieve a failed machine; (3) adequate accommodations for equipment decontamination; and (4) ability to perform maintenance on a contaminated machine.

The TMI-2 Remote Technology Program has demonstrated that the practical development and use of this equipment in a hostile environment is achievable. The continued development of this program promises gains not only in the cleanup of TMI-2, but in any radiation environment application requiring the substitution of machine for man.

QUESTION AND ANSWER SESSION

Question: When you brought the vehicle down the basement, did you put them through the spray rings to decontaminate it?

Mr. Bengel: Yes.

Question: Did you get a smear to see how effective your decontamination was? If so, was it before you put the water on, or after?

Mr. Bengel: We did get a smear afterwards. We did not try to take a smear reading prior to lifting it up.

Question: Are you looking in your decontamination program toward eventual decommissioning of the facility or toward the rehabilitation of the facility?

Mr. Bengel: That's a very good question. I don't have that answer because GPU has not made the decision yet. Quite honestly, we go to a lot of effort to maintain the integrity of the plant, which is very expensive. But presently we have been maintaining all the integrity requirements of the plant, mainly because we still have fuel in the vessel. Once we remove the fuel, we could reduce the life safety requirements and make a decision on whether we're going to recover the plant. But that decision has not been made. The planning studies only talk about a Phase III criteria. Phase III essentially sets the conditions for making that decision; it does not make the decision.

Question: Have you kept track of the integrated dose of these vehicles as you've used them; and have you seen any problems with the lubricants or materials that might be related to deterioration of air?

Mr. Bengel: We have not specifically tracked the integrated dose of the vehicle. The radiation levels are not high enough to cause us concern with failure of the equipment in the lifetime we expect to use it. For example, some early concern was voiced about the browning of camera lenses and the cameras' ability to withstand the radiation levels. We found out that the radiation levels in the time periods we were talking about essentially weren't close to the threshold. And even if they were, it's much cheaper to replace the camera than to invest in nonbrowning lenses.

As far as lubricants and wear, we just don't expect that type of problem with entries of these durations.

Question: It might be more of a concern when you get into longer-term recovery operations, mightn't it?

Mr. Bengel: We are more concerned about that type of question as we get into the work-ups, but the reconnaissance vehicle entries are of very short duration. For instance, only one or two entries for RRV-1 are planned. Taking the core bores and the sludge samples will probably be the extent of RRV-2's entries. Again, these are one or two-day entries, maybe four to eight hours per entry.

ORDNANCE DISPOSAL EXPERIENCE WITH MOBILE TELEOPERATORS

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Our major mission at the Center is research and development; our specific explosive ordnance disposal (EOD) mission is detection and rendering safe. We have as our development goal the use of teleoperators, robots, and remotely controlled mobile tools to reduce the risk to personnel. In that respect, our role in the EOD world is similar to that of people working in nuclear systems.

Our first system dates back to the early 1970s. It was a mobile master/slave teleoperated system in which the operator wears a complete harness. The slave portion is mounted on the front of the vehicle. This vehicle had relatively high capabilities; the arm was hydraulic and had pneumatic force feedback, and there was enough strength to unscrew fuses from ordnance devices. Control was precise enough that the machine could actually thread a needle. This was our first look at mobile teleoperator systems. While it had significant technological capabilities, it really did not have the right capabilities for EOD applications. It required much maintenance and specialized operator training; the latter in particular was a problem, because we want our equipment to be operable by anyone in EOD.

After looking at that system (which cost about $250,000 back in 1970), we decided to develop a very simple, low-cost machine -- in large part because we expect our equipment to be damaged or destroyed at some particular rate. This system (called ROVER) evolved over a number of years. When we began, we were involved with NASA, National Bureau of Standards, and Atomic Energy Commission. Recently, researchers at George Washington University (GWU) developed robotic control of the second machine, using an English-language control system developed by Peter Bock of GWU. Instead of using machine language, the operator can use plain English and have the machine understand what is to be done.

In about 1979, we decided to convert an electric wheelchair -- which was available then for about $1500 -- because it appeared to have all the components we needed except a vision system. We tried to keep the wheels but eventually settled on the tracked system. The total cost of the converted unit came to about $5000. This was a basic machine with a camera system for reconnaissance, a grapple for picking up and moving objects, and some special tools needed in EOD operations. The machine, which we now call RAMROD, is equipped with a telescopic boom and uses microprocessor control. Currently, we are looking into more advanced systems that will use microprocessor controls.

Because EOD also requires outdoor work with sometimes large and heavy pieces of ordnance, we developed what we call a heavy equipment remote control kit. This is a system that can be installed on a large vehicle relatively quickly and easily so that the vehicle can be used remotely. We have used two large vehicles. The only difference between the remoting control kit for the vehicles is in the mechanical linkage; the electronics, actuators, and radio control are the same in both vehicles. Such an arrangement is not as sensitive or precise as one originally designed to be remotely controlled, because slack in the vehicle's controls is compounded by slack in the add-on remote unit.

We also developed the Remotely Operated Mechanical Excavator, or ROME, system to deal with various ordnance devices after attacks on air fields. The controller for the ROME system is a complete seat mounted inside an armored personnel carrier (APC). The control station is a complete system designed to operate just as if the operator were sitting in the excavator itself. Audio feedback lets the operator hear the machine running, which is important for judging how the operation is proceeding. In comparison tests using both manual and remote modes, we measured a degradation of only about 10% for the remote system, a very good number.

What aspects of this field are common to both EOD and radiological emergency teleoperators? Certainly, mobility and manipulation, as well as the need to use special tools. User friendliness is essential; in EOD, every operator must be able to use the machine whenever called upon at irregular intervals. Another very important point is reliability, because the job must be done when it arises; there probably won't be an opportunity for a second try later. In regard to what has been called the robotic teleoperator, we in EOD believe that our human operators will always be a part of the loop and that is the direction our development is taking us.

In an attempt to chart just where we are going in robotics and EOD, I have categorized the work into low- and high-level phases. The low level is our current threshold, that is, a system that uses a human and a machine. The human operator's vision far surpasses that of any machine to date when it comes to searching and discriminating, as well as what I call initializing -- that is, finding the starting point for a given operation (once this point is found, the machine could then operate in a preprogrammed mode to carry out the task). This is still three to five years away for EOD use.

In the high-level phase, the human operator would be replaced almost entirely by robotics. The operator is limited mainly to monitoring, correcting, and some decision making, while the machine would have sophisticated vision and sensor systems. The chief challenge here is the development of the vision system. This level of operation should be available within 10 to 20 years.

The ultimate threshold is that of the completely autonomous machine, which is at least 20 to 50 years away. This concept is perhaps so broad that current individual efforts will not be adequate; it will probably require a highly coordinated, multiagency effort. Such a system will be highly mobile, perhaps in humanoid form, and available in various sizes for different tasks. It will be capable of instant training; for example, today it could function as an EOD technician, tomorrow as a tank driver, and another day as a sentry.

As we look to the future, we realize that our current capabilities are limited. The ROVER system, for example, is limited in its manipulations and tool operation, but it is a system from which we are attempting to branch out. One way to branch out is to enhance the human operator, if he is to remain in the loop. Or the branching can be toward robotic systems. We are trying to do both within the limits of our resources. Another area with much potential for improvement is that of tool operation. Most of the tools we now use were designed to be used by humans. We are looking at various sets of tools and trying to classify them in order to develop an interface system for our mobile teleoperator. The expectation is that additional tools, which permit new tasks to be done, will become available.

One approach to obtaining more and better information for the human operator is the use of three-dimensional (3-D) vision. A two-axis table for a 3-D video system was developed by Honeywell. A different approach to the problem is seen in a robotic system being developed at the University of Texas. That system's two arms manipulate a camera and a work tool, and a machine vision system provides a 3-D view so that both arms are coordinated and the operator knows exactly where the target is.

Just what is our desired capability? It is to perform all EOD functions robotically, and to move toward this goal, we make use of scenario analysis and decision criteria for guidance. In scenario analysis, we try to determine all the machine functions that would be needed to resolve a particular problem. If there were, for example, an explosive device concealed somewhere in a room, what would an operator do, or like to do? We must decide whether, for example, to prepare for a worst-case problem, perhaps functions that may put the machine in the greatest danger. Or we may want to attack the easiest problems in order to achieve success quickly.

If we approach each function as a series of discrete categories, we may find that development time and costs are much lower than if we try to develop the entire function at once. The analogy would be the human arm; it can perform many different categories of operations, and presumably a developer could produce a very sophisticated mechanical arm that could virtually duplicate the human version. All we really need, however, is for the arm to operate within perhaps six of those categories in our work. By concentrating on those six and ignoring the rest, we save money and effort and still achieve our goal.

In summary, I see our development direction as taking us from a system that is operator-dependent to one that is both operator- and robotic-interdependent and finally to a system that is fully robotic-dependent.

QUESTION AND ANSWER SESSION

Question: Did you evaluate the probability of detonation of some of the ordnance devices you deal with, versus the amount of technology that you put in your machine? I think that the cheaper machines may blow up more often than the more sophisticated ones.

Mr. Butler: The problem lies chiefly in the wide range of fusing that we must deal with. Some fuses will not allow anything within close range without blowing; others are sensitive to shaking or vibration. There are also radio-controlled ordnance devices that can be set off by a terrorist, for example, who is watching the scene. If we tried to design one piece of equipment that could handle every conceivable type of ordnance, we'd get nowhere. Therefore our approach has been to develop a machine at the lowest possible cost.

Question: You discussed development of sensor-feedback equipment in conjunction with the use of a computer. This seems to be at odds with your low-cost philosophy, especially if the manpower to operate your machine is relatively inexpensive.

Mr. Butler: What we are trying to do is cross the threshold from the teleoperated system to joint teleoperator and robotic control. My interpretation of the latter, at least for EOD, is to have the human operator move the machine to the work scene, carry out the initializing -- this may be nothing more than focusing the 3-D machine vision on the target -- and allowing the machine to start its assigned tasks by working from a canned program. We don't really know whether this will require additional sensors beyond 3-D vision.

Question: You mentioned only a 10% degradation from manual to remote operation in your excavator; were you referring to speed of operation?

Mr. Butler: Yes, the figure is based on the difference in time required to complete the operations. The operator first sat in the excavator's cab and opened a nine-by-nine-foot hole in concrete, after which he dug a nine-by-nine hole down to the ordnance device, which had been buried approximately 10 feet deep. We then installed our remote-control equipment and had the operator do the same task from the remote station. The time required to do the task remotely was 110% of that with the operator working from the cab itself. Admittedly, the task did not require as much precision as is sometimes needed by teleoperator devices. Nevertheless, for a nine-by-nine hole, 81 reorientations are needed to get through the concrete, and another 80 or so must be made to dig the hole itself.

CURRENTLY AVAILABLE MOBILE TELEOPERATORS AND THEIR APPLICABILITY TO RADIOLOGICAL EMERGENCIES

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NOTICE

In compiling the information for this paper, every attempt has been made to assure accurate reporting. Also, although this list is extensive, it is not necessarily complete. New systems continue to be "discovered" at the rate of about one per week. Therefore, if errors are noted or if you know of a mobile teleoperator that is not included, please contact the non-EPRI author and provide the correct or new data for subsequent publications.

BACKGROUND

As part of the planning for its Mobile Robotics Workshop in October, 1984,[1] EPRI began to expand the list of available mobile vehicles that could be displayed at that meeting. That list quickly grew in size from less than one dozen to more than thirty systems.

Under Research Project 2232-5, EPRI has continued to categorize mobile robotic devices and the list now includes sixty-nine terrestrial systems. The presentation utilizes certain details excerpted from that most recent compilation, and a copy of the RP2232-5 report draft constitutes the main text of this paper.

PERSPECTIVE

To offer the nuclear power industry a half-million-dollar mobile teleoperator that, because of its capabilities would sit in a corner waiting for a radiological emergency to occur so that it can be utilized, is a difficult if not impossible concept to sell. However, if the staff of robotic devices to be configured for power plant use[2] is developed jointly with another staff for radiological emergencies, the use factor for all members of these staffs can be optimized. It is the opinion of the EPRI author that the Department of Energy should consider acquiring not one, but several devices and that this staff for radiological emergencies should be developed as part of the larger family of systems that will meet industry-wide needs.

INTRODUCTION

This paper presents a summary of information regarding specific mobile teleoperated/robotic devices which are employed in hazardous environments, including the nuclear industry. These devices can be used to inspect, locate, identify, and/or maintain components and items in the hazardous environment as well as act as mobile surveillance devices while monitoring the various constituents in the hazardous atmosphere. Furthermore, they can be used as transporters of materiel to and from the hazardous environment. This summary is restricted to those devices which maneuver on the surface of floors and other terrain features or in both out-of-water and underwater situations.

Table 1 shows how the technology developed for other applications can apply to use by the nuclear industry. The message of this table is clear: the nuclear industry must take advantage of developed technology and, in its development of robotic staff devices, transfer the applicable portions of these existing systems into our robotic family.

Table 2 lists the devices that are each described by a short text paragraph. A numbering system is provided to help access the description once a device of interest is located in the table.

DESCRIPTION OF MOBILE TELEOPERATED/ROBOTIC DEVICES

1. SURVEYOR (Fig. 1)

Automation Technology Corporation, Columbia, MD

This 2-tracked, remotely controlled tetherless device, one of the IRIS series, is used to conduct surveillance and inspection missions in nuclear power plants. Surveyor's relatively light weight of less than 150 kg (330 lbs), including a 1.8 m (6 ft) long telescoping manipulator arm, enables it to be easily transported manually from location to location. The total maximum payload of the device, which is able to climb 45 degree stairs, is up to 113 kg (250 lbs) when transported on a level floor and its maximum speed is 18 m/min (60 ft/min). The lifting capacity of the arm is 4.5 kg (10 lbs). SURVEYOR can traverse through 152 mm (6 in) deep water and over 229 mm (9 in) high obstacles. Standard accessories include radiation detectors, humidity monitors, temperature measurement, sound detection and location, a standard video or CCD camera having a wide-angle and telephoto lens which is mounted on a pan-and-tilt mechanism and extendable arm, and halogen lights. The maneuverability of the device is enhanced with a pair of video or CCD cameras which generate a 3-D stereo visual image which is transported back to the teleoperator. The sensory packages can be placed onto the end of a telescoping arm which will eventually be extendable to 4.5 m (15 ft). Furthermore, this arm can transport an optional auto telesampler smear sampling device which can automatically take and retrieve up to 10 smear samples. The dimensions of the SURVEYOR platform are: 1143 x 572 x 521 mm (l x w x h) (45 x 22.5 x 20.5 in.). The power supply is provided by four on-board sealed lead-acid 24V batteries which enable the device to operate up to 5 hours before requiring recharging or battery replacement.

TABLE 1 Mobile Robots - Sensory and Applications Matrix

	Nuclear	Civil Ord	Security	Military Ord Recon.	Fire Fight
Autonomous Navigation	X	X	X	X	X
Biological Detection		X		X	
Chemical Detection		X		X	
Collision Avoidance	X	X	X	X	X
Explosive Ord. Detect.		X		X	
Heat Source	X	X	X	X	X
Humidity Detection	X	X		X	X
Manipulate Loads					
Light (0-5 kg)	X	X		X	
Moderate (5-25 kg)	X	X		X	
Heavy (G.T. 25 kg)	X	X		X	X
Object Detection					
Animate		X	X	X	
Inanimate	X	X	X	X	X
Radiation Detection	X	X		X	
Smoke Detection	X	X	X	X	X
Sound Projection (voice)		X	X	X	
Sound Source	X	X	X	X	X
Temperature	X	X	X	X	X
Vibration Detection	X	X	X	X	
Vision - Video	X	X	X	X	X
CCD	X	X	X	X	X
X-ray Analysis	X	X		X	

TABLE 2 Summary of Mobile Teleoperated/Robotic Devices

Manufacturer (Supplier/User)	Device Name	Country[a]	Loco-motion[b]	Missions[c]
1. Automation Tech. Corp.	Surveyor	US	T	N
2. Automation Tech. Corp.	Sentry	US	T	S
3. Automation Tech. Corp.	Scout	US	T	M
4. Battelle Colum. Lab.	Rocomp	US	T	N
5. Battelle Colum. Lab.	Minirocomp	US	WT	M
6. Blocher-Motor (CMS Technologies)	MF3	WG	T	N
7. Blocher-Motor (CMS Technologies)	MF4	WG	T	E
8. Carnegie-Mellon Univ.	RRV	US	W	N
9. Carnegie-Mellon Univ.	Remoteborer	US	W	N
10. Cybermation	Kluge	US	W	MI
11. Denning Mobile Robot	Sentry	US	W	S
12. Fire-Tech	Fire-Cat	US	W	F
13. Foster-Miller	Ramrod	US	T	E
14. GCA/PAR	PAR-1	US	T	N
15. GCA/PAR	PAR-2	US	T	N
16. GCA-PAR (Martin-Marietta/OR)	Herman	US	T	N
17. GCA/PAR (Westinghouse-HEDL)	Louie	US	T	N
18. GCA-PAR (Taiwan)	GCA/PAR-1	US	T	N
19. GMH Associates	Snoopy	US	W	E
20. Hitachi	RIS	JA	W	N
21. Hitachi		JA	L	N

TABLE 2 (Cont'd)

Manufacturer (Supplier/User)	Device Name	Country[a]	Locomotion[b]	Missions[c]
22. Hodges Robotics	Fred	US	W	FN
23. Inspectronic	Ariane	FR	T	N
24. Inspectronic	Oscar	FR	T	N
25. Inspectronic	Oreste	FR	T	N
26. ITI Security	RO-VEH	US	WT	E
27. Jaeri		JA	T	N
28. Kentree Ltd.	Hobo	IR	W	E
29. Lawrence Liver. Lab.	Atom	US	T	N
30. Meidensha	Meirobo	JA	T	NH
31. Meidensha	DCR	JA	W	H
32. Meidensha	DIR	JA	W	H
33. MITI		JA	T	N
34. Mitshu.-Kobe Ship.		JA	W	N
35. Mitshu.-Kobe Ship.		JA	WL	N
36. Mitshu.-Kobe Ship.		JA	W	N
37. Monitor Eng. (Monitor Robotics)	Hadrian	UK	W	E
38. MBA	Roboteer	US	T	EM
39. Morfax (NAECO)	Wheelbarrow	UK	T	EM
40. Morfax (NAECO)	Marauder	UK	T	E
41. NTG Nucleartechnik (Scientific Int'l)	MF3	WG	T	N
42. NTG Nucleartechnik (Scientific Int'l)	(2 arms)	WG	T	N
43. Odetics	ODEX-1	US	L	MI

TABLE 2 (Cont'd)

Manufacturer (Supplier/User)	Device Name	Country[a]	Loco-motion[b]	Missions[c]
44. Odetics	ODEX-N	US	L	N
45. Odetics	ODEX-A	US	L	MI
46. Odetics	ODEX-M	US	L	M
47. Pedsco-Canada	RMI-1	CN	W	E
48. Pemtek	Moose	US	W	N
49. Remotec	Surbot	US	W	N
50. Robot Defense Systems	Prowler	US	W	M
51. Robot Systems Int'l.	Hazcat-M500	CN	W	NH
52. Robot Systems Int'l.	Hazcat-M100	CN	W	NH
53. Rockwell Int'l (Rocky Flats Plant)	Worm	US	T	N
54. SAS R&D Services (1ARM)	Hunter	UK	WT	E
55. SAS R&D Services (2ARM)	Hunter	UK	WT	E
56. Standard Manufacture	MARS-V	US	W	MI
57. Sumitomo		JA	W	N
58. ACEC (Teleoperator Systems)	Telemac	BL	T	N
59. 21st Century Robotics-Sivan	WASP-700	IS	W	EM
60. 21st Century Robotics-Sivan	TSR-150	IS	T	EM
61. 21st Century Robotics-Sivan	TSR-50	IS	T	EM
62. US Bureau Mines	ARM	US	W	MG
63. US Bureau Mines	REM	US	W	MG

TABLE 2 (Cont'd)

Manufacturer (Supplier/User)	Device Name	Country[a]	Locomotion[b]	Missions[c]
64. US Bureau Mines	MRS	US	W	MG
65. US Navy	Rover	US	I	EM
66. US Navy	RCFF	US	T	F
67. Westinghouse-Hanford	SISI	US	T	N
68. Viking Energy	ROD	US	W	N

[a]Country of manufacturer: BL = Belgium, CN = Canada, FR = France, IR = Ireland, IS = Israel, UK = United Kingdom, US = United States, WG = West Germany.

[b]Locomotion Method: T = tracked, W = wheeled, L = legged.

[c]Primary Missions: N = nuclear, H = hazardous, E = explosive ordinance disposal, S = security, F = fire fighting, M = military, MI = misc., MG = mining.

The maneuverability of the device is enhanced by the generation of a 3-D stereo image produced by a pair of on-board video or CCD cameras (standard items) which are communicated back to the teleoperator's control panel via a high radio frequency, along with the other sensory and operating data, in which there is a minimal amount of RF interference. The vehicle is able to be easily decontaminated. The supervisory control panel contains 4 TV monitors and a microcomputer which monitors all performance and sensory data.

2. SENTRY

Automation Technology Corporation, Columbia, MD

This tetherless, remotely controlled teleoperated device is similar to the SURVEYOR and is also a member of the IRIS series. It is structured to assume the role of a sentry or guard in both indoor and outdoor security situations (warehouses, perimeters of military bases, etc.)

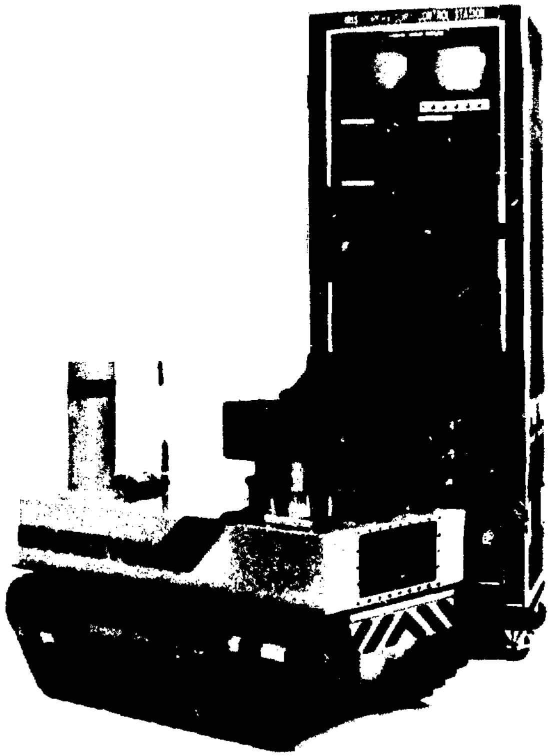

FIGURE 1 SURVEYOR, Automation Technology Co.

3. SCOUT

Automation Technology Corporation, Columbia, MD

This tetherless, remotely controlled teleoperated device is a slightly larger version of the SURVEYOR and is also a member of the IRIS series. It can be used to perform indoor and outdoor reconaissance and surveillance missions in military situations.

4. ROCOMP (Radio or Computer Operated Mobile Platform)

Battelle - Columbus Laboratories, Columbus, OH

This tetherless, remotely controlled 2-tracked device has been built for applications in nuclear power facilities and other chemical/explosives handling/hazardous environments. The radio-controlled platform can climb stairs and has two speed ranges: 0-27 and 0-46 m/min (0-90 and 0-150 ft/min). Its two tracks can be replaced by wheels to facilitate rapid movement over flat terrain. The platform is designed to perform 5 tasks: (1) detect radiation, (2) collect air samples, (3) obtain smear samples, (4) perform mechanical tasks, and (5) act as a tool caddy. In addition to a 4-axis manipulator arm, the device will have a video camera. The on-board power source of two 12V batteries permits continuous operation of 2-4 hours between battery charges. The ROCOMP platform dimensions are 1372 x 711 x 457 mm (l x w x h) (54 x 28 x 18 in); it can carry loads of up to 113 kg (250 lb). On-board computers will enable ROCOMP to support some form of autonomous navigation. The extended manipulator arm can lift 23 kg (50 lb) when fully extended and up to 91 kg (200 lb) when the shoulder and the elbow are flexed forward and down. The arm can reach up to an elevation of 2030 mm (80 in.) and reach 914 mm (36 in.) behind the platform.

5. MINIROCOMP

Battelle - Columbus Laboratories, Columbus, OH

This tetherless, remotely controlled 4-wheeled device was designed to serve as a low-profile vehicle for use in site reconnaissance applications. The vehicle is battery-powered (on-board) and is capable of operating 2-4 hours between battery charges. Video and acoustic information can be transmitted back to a central control station located more than 1.6 km (1 mile) from the vehicle via RF modulation techniques. Expansion ports for additional sensors have been incorporated for use in specific applications. An on-board computer monitors the data link and converts operator commands into actual vehicle movements. The lower portion of the chain drive for the wheels runs under the vehicle undercarriage and enables MINIROCOMP to climb over 50 mm (2 in.) high obstacles. The overall size of this 11 kg (25 lb) vehicle is 457 x 203 x 254 (l x w x h) (18 x 8 x 10 in.), excluding the antenna. The maximum speed of MINIROCOMP is 40 m/min (130 ft/min); it is capable of traversing slopes of up to 45 degrees. Its critical components are protected from moisture and there is a possible modification of the communication link to incorporate fiber optics rather than RF.

6. MF3 (Fig. 2)

Blocher-Motor GmbH & Co. KG, Metzingen, West Germany
CMS Technologies, Inc., Ft. Lee, N.J., U.S. Distributor

This device is a remotely controlled, tethered 4-tracked vehicle which is used in the nuclear industry and other hazardous environments. It was initially conceived and developed at the KFA Julich Research Laboratory in West Germany. Its single, light-duty, electric-powered manipulator arm can lift up to 20 kg (44 lb); the heavy-duty arm can lift up to 80 kg (176 lb). Both arms have 6 axes of movement and possess infinitely rotating long openings. Optional 7-axes electric lightweight master-slave arms (single or dual) which can perform extremely delicate operations by means of power feedback can carry 12 kg (26 lb) in a sustained operation or up to 24 kg (53 lb) in a temporary capacity. The MF3 is remote controlled from a portable control desk located up to 100 m (328 ft) from the 408-kg (900 lb) device. The MF3 dimensions are: 2264 x 720 x 400

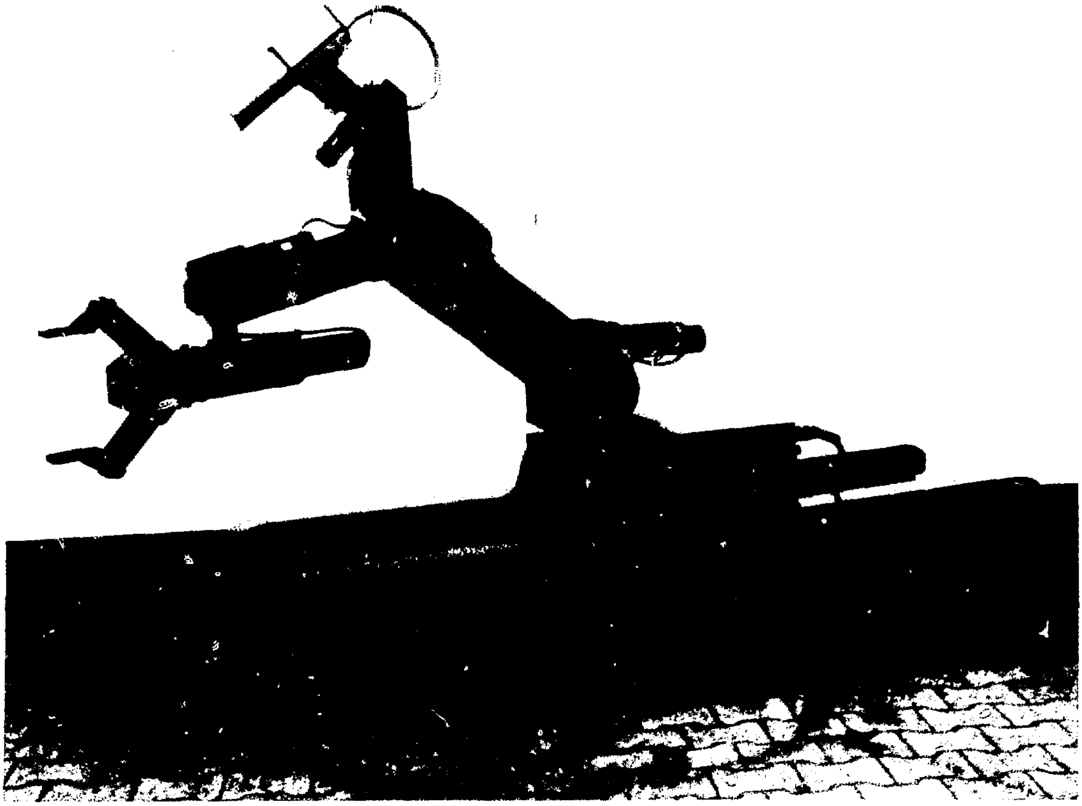

FIGURE 2 MF-3, Blocher Motor GmbH & Co.

mm (l x w x h) (89.1 x 28.3 x 15.7 in.); with track adjustment, the length and height are, respectively, 940 and 1080 mm (37.0 and 42.5 in.). It can climb stairs with a gradient of up to 45 degrees, turn on a 1200 mm (47.2 in.) radius, and can surmount 600 mm (23.6 in.) high obstacles, and traverse 1 m (3 ft) wide chasms (gaps). Its maximum speed is 30 m/min (99 ft/min), optional accessories are video cameras, TV monitor at the control desk, headlights, noise transmission system, X-ray unit with mounting arm, and alternate grippers. Power (220V, 50 Hz) and communications are made through an umbilical cord (cable). On-board electrical tools are powered through on-board sockets. An alternate model can operate with four on-board 12V batteries.

7. MF4

Blocher-Motor GmbH & Co. KG, Metzingen, West Germany
CMS Technologies, Inc., Ft. Lee, N.J., U.S. Distributor

This device is a tethered, 2-tracked, remotely controlled vehicle which is used in the civil/military ordinance disposal and nuclear industries. It was conceived and developed at the KFA Julich Research Laboratories in West Germany. Its single light-duty electric-powered manipulator arm can carry up to 20 kg (44 lb) in all positions. The MF4 is remotely controlled from a portable control desk located up to 100 m (328 ft) from the device. The MF4 dimensions are 1320 x 584 x 406 mm (l x w x h) (52 x 23 x 16 in.). It can climb stairs, climb 32 degree slopes, turn in a 1460 mm (57.5 in.) circle, surmount small obstacles, and travel up to 30 m/min (100 ft/min). Its two types of power sources are 220/110V (50/60 Hz) supplied by cable or two on-board 12V, 60 amp-hr batteries which can be recharged from the control desk. The device weight is 165 kg (365 lb) or 202 kg (445 lb) for line-supplied or battery-powered units, respectively. The payload capacity of the MF4 is 154 kg (340 lb) or 118 kg (260 lb) without or with battery power, respectively. Optional accessories are: video camera, TV monitor at the control desk, spotlight, force measuring device for manipulator gripper, sound detection facility, directional microphone, and socket to supply 24V dc for on-board electrical tools. Operational times with battery power are 1-2 hours.

8. RRV-1, Remote Reconaissance Vehicle (Fig. 3)

Carnegie-Mellon University, Pittsburgh, PA

This device is a tethered, remotely controlled, 6-wheeled vehicle which has been designed to operate in the Three Mile Island Unit No. 2 (TMI-2) nuclear power plant. The power supply (110V, 60 Hz), the video/sensory data (radiation level monitoring), and the command instructions are transmitted to and from the vehicle by a 400 m (1312 ft) long cable from the control console. The cable retractor located on board the RRV is remotely operated by one of the two teleoperators. Two of the three on-board video cameras are used for navigation for the vehicle and the third is used for general surveillance and to monitor the cable retraction. The visual observations are enhanced by high-intensity lights located on board the RRV. The dimensions of the Standard Manufacturing Co. (Dallas, TX) supplied base are 1270 x 734 x 483 mm (l x w x h) (50 x 29 x 19 in.). The total height and the approximate weight of the vehicle, which includes a lift cage, is 1.5 m (5 ft) and 453 kg (1000 lb), respectively. The maximum speed of the vehicle is 13.4 m/min (44 ft/min). The device can travel through 305 mm (12 in.) deep water and it has been designed for quick wash-downs and easily applied decontamination procedures.

9. REMOTEBORER

Carnegie-Mellon University, Pittsburgh, PA

This device is a tethered, remotely controlled, 6-wheeled vehicle which has been designed to drill and retrieve concrete bore samples from the TMI-2 nuclear power plant. This vehicle is a modification of the RRV. The microprocessor-controlled core borer can take a multiple number of 50 mm (2 in.) diameter samples, each of which is individually stored after being retrieved from the concrete wall. The total approximate weight of the device is 906 kg (2000 lb). The diamond-tipped drill and sample acquisitioner can reach elevations of 0.6-12.4 m (2-8 ft).

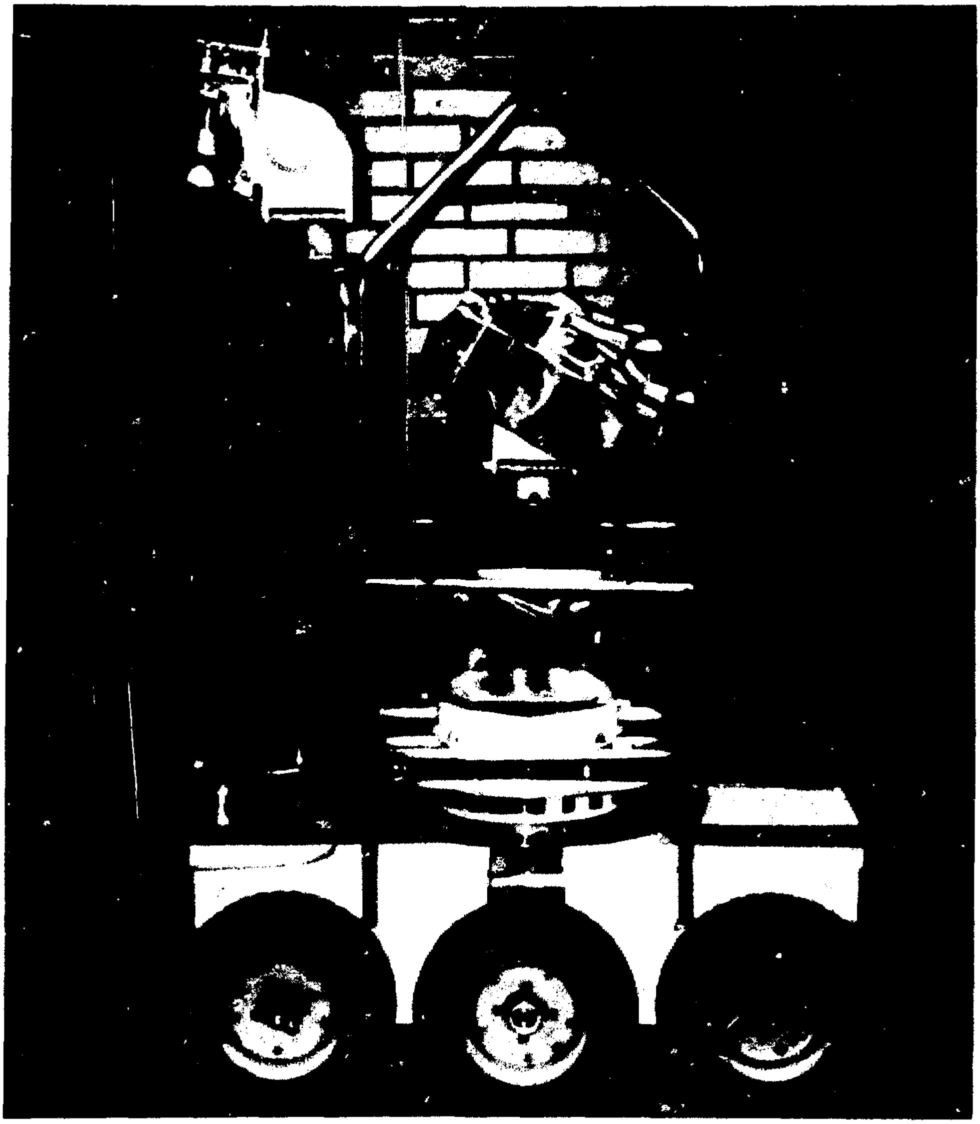

FIGURE 3 RRV-1, Carnegie-Mellon University

10. KLUGE (Fig. 4)

Cybermation, Inc., Roanoke, VA

This teleoperated, 3-wheeled, tetherless device is designed to act as a mobile material and tool transporter platform in factories and other industrial facilities. Its three extendable wheels and coupled working platform are omnidirectional, thereby enabling the device to rotate on its own axis (zero turning radius). The working platform has 508 mm (20 in.) height and a 804 mm (33.5 in.) width; it can support a load of 113 kg

FIGURE 4 KLUGE, Cybermation, Inc.

(250 lb). The device can climb a 30 degree slope. Sensory information available on the KLUGE includes video and two audio communications. Power to the KLUGE is supplied by on-board batteries.

11. SENTRY-1

Denning Mobile Robots, Inc., Woburn, MA

This autonomous, 3-wheeled, tetherless robot was designed to act as a sentry in factories, warehouses, prisons, and act as a mobile electronic perimeter system guard. Its on-board ultrasonic sensors and off-board computers enable the robot to avoid obstacles, find global navigation paths, and recognize positions. Its RF-based communication system to the control console can permit optional video signal transmission. This 1.2 m (4 ft) high, 181 kg (400 lb) vehicle can travel at a speed of up to 80 m/min (264 ft/min). Power to the SENTRY is provided by three 40 amp-hr, 12V gel-type batteries. On-board microprocessors include a Z80 for motor control, Z80 for control of the 24 peripheral ultrasonic sensors, and a Motorola M68000 for general processing.

12. FIRE-CAT

Fire & Technical Equipment Corp., Ft. Worth, TX

This tethered (fire hose only), remotely controlled, 2-tracked vehicle has been designed to operate as a manless firefighter. Its nozzle turret is radio-controlled (RF) and can supply a 4228 L/min (1000 gal/min) water spray. The power for this 898 kg (1980 lb) vehicle is furnished by six on-board 12V, 90 amp-hr batteries. The FIRE-CAT can drag three 63.5 mm (2.5 in.) diameter hoses 152 m (500 ft) or drag one 63.5 mm hose 457 m (1500 ft). It can utilize water, foam, or any extinguishant. The vehicle can maneuver on muddy ground and can climb a 60 degree slope. It is waterproof, can respond instantly to remote-tone coded signal instructions, and its communication system will not be affected with/by other electronic gear or signals.

13. RAMROD

Foster-Miller Co., Boston, MA

This remotely controlled, tethered, 2-tracked vehicle has been designed to support explosive ordnance disposal activities for the U.S. Navy. The length of its fully extended manipulator arm is 3.35 m (11 ft); the maximum height it can reach is 2.74 m (9 ft). RAMROD is weatherproofed and is amenable to being decontaminated. The on-board video camera has a pan-and-tilt mechanism and has zoom capabilities; the camera remains on the vehicle centerline at all times. Although the main form of communication with the vehicle is via cable, there is an automatic switchover to RF in the event that there is a loss of cable signal. The cable supports a one-way audio link. This battery-powered system is a next-generation version of the ROVER device built by the U.S. Navy.

14. PAR-1

GCA/PAR Corporation, St. Paul, MN

The PAR-1 device is a remotely controlled, tethered, 2-tracked vehicle which is used in the nuclear industry. Its PAR model 150 or 3500 manipulator arm can carry up to 22.7 kg (50 lb) at the hand with manipulator elements in any position. An additional 22.7 kg may be placed on the video camera mounting surface and 91 kg (200 lb) in the vehicle tray. A telescoping tube on which the arm is mounted allows the grippers to reach up to a height of 3.3 m (11 ft). The PAR-1 dimensions are 914 x 762 mm (l x w) (36 x 30 in.) and the device can travel at speeds of up to 15 m/min (50 ft/min). The vehicle weight is 408 kg (900 lb). The power is supplied by a cable from a self-contained power/motor generator or by any 220/440V, 60 Hz commercial source. The vehicle can be easily decontaminated and its optional accessories include towing hooks, lights, microphones, and video cameras. Thirty of these units have been sold worldwide since 1961.

15. PAR-2

GCA/PAR Corporation, St. Paul, MN

The PAR-2 device is a remotely controlled, tethered, 2-tracked vehicle which is used in the nuclear industry. It is similar in design and configuration to the PAR-1 vehicle except for the layout of the telescoping tube and the track propulsion mechanisms.

16. HERMAN (Fig. 5)

GCA/PAR Corporation, St. Paul, MN

This device is a remotely controlled, tethered, 2-tracked vehicle which is used in the nuclear industry. It is similar in design and configuration to the PAR-1 vehicle except for the layout of the telescoping tube and the track propulsion mechanisms. HERMAN has been located at the Oak Ridge Y-12 plant, operated by Martin Marietta for the U.S. Dept. of Energy, since 1966. The vehicle carries two video cameras, along with their individual pan-and-tilt mechanisms and support platforms, and is designed to operate at distances up to 213 m (700 ft) from the control console. The manipulator arm can lift 72.5 kg (160 lb) and can drag up to 228 kg (500 lb). The vehicle dimensions are (with the manipulator arm in a stowed position): 1143 x 737 x 1575 mm (l x w x h) (45 x 29 x 62 in.). The arm can reach up to an elevation of 3.4 m (133 in.) and forward to 1.3 m (50 in.). The total weight of HERMAN, which is transported by a 12.2 x 2.4 x 3.8 m (40 x 8 x 12.5 ft) trailer, is 816 kg (1800 lb). The trailer also acts as a decontamination chamber and repair shop for the device. The power is supplied by a self-contained power/motor generator, or by 220/440V, 60-Hz commercial source.

17. LOUIE

GCA/PAR Corporation, St. Paul, MN

This device is a remotely controlled, tethered, 2-tracked vehicle which is used in the nuclear industry. It is similar in design and configuration to the PAR-1 vehicle except for the telescoping tube and the track propulsion mechanism. This vehicle has been located at the Hanford Engineering Development Laboratory, operated by the Westinghouse Hanford Company for the U.S. Dept. of Energy, since January 1963. This device is on loan to the GPU Nuclear Corp. in support of the cleanup activities at the TMI-2 nuclear power plant.

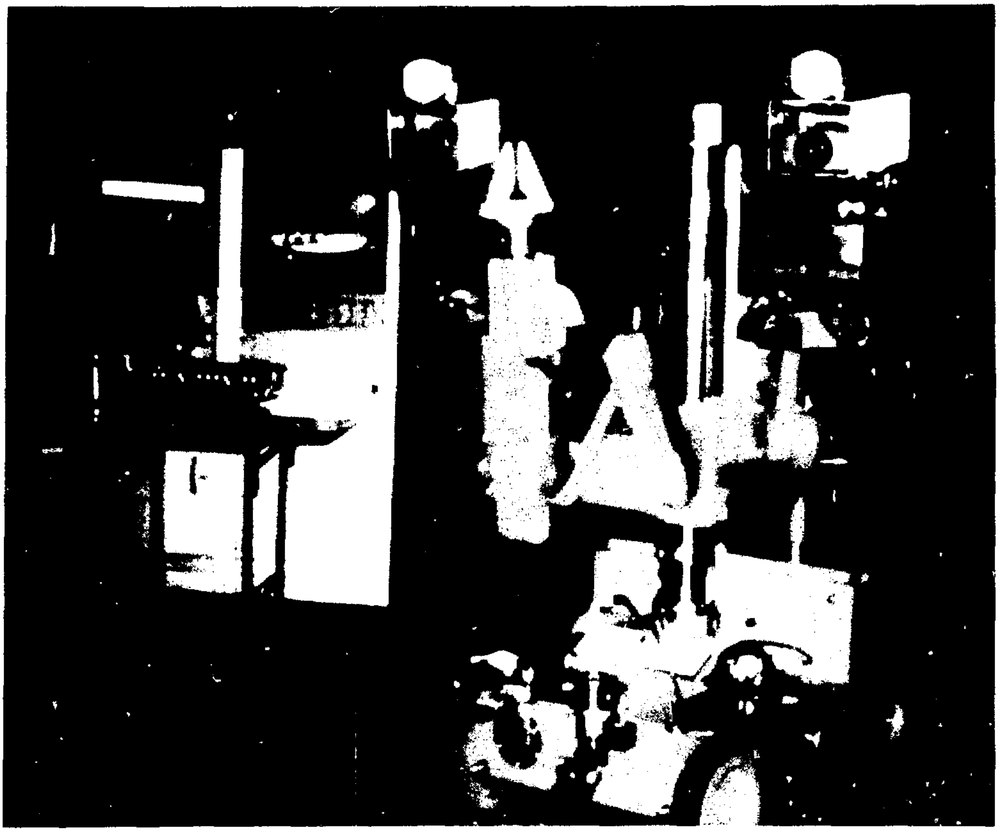

FIGURE 5 HERMAN, GCA/PAR Corp.

18. GCA/PAR-1

GCA/PAR Corporation, St. Paul, MN

This device is a remotely controlled, tethered, 2-tracked vehicle which is used in the nuclear industry. It is similar in design to the PAR-1 vehicle except for modifications in the manipulator arm support and track propulsion mechanisms. Two units of this latest of the PAR series have been supplied to Taiwan in 1981 and 1983; both units have the model 3500 manipulating arm.

19. SNOOPY

GMH Associates, NJ

This tetherless, remotely controlled, 2-tracked device was designed to support explosive ordnance disposal and other civilian emergency situations. This 272-kg (600-lb) vehicle has a claw that can lift 68 kg (150 lb) and is equipped with two video cameras. Although this device has been supplied to at least two domestic police departments and was available for the 1984 National Democratic Party Convention held in San Francisco, it is no longer being manufactured.

20. RIS (Remote Inspection System)

Hitachi, Ltd., Japan (Sponsored by MITI)

This tethered, remotely controlled, 4-wheeled device is being used for inspection and surveillance of nuclear power reactor and turbine buildings. Its navigation is being controlled by guide tapes pasted onto the floor of the facility which are read by an on-board optical reflective sensor. The sensory, inspection, and surveillance equipment carried on board the vehicle includes a video camera, microphone, temperature measurements, and humidity level detectors. All sensory data is transmitted to the control console via transmission cables. The vehicle dimensions are: 1000 x 520 x 1300 mm (l x w x h) (39.4 x 20.5 x 51.2 in.). The height of the vehicle includes the top dimension of the stowed manipulator arm. The device can reach top speeds of 80 m/min (262 ft/min). Power to the vehicle is supplied by an on-board battery pack and the data/communication cable is played out/in by an on-board cable reel drum. Capabilities of the manipulator arm, when located on the vehicle, are not known at this time.

21. (No Name) (Fig. 6)

Hitachi Energy Research Laboratory, Hitachi, Ibaraki, Japan

This device is a remotely controlled, teleoperated, tethered 5-legged/wheeled vehicle which is to be used for remote maintenance in the nuclear industry. Each leg has four degrees of freedom and one wheel. The design enables the vehicle to have vertical as well as horizontal mobility, thus enabling it to climb stairs. The master-slave manipulator has 6 degrees of freedom and a pair of parallel tongs. All motors are supervised by on-board microprocessors. Belt-type sensors equipped around every wheel and floor detection sensors mounted in the front of each wheel are used to detect obstacles and the floor, respectively. The maximum and normal operating speeds (on a flat floor) are, respectively, 21 m/min (69 ft/min) and 6 m/min (20 ft/min). In addition to being able to climb stairs, the vehicle can climb 15-degree slopes. The elevation of the top of the working platform is 1.9 m (6.2 ft) and the tip of the manipulator arm can reach an elevation of 1.2-2.5 m (3.9-8.2 ft).

FIGURE 6 Unnamed Device, Hitachi Energy Research Laboratory

22. FRED (First Remote Entry Device) (Fig. 7)

Hodges Robotics, Lansing, MI
(Also referred to as the RCMM, Remote Controlled Mobile Manipulator)

This tethered/tetherless, remotely controlled, 6-wheeled vehicle was initially designed to support fire-fighting activities and was later adapted to work in the TMI-2 nuclear power plant. On-board sensory equipment includes video cameras and a radiation detector. This 181-kg (400 lb) vehicle possesses a manipulator arm which can lift 68 kg

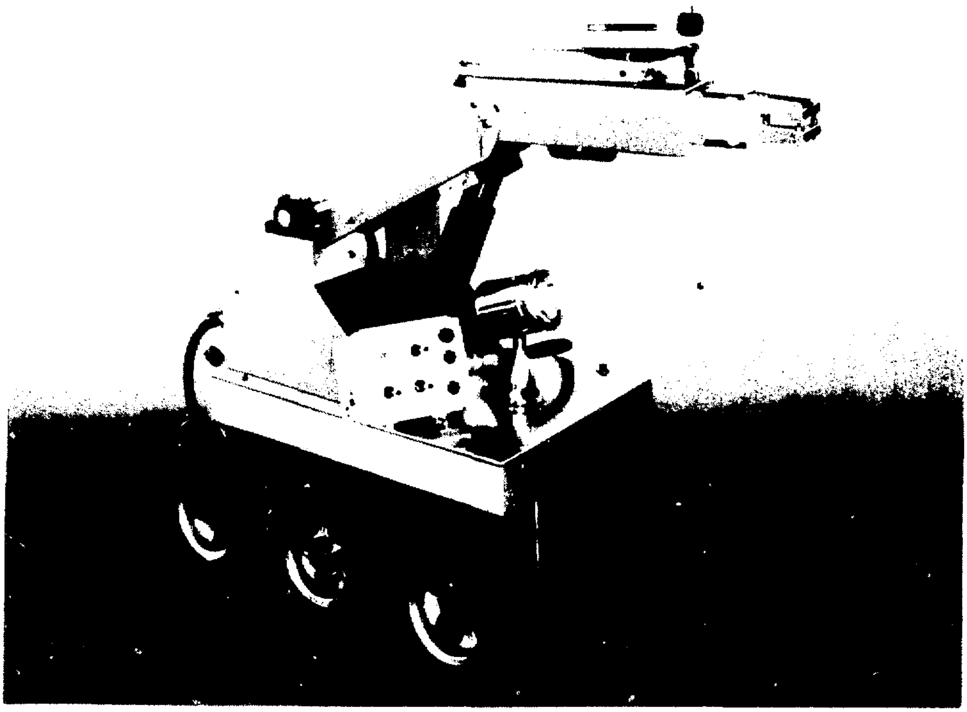

FIGURE 7 FRED, Hodges Robotics

(150 lb) and can reach a height of 1.8 m (72 in.). This device was initially used in TMI-2 to decontaminate the walls and the floor of the pump cubicle in the basement of the auxiliary building with a 66 C (150 F), 4000-psi water spray. The power is supplied by an on-board battery package or by a cable from house power. This device is no longer being manufactured.

23. ARIANE

Inspectronic, Asnieres, France

This tethered, remotely controlled 2-tracked vehicle is designed to operate in the nuclear industry, to include the conduction of underwater missions in completely submerged environments. Its platform can support a variety of sensors, detectors, video cameras, etc. The vehicle is controlled from a panel located on a remote control unit which may be fitted with a second electronic module and the remote control unit with an additional panel can allow simultaneous use of two vehicles. The dimensions of this 13-kg (29-lb) platform are: 450 x 275 x 170 mm (l x w x h) (17.7 x 10.8 x 6.7 in.). The platform can support 20 kg (44 lb), carry a 20-kg load up a 30-degree slope, and can travel at speeds up to 4 m/min (13 ft/min). The control unit is connected to the vehicle with a 25-m (82-ft) cable. The control unit and the remote control unit are linked together with a 25-m cable. The power requirements for this vehicle, which is corrosion resistant and can be easily decontaminated, is 32 VA at 220V.

24. OSCAR

Inspectronic, Asnieres, France

This tethered, remotely controlled 2-tracked vehicle is designed to operate in the nuclear industry, to include the conduction of underwater missions in completely submerged environments. Its platform can support a variety of sensors, detectors, video cameras, manipulator arms, etc. The vehicle is controlled from a panel located on a remote control unit which may be fitted with a second electronic module and the remote control unit with an additional panel can allow simultaneous use of two vehicles. The dimensions of this 40-kg (88-lb) platform are: 525 x 311 x 211 mm (l x w x h) (20.7 x 12.2 x 8.3 in.). The platform can support 80 kg (176 lb), carry a 60-kg (132 lb) load up a 30-degree slope, and can travel at speeds up to 15 m/min (49 ft/min). The control unit is connected to the vehicle with a 25-m (82-ft) cable. The control unit and the remote control unit are linked together with a 100-m (328-ft) cable. The power requirement for this vehicle is 1120 VA at 200V. The vehicle is corrosion resistant and can be easily decontaminated.

25. ORESTE

Inspectronic, Asnieres, France

This tethered, remotely controlled 2-tracked vehicle is designed to operate in the nuclear industry, to include the conduction of underwater missions in completely submerged environments. Its platform can support a variety of sensors, detectors, video cameras, manipulator arms, etc. The vehicle is controlled from a panel located on a remote control unit which may be fitted with a second electronic module and the remote control unit with an additional panel can allow simultaneous use of two vehicles. The dimensions of this 150-kg (331-lb) platform are: 800 x 600 x 300 mm (l x w x h) (31.5 x 23.6 x 11.8 in.). The platform can support 150 kg (331 lb), carry a 150-kg load up a 30-degree slope, and can travel at speeds up to 20 m/min (66 ft/min). The control unit is connected to the vehicle with a 25-m (82-ft) cable. The control unit and the remote control unit are linked together with a 100-m (328-ft) cable. The power requirement for this vehicle, which is corrosion resistant and can be easily decontaminated, is 2000 VA at 220V.

26. RO-VEH

ITI Security, Burlington, MA

This tethered, remotely controlled, 2-tracked or 3-wheeled vehicle is designed to support explosive ordnance disposal activities directed by civilian authorities. The tracked vehicle can climb stairs and the wheeled vehicle can operate quicker and turn faster on flat ground. The two-part manipulating boom can be extended to 2.1 m (81 in.) on the tracked and to 2.2 m (84.6 in.) on the wheeled vehicle. The complement of standard equipment includes an upper and lower boom, a video camera used for inspection, a 15-kg (33-lb) cable reel, a control console, and wheels. Optional accessories include a second video camera to assist in maneuvering the vehicle, floodlights, a water disrupter, for explosives, a boom extension kit, a rake, a grab, an argon purge cylinder rack, and a thermal imaging clamp. The dimensions for this 95 kg (209 lb) chassis are 1120 x 600 x 370 mm (l x w x h) (44.1 x 24.4 x 14.6 in.) without the superstructure; the height of RO-VEH with the superstructure is 460 mm (18.1 in.). The turning circle for the vehicle is 1.2 m (3.9 ft) and the maximum speed is 15.6 m/min (51 ft/min). The 2500 VA power requirements via 220-240V, 50 Hz or 110-120V, 60 Hz can be supplied by house power or by an optionally available 220V portable generator through the 100-m (328-ft), steel reinforced cable. This cable can be used to drag the device out of trouble. All commands are digitally coded. RO-VEH can tow a full-sized vehicle and can act as a hose-supporting firefighter.

27. (No Name)

Japan Atomic Energy Research Institute, Tokai, Ibaraki, Japan

This tethered device is a remotely controlled, 2-tracked vehicle which is used in the nuclear industry. The 7-axis manipulator arm, including one for the fingers, weighs 38 kg (84 lb), can lift 2 kg (4.4 lb), and has a gripping force of 15 kg (33 lb). The fingers have weight and force sensing sensors (force feedback) and the arm can be extended to 1.2 m (47 in.). The manipulator can be controlled by a master-slave unit (located at the control console), teach and playback, or by a programmed control mode. The system is controlled by two microcomputers. The package of on-board sensory equipment includes four sets of ultrasonic transmitters used to measure the distance between obstacles and the vehicle, four sets of strain gauges (for force feedback of the manipulating arm fingers), a video camera, and a microphone. The manipulator support system is directed to supporting a manipulator in the reactor vessel and is a tripedal mechanism which has three independently extendable legs for horizontal support. The dimensions of the vehicle chassis are 1000 x 700 x 400 mm (l x w x h) (39.8 x 27.5 x 15.7 in.) and the maximum speed is 3 m/min (10 ft/min). The vehicle with all the mounted equipment weighs 180 kg (397 lb) and can surmount a 100 mm (3.9 in.) high obstacle. Electric power is supplied either by two on-board batteries or by a cable from a power supply unit installed in the control station.

28. HOBO

Kentree, Ltd., Kilbuttain, County Cork, Ireland
Winn Technology Ltd., New York City, N.Y., U.S. Distributor

This tethered, remotely controlled, 6-wheeled vehicle was designed to support explosive ordnance disposal activities directed by civilian and military authorities. Its manipulation arm can reach 2.4 m (8 ft) and possesses a 229-mm (9-in.) claw. The following standard equipment is available for the HOBO: an electronic range finder, three video cameras with lights, two water disrupters, a front-mounted shovel which can lift 91 kg (200 lb), rear load hod, firing cable reel, a car tow hook, grapple, and a rope reel. The operation console has a deep-view TV monitor, 5-axis manipulator joystick, and vehicle controllers. On-board batteries can be charged via a 229-m (750-ft) umbilical cord, which is mounted on a slip ring drum, from a power unit accommodating 12/24V dc and 100-260V, 50-90 Hz.

29. ATOM

Lawrence Livermore National Laboratory, Livermore, CA

This tethered, remotely controlled, 2-tracked vehicle was designed for the nuclear industry. It uses six 12V batteries for propulsion power and two 12V batteries for communications and video operation. ATOM can climb stairs. Its robotic arm has 6 degrees of freedom and can lift a load of 20 kg (44 lb) 750 mm (30 in.) from the shoulder. Control input and sensor output from the machine is through a 305-m (1000-ft) coaxial cable which is stored on board the vehicle. A 1524-m (5000-ft) optical fiber control cable can be inserted in the system with appropriate transducers. There are three video cameras, one of which is set up for 3-D viewing. There are provisions for an optional two-way radio control system. An on-board computer operates with a computer in the control unit; this controls some of the arm functions. On-board sensory equipment includes ultrasonic range finders, radiation detectors, and a neutron detector. There are monitors for internal machine functions, such as temperature.

30. MEIROBO

Meidensha Electric Manufacturing Co., Ltd., Japan

This tethered, remotely controlled, 2-tracked robot has been developed to remove sludge in garbage disposal and sewage plants. It then transfers these products to a tank placed outside the sludge pit. The system consists of a cleaning robot, controller, and a video camera. Elimination of the accumulated sludge is achieved by a high-pressure jet unit installed in the front and rear of the robot and a suction hose. The operation of the robot can be directed by either an automatic or a manual controlled mode. The dimensions of this 170-kg (375 lb) device are 480 x 950 x 245 mm (l x w x h) (18.9 x 37.4 x 9.6 in.) and the driving speed is 6 m/min (20 ft/min). Its absorption capacity is 18 cu m/hr (645 cu ft/hr). This robot requires two-three operators.

31. DCR (Duct-Cleaning Robot)

Meidensha Electric Manufacturing Co., Ltd., Japan

This tethered, remotely controlled, 4-wheeled robot has been designed to remove dust, microorganisms, and particles which have accumulated in air conditioning ducts. The dust, etc. material in the duct is removed from the surface by a rotary brush attached to the lower section of the robot and removed by vacuum suction. The robot is designed to clean both the vertical and horizontal surfaces and its operation can be conducted by either a manual mode or by automatic remote control using a microcomputer. The dimensions of this 25-kg (55 lb) robot are 280 x 600 x 240 mm (l x w x h) (11.0 x 23.5 x 9.4 in.). The driving speed of this robot, which requires 1-2 operators, is 5-12 m/min (16-39 ft/min). The control unit contains ROM and RAM microprocessors using 32KB of memory.

32. DIR (Duct Inspection Robot)

Meidensha Electric Manufacturing Co., Ltd., Japan

This tethered, remotely controlled, 4-wheeled robot has been designed to assist the Meidensha DCR duct-cleaning robot; this robot's video camera monitors the duct-cleaning work. Its operation can be controlled by either a manual mode or by automatic remote control using a microcomputer. The dimensions of this 20-kg (44 lb) robot are 280 x 500 x 235 mm (l x w x h) (11.0 x 20.0 x 9.3 in.). The driving speed of this robot is 5-12 m/min (16-39 ft/min). The control unit contains ROM and RAM microprocessors having 32 KB of memory.

33. (No Name)

Ministry of Trade and Industry, Japan

This tetherless, remotely controlled, 4-tracked vehicle has been designed to operate in nuclear power plants. The vehicle is able to climb stairs and is equipped with batteries for DC motors and electrical circuits. The vehicle motors are controlled automatically by microcomputers combined with EM wave guide along the limited space for position correction. A wireless telecommunication system is employed for remote communication between the vehicle and the control station.

34. (No Name)

Mitsubishi Heavy Industries, Ltd., and Kobe Shipyard & Engine Works, Japan

This tethered, remotely controlled, 3-wheeled device was designed to conduct ultrasonic flaw inspections of guide tube support pins in nuclear power plants. It operates underwater on the cavity floor. On-board sensory and other instrumentation items include: video camera with pan-and-tilt mechanism, lights, ultrasonic sensor, and wheel rotation driving mechanism monitor. The dimensions of this device are: 900 x 750 x 470 mm (l x w x h) (35.4 x 29.5 x 18.5 in.).

35. (C/V Robot)

Mitsubishi Heavy Industries, Ltd., and Kobe Shipyard & Engine Works, Japan

This tetherless (?), remotely controlled device was designed to conduct maintenance functions during the operation of nuclear power plants. Some of the functions include (manipulating) operating valves, light work with special tooling, and periodic inspection. This device possesses 8 legs, each of which has a wheel (at the bottom of the leg). A 7-axis master-slave manipulator arm with a force sensor can lift 10-20 kg (22-44 lb). The vehicle can transport 200 kg (440 lb). The dimensions of this vehicle are: 500-2000 x 500 x 1500-2200 mm (l x w x h) (19.7-78.8 x 19.7 x 59.0-86.6 in.). The range in length and height dimensions reflect the changes in physical configuration of the device as it "walks" and maneuvers. The maximum speed of this vehicle, which can traverse over rough surfaces, is 3 m/min (9.8 ft/min). The on-board control unit possesses a CPU-type computer and has 128 KB of extendable memory.

36. (No Name)

Mitsubishi Heavy Industries, Ltd. and Kobe Shipyard & Engine Works, Japan

This tethered, remotely controlled, 4-wheeled device was designed to clean cooling water channels and culverts underwater. The robot mechanically removes aquatic life which adheres to the side, top, and bottom walls of concrete channels with an impeller and rotating brush. The reacting forces due to the jet of water from the impeller sucks the robot to the side, top and bottom walls of these channels. The robot moves by means of independent wheels. The body of the robot is designed to become weightless in the water while maintaining its position in relation to the wall being cleaned. The dimensions of this robot are: 1780 x 1270 x 800 mm (l x w x h) (70.1 x 50.0 x 31.5 in.).

37. HADRIAN

Monitor Engineering Ltd., Wallsend, England
Monitor Robotics, Inc., Houston, TX US Distributor

This tethered, remotely controlled, 6-wheeled device was designed to support explosive ordnance disposal missions directed by civilian and military authorities. A front-mounted lift scoop can lift and carry 75-kg (165-lb) objects. The on-board manipulator arm can extend to 28.7 m (94 in.) and its claw can lift 10 kg (22 lb). The complement of on-board sensory and other equipment includes: three video cameras, a water disrupter, a floodlight, and microphones which can carry two-way communications. The rechargeable 240V power source is provided via a 226-m (740-ft) umbilical control cable, which also transmits the video images. The umbilical cable control arm is fitted near the rear axle and pivots to keep the cable clear of the wheels and accessories while the vehicle is maneuvering. The dimensions of this 373-kg (822-lb) vehicle are: 1702 x 659 x 787 mm (l x w x h) (677 x 27 x 31 in.). The arm can reach up to an elevation of 2.7 m (9 ft). The turning circle for the HADRIAN is its own length of 1702 mm.

38. ROBOTEER

MBAssociates International, San Ramon, CA

This tethered, remotely controlled, 2-tracked device was designed to serve as an explosive ordnance disposal and surveillance vehicle for the military. It can maneuver in open terrain (soft, muddy, or steep) and indoors (can climb stairs and surmount small obstacles). Its 7-axis manipulator arm can lift 11.3 kg (25 lb) with a 1092 mm (43 in.) reach. In addition to the standard equipment package, which includes a video camera, optional sensory and instrumentation items include AC to DC inverter, portable gasoline-powered motor generator, audio transponder (which allows two-way communication and sound transmission), water proofing, vehicle-mounted rechargeable battery power supply, pulse width modulation command system, and a minicomputer for autonomous control of the system. The dimensions for this 127-kg (280-lb) vehicle are: 1016 x 508 x 1143 mm (l x w x h) (40 x 20 x 45 in.) (with video camera and manipulating arm in the stowed positions). The 250-W, 117V, 60-Hz power requirements are provided by a 30.5-m (100-ft) control cable [optional extension to 152 m (550 ft)].

39. WHEELBARROW

Morfax, Ltd., Mitcham, England
NAECO Associates, Inc., Arlington, VA, U.S. Distributors

This tethered/tetherless, remotely controlled, 2-tracked device was designed to serve as an explosive ordnance disposal vehicle for civilian and military authorities. The on-board boom, which can support a variety of equipment, can be extended to 2.4 m (8 ft) and its electro-mechanical grab can pick up 208-L (55-gal) drums. Power is supplied by two on-board 12V, 50 amp-hr lead-acid batteries which must be charged after each 2 hours of operation. The charging can be made via the built-in trickle charger or by removal of the batteries for rapid boost charge. The range of the standard cable and drum (storage facility for the cable) is 100 m (300 ft). The dimensions for this device are: 1220 x 686 x 1372 mm (l x w x h) (48 x 27 x 54 in.). The maximum speed for the 182-kg (402-lb) WHEELBARROW is 33 m/min (110 ft/min). The video camera can operate with a separate 12V lead-acid battery. An optional radio communication package eliminates tether requirements.

40. MARAUDER

Morfax, Ltd., Mitcham, England
NAECO Associates, Inc., Arlington, VA, U.S. Distributors

This tethered, remotely controlled, 6-tracked device was designed to serve as an explosive ordnance disposal vehicle for military and civilian authorities. It is two-armed and supports a host of sensory and instrumentation items. It is able to climb stairs and surmount obstacles.

41. MF3

NTG Nukleartechnik GmbH, West Germany
Scientific International, Inc., Princeton, N.J., U.S. Distributor

This tethered, remotely controlled, 4-tracked device was designed to operate in the nuclear industry. It was initially conceived and developed at the KFA Julich Research Laboratory in West Germany. The vehicle is similar to the MF3 device manufactured by Blocher-Motor GmbH & Co. The power supply for an alternate model is provided by interchangeable storage batteries and motor-generator power modules. Radio control is available as an optional communication technique.

42. (No Name) (2 arms)

NTG Nukleartechnik GmbH, West Germany
Scientific International, Inc., Princeton, NJ, U.S. Distributor

This tethered, remotely controlled, 4-tracked vehicle was designed to operate in the nuclear industry. The device has two master-slave, bilateral manipulating arms, each having force feedback (reflecting) grippers, mounted on the same chassis as that used for the MF3. Each arm has six degrees of freedom and will have the capacity to lift 20 kg (45 lb). This device will have the ability to climb stairs, maneuver within buildings, and travel over moderately rough terrain. This device will possess three high-resolution video cameras and will be able to be controlled by optional wire or radio techniques.

43. ODEX-1 (Fig. 8)

Odetics, Inc., Anaheim, CA

This tetherless, remotely controlled, 6-legged device was designed to serve as a test platform for other similar devices to be employed in a variety of hazardous industries. Each of the articulated legs is controlled by a computer; a seventh computer is used to interface with the other six and is used for supervisory control. The ODEX can assume different postures and can maneuver through standard doorways as well as climb stairs without the aid of the teleoperator. The 168-kg (370-lb) vehicle is able to lift 816 kg (1800 lb); each of the legs can be used as an individual transporter and can lift 136 kg

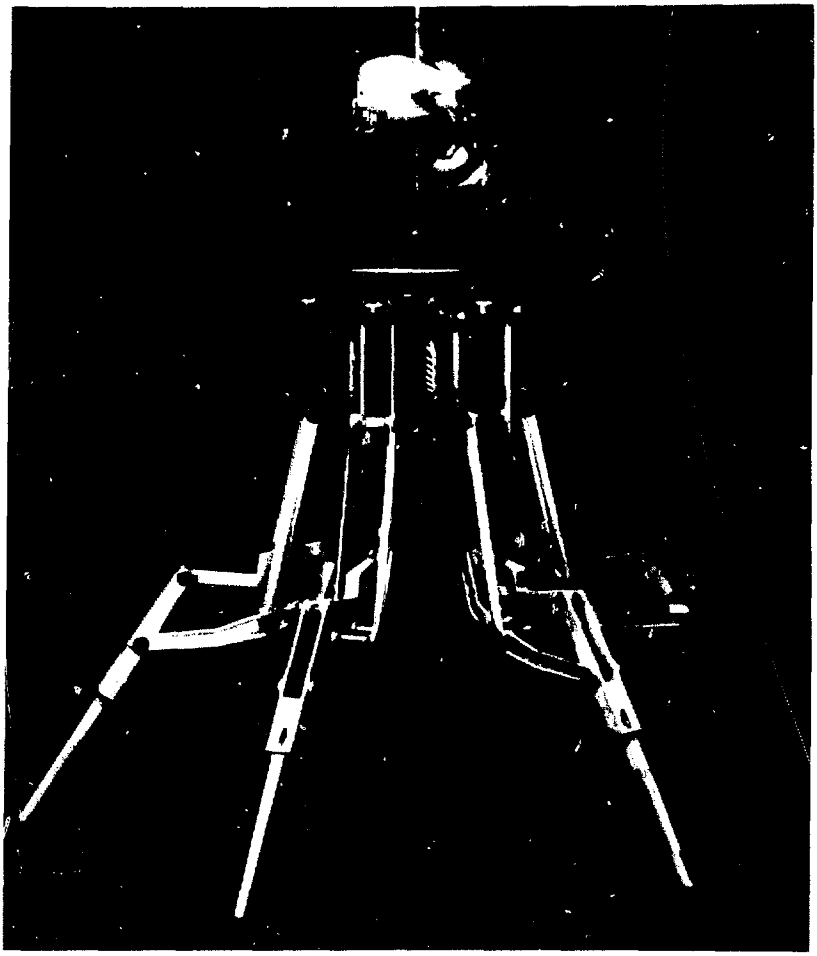

FIGURE 8 ODEX-1, Odetics, Inc.

(300 lb). The total load capacity of the robot is 204 kg (450 lb) in a moving mode and 272 kg (600 lb) while stationary. The dimensions of the ODEX-1 are: 686 x 1219 mm (d x h) (27 x 48 in.) in the tucked position; the top of the platform is 1981 mm (78 in.) high when fully extended and 914 mm (36 in.) high in the squat/low position. An articulator (leg) can reach up to a height of 1651 mm (65 in.). The stepping height of the vehicle is 762 mm (30 in.). It can carry a variety of sensory equipment and possesses a pair of CCD cameras. The sensors located in each leg can detect obstacles and assist the device in its stair-climbing mode. The power supplied by a 24V AH aircraft battery (360 watt-hours) will enable the ODEX-1 to operate 1 hour between charges.

44. ODEX-N

Odetics, Inc., Anaheim, CA

This tetherless, remotely operated 6-legged device is being developed to opera in the nuclear industry. The sponsor for this development effort is the Electric Pov Research Institute. Although it is similar to the ODEX-1, it will have a special platfo and an on-board manipulator arm which will enable the device to conduct so maintenance activities in the nuclear plant. The dimensions of this 408-kg (900-lb) rol will be 610 x 1346 mm (d x h) (24 x 53 in.) in the stowed position. The elevation of base of the working platform in the fully extended vertical position will be 2.134 m in.) and the bottom of the body assembly will be 0.914 m (36 in.) above the floor. T manipulator will be able to reach to an elevation of 4.470 m (176 in.) when fully extend and will be able to vertically lift a 113-kg (250-lb) load when extended to a 1.83 m (6 horizontal reach. The maximum stationary, vertical centerline lift of the robot will 2041 kg (4500 lb) with all six legs placed on a flat floor; it can transport a centerli balanced load of 454 kg (1000 lb) with a tripod gait on a flat floor. It can carry centerline balanced load of 181 kg (400 lb) with a tripod gait on any terrain or stai The on-board sensory/equipment package will consist of measurements of temperatu pressure, humidity, liquids, radiation levels, contamination/dust, EMI, and sound. It w carry its own illumination and possesses 2 CCD cameras.

45. ODEX-A

Odetics, Inc., Anaheim, CA

This remotely controlled 6-legged device is being developed for applications the agriculture industry and is similar to the ODEX-1 robot.

46. ODEX-M

Odetics, Inc., Anaheim, CA

This remotely controlled 6-legged device is being developed for applications f the military and is similar to the ODEX-1 robot.

47. RMI (Remote Mobile Investigation Unit)

Pedsco Canada, Ltd., Scarborough, ON, Canada

This tethered/non-tethered, remotely controlled, 2-armed, 6-wheeled device w developed to support explosive ordnance disposal activities. The dimensions for this 10 kg (230-lb) vehicle are: 1016 x 660 x 457 mm (l x w x h) (40 x 26 x 18 in.) for the chass the height is 711 mm (28 in.) with the boom structure (the supporting member for the tw arms) down and 1524 mm (60 in.) with the boom structure up. The length of the fro arm is 559 mm (22 in.) in the horizontal position and that for the back arm is 787 mm (

in.). Each arm can pick up 32 kg (70 lb) and the grippers have some sensitivity for a "soft touch" for fragile objects and a powerful grip for heavy objects. The hand can be easily removed and a number of universal accessories (tools) can be attached in its place. The boom can be easily removed from the main unit by removing two pins and one multi-connector. The device is powered by two 12-volt lead/acid batteries, each of which can be charged by a system-supplied battery charger. The maximum speed of the RMI is 80 m/min (3 mph) and its movements are controlled by a joystick. The on-board sensory/equipment package consists of a video camera, water disrupter, stethoscope, car hook (for towing other vehicles), and an x-ray system. The operator's dolly (control station) contains a video monitor, battery charger, cable drum, and a public address system.

48. MOOSE (Fig. 9)

Pentek, Inc., Coraopolis (Pittsburgh), PA

This tethered, remotely controlled, 6-wheeled vehicle was developed for the nuclear industry and is to be used as a "scabbler" for the removal of surface contamination in facilities which are being decontaminated or decommissioned. The dimensions of the 256-kg (570-lb) chassis, which was supplied by the Standard Manufacturing Co. (Dallas, TX) are: 1270 x 734 x 483 mm (l x w x h) (50 x 29 x 19 in.). The ground clearance for the chassis is 127 mm (5 in.) and it is supplied by 110V (house power). The size of the scabbler, which contains seven 57.15-mm (2.25-in.) diameter tungsten-carbide tips, is 381 x 178 mm (l x w) (15 x 7 in.). The scabbler requires 4955 L/min (175 scfm @ 80 psi) air and operates at a frequency of 1200 strokes/min. The self-contained vacuum system dual HEPA filters, five primary filters, and a dust/debris/liquid collector. The normal operating vacuum range is 6-27 in WG and the flow is 4247 L/min (150 scfm). The air consumption for the scabbler is 1833 L/min (65 scfm @ 80 psi). The dual filters are 203 x 203 mm square (8 x 8 in.) cartridges which are 99.97% efficient for 0.3 micron particles. The primary filters are self-cleaning cartridge type pleated papers and have a total surface area of 2.32 square meters (250 square ft). The capacity of the collector is 0.10 cubic meters (3.4 cubic ft or 25 gal). The MOOSE can cover a floor area of up to 37.2 square meters (400 square ft) per hour at a 1.59 mm (0.0625 in.) depth-of-cut, which can range from 0 - 4.77 mm (0 - 0.1875 in.). The path width is 483 mm (19 in.) and the vacuum pressure is 203 mm (8 in.) mercury. The tether length is 15 m (50 ft).

49. SURBOT

REMOTEC, Oak Ridge, TN

This tethered, remotely controlled, 3-wheeled device will be used for surveillance and maintenance missions in nuclear power plants. This 181-kg (400-lb) device can maneuver through standard doorways, can climb 15-degree slopes, and can travel through 76 mm (3 in.) deep water. It can travel in a forward or reverse mode, turn with a 0-degree turn radius, and climb over 38-mm (1.5-in.) high obstacles. The on-board sensory/equipment package consists of a video camera, sound detection, temperature measurement, humidity level indication, radiation measurements, and lights. The cable

FIGURE 9 MOOSE, Pentek, Inc.

reel is located on the device. Room air and contamination smear samples can be obtained. The manipulator arm can lift 10 kg (22 lb) and a telescoping arm onto which the camera and lights (with their pan-and-tilt mechanisms) are mounted can be raised 4.27 m (14 ft). The vehicle can be decontaminated.

50. PROWLER

Robot Defense Systems, Inc., Denver, CO

This remotely controlled, tetherless, 6-wheeled robot is to be employed as a security device which conducts perimeter patrols and intruder detection missions. The weight of this vehicle is 907 - 1814 kg (2000 - 4000 lb) and it can draw bar pull 1949 kg (4297 lb). The gasoline engine can propel the PROWLER at speeds of up to 27 km/hr

(16.8 mph). The on-board 32-bit microprocessors (M68000 class) enable the vehicle to have a high degree of autonomy. The on-board equipment/sensory package consists of 2 video cameras, laser range finder, multiaxis vehicle attitude sensors, distanced measuring sensors, infrared scanners, two-way communication systems, electromagnetic motion detector, and a seismic monitor.

51. HAZCAT-M500

Robotic Systems International, Ltd., Sidney (Victoria), BC Canada

This tetherless, remotely controlled, 4-wheeled, modified fork-lift truck is to be used in chemically hazardous and nuclear environments. It possesses two robotic arms in addition to the normal complement of lifts and back hoes. The teleoperator/vehicle communication is made through radio control or umbilical systems. The on-board equipment/sensory package consists of video cameras, selectable tools, microphone and speakers, lights, life support cab, and an umbilical cord reel. The control console contains the robotic arm controls, lift controls, steering wheels, system status monitors, and a video monitor. The device can package and seal/unseal and transport 55-gal drums, each weighing up to 295 kg (650 lb).

52. HAZCAT-M100

Robotic Systems International, Ltd., Sidney (Victoria), BC Canada

This tetherless, remotely controlled 4-wheeled vehicle was designed to operate in chemically and radioactively hazardous environments. The communications between the teleoperator and the device is by radio. This HAZCAT model supports a video camera and a robotic arm which can lift 454 kg (1000 lb).

53. WORM

Rocky Flats Plant, U.S. Dept. of Energy, Rockwell International, Rocky Flats (Denver), CO

This tethered/tetherless, remotely controlled, 2-tracked vehicle was designed to operate in nuclear facilities. It has a 5-degree-of-freedom manipulator arm and an on-board video camera. Although the battery-powered WORM is normally controlled through a coaxial cable, a radio control system has been employed.

54. HUNTER

SAS R & D Services, Ltd., Beaconsfield, Bucks, England

This tethered/tetherless, remotely controlled, 2-tracked/2-wheeled device was designed to serve as a vehicle to assist explosive ordnance disposal activities. This device has a telescoping boom/arm which is able to lift 100 kg (220 lb). The boom can be extended to a length of 3 m (9.8 ft). The chassis weight of the vehicle is 115 kg (254 lb) and its dimensions are: 1200 x 630 x 350 mm (l x w x h) (45 x 25 x 14 in.) with the hamper housing the boom lowered and 480 mm high (51 in.) with the hamper raised. The vehicle is powered with two 12V batteries which can be charged with a battery charger located on board the HUNTER. The package of sensory/equipment consists of a video camera, portable X-ray, water disrupter, long and short reach cranked arms, a scoop, scissors grip, a car hook and rope, two 24V dc power outlets, a window breaker, and a stethoscope (explosives detector). A second pair of CCD or video cameras provides the teleoperator of the HUNTER with a 3-D image of the environment. Although the device is normally controlled by a cable, an optional radio-controlled communication system is available. The mobility and the speed on the vehicle can be enhanced in the field by placing two wheels at the rear of the HUNTER (to augment the 2 tracks, the "Travads" system).

55. HUNTER (2 arms)

SAS R & D Services, Ltd., Beaconsfield, Bucks, England

This tethered/tetherless, remotely controlled, 2-tracked/2-wheeled device was designed to serve as a vehicle to assist explosive ordnance disposal activities. This device is similar to the one-armed HUNTER vehicle described elsewhere.

56. MARS-V (Multipurpose Area Remote Surveillance Vehicle)

Standard Manufacturing Co., Inc., Dallas, TX

This tethered, remotely controlled, 6-wheeled vehicle serves as a base platform (transporter) for several other devices used in hazardous environments: (1) the Carnegie-Mellon University RRV used in the TMI-2 nuclear power plant; (2) the Carnegie-Mellon University REMOTEBORER used in the TMI-2 plant; (3) the Viking Energy Corp. ROD mobile vehicle with robotic arm used in the to-be-decommissioned West Valley Chemical Plant (for reprocessing nuclear fuel); and (4) the Pentek Inc. MOOSE vehicle used in various nuclear facilities to remove ("scabble") contaminated layers from the surface of floors. The dimensions of this 259-kg (570-lb) transporter are: 1270 x 734 x 483 mm (l x w x h) (50 x 29 x 19 in.). The payload capacity is 227 kg (500 lb) and its ground clearance is 100 mm (5 in.). The 100-m (300-ft) tether supplies 110V power to the vehicle, which has a top speed of 66 m/min (0.25 mph). The MARS-V can climb a 32-degree slope while carrying 63% of its maximum payload.

57. (No Name)

Sumitomo Electric Industries, Ltd., Japan

This tethered, remotely controlled, 3- (or more) wheeled device was designed to serve in the nuclear industry. The vehicle can recognize routes and its 6-degree-of-freedom arm has a 2-fingered gripper. Communication with the vehicle is through a multichannel fiber-optic cable and the motions of the arm and the device can be controlled by voice and recognizable commands. The dimensions of the main body, which weighs 100 kg (220 lb), are: 1000 x 600 x 1200 mm (l x w x h). There are several computers which assist in the direction of the vehicle: one for a three-stage hierarchal control, one minicomputer, three 16-bit microcomputers, and eleven 8-bit microcomputers; there is 99 kb of ROM and RAM. The package of on-board sensors and equipment include: position access readers, video camera, object recognition route detector, and collision avoidance detectors. The maximum speed of the vehicle is 15 m/min (50 ft/min).

58. TELEMAC (Fig. 10)

ACEC, Charleroi, Belgium, and
Teleoperator Systems, Inc., Bohemia, Long Island, NY (and U.S. Distributor)

This tetherless, remotely controlled, 6-tracked vehicle was designed to operate in the nuclear industry. It has two bilateral, force feedback reflecting arms, each of which has 6 degrees of freedom and can lift 10 kg (22 lb). The arms can be extended to reach an elevation of 2.25 m (82 in.) above the floor. The minimum dimensions of this 450-kg (995-lb) vehicle are: 690 x 690 mm (l x w) (27.1 x 27.1 in.) when the tracks are folded up and the length is increased to 1440 mm (56.5 in.) when the tracks are fully extended (for normal mobility). The TELEMAC can climb 45-degree stairs while the track configuration assumes a different geometry. The device, the base of which was supplied by the Morfax Co. (England), can travel at speeds of up to 42 m/min (138 ft/min). The on-board equipment/sensor package includes: video camera, radiation sensors, temperature measurements, pressure readings, humidity levels, fault-indicating diagnostics, and vibration readings. The data transmission/communication technique is wireless and there is a one-way transmission of the video image. Power is supplied by on-board batteries which must be charged every 1.5 hours. The degree of on-board intelligence enables the TELEMAC to follow a pre-layed bar code path in an automatic mode and to retrace its path.

59. WASP-700 (Fig. 11)

21st Century Robotics, Inc., Norcross, GA

This tetherless, remotely controlled, 4-wheeled device was designed to serve as an explosive ordnance disposal and surveillance vehicle for military and civilian authorities. It is powered by an 18 hp gasoline engine and utilizes a 4-wheel independent

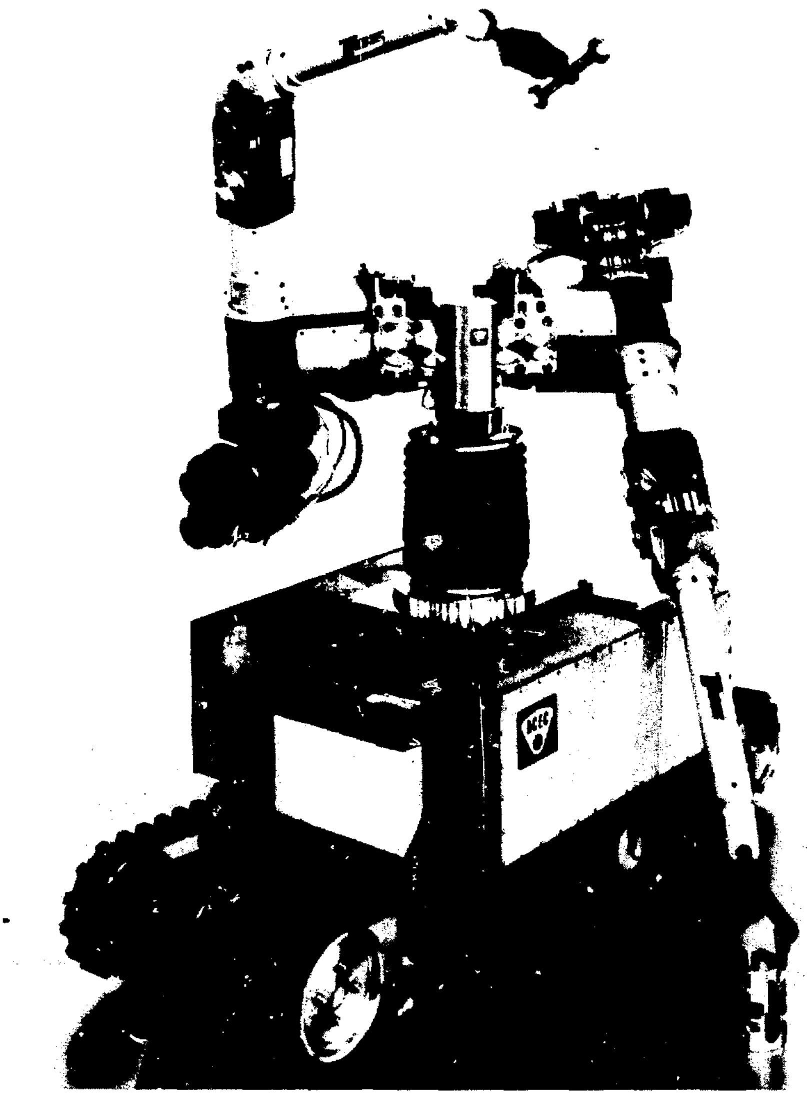

FIGURE 10 TELEMAC, ACEC and Teleoperator Systems, Inc.

drive system. The WASP-700 features a 7-degree-of-freedom arm with a maximum lifting capacity of 110 kg (240 lb) with the arm not extended and 50 kg (110 lb) with the arm fully extended to 2.5 m (100 in.). The vehicle is capable of traveling over most terrain and water up to 305 mm (12 in.) deep. Indoors, the WASP can climb stairs. It has a maximum speed of 12 km/hr (7.5 mph) and can maintain continuous operation for periods up to 9 hours. The dimensions of this 700-kg (1543-lb) vehicle are: 1700 x 1040 x 1150 mm (l x w x h) (67 x 40 x 45 in.). It can tow a 100-kg (220-lb) load on the ground and up to 1500 kg (3307 lb) on wheels (a full-sized vehicle). On-board equipment includes two video cameras, 6 halogen-projection lamps, a pyrotechnic chisel installed on the arm, a

FIGURE 11 WASP, 21st Century Robotics

smoke screen generator, a tear gas launcher, and a water disrupter. Remote firefighting is made possible via arm mount attachment which enables the device to maneuver a 38 mm (1.5-in.) diameter fire hose. The remote-controlled system is controlled by a microcomputer and the communications are made via UHF and VHF antenna. Communication to and from the vehicle can be made to a distance of up to 1.5 km (0.8 mile) in a built-up area and up to 3 km (1.9 mile) in open territory.

60. TSR-150

21st Century Robotics, Inc., Norcross, GA

This tetherless, remotely controlled, 2-tracked device is designed to serve as an explosive ordnance disposal vehicle for military and civilian authorities. It carries 2 video cameras and a 6-degree-of-freedom manipulator arm which can lift 12 kg (26 lb) when fully extended. It is equipped with a quick-charge battery pack and has a range of optional accessories, such as explosive detectors, gas or chemical fume detectors, and radiation detectors. The dimensions for this 150-kg (331-lb) device are 1100 x 600 x 800 mm (l x w x h) (43.3 x 23.6 x 31.5 in.). This device is operated by Remote control from distance of 1.5 km (0.8 mile) or 3 km (1.9 mile), depending upon the terrain. It can travel at a speed of 53.6 m/min (2 mph) and can operate for 2 hours between charges. Wheels can be added to this vehicle to give it additional manueverability and more rapid travel in open terrain. A fiber optics control cable is an available option. A special designed encoded digital control system prohibits interference from other extraneous signals and allows operation of more than one vehicle simultaneously. The VHF return link allows the robot to collect various data from a variety of sensory equipment.

61. TSR-50

21st Century Robotics, Inc., Norcross, GA

This tetherless, remotely controlled, 2-tracked device is designed to serve as an explosive ordnance disposal vehicle for military and civilian authorities. It carries 1 video camera and a 4-degree-of-freedom manipulator arm which can lift 2 kg (4.4 lb) when fully extended 500 mm (19.7 in.). It is equipped with a quick-charge battery pack and has a range of optional accessories, such as explosive detectors, gas or chemical fume detectors, and radiation detectors. This device is operated by Remote control from distance of 1.5 km (0.8 mile) or 3 km (1.9 mile), depending upon the terrain. The dimensions for this 50-kg (110-lb) vehicle are: 600 x 350 x 700 mm (l x w x h) (23.6 x 13.8 x 27.6 in.). A fiber optics control cable is an available option. A special designed encoded digital control system prohibits interference from other extraneous signals and allows operation of more than one vehicle simultaneously. The VHF return link allows the robot to collect various data from a variety of sensory equipment.

62. ARM (Articulated Remote Manual)

U.S. Bureau of Mines, Spokane, WA

This wheeled ARM is an automatic roof-bolter for coal mines which enables an operator to perform roof-bolting functions remotely from a position under a canopy protection and permanent roof support. The manual dexterity, memory, logic, audio, visual, and sensory capabilities of the operator have been replaced. The roof-bolter component assembly carriage houses a flexible roof drill, roof-bolt inserter, torque thrust assembly, plate magazine, and feed and receive mechanisms.

63. REM (Remote Manual Bolter)

U.S. Bureau of Mines, Spokane, WA

The wheeled REM is a semiautomatic roof-bolter for coal mines which enables an operator to perform remotely controlled roof-bolting functions. After the REM has been placed into a position, holes for roof bolts are drilled. The roof-bolt inserter is mounted on a track which allows it to slide back near the operator where the assembled bolt is manually placed into the inserter. The inserter then rides to the position under the pre-drilled hole, from which the drill has been removed and stored, and inserts the bolt into the hole. After the bolt is stowed, the floor jack is released and the REM is then ready to be placed into the next bolting position.

64. MRS (Mobile Roof Support)

U.S. Bureau of Mines, Spokane, WA

The 4-wheeled, remotely operated, battery-powered MRS is used to support roofs of coal mines in retreat mining applications. It carries four jacks, two on the body of the machine and two at the end of hinged arms. The jacks extend to form columns between the floor and the roof, each up to 23 te (50 tons) of potential support. The jacks are hydraulically locked into place and the load is distributed to three points on each jack, thereby eliminating loads to the machine chassis. A second-generation machine consists of independently controlled crawlers that exert less than 20 psi ground pressure. The machine is powered by a 40-hp, 460V AC permissible motor from a 78-m (260-ft) reeled trailing cable and transmitter Remote controls. The device can travel up to 24 m/min (80 ft/min) on a 20-degree slope and is free-wheeling for emergency tow. Stability of the machine is maintained by 300 mm (12 in.) high front and back mounted dozer blades.

65. ROVER

U.S. Navy Ordnance Disposal, Indian Head, MD

This tethered, remotely controlled 2-tracked vehicle was designed to serve as an explosive ordnance disposal device for the U.S. Navy. It is battery powered and carries video cameras, a boom which carries appropriate end-effectors which can manipulate and carry large-diameter objects. The tether provides a conduit for data transmission and communication to and from the device.

66. RCFF (Remote Controlled Fire-Fighter)

U.S. Navy, White Oak, MD

This tethered, remotely controlled, 2-tracked device was designed to serve as a firefighter. The dimensions of the device are: 1524 x 914 x 1219 mm (60 x 36 x 48 in.). It drags its hose to the location of the fire and can direct a 100 psi water jet at a rate of 1890 L/min (500 gal/min) toward the fire. It can connect up to any standard fire hydrant.

67. SISI (System In-Service Inspection)

Hanford Engineering Development Laboratory, Westinghouse-Hanford Company, Richland, WA

This tethered, remotely controlled, 2-tracked device assisted in the initial surveillance around the makeup water system and purification demineralizer in the auxiliary building of the TMI-2 plant. In addition to monitoring radiation levels and providing a video image of the inspected area, SISI provided a computer-controlled MICROBOT robotic arm to take smear samples from the floor area. The power for this 11.3-kg (25-lb) vehicle was supplied by cable.

68. ROD (Fig. 12)

Viking Energy Company, Pittsburgh, PA

This tethered, remotely controlled, 6-wheeled device was designed to assist in the decommissioning of nuclear facilities; the first plant it will be used in is the West Valley Chemical Plant, N.Y., for reprocessing nuclear fuel. The on-board industrial robotic arm supplied by the American Robot Company, Pittsburgh, Pa., is able to lift up to 22.7 kg (50 lb), depending upon the model of the arm. The working envelope of the arm is 1016 or 1524 mm (40 or 60 in.), depending upon the arm model. Various end-of-arm tooling permits ROD to conduct specific missions and tasks, such as sand-blasting, pipe cutting, and vacuuming. In addition to being able to clear 100-mm (4-in.) high obstacles, ROD can climb slight inclines and pull (with its on-board drawbar) up to 590 kg (1300 lb) on a dry pavement. Both the tether and the wheels are capable of being decontaminated by spray cleaning or wiping. Video signals, radiation monitor readings, and power supply are transmitted along a 61-m (200-ft) cable. The robot arm can be controlled by joystick or by programming; its controller is a 32-bit architecture, Motorola MC68000 based UNIX operating system. The dimensions of the Standard Manufacturing Co. (Dallas, TX) supplied base are 1270 x 734 x 483 mm (l x w x h) (50 x 29 x 19 in.). The weight of the vehicle is in excess of 544 kg (1200 lb), including the 304-kg (670-lb) industrial robotic arm.

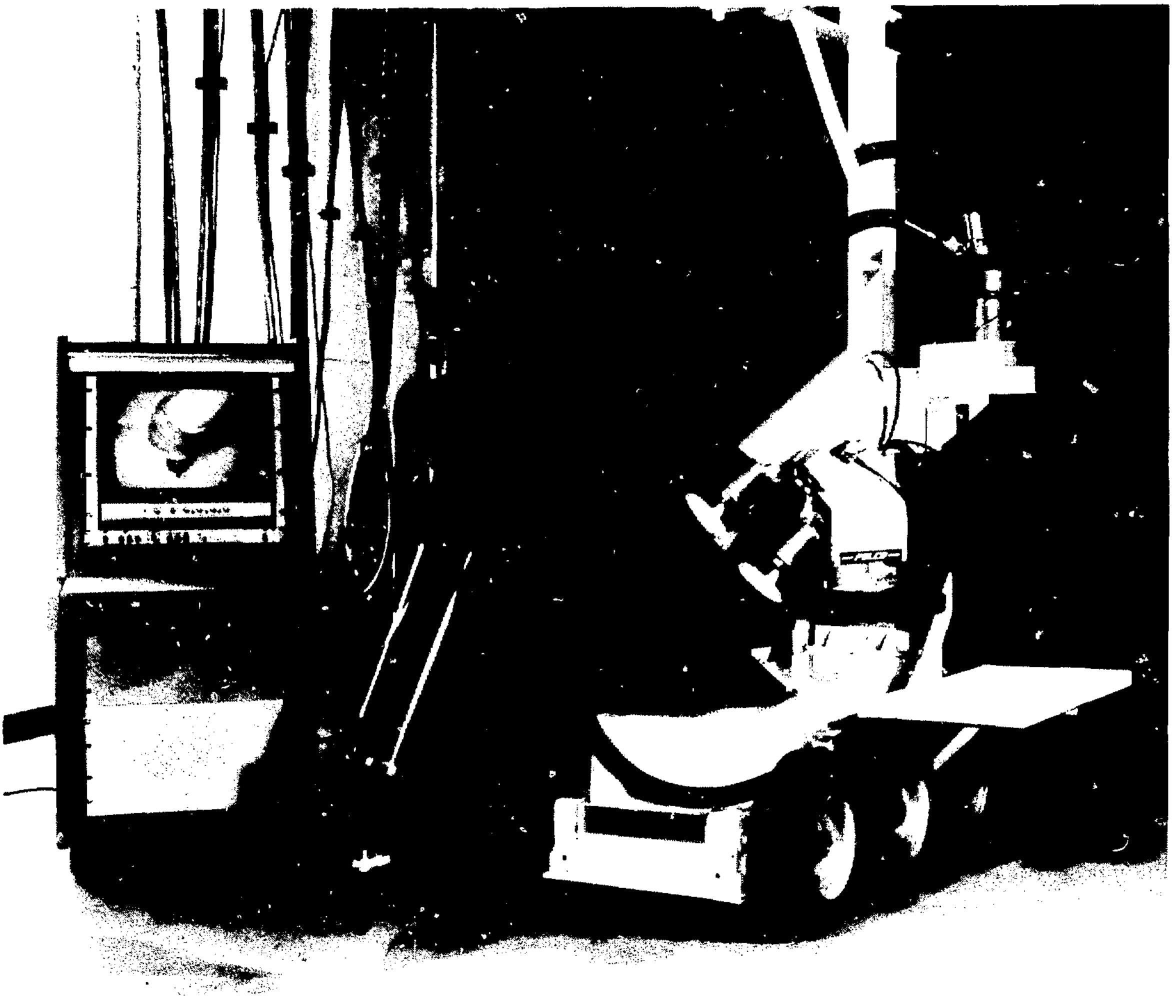

FIGURE 12 ROD, Viking Energy Co.

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FUTURE DIRECTIONS IN MOBILE TELEOPERATION

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ABSTRACT

Mobile teleoperator systems are the subject of an increasing amount of research and development. This work is motivated by general problems of remote operations in hazardous environments, some of which are very similar to the challenges of radiological emergency response and recovery.

Current work appears to fall into two broad economic classes, one in the $100 K range and the other in the $1000 K range. Both are believed to be important for technology development and deployment. Recent developments confirm that we are at the technical doorstep of next-generation mobile systems which integrate dexterous manipulation, high mobility, and telerobotic operation.

INTRODUCTION

The purpose of this paper is to discuss future directions in mobile teleoperator systems. The objective of this discussion is to present information which highlights current research, summarizes key issues related to the utilization of the technology, and attempts to predict future concepts.

The entire discussion is couched in terms of practical applications in radiological emergency response and recovery (RERR) in the sense of requirements discussed in Ref. 1. An ideal RERR system would replicate the capabilities of human workers through the safety of remote control and surveillance. In reality, we are a very long way from replicating human dexterity and sensory functions using mechanisms and electronics. We can, however, approximate those functions with varying degrees of fidelity. Because teleoperated systems are approximations, their interjection into human operations generally results in performance limitations and functional constraints. Teleoperator research for the most part seeks to minimize these limitations and constraints. From a practical viewpoint, it is desirable to have a reference from which one can judge the merits of technical options. In the case of radiological emergencies, experience suggests that a "good" teleoperator should be able to (1) move about the passageways and geometry of typical industrial plant environments, (2) operate typical human-operated equipment such as valves and switches, and (3) perform simple RERR functions such as obtaining surveys, smears and samples and establishing temporary shielding barriers. Unfortunately, the need does not end with these functions. Emergency conditions

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inherently imply a high degree of uncertainty in terms of the actual state of the work environment and the tasks which must be performed to accomplish recovery. Consequently, it is desirable for the mobile teleoperated system to be a general-purpose tool capable of performing complex tasks such as clearing out a damaged area through cutting, lifting, and stacking equipment and material. This last proviso creates a leverage-like situation which is asking for optimum performance. The inherent competition between performance, cost, and reliability are the constraints that control the future direction in mobile teleoperators.

DEFINITIONS AND TERMS

Before going further, it will be helpful to the subsequent discussion to establish the definitions and structure related to the notion of a mobile teleoperator system. Johnson and Corliss[2] first introduced the term teleoperator, which they defined as a system that effectively projects man's sensory capabilities and ability to do useful work across physical barriers with both spatial and temporal dependence. The early teleoperators developed in the nuclear industry might be more correctly called telemanipulators[3] since these systems involved tightly coupled (i.e., physical separation) master/slave manipulator pairs. The original mechanical master/slave manipulators quickly evolved into electrical bilateral servomanipulators that permitted the master and slave components to be electrically interconnected. This extension essentially allowed the remote control station and the remotely controlled slave manipulators to be separated by an arbitrary physical distance limited only by electrical wiring considerations. At this stage, the telemanipulator concept became a mobile teleoperator system. This was certainly a subtle, but technically significant, transition as it introduced many new design and operational issues. Today we understand very well that mobile teleoperator systems represent the extremely difficult integration of remotely piloted vehicles and remote manipulation.

For purposes of discussion, a mobile teleoperator system can be subdivided into at least eight subsystems or functions. This breakdown is depicted in Fig. 1. The overall

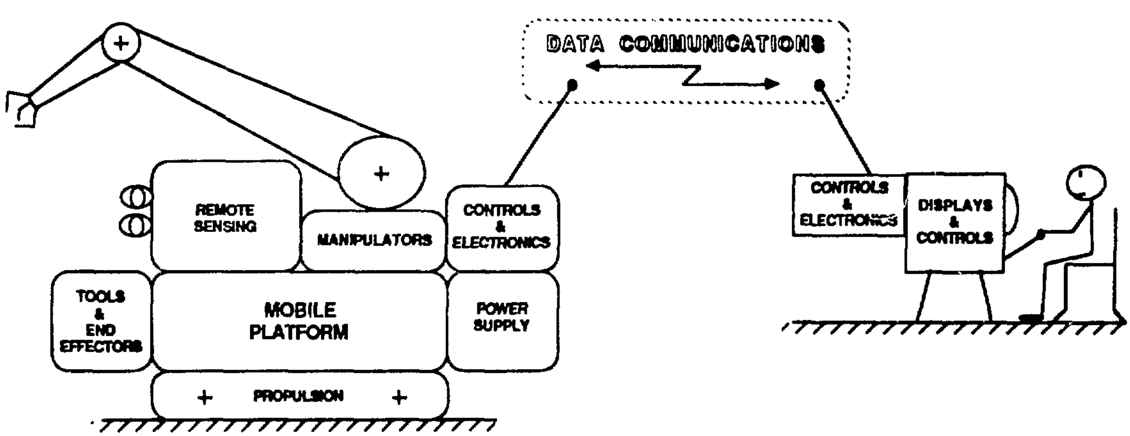

FIGURE 1 Basic Structure of a Mobile Teleoperator

system consists of a remotely operated vehicle which communicates through a signal or data communications system to a remote control station which serves as the human-machine interface. The remotely controlled vehicle is basically a mobile platform which provides the propulsion functions necessary to move about the remote environment (analogous to human legs and feet). It also includes a manipulator system(s) which provides the kinematic and dynamic dexterity to perform useful work (analogous to the human upper torso, arms, and hands). The remotely operated vehicle must also include a remote sensing subsystem which gathers data for the human operator (analogous to human sight, touch, and hearing). The concept of a mobile teleoperator system is to translate the worker to the work site; consequently, the system must also incorporate an appropriate complement of tools and an energy supply/storage system.

In contrast to autonomous robotic operation, teleoperation means remote human control (e.g., man-in-the-loop operation). The controls and electronics subsystems and the data communications subsystem constitute the bidirectional information linkage between the electronics and electromechanical functions of the vehicle and the controls and displays of the human-machine interface (analogous to the brain and central nervous system). This linkage is to a great extent the essence (some might say the Achille's heel!) of the mobile teleoperator. This linkage also is where modern day advances in microelectronics and digital systems are playing a key role in establishing future directions.

CURRENT RESEARCH

Robotics and artificial intelligence (AI) have become two of the most popular buzz words of "high tech" society. They are major research topics in industrial automation, military applications, and hazard reduction. Such research is being performed in universities, industry, and government laboratories all around the world. Most will agree that the goal of the bulk of robotics/AI research is the replacement of human workers. In spite of the difference in purposes there are extensive technical similarities between teleoperator research and robotics/AI research, and the discussion of one essentially necessitates the discussion of the other. Areas of commonality include all aspects of equipment design, digital servocontrols, electronics, and software. The following discussion highlights representative robotics and teleoperator research activities and provides insight into the likely future of mobile teleoperator systems.

Current research will be described here by using representative examples. This is not intended as a comprehensive review of current research (which would not be appropriate for this paper) but rather a brief review which indicates trends. The specific topics were selected by the author as a matter of convenience.

Mobility

Mobile platforms which can transport work and sensor packages are being developed widely, as reported at the recent EPRI-sponsored conference. Recent work has focused on new locomotion concepts and new implementations of previous concepts. Three basic forms of locomotion are in various levels of development: (1) wheel-driven,

(2) tracked, and (3) legged. The Automation Technology Surveyor Vehicle[4] exemplifies recent work in small-tracked vehicles for surveillance in nuclear power plants. The NAVY RAMROD vehicle for explosive ordnance disposal is another example. Tracked vehicles of this type are relatively efficient, use skid steering, and are effective stair climbers, but they are limited with respect to operating speed and the ability to navigate obstacles. Most emergency-response vehicles now in existence are track-driven. Tracked vehicles are able to negotiate steeper angles if the track footprint is enhanced by using additional articulation such as the Blocker Vehicle,[5] the MORFAX MARAUDER, and the transformable crawler vehicle at the Hitachi Mechanical Engineering Research Laboratory.[6]

Most robotics researchers probably are using wheel-driven vehicles primarily because of their cost, availability, and compatibility with laboratory environments. Steering is by wheel rotation or skid steering such as the Standard Manufacturing MARS vehicle. The DARPA Autonomous Land Vehicle uses a larger Standard Manufacturing[7] wheeled vehicle with diesel power, skid steering, and trailing arm suspension.

The most significant current vehicle research is occurring in legged motion or walking machines. Distributed microprocessor control and modern servoactuator design have made it possible to implement the large number of servo-controlled degrees of freedom necessary for leg-like mechanisms. Microprocessor software control has also facilitated the development of the coordinated real-time algorithms which can create walking action for almost any topology. Reference 7 is indicative of the large amount of legged-motion research occurring in Japan and the U.S. The U.S.S.R. is active in this area as well. Ozaki's work at Hitachi[8] has been directed toward a hybrid concept where five legs move straight up and down (in a single degree of freedom) for climbing and stepping. Each leg also incorporates a wheel drive for propulsion and steering.

The DARPA Adaptive Suspension Vehicle[7] (ASV) is a famous research activity at Ohio State University with support from ERIM, Battelle Columbus Laboratories, and others. The ASV is a rather large six-legged, man-driven vehicle which will demonstrate the feasibility of future military applications. The ASV weighs 2600 kg and is designed for a 2.0-ms cruise speed. Thirteen 16-bit microprocessors have been used to implement the digital control system, which provides servocontrol of the hydraulic leg actuators and integration of reference and rate gyroscopes, accelerometers, and leg force transducers. The system also includes a laser terrain scanner (built by ERIM) that provides preview information for proper leg control and foot placement.

Another famous legged vehicle is the ODEX functionoid developed by Odetics, Inc.[9] ODEX (Fig. 2) is a symmetrical 6-legged system which has undergone continued development in several application projects since its introduction in 1984. This machine has a very wide range of motion by virtue of its unique 3-degree-of-freedom leg articulator design, which inherently segregates vertical and horizontal lifting forces. It operates with a high degree of mechanical efficiency and can translate at speeds up to 3.5 km/h while having a capacity-to-weight ratio between 3:1 and 6:1. In recent work, the on-board sensory functions have been extended to include vertical referencing and fast touch sensors. Autonomous stair climbing has been demonstrated using these sensors and special software routines. ODEX is also based upon distributed-digital control, the details of which are proprietary.

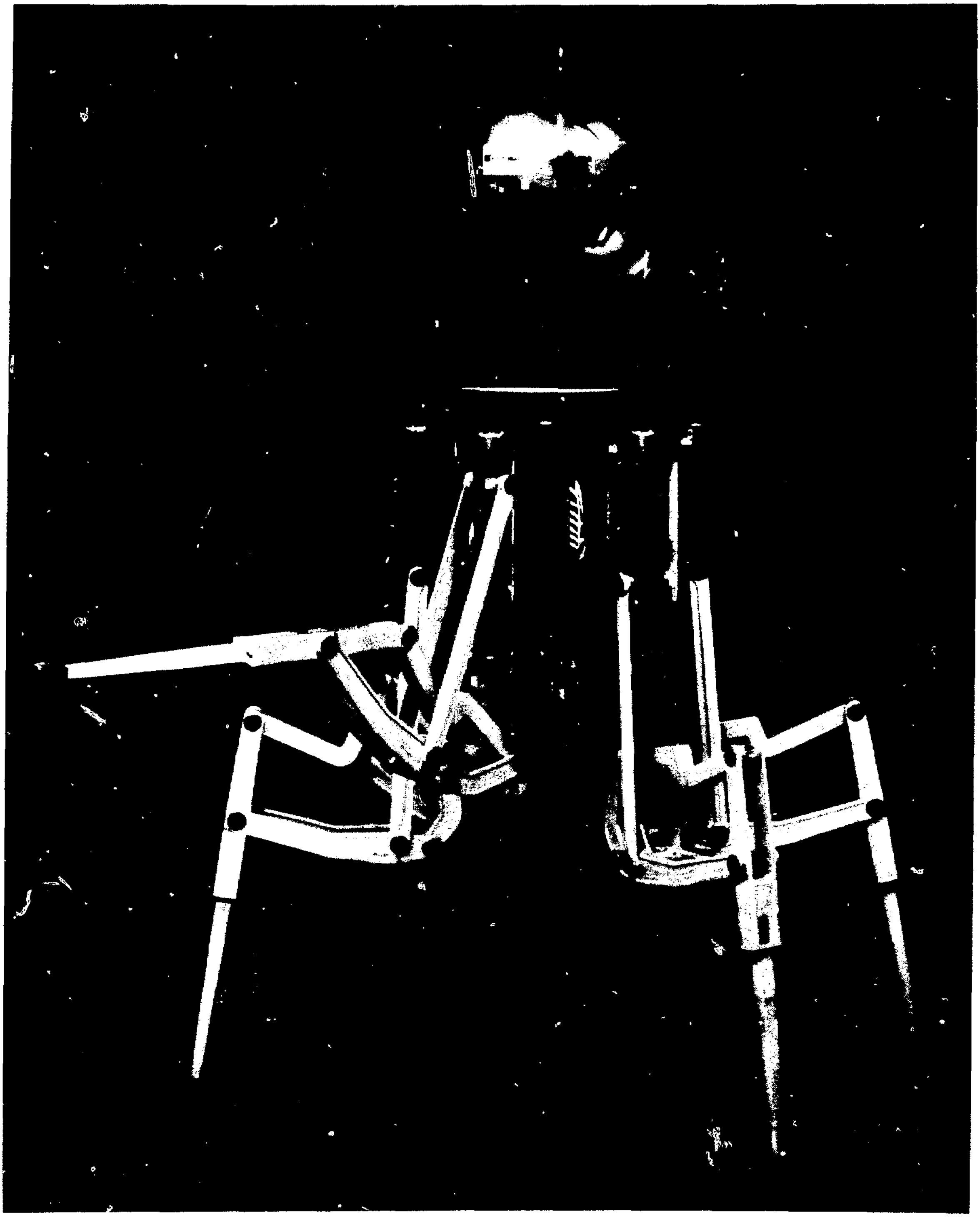

FIGURE 2 ODEX Functionoid (Photo courtesy of Odetics, Inc.)

Manipulation

If a mobile teleoperator system is to perform useful work, it must have some type of master/slave manipulator that an operator can use to handle objects and tools. This need is analogous to the general problem of remote handling in hazardous environments (e.g., nuclear, space). Manipulators have a wide range of performance capabilities related to kinematic sophistication, speed of operation, position resolution, and force sensitivity. Needless to say, manipulator research is a very active area, especially in the unstructured environments associated with nuclear, space, and military operations.

The Oak Ridge National Laboratory has been very active in the development of a next-generation remote maintenance system for the DOE Consolidated Fuel Reprocessing Program. This work has concentrated on the development of a high-speed, force-sensitive manipulator concept called the advanced servomanipulator (ASM).[10] The principal mode of operation for this system will be master/slave teleoperation. The ASM has been designed for increased reliability and modular repair by other manipulators (see Fig. 3). The ASM has a capacity of 22 kg and a maximum no-load tip speed of 1.2 m/s, and its extremely low mechanical friction allows force interaction at the slave manipulators to be "reflected" back to the remote operator via bilateral servocontrol between the master and slave manipulators. It has been shown that force feedback from the remote work environment is a key parameter affecting the types (i.e., complexity) of work tasks which can be accomplished. Force-reflecting manipulators similar to the performance range of the ASM are also being developed in France and Japan. The pioneering work of the late Jean Vertut[11] is particularly noteworthy.

The importance of force-reflection for effective teleoperation is not universally accepted, and others have concentrated on the development of simpler unilateral (or non-force-reflecting) concepts. Unilateral telemanipulators are more comparable in their design parameters to industrial robots. Generally, these designs use smaller drive motors with high gear ratios, operate at lower speeds, and are non-backdrivable. The non-backdrivability characteristic means that they are not well suited for force feedback. The unilateral design philosophy basically trades performance for mechanical simplicity and lower cost. The most recent unilateral design is the Remote Technology Corp. RM-10 (Fig. 4). The RM-10 is unique in that it is controlled via a kinematic replica master and has a relatively fast 0.6 m/s no-load tip speed.

A few other significant manipulator research activities such as H. Asada's work at MIT are currently under way. The U.S. Army has recently initiated projects that involve manipulator development. For the most part, though, manipulator research, particularly in academia, is not as active as legged-motion technology. It appears that this situation may be changing as it is becoming recognized that the mechanical systems aspect of robotics technology is a greater limitation to advanced concepts than sensors and controls. Two new areas of manipulator research are degree-of-freedom (DOF) kinematics and flexible manipulator dynamics. Arms which incorporate more than the minimum 6-DOF kinematics necessary to orient and position an end-effector in space promise much higher maneuverability and dexterity. Examples of this type of geometry include Hitachi's flexible reactor maintenance manipulator[12] (see Figs. 5 and 6) and the

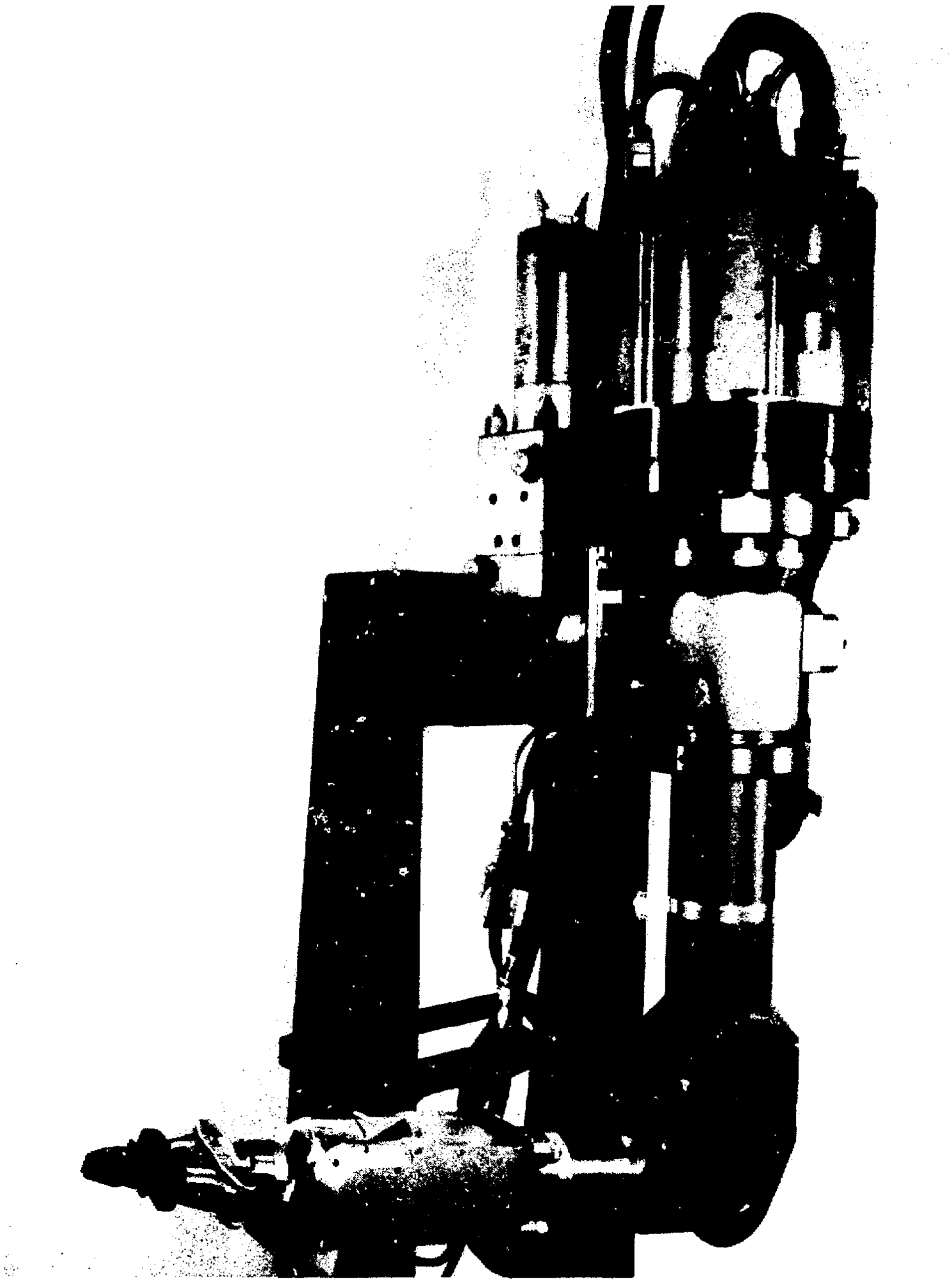

FIGURE 3 Advanced Servomanipulator Slave

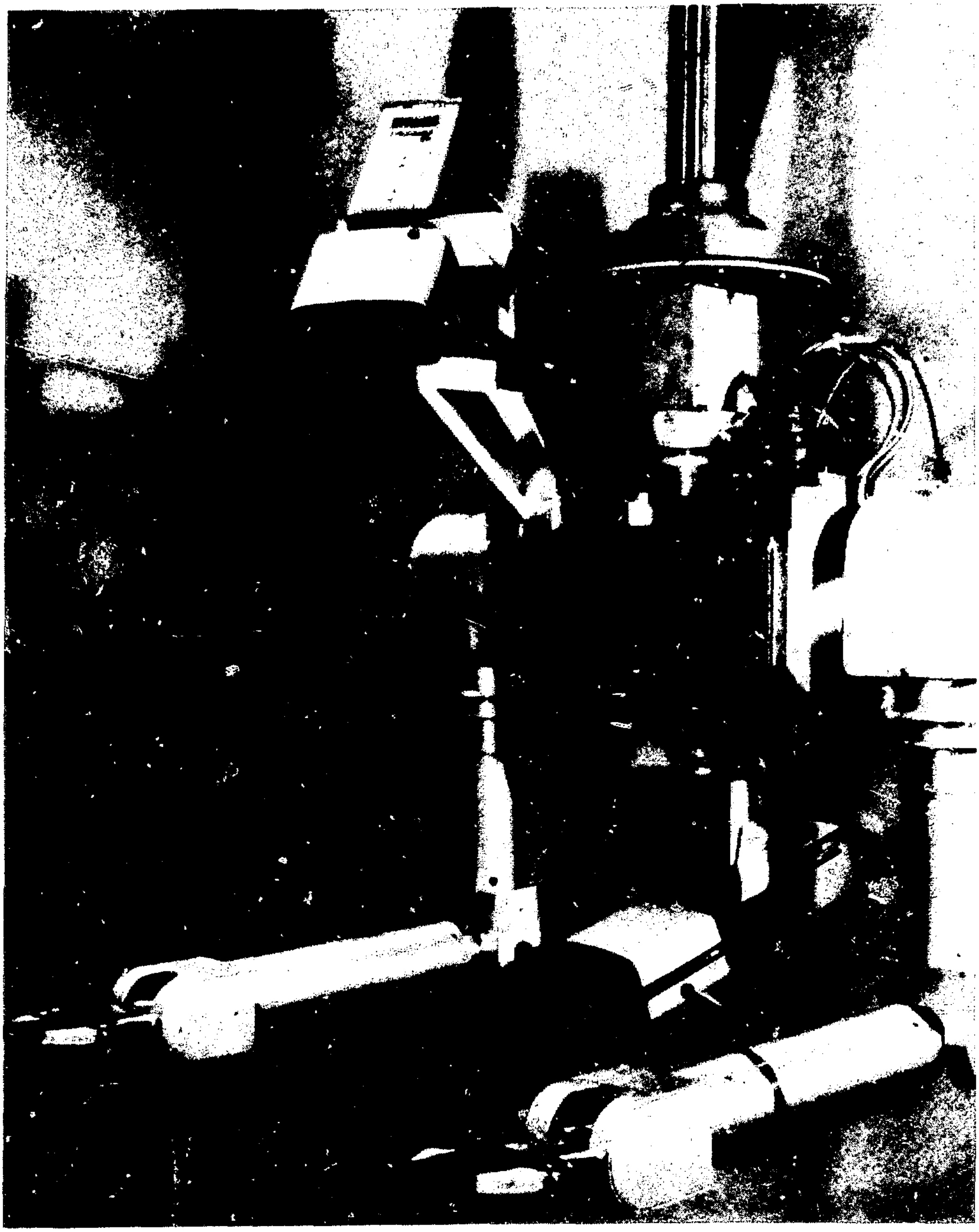

FIGURE 4 Remote Technology Corp. RM-10 Manipulator System (photo courtesy of Remote Technology Corp.)

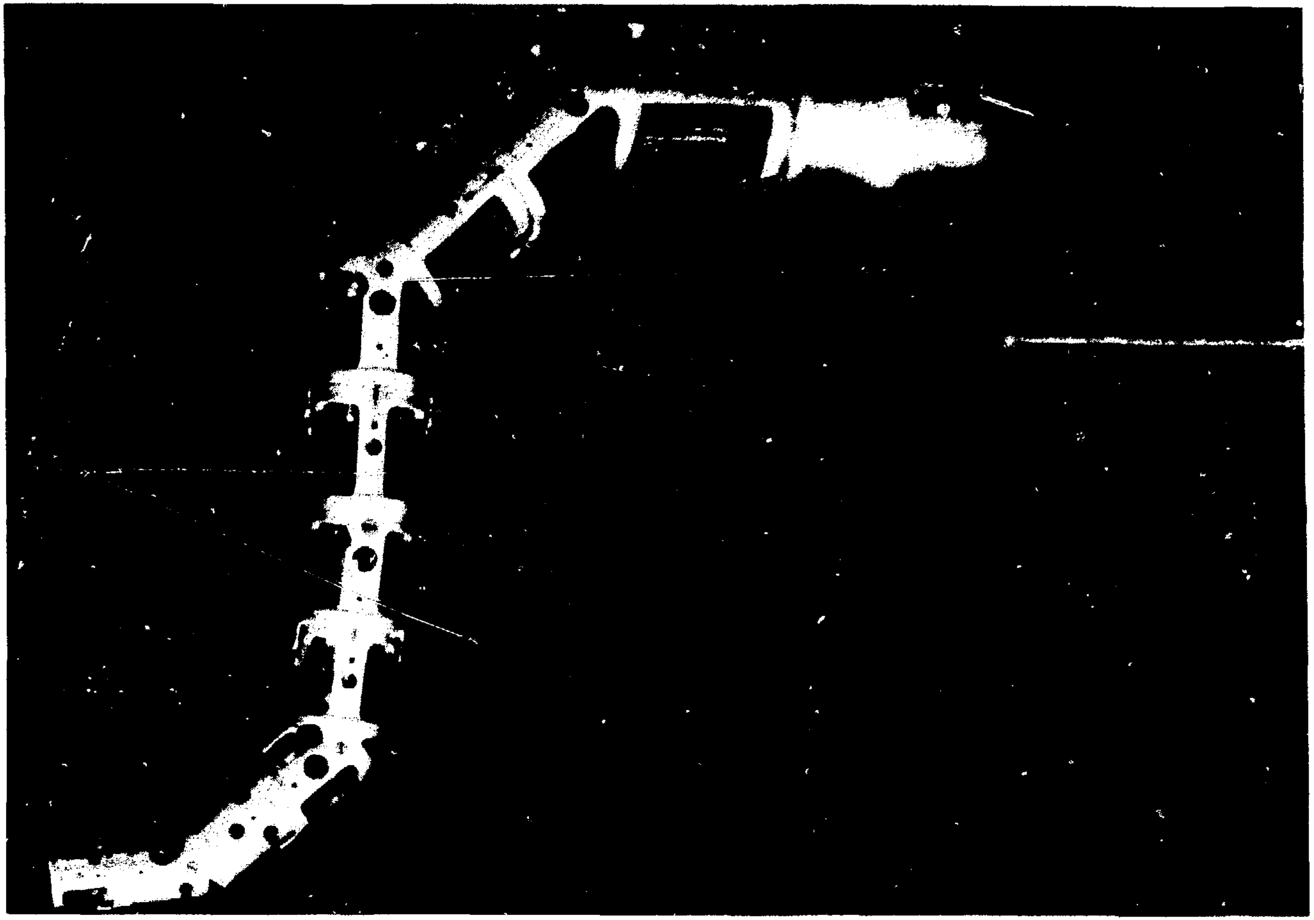

FIGURE 5 Hitachi Flexible Manipulator

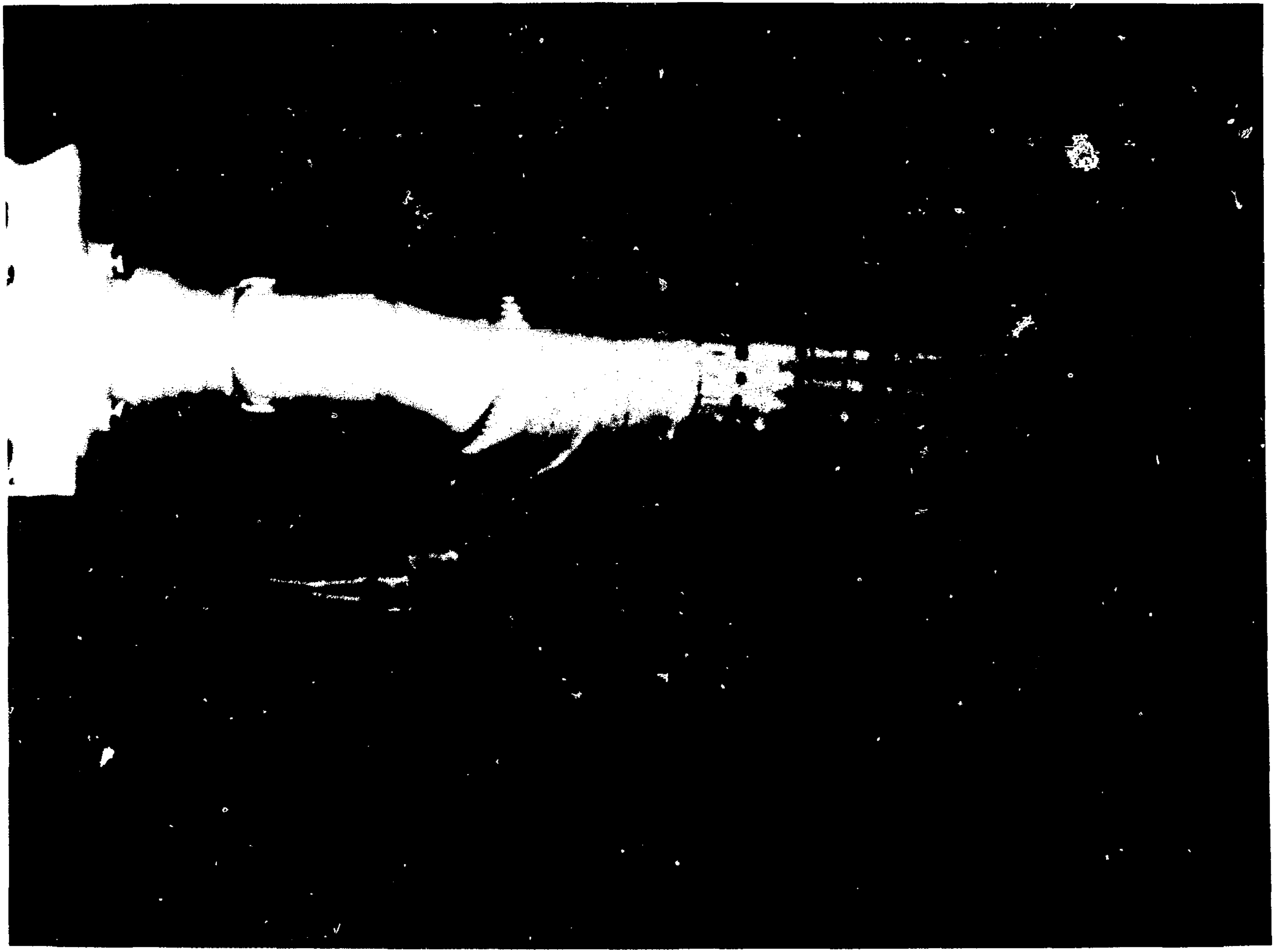

FIGURE 6 Stop Motion of the Hitachi Flexible Manipulator

Spine Robot from Sweden. Systems of this type increase mechanical design complexity and control algorithm complexity in proportion to the number of DOFs.

Mobile teleoperators imply mobile manipulators. The overall weight and power consumption of a mobile teleoperator are important because they are significant factors in defining a system's operating envelope. To make a system as useful as possible, one would like to minimize constraints such as manipulator weight-to-capacity ratio and overall vehicle power supply-to-weight ratio. The by-products of minimizing manipulator weight-to-capacity are minimum inertia and reduced stiffness. The comparative appearance of industrial robots and force-reflecting servomanipulators exemplify these effects. As manipulator stiffness is reduced, the dynamic effects of structural and drive-train compliance become significant elements of the manipulator's dynamic behavior. New research[13] is focusing on the description (modeling) of compliant arms and the development of control and sensor methodologies that will compensate for structural compliance and dynamics.

Systems

Several projects have emerged recently in which manipulators have been integrated with mobile platforms. TeleOperator Systems (TOS) joined with AECE of Belgium in the development of the TELEMAC[14] system (Fig. 7). TELEMAC is essentially a pair of TOS SM-229s mounted on an articulated track chassis, which is a variation of the British MARAUDER. The TOS SM-229s are 10-kg force-reflecting servomanipulators which make the TELEMAC the most dexterous system yet built. TELEMAC reportedly incorporates an all-digital control system and high-frequency radio signal transmission.

Remote Technology Corporation is presently constructing for the Nuclear Regulatory Commission a surveillance and inspection robot which incorporates a single RM-10 manipulator on a wheel-driven chassis.[15]

Odetics, Inc. is building an ODEX for the Savannah River Laboratory. It will also incorporate a simple telescoping boom and manipulator.

These systems have not been deployed in actual work missions, so one can only speculate as to their performance. As they all include modern digital controls and electronics, it is anticipated that each will demonstrate important advancements. The mobility and functionality of the ODEX concept for emergency response and recovery (as well as routine maintenance) creates exciting new opportunities, as a recent EPRI study suggests.[16] Clearly, if one were to deploy modern force-reflecting manipulator technology on a vehicle of the ODEX capability (which is a very reasonable consideration), the result would be much closer to the practical replication of human mobility and manipulation in unstructured work environments that many might anticipate.

Supporting Technologies

There is no question that modern digital electronics, particularly the microprocessor, have made possible many of the advances in mobile teleoperators, and

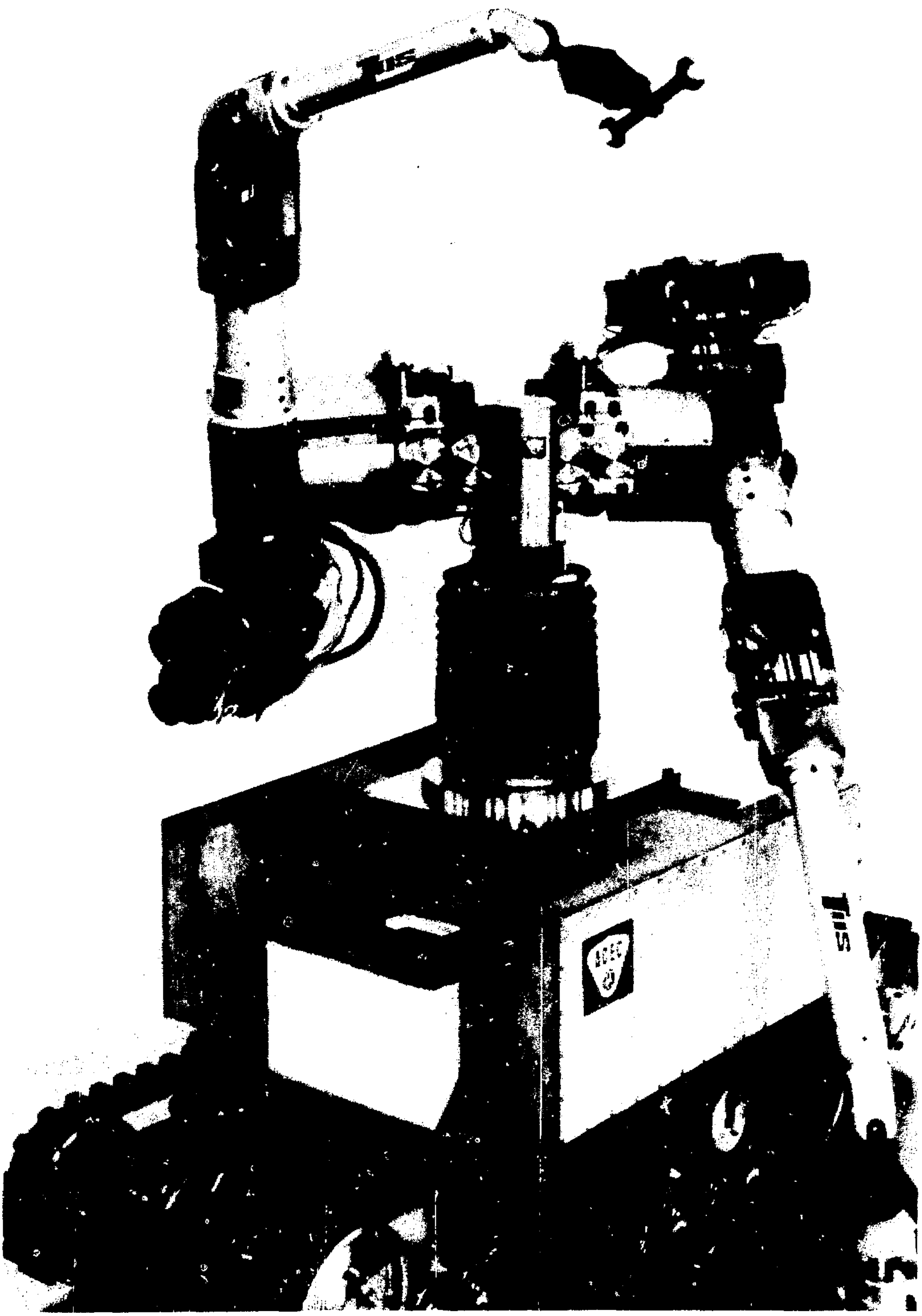

FIGURE 7 TOS SM-229 Manipulators and Mobile Platform, circa 1985 (photo courtesy of TeleOperator Systems Corp.)

the microelectronics revolution is far from over. Both 16-bit and 32-bit microprocessors now operate in the range of 0.5 to 1 million instructions per second. New architectures will soon provide an increase of at least one order of magnitude in the computational speed of the type of electronics that can be practically used in mobile teleoperators. Mainframe computer capacities will allow designers to incorporate cooperative automation (e.g., computer-assisted teleoperation), which will increase work efficiency and decrease operator fatigue.[3] Jean Vertut's last research was focusing on computer-assisted teleoperation (CAT). (At ORNL this concept has been called telerobotics.) CAT involves using automated functions and software aids to essentially augment an operator's remote control performance. Appropriate software can be used to confine force-reflecting telemanipulators to constrained motion along lines, in planes (e.g., a miter box saw), and within three-dimensional boundaries that help the operator accomplish specific tasks which inherently desire these constraints. This type of research will continue to grow as teleoperation and robotic automation converge.

Energy supply and management and signal transmission will be discussed in another paper in this workshop. However, it should be noted here that improvements in energy storage density and data communications are needed to allow realization of the increased functional capabilities promised by computer technology advancements.

FUTURE CONCEPTS

From a technical perspective, it is time for the development of a next-generation radiological emergency response and recovery (RERR) vehicle which incorporates dexterous manipulation, high-mobility location, tetherless operation, renewable energy storage, and advanced control function including selectable automation.

Two constraints will restrict the evolution of such a vehicle: (1) funding, and (2) technical issues. Unfortunately, the RERR environment does not appear to be in the position to fund multimillion-dollar efforts for machines which are needed for off-normal conditions. Machines in the class of TELEMAC will cost several million dollars to deploy because of their complexity and because many subsystems such as force-reflecting manipulators are built by hand. In contrast, simpler systems such as SURBOT will cost hundreds of thousands to deploy, which is likely to be much more palatable to operating plant budgets. There should be no illusions as to the relative performance of these two classes of systems. Experience in remote operations indicate that the more sophisticated approach would provide a degree of telemanipulation quality (with remote force sensing) capable of performing tasks over a very wide range of complexity. This seems to be a very desirable form of RERR insurance, which is perhaps why Japan is pursuing projects of this scope and proportion.

Specific project endorsement comes down to matters of judgment pertaining to the ever-present tradeoffs between performance and cost, development risk, reliability, and technical constraints. Manipulator technology is now more than 40 years mature; ODEX in particular has shown that successful development of sophisticated locomotion is possible in spite of the risk and technical constraints. Thus, the principal issue now is not "how much can be accomplished (technically)" but rather "how much can be invested?". The author believes that both the 0($100 K) scale project(s) and the 0($1,000 K) project are important. The more costly project will push the state of the art and, if managed correctly, provide results that will enhance the performance of less expensive systems. The lower cost projects play the important role of activating the technology by involving a wide range of businesses and getting systems deployed in actual operating environments.

Even though the time has come for a system with highly dexterous arms and leg-like mobility that is nearly able to replace humans, some major challenges remain. The biggest problem is the poor weight efficiency of electrical power storage and electrical servoactuators. With high-performance force-sensing manipulators (capacity-to-weight = 2 or 3 to 1), on-board electronics, battery power storage, and other needed auxiliaries, it will be difficult to keep the total system weight below 400 to 500 kg including payload. Higher power density batteries and actuators and efficient design concepts are the improvements needed to reduce weight (which is closely related to operating envelope).

Tetherless operation is essential (in the long term) for RERR mobile teleoperators. Tetherless signal communication is dominated by video requirements, although control data rates will need to be in the range of 10 Mbits/s. High-quality remote viewing is critically important for effective remote control. Three to five noise-free on-board video channels will be necessary for a manipulator-based system. These requirements translate into signal transmission in the GHz range with several hundred MHz of bandwidth. Such systems are readily achievable with Gunn-diode microwave technology, which is also radiation hardened to megarad level. It is generally recognized that reasonably fail-safe operation in typical reactor or industrial facility building environments will require adaptable multiple frequency systems to mitigate signal dropout to multipathing and other effects. Detection and control circuits for this type of operation have been developed. In high-speed signal communications the principal difficulty will be obtaining FCC licenses in these microwave bands for routine industrial use.

As discussed in the Current Research Section, control and sending complexity will increase as efforts to reduce weight also reduce system stiffness. Research in compliant controls and coordinated multiple manipulator control are in embryonic stages. We have yet to establish that such systems can be integrated into effective mobile "telerobotic" systems.

SUMMARY

The RERR problem implicitly addresses events which are unexpected and uncertain. Ideally, one would like to have as much reliable functional ability to respond to RERR conditions as technically feasible. A significant amount of related and direct research and development in mobile teleoperator systems is now in progress. This work appears to fall into two broad economic classes, one in the $100 K range and the other in the $1000 K range. Both are believed to be important for technology development and deployment. Recent developments confirm that we are at the technical doorstep of next-generation mobile systems which integrate dexterous manipulation, high mobility, and telerobotic operation. U.S. programs can and should set the international pace in this area if the necessary funds are made available.

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MOBILE TELEOPERATOR RESEARCH AT SAVANNAH RIVER LABORATORY

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ABSTRACT

A Robotics Technology Group was organized at Savannah River Laboratory to employ modern automation and robotics for applications at the Savannah River site. Several industrial robots have been installed in plant processes. Other robotics systems are under development in the laboratories, including mobile teleoperators for general remote tasks and emergency response operations. This paper discusses present work on a low-cost wheeled mobile vehicle, a modular light-duty manipulator arm, a large gantry telerobot system, and a high-technology six-legged walking robot with a teleoperated arm.

INTRODUCTION

The Robotics Technology Group was organized at the Savannah River Laboratory in August 1982. The objectives were to employ modern industrial robots, to develop unique robotic and automation systems in new processes, and to enhance present process operations for the Savannah River site, Savannah River Plant (SRP) and Laboratory (SRL). The incentives for this activity are to improve safety, reduce personnel radiation exposure, improve product quality, improve productivity, and reduce operation costs. Robotic systems have been installed to fill chemical dilution vials in the laboratory, to remove radioactive waste materials from a production facility, to lubricate a large extrusion press, and to enhance operations in a separations process. Two other industrial robot systems are scheduled for installation in a fuel assembly manufacturing area during this year. Other systems under development in the robotics laboratories include mobile teleoperator systems for general remote tasks and emergency response operations.

We have participated in two Department of Energy Robotics Seminars (sponsored by IMOG, CAD/CAM Subgroup) at Rocky Flats Plant and Pinellas Plant and a JOWOG Robotics and Automation Seminar at Rocky Flats Plant. A Savannah River Site Activity Report was presented at each seminar. We have also presented papers at American Nuclear Society conferences and other robotic conferences (References 1-4). Recognizing the need for strong safety considerations in the design and implementation of all automated systems, we have published an in-house document on robotics safety (Reference 5).

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TELEOPERATORS DEVELOPMENT

Pedsco Mobile Vehicle

Many emergency response operations can be performed with a simple teleoperated mobile vehicle and a manipulator arm. We identified such a vehicle, manufactured by Pedsco Canada Limited, and have employed these units for several site applications. We are presently enhancing this vehicle to increase its versatility.

The Pedsco RMI (Remote Mobile Investigation) vehicle is a six-wheeled unit equipped with a controllable arm and hand (Fig. 1). A closed-circuit TV system and 200-foot-long umbilical cable permits remote control with a joystick and switches from a portable control station. It is approximately 40" long, 26" wide, and 28" high, is battery powered, and can operate at speeds up to 3 miles per hour. The boom structured arm has two degrees of motion. The hand is a simple claw with binary operation; however, it has a "soft touch" closure mode for handling more fragile items. The arm and hand can lift up to 70 pounds, but it can easily drag objects over 100 pounds. Total vehicle weight is 230 pounds.

The RMI vehicle was developed in 1976 by Pedsco for the Royal Canadian Mounted Police and is used primarily for police and military applications for bomb disposal and hostage situations. In late 1982 a modified Pedsco RMI was employed by Ontario Hydro at their Bruce NGS-A reactor for an emergency cleanup operation in a highly radioactive nuclear environment. The reported success of this operation called our attention to the potential use of this vehicle.

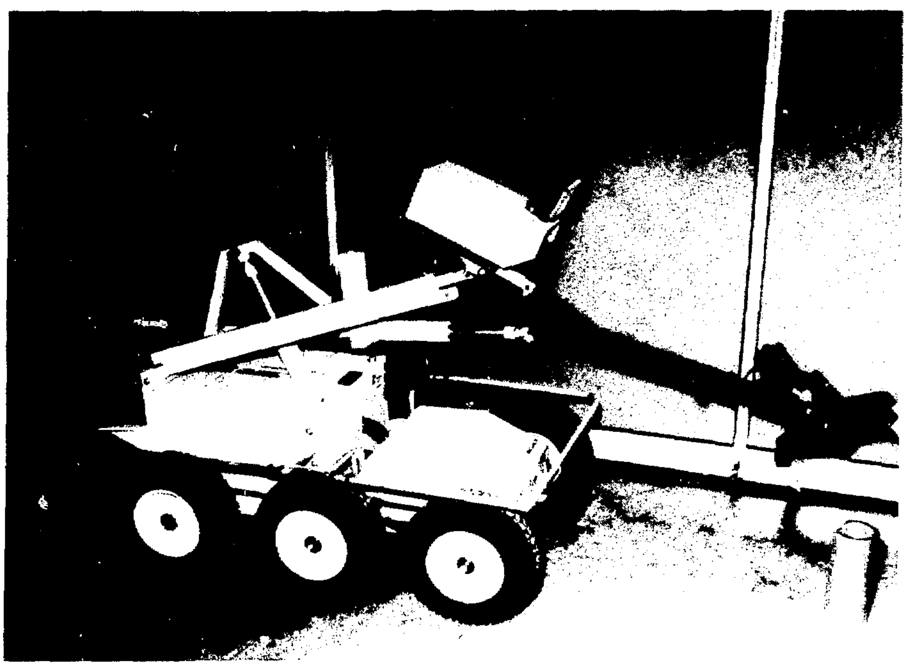

FIGURE 1 PEDSCO Mobile Vehicle

We have successfully used this vehicle at Savannah River for radiation monitoring and mapping on the top of an outdoor waste storage tank and for an emergency operation involving a suspected explosive package that was discovered in the administration building mail room. Its capabilities are presently being explored for several decontamination and cleanup applications in process areas. We have successfully tested the Pedsco vehicle in a reactor process room in which we found the retrieved simulated reactor fuel assembly components. We have modified one radio-controlled unit with a microwave TV system, have waterproofed it, and will test it in a reactor process room with the water spray system operating. We have designed an improved arm and control system to enhance the manipulator capabilities of the vehicle. In the near future we will have a relatively low-cost mobile vehicle suited for a variety of nuclear service applications including surveillance, monitoring and equipment handling.

Modular Light Duty Manipulator

A teleoperated manipulator arm is being developed by Teleoperator Systems, Inc., Troy, N.Y., to perform general remote operations tasks (Fig. 2). An in-house development program will upgrade the system to telerobotic operation. The design objective for this arm is to produce a low-cost, modular arm to perform manual and programmed tasks. The arm has a 52-in reach capability and a lifting capacity of 50 pounds. The manipulator, including its base, will fit through a 30-inch opening. The joint motions will be powered by DC motors enabling its employment on mobile vehicles.

The arm consists of seven modules which are easily detachable and replaceable. A design criteria states that these modules be inexpensive, typically less than $5000 each

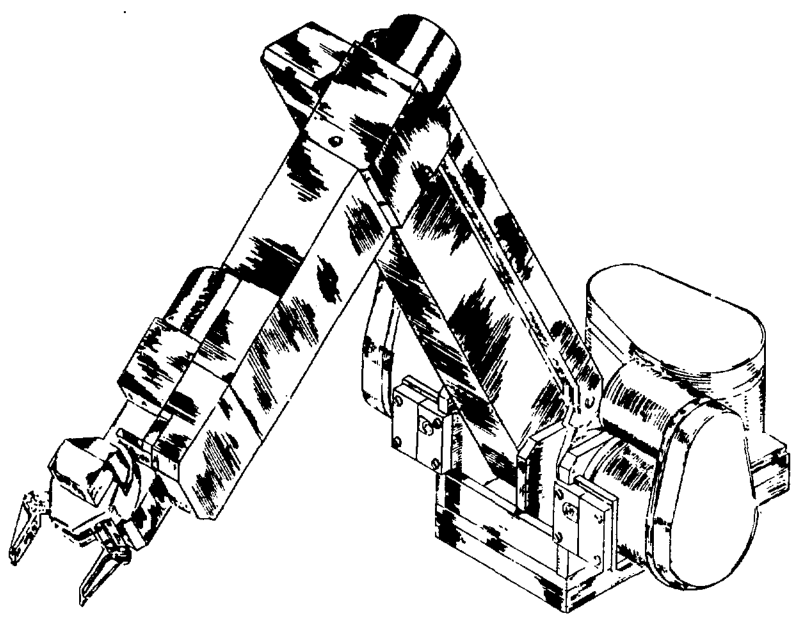

FIGURE 2 TSI Modular Arm

except for the base module. No module except the base will weigh more than 25 pounds. All joints will operate with slip clutches that can be programmed for maximum desired torque. A manual joystick and an ICC 3220 robot control will be used for operation.

TELEROBOT DEVELOPMENT

Large Gantry Telerobot Facility

Telerobotics technology combines the "man in the loop" teleoperated systems and programmable robot systems. Many applications require both operations, the robot to perform the routine programmable tasks and the teleoperator to perform unique real-time tasks. A substantial engineering development is required in hardware, firmware, software, and human factors to effectively integrate robotic and teleoperator operations.

At Savannah River a telerobot system will be employed in a new facility to decontaminate and dismantle obsolete nuclear equipment (glove boxes, etc.) A five-axis manipulator integrated with a three-axis gantry robot system will serve a 70' x 20' x 20' work area (Fig. 3). The telerobot system, being manufactured by GCA Corporation, St. Paul, Minn. to SRL specifications, will handle up to 300 pounds at its end-effector. Operators will control the manipulators with joysticks, function switches, and a computer terminal. Programmed robotic operations will include the tasks of changing manipulator hand tools for specific operations and of performing routine maintenance operations. System controls will coordinate motions for the nine system axes to move end effectors in straight-line trajectories. Cutting and drilling operations will require this. Human factors engineering is a prime consideration in the overall design and development. The telerobot will communicate process information to a process computer network.

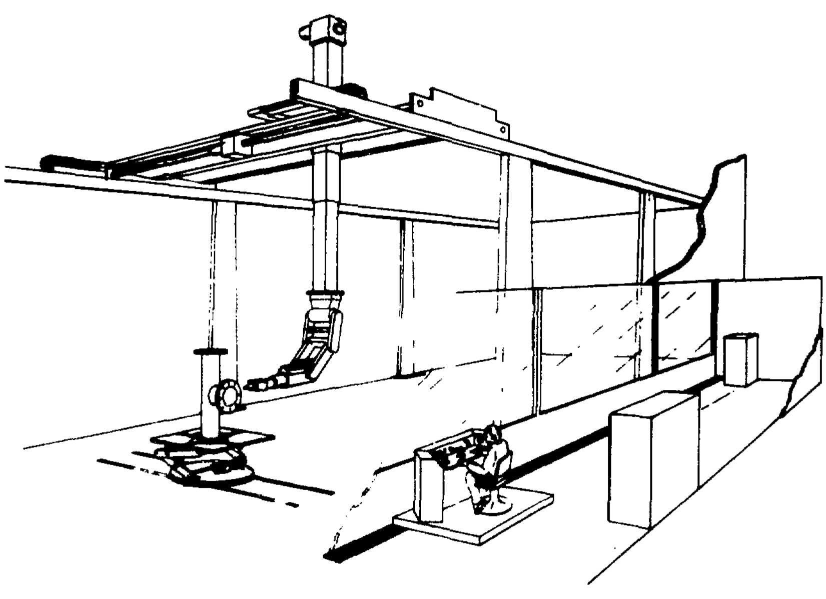

FIGURE 3 GCA Telerobot System

This robot is scheduled for September delivery to SRL. Development work, evaluation, and demonstration will be performed in the robotics laboratory prior to installation in a full-scale prototype facility in another area.

Odex Walking Telerobot

The six-wheeled, unintelligent, teleoperated mobile vehicle is applicable for simple tasks. However, even an enhanced version of that vehicle is quite limited in versatility. The state-of-the-art in mobile vehicles is the more intelligent, six-legged walking machine. A commercial, research-oriented company, Odetics, Inc. of Anaheim, California developed and demonstrated a prototype model of this type, the Odex-I robot, in March 1983 (Fig. 4). Advantages of walking vehicles, as opposed to the more common wheeled and tracked types, are the capabilities to assume a stable foothold to improve traction, to minimize lurching, and to step over obstacles while maintaining a stable payload platform. The Odex walking machine can operate in a variety of stances and modes. It has built-in firmware that includes the walking, stance, and reflexive intelligence algorithms that minimize the required control operations from a human operator. It can be classed as a mobile telerobot.

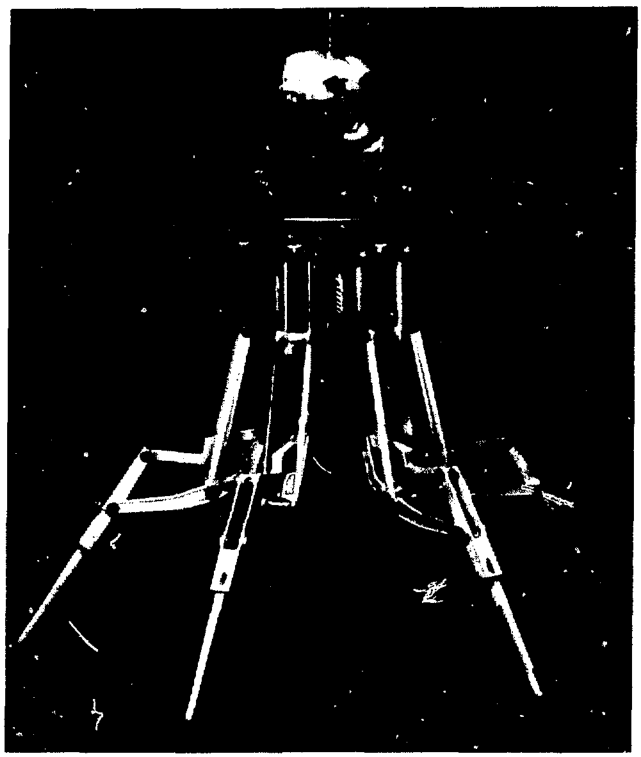

FIGURE 4 ODEX-1 Prototype

We have a contract with Odetics to develop, fabricate, demonstrate and deliver a telerobot, ROBIN (Robotic Insect), to the Savannah River Laboratory in January 1986. It is not being built to withstand a hostile radioactive environment but will be used in a laboratory environment to develop and demonstrate techniques, procedures, and applications for mobile robots at the Savannah River site. Applications include emergency response operations, routine maintenance, radiation surveillance, decontamination and removal tasks. It will also be used in a research and development program for expert robot systems.

ROBIN's walking mechanism will be an improved version of the original ODEX-I prototype, incorporating better control algorithms and aesthetics (Fig. 5). Some of the unique differences are a teleoperated manipulator arm, a fiber optic umbilical cable with an automatic take-up reel, and a TV/lighting system. The telescoping arm, that normally resides within a turret at the top of the robot, will handle up to 50 pounds in a work envelope that extends from 7 feet above the robot to the floor over full circumference of the vehicle. Six degrees of freedom and a programmable force limited binary action for the gripper are available for operation. Three TV cameras, two on the turret and one at the end of the arm, may be selected in pairs for viewing from the control console monitors. The 3/8-inch, 250-foot umbilical cable system will have programmable tension in its servocontrolled reel system.

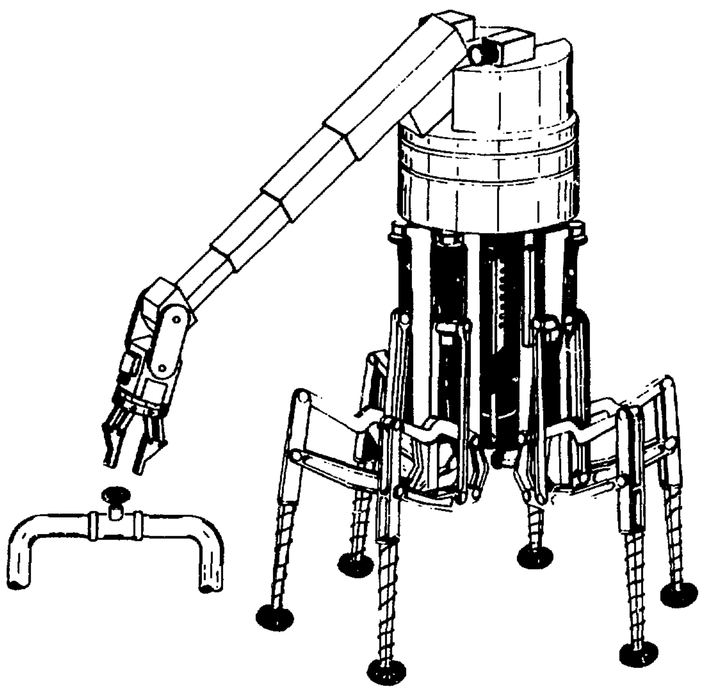

FIGURE 5 Conceptual Drawing of ROBIN

The computer on board the robot controls all motions, stances, reflexive actions (to step over obstacles), and maintains stability once desired operations have initiated from the human operator at the control console or from a control computer. Overload conditions and safety alarms are automatically sent to the controlling device. A data acquisition system integrated with the robot computer can be connected and interrogated to monitor various analog and digital process conditions. Analog and digital outputs are available to control special tools and external processes.

All control functions (inputs and outputs) are available at the control console unit for teleoperated human control or for external computer control through a standard serial communications channel. The control console contains three joysticks for walking, cameras, and manipulator/gripper control, a key pad for programming special modes and limit values, and switches for several common operations. Two TV monitors are used for cameras and status information.

OTHER RESEARCH PROJECTS

Expert Robotic Systems

Our program plans include the development of expert robot/telerobot systems for site applications, using knowledge bases and artificial intelligence techniques. A solution to many general process and emergency operations problems in nuclear plants and other industrial plants is the effective employment of intelligent robots. Intelligent robots are in their infancy and are not an off-the-shelf item available to industry. Research programs are well under way at major universities and research centers throughout the world and many experimental intelligent prototype machines are being developed at those institutions. Robots with sensory capability (vision, tactile, etc.) are often referred to as intelligent. However, having sight, hearing, voice, and a sense of feel does not make a human an intelligent person nor does it make a machine an intelligent robot. Cognitive reasoning ability and knowledge must be present.

An expert system is one that incorporates knowledge-based artificial intelligence dedicated to very specific and limited tasks. The first truly intelligent robot systems in industry will appear as expert robot systems, not as a generic robot with enough intelligence to perform any job in a plant. Extensive experimental and development work will be required to program the system with the knowledge base and instructions necessary to expertly perform a given task. A desirable system would be a hierarchical system that contains a large intelligence data base made up of expert modules (Fig. 6). That system would be capable of recognizing a process problem, taking direct action through a standard process control network, then making the decision whether or not to call on the expert robot. A network of generic mobile robots, telerobots, or modular manipulator arms would be on standby at work stations located at strategic places in the process. Each work station would contain special tools and special equipment that the robot may need to perform many different jobs in its area. When called on to work, the robot would be instantly trained from the knowledge base to perform expertly in the task.

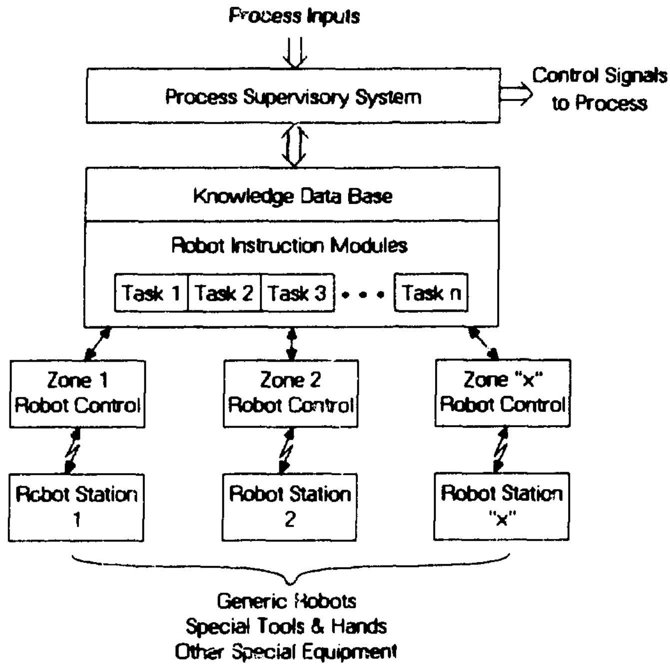

FIGURE 6 Network of Expert Robots

Vision and Other Sensory Systems

We have set up a laboratory to develop product inspection techniques and systems for both real-time and batch applications. Automated expert inspection systems will improve product quality and productivity for many processes. Our laboratory contains an Automatix AV-4 Computer Vision System with the capacity for 16 cameras and 32 input/output control signals. It is a completely self-contained unit, enabling it to operate as an autonomous inspection station, a sensory system for a robot, or a process control sensor. Special peripheral laboratory equipment includes a low-power (1 mw) Helium-Neon laser, a laser scanner for use in 3-D inspection, several computer controlled positioning tables, and various cameras, lenses, and light sources.

Commercially available, six-axis force sensors are being evaluated and integrated into several of our robotic systems.

CONCLUSIONS

The Department of Energy and DuPont management at Savannah River have recognized the need for robots, telerobots, and teleoperators for emergency response and many routine operations at the site. We have organized an in-house research and development activity and much progress has been made in developing techniques and systems and in applying them to practical applications. In the mobile robotics field we are developing low-cost wheeled vehicles and the most sophisticated walking machine presently available in the world. Future plans call for more involvement in expert systems incorporating artificial intelligence. We plan to maintain an engineering group with expertise in state-of-the-art robotics technology.

QUESTION AND ANSWER SESSION

Question: Have people gone back and analyzed specific accidents and their recovery scenarios to see how your robots might be modified to facilitate response to those types of accidents?

Mr. Byrd: We're definitely going to do that, but we haven't gotten into a real analysis of those problems. We're now starting to look at the more long-range programs, and we're going to go back and start trying in this experience base within our systems under development.

Question: The new waste processing facility is pretty much under design now. Do you think that, if they were starting out now, they might employ more complex remote systems than they presently have in the design?

Mr. Byrd: Definitely. Our group got involved after most of this design work had been done. We are now trying to get in very early on designs like that so we will have an impact on the kind of equipment that goes in it.

Question: A lot of us are beginning to step out into the unknown world of AI and find that the computers and software tools are very personal. What type of symbolic processes on the computer are you thinking of using?

Mr. Byrd: We're really just getting into that: it's a brand new program. We are purchasing a couple of symbolic machines which we will be using to look at process control in expert systems. Right now I'm really educating my system and trying to look at a lot of AI shells and things. We'd like input and feedback from anyone that may have some experience with that.

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TELEOPERATOR TRANSPORTERS FOR RERR

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This discussion addresses transporter technology for teleoperators in Radiological Emergency Response and Recovery (RERR). In nuclear operations Transporter refers to a base vehicle that locomotes to deploy a remote operation. Locomotion is first introduced in a general sense, then specialized to the unique constraints of RERR. Transporter requirements and ambitions are examined for the specific constraints of RERR.

In remote operations the phrase "Veni, vidi, vici" translates loosely as "I locomote, I sense, I act." The three capabilities are essential ingredients of successful remote operations, but the first, locomotion, is the most critical. Though locomotion is not an impressive end in itself, it is an indispensable means to an end goal. There are occasions when locomotion becomes the mission, such as when a system must egress from a committing location. If a system fails to return from an inaccessible area, then it becomes a problem, not a solution.

The broad classes of existing teleoperated locomotion include:

- Serpentine
- Ambulant
- Hopping/running
- Prehensile
- Swimming
- Flying
- Rolling

Serpents are indeterminate, continuum, snake-like mechanisms. They develop motive traction by reconfiguring their frictional contact with the environment. Snakes perform self-equilibrating isometrics along one axis to generate a net tractive force along the other axis. Serpents are useful for slinking under low overheads, for pipe traveling, for circuitous reaches, and where thin aspect ratio is important. Mechanical serpents to date have used both tendons and skeletal linkages.

The ambulants are legged walkers. They locomote by sequencing foot placements against the environment, always configuring themselves in equilibrium above the foot placement. The simplest example is a hexapod walking in triangular gait. Starting from a three-leg stance, the hexapod keeps its center of gravity over the triangular foot pattern, lifts and places its three other legs in a new contact triangle, balances over the new triangle, and repeats. Mechanical ambulants include bipeds, quadrupeds, hexapods and multipedes in addition to configurations without precedent in the animal kingdom.

Unlike ambulants, equilibrium is dynamic in hopping and running locomotors. Nuclear service work is not a likely niche for this otherwise important class of mechanical locomotion.

Prehensile locomotors grab against their environments to locomote by pushing and pulling. Tree dwelling monkeys are good examples from the animal kingdom. Teleoperated ladder and column climbers are mechanical counterparts of prehensile animal locomotion.

Swimmers locomote by means of hydrodynamic interactions with fluid environments (buoyancy is the important hydrostatic phenomenon). Although biological swimmers utilize hydrodynamic inertia (with little dependence on lift and drag), machines typically rely on thrusters for propulsion.

Locomotion aside, submersible teleoperators are more advanced as integrated work systems than mobile remote nuclear teleoperators are. The hermetic seal of submersibles would help to preclude internal contamination, and would facilitate decontamination wash-downs. The rich spectrum of submersible hardware, logistics, economics, work experience and system view have general utility to nuclear recovery operations, and especially to flooded settings like the TMI-2 reactor containment basement and aging liquid waste storage facilities.

Flyers differ from swimmers as aerodynamics differ from hydrodynamics (there are instances where buoyancy is still important). While teleoperated flight is an expanding niche elsewhere, application to nuclear recovery is unlikely.

Rolling locomotion continuously reconfigures a normal contact with the ground surface. The oldest rolling mechanism is the wheel (which will not be redescribed or reinvented here). Tracked locomotion mechanisms are simply contorted wheels (usually to place more surface in contact with the ground, or to alter the leading edge to facilitate terrainability). It is notable that rolling is the preeminent mode of mechanical terrestrial locomotion (for excellent reasons not expanded here), but that rolling is unimportant as a mode of animal locomotion.

> (Here a video presentation augmented the discussion. The video presented animal and machine locomotion in juxtaposition: clips of mechanical serpents were followed by clips of living serpents, and so on. All modes from this discussion were similarly presented. A few examples of nuclear service locomotors were then illustrated.)

Some of these locomotion modes (with the important exceptions of rolling and the specific mechanism of machine flight and swimming) mimic animal locomotion. Other forms of animal locomotion are not yet emulated by machines, and remain a rich agenda for investigation. These biological examples have already weathered the judgment of natural evolution. Natural selection has certified each of the biological modes for a class of tasks under a class of constraints.

Rolling on surfaces, swimming in fluid and flying in air are proven mechanical locomotion modes. The more recent forms (walkers, serpents, hoppers, grabbers) have strong positions within the research community, but currently lack dimensions important to RERR. The classes of locomotion relevant to RERR will be emergent forms (including hybrids) that survive the long-term challenge of RERR's diverse demands.

To deploy remote mission payloads, an RERR transporter must provide functionalities (manipulation, sensing tooling, logistical interfaces treated elsewhere in this conference) beyond locomotion. It is inappropriate to view locomotion in isolation from these other system considerations.

Capability is the first yardstick of mobile transporter relevance. RERR equipment must overcome or gracefully recover from the innumerable frustrations to locomotion. The highest standard of reliability and maintainability (more extreme than in nonnuclear domains) pertains to RERR equipment due to concerns for human rad exposure. Survivability must consider the long-term effect of accumulated rad dosage to a system. Decontaminability is a unique requirement of nuclear service equipment: contamination proofing precludes the problem where possible, and decontaminability ameliorates the problem after the fact.

Relevant RERR equipment must respond to conditions as they are encountered, not as idealized. In crisis response the do-nothing option is generally unacceptable. Action will be necessary in the face of imperfection, so risk is a special issue to RERR operations. Every capability bears a corresponding liability. Risk does not govern inspection or low-force manipulation in mild radiation though it will as RERR expands ambitions to address heavy work in hot conditions.

Development agenda should aspire to remotely move cubic yards of water and sludge, wash down extensive areas to ceiling heights, surface and demolish masonry, containerize debris and plug piping. The locomotion requirements are significant for work of this scope. To meet these challenges RERR development could benefit immensely from interactions with remote work experiences from the undersea and construction domains.

In summary, it appears that statically stable modes of locomotion are the best prospect for RERR. Those that jump, fly, and run are not apparently relevant. Serpentine, ambulant (walkers), rolling, and prehensile locomotion modes are all candidates for rad response and recovery. All are important and deserve continuing development. The rolling solutions (both wheeled and tracked) are practical now and possibly for the long run. In any case, rad locomotors must be capable, reliable, extensible and decontaminable to meet the challenge of RERR.

MOBILE TELEOPERATOR REMOTE SENSING

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ABSTRACT

Sensing systems are an important element of mobile teleoperators and robots. For radiological accident operations, the hazardous environment must be carefully considered, not only for selecting the sensors to be employed but also because of the limited capability of certain sensors in such an environment. The purpose of this paper is to discuss certain problems and limitations of vision and other sensing systems with respect to operations in a radiological accident environment to encourage the development of hardened, robust sensors systems for integration into modern teleoperators. Methods which appear promising for near-term improvements to sensor technology are described.

INTRODUCTION

Industrial robot manipulators and automated guided vehicles are now considered proven technology in many industrial applications (Hall and Hall, 1985). A more dexterous form of robot, the intelligent mobile teleoperator, now promises to become an important tool for the nuclear work force by performing inspection and maintenance while the nuclear plant remains on-line and improving radiological accident recovery operations (Brookman, 1985). Recent studies indicate that a major economic benefit could be realized by nuclear power plants if major technical advances were made in the use of sensors and intelligence of mobile teleoperators. A study conducted for the Nuclear Regulatory Commission (NRC) by Remote Technical Corp. focused on the detection of steam or water leaks, verification of valve positions, reading of gauges, measuring component radiation levels, and sampling methods to detect contamination. The report points out that today's plants differ significantly in design and present technical difficulties because they were not built to accommodate mobile teleoperators. Another related study conducted by Battelle Laboratories for EPRI (Kok, et al., 1985) surveyed 22 routinely performed tasks such as control drive maintenance, steam generation, tube repair, and repair or replacement of pumps and valves. Battelle's study indicated that robot cleaning of reactor cavities, unbolting and rebolting of flanges and making radiological surveys could not be done adequately without technical advances. Advances in manipulators, on- and off-board computers and sensors are required. The purpose of this paper is to attempt to identify the advances required in sensing and intelligence which may make the required tasks feasible.

In the following section a brief review of sensors for mobile teleoperators will be given. Then an assessment of sensor advances required for future mobile teleoperators is described.

SENSORS — CAPABILITIES AND LIMITATIONS

The capabilities and limitations of current sensor systems will be described in this section. The basic sensory requirements must be derived from the tasks. Since the tasks such as opening a valve or cleaning require hand-eye coordination even when accomplished by a human, it is difficult to isolate only the sensor requirements. The following sensor requirements will be developed under the assumptions that manipulators with human-like versatility and mobility can be developed and furthermore that the sensors can be interfaced with the manipulators to achieve intelligent operation.

Sensors may be classified into contact and noncontact devices. Tactile sensors are typical of contact sensors which may measure force, torque, pressure or simply surface contact. Vision sensors typify the noncontact variety which measure spatial distributions of information. Even though many tasks such as object recognition or environmental mapping can be accomplished with either type sensor, noncontact sensors *offer the generic advantage* of providing a time for planning before contact or collision with the environment. The contact sensors offer an inherent advantage in that the placement location provides some fundamental information.

Sensors may also be classified as internal or external. One important fact about most intelligent systems such as the human, is that a variety of sensors are internal. For example, the human has in addition to the five common senses of sight, hearing, touch, smell and taste, other sensors for balance, kinetic and many others which are not yet understood. In existing power plants, there are a very limited number of internal sensors. Due to cost or maintenance complexity, has limited the number of sensors which are built into current plants. In some cases this is due to the fact that sensors which have lifetimes in the high radiation environment are simply not available. For example, cameras which can withstand mega-rad exposures are not available. Internal sensors offer the significant advantage of known placement and can be selected in the design stage to measure critical parameters. Certainly, any sensors which are internal to the design must either be capable of performing for the lifetime of the plant, or be carefully maintained and replaced.

Most sensors which are currently applicable to remote maintenance are external. Tasks such as control rod drive removal, scrubber inspection, reactor cavity cleanup or valve replacement require a sensor system which can be moved to a desired location in the environment. Mobility and the ability to maneuver in a complex requirement are essential. Adding the capability to manipulate objects gives the basic motivation for remote manipulators. At this point it is appropriate to divide the sensor considerations to those required to perform the task and those required to maneuver through the environment.

The sensors required to perform the required task may generally be considered as those required for hand-eye manipulation. This class of robotic manipulation is now being studied extensively in the manufacturing field, especially in assembly research. Although many successful assembly applications have now been completed, a new concept "design for assembly" has also emerged from this research. In many cases, difficult assembly tasks can be avoided by a slight change in the product design. Leaders in this field are encouraging the formation of teams of product designer and manufacturing engineers in the design stage of a product to insure that the product can be automatically assembled. A similar concept "design for maintainability" could be valuable in this industry.

Sensors required for maneuvering in an environment are currently being studied. An industry has developed around the use of automated guided vehicles (AGVs) in industry, with the majority of these AGVs using wire guidance systems. A major DARPA-sponsored research effort is also under way to demonstrate an autonomous guided vehicle maneuvering through open terrain. Neither of these efforts are directly applicable, although certain technologies are applicable. The requirements of maneuvering in a power plant fall between the totally structured environment encountered in a well-designed factory and the totally unstructured environment encountered on a battlefield. Since a three-dimensional map is available or could be made available for any power plant from the design, the sensor maneuvering problem should be simplified to change detection. Even with a map available, the design of a device which could maneuver through this environment is very difficult and could require walking, stair-climbing and other dexterous capabilities.

SENSORS — FUTURE DIRECTIONS

Likely near-term improvements and availability of improved remote manipulator sensing technology will now be considered.

Safety

A fundamental premise of any new design components is that they must be proven to be reliable for the lifetime of the plant. Valves which last only 10 years, cameras which can operate only a few hundred hours, must be considered not acceptable. New component designs, redundant system designs and major plant design innovations must be developed.

A conflicting premise is that new designs which contain integral sensor systems must be used. It is not acceptable to leave important diagnostics, repair operations and routine maintenance to chance. Sensors which insure adaptability to environmental changes are essential.

Redundant system designs have been successfully used by NASA and the military to provide fail-safe or at least fail-soft systems. Much more attention is needed to this design strategy.

Integral Sensors

The development of hardened sensors is an important requirement. However, it is now clear that the sensors must be task-oriented and integrated into the initial design.

Sensors for Coordination

Vision, tactile, and other sensors required for achieving the type hand-eye coordination achieved by humans is certainly an area requiring a great deal of research. interestingly, even humans cannot function with only one of these sensors. We cannot expect machines to do more. A specific example of the type machines needed is the robot demonstration at the 1985 Exposition in Japan. A demonstration of a robot manipulator which uses a camera to read music, two arms with fingered hands which operate the keys of an organ and two legs which operate the foot pedals of the organ, plays a variety of songs for the visitors. Such demonstrations provide valuable research experience with what can be achieved with current technology and point to further research requirements.

Research issues in this area include: machine vision, tactile sensing, vision tactile sensor coordination, sensor manipulator coordination, and demonstrations.

Sensors for Maneuvering

The use of mobile manipulators, whether wheeled, tracked, or legged, are essential for many remote maintenance operations. These devices require sensors for navigation, maneuvering and safety in addition to the coordination requirements.

Research issues in this area include: vision-guided navigation; radio, ultrasonic and other navigation aids; proximity sensing; safety sensing; measurement sensing; and demonstrations.

Human Versus Machine

A fundamental issue related to the safety of nuclear power plants is the use of humans or automated machines for control, operation and maintenance. To err is human, to really foul up requires a machine. Neither humans nor machines have yet proven totally reliable. New designs which include such sensors as machine vision as integral components are now accepted for industrial robots for a variety of manufacturing tasks. It seems clear that a similar approach must be followed in the nuclear industry to provide safe, reliable operation for periods of time much greater than the lifetimes of the original plant designers.

QUESTION AND ANSWER SESSION

Question: An operator working in a rather close environment doesn't want to bump into anything. What would it cost to put a warning system on a mobile robot to prevent it from bumping into things?

Mr. Hall: Probably the least-expensive obstacle avoidance system that's available now, is based on polaroid ultrasonic sensors. These sensors send out a wave in a cone pattern and can detect everything from about 0.9 ft to 35 ft with about 0.1 ft resolution, and they cost about $7 apiece.

Question: What about the computer software that would have to go with it?

Mr. Hall: It think a standard microprocessor could handle 30 more more of those sensors. A single board microprocessor, which would cost a few hundred dollars, could do that as well. I always underestimate cost. But you could probably build an ultrasound sensing capability into almost any mobile robot for a few thousand dollars. There are more sophisticated ways to do it, but that's probably the cheapest and most practical.

Comment from the Audience: I put together a mapping machine with 24 of these acoustic sensors. The 24 operate simultaneously; one emits and the next one listens. Then you need 32 timers besides that issue, and the computer architecture. I brought in two bare-board 68K's with a lot of peripherals. My implementation took about six months and maybe $25,000 to actually complete.

Comment from the Audience: With regard to the sensors, I came across a toy made by Hard-Tech which is called GEMINI and has a fully integrated package of ultrasonic sensors on it. I spoke with Jack Louis a couple of weeks back, and he indicated that the sensors themselves are on the order of $8 and the microprocessor on the order of $50 or $75, so you're talking of a well-integrated system on the order of a few hundred dollars. So I would support your numbers, as far as price. All the capability exists.

Comment from the Audience: Just to enforce that, at Drexel University they've had a sensor mounted on a stepper motor to get fixed increments; that took care of some of the ranging in software. They were able to build it with an 8-bit single-board computer that cost a couple hundred dollars, with a $10 sensor and the stepper motor. Again, the software became the most expensive portion, but it was relatively inexpensive.

Mr. Hall: Maybe just as a closing point, sensors are now becoming cheap enough that the machine tool industry is trying to use sensors as integral parts of the machines. They wouldn't do that while the sensors were $20,000. Now with low-cost sensors, they're starting to consider that seriously.

Comment from the Audience: I'd like to make one more point. Sensors of this type should be looked at very closely because they basically do two things for us. They reduce the requirement for operator training; operator training is quite expensive and we change operators from time to time. They also reduce the probability of damaging the robot or damaging the equipment that they may be working on.

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MECHANICAL ACCESSORIES FOR MOBILE TELEOPERATORS*

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ABSTRACT

The choice of optimum mechanical accessories for mobile teleoperators involves matching the criteria for emergency response with the available technology. This paper presents a general background to teleoperations, a potpourri of the manipulator systems available, and an argument for force reflecting manipulation. The theme presented is that the accomplishment of humanlike endeavors in hostile environments will be most successful when man model capabilities are utilized. The application of recent electronic technology to manipulator development has made new tools available to be applied to emergency response activities. The development activities described are products of the Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory.

INTRODUCTION

We have been asked in this paper to confine our thoughts to the mechanical accessories that should be added to a mobile platform to be used to respond to radiological emergencies. In reality, each of the subsystems of a mobile response system is interdependent, so while our remarks will treat the mechanical accessories, one must be aware that in the final marriage of the subsystems, the compromises of optimization will be necessary.

The major theme of this paper will be the choices involved in selecting the proper manipulator(s) for the mobile platform. There are in existence other mechanical accessories of which one should be aware. Proceedings from a series of recent conferences, Robotics and Remote Handling in Hostile Environments in Gatlinburg, Tennessee, April 23-27, 1984; Fuel Reprocessing and Waste Management in Jackson, Wyoming, August 26-29, 1984; Robotics and Remote Handling in Toronto, Canada, September 23-27, 1984; and Remote Operations and Robotics in the Nuclear Industry in Pine Mountain, Georgia, April 21-24, 1985; and a recent EPRI Journal (November 1984) catalog many of these mechanical accessories and their uses. A typical accessory is an elevating mechanism used generally to accomplish a change in vertical position. The elevating mechanism with a rotation is used to supply manipulation or viewing at varied

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‡Operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy.

heights and with a 360° vista. If one adds a bending joint to the elevating mechanism, then objects surrounding the platform can be reached. The addition of a second bending motion allows the floor surrounding the platform to be reached with the motion supplied by the mobile platform.

APPLICATIONS OF MANIPULATION

Of all the potential applications of manipulation, the application to emergency response and recovery is the easiest to address. The emergency response problem provides a minimum of structure to the environment and, therefore, a maximum reliance on flexible humanlike response. The opening and oversimplistic account of mechanical accessories had as its purpose a visual reference to structured environments where two, three, four, five, or six manipulation degrees of freedom could be used to accomplish a given function or work routine. It is of major importance to have a clear understanding of the relationship between the structure of the environment and the attributes of human capabilities. The logic that we employ in analyzing a response to an emergency situation relies on our understanding of the physical and chemical conditions of the emergency and the application of disciplined motion allows us to moderate or overcome the emergency. The understanding of the emergency and the planned and executed motions are human attributes. The model we use to respond to the emergency is the man model. For this type of application, the man model is the only model we have. We interpret and act within the confines of the man model.

Of the three possible systems that could be employed for performing remote work, programmable robotics, intelligent robotics, and teleoperation, only two, intelligent robotics and teleoperations, offer useful potential for emergency response.

The goal of today's developments in artificial intelligence (AI), in the context of emergency response applications, is to acquire knowledge of the environment from sensory input, represent this knowledge in a useful manner, build context-dependent knowledge bases and provide reasoning functions, and execute task and mission level control. Although useful AI techniques are now at commercial or lab bench scale development, the techniques to control a truly autonomous vehicle for performance of emergency response tasks probably won't be available for at least ten years. Therefore, the focus must be on teleoperation.

Teleoperation maintains man in the operations loop. Sensory information is fed to an operator and from that sensory information the operator defines and executes the necessary motions. Our development activities at Oak Ridge National Laboratory have been centered on improving the flow of information to and commands from the man in the loop. In addition to improving the flow of information, we have executed designs that increase the reliability of the maintenance equipment and we have provided equipment that can be maintained by another manipulator.

The development activity has been applied to the problem of maintaining a nuclear fuel reprocessing plant. That development activity has a common base with radiological emergencies in at least two important areas. The first is that reprocessing facilities are large plants. The mobility and support equipment needed in large facilities require solutions that are similar to the solutions required for unrestricted environments. Second, maintenance and operational solutions required to respond to a broad spectrum of planned and unplanned events are again similar to the solutions or capabilities envisioned for radiological emergencies.

HISTORY OF MANIPULATOR DEVELOPMENT

Historically, the initial attempts at nuclear manipulator development happened nearly simultaneously at a number of facilities. Once "reach rods" no longer solved the problem and totally enclosed shielding was required, the first of the hot cell facilities was constructed. In facilities at Oak Ridge, Los Alamos, Brookhaven, Argonne, Westinghouse-Bettis, General Electric-Knolls, and Atomics International-Canoga Park, a form of the stiff-armed crane with finger closure was developed. There was some variation in the amount of articulations but there were more similarities than differences. In general, these were switch controlled unilateral manipulators and the force was supplied by electric motors.

Feedback to the operator for control of this type of manipulation was visual. It was in essence control by interference. Ray Goertz of the Remote Control Engineering Division of Argonne National Laboratory, whose work is described in a following section, is credited with the observation that "manipulation is a series of collisions." The unilateral electric manipulator work was paralleled by work at Argonne in which a second of man's five senses - feel - was utilized to control manipulation.

Ray Goertz's work at Argonne produced a series of manipulators that were mechanical parallelograms capable of transmitting back to the operator (master) the interferences to which the projected hand (slave) was subjected. The mechanical devices were also capable of transmitting the operator's force to a work piece (bilateral). The mechanical unit was inserted into the hostile environment through the shielding wall and because of the fixed wall mounting, the volume of manipulation was limited to the reach of the operator. A series of master-slave mechanical manipulators which are variations of this initial theme have been produced. Variations included extending the manipulator's reach, increasing the force capacity, and providing sealed insertion. The basic development of the mechanical master-slave manipulator and its force reflecting capabilities was so successful in its application that the design of hot cell facilities for the next thirty years - up to and including the present time - have been based on the capabilities of this type of manipulator.

The Goertz group at Argonne recognized the fundamental limitation of the "through the wall" manipulator and responded to that limitation by designing the bilateral force-reflecting (BFR) servo master-slave, a manipulator system where the master and slave were no longer mechanically attached. This allows the manipulator system to be freed from the wall and allowed it to function in any area its transporter would carry it to. With the introduction of an attached television camera as the viewing mechanism, the slave was free to be transported to any location within the working volume of a transporter and the master control station could be placed at any convenient position. Signals transmitted between pairs of servo motors provided both replica motions between the master and slave and a means of generating a sense of feel when interferences occurred. The tape or cable driven master and slaves were counterbalanced and lightweight to minimize the effects of system weight, friction, and inertia. The original BFR servo master-slaves of the mid-1950s were successful mechanical devices, but had electronic requirements that were beyond the technology of that day. Argonne's development carried to completion four models, culminating in the Mark E4A in the early 1960s. Variations of this unit are offered by Central Research Laboratories as the Model M and Model M-2.[1]

The general ideas embodied in the initial servo master-slave unit were attractive enough to generate four additional development activities. A second unit was developed in the U.S. at Brookhaven National Laboratory and that unit spun off a private company, Teleoperator Systems Incorporated. In addition, three units were developed in France, Germany, and Italy.[2]

At about the same time as the mechanical master-slave was developed, an improvement in the electric unilateral manipulator was marketed. The General Mills manipulator took the principles of the stiff-armed crane and added articulation to provide seven degrees of freedom for improved dexterity. The General Mills manipulator transported on an overhead bridge and the window mounted master-slave became the standard tools around which facilities were designed. Variations are marketed by at least eleven firms worldwide. This includes GCA/PaR and Teleoperator Systems Corporation in the U.S.

DEVELOPMENTS AT ORNL

At this point in the development chain, most facilities were equipped with force reflecting mechanical master-slave manipulation with restricted working area and a non-force reflecting electric unilateral unit that covered the entire volume of the shielded area. A series of facility design challenges came on the scene in the late 70s that required either large volume shielded areas (such as reprocessing or waste solidification) or manipulation in unrestricted areas (such as space, undersea or emergency response). A potential solution to these design challenges resulted in the further development of the bilateral force reflecting servomanipulator. At Oak Ridge National Laboratory the decision was made to pursue the development of the advanced servomanipulator as an integral part of the program of the Fuel Recycle Division.

The thrust of the development at ORNL has been to produce a workable operations and maintenance system that would be incorporated into a nuclear fuel reprocessing facility design. Early in the development activities, it became obvious that the development avenues being pursued had application and positive benefit in a number of nuclear and nonnuclear areas. The radiological emergency response system is one of those.

The development activities at ORNL were divided into seven subsystems. A range of options for each of the subsystems was evaluated and development activities proceeded in those options judged to have the higher probabilities of contributing to a successful solution. The subsystems were: control system design, manipulator mechanical design, transporter design, television viewing, man-machine interface, signal transmission, and power transmission.

These subsystem evaluations and the subsequent development activities provided a base for staged application of our progress. Our development activities in the area of servomanipulators has been conducted in three distinct stages that are identified with three different servomanipulators. Our first experience with servomanipulators and with total television viewing was conducted in an unused hot cell facility at Oak Ridge. We installed the control station 150 cable feet from the manipulator and the hot cell. A set of TOS-SM-229 servomanipulators were loaned to us by a sister laboratory. We incorporated these servomanipulator arms into this facility for remote systems development. Starting in 1981, we did our initial investigations in two areas. The first was the investigation of control systems for the transporter and manipulator systems which led to the development of the digital control system now in use, and the second was a detailed study of the man-machine interface. A series of studies was conducted which attempted to optimize the relationship between man, the television camera, and the servomanipulator. The studies have been documented in the literature.[2,3]

We also used the facility to evaluate voice control of television cameras and introduce the necessary software for automatic camera tracking. Figures 1 and 2 show the slave and master as installed in the Remote Systems Demonstration Facility.

At about the same time, we undertook upgrading an existing commercial servomanipulator system by designing and integrating to it a digital control system. We worked with Sargent Industries, Central Research Laboratories, and the cooperative effort produced what we strongly feel is one of the better servomanipulator systems available today.[1,4] We have been using the unit to perform remote maintenance routines on various pieces of reprocessing equipment in our nonradioactive mock-up test area. The M-2 slave system as we employ it consists of the slave arms, two television cameras with pan and tilt mounted on rotate-extend arms and motorized zoom/focus/iris lens, a fixed camera mounted at a belly position, and a 500-pound hoist positioned between the arms. The system uses a coax cable interconnection for the high speed serial digital communication link to the bridge and manipulators.

In addition to simplifying cable handling systems, the digital control system allowed us to demonstrate a series of operational modes that indicate the versatility of the manipulator and its control system.

We utilize a "dead man" switch on the master handle which provides "free wheeling" of the master when the operator's hand is remoted from the grip - the slave is servoed in position. The master can also be easily indexed with respect to the slave to provide an optimum operator position. Presently the force feedback ratio can be varied from 1:1 to 8:1 and could be varied in other ratios if the need arises. All of these controls are menu driven and the selection process is by touch screen. We have implemented a routine that brings the master and slave into synchronous position at a controlled slow speed. The digital control system is utilized for a diagnostic system that indicates to the operator the condition of the system in use. The diagnostic system provides valuable information in attaining optimal system performance. Figures 3 and 4 show the M-2 manipulator as installed in the Remote Operations and Maintenance Demonstration Facility.

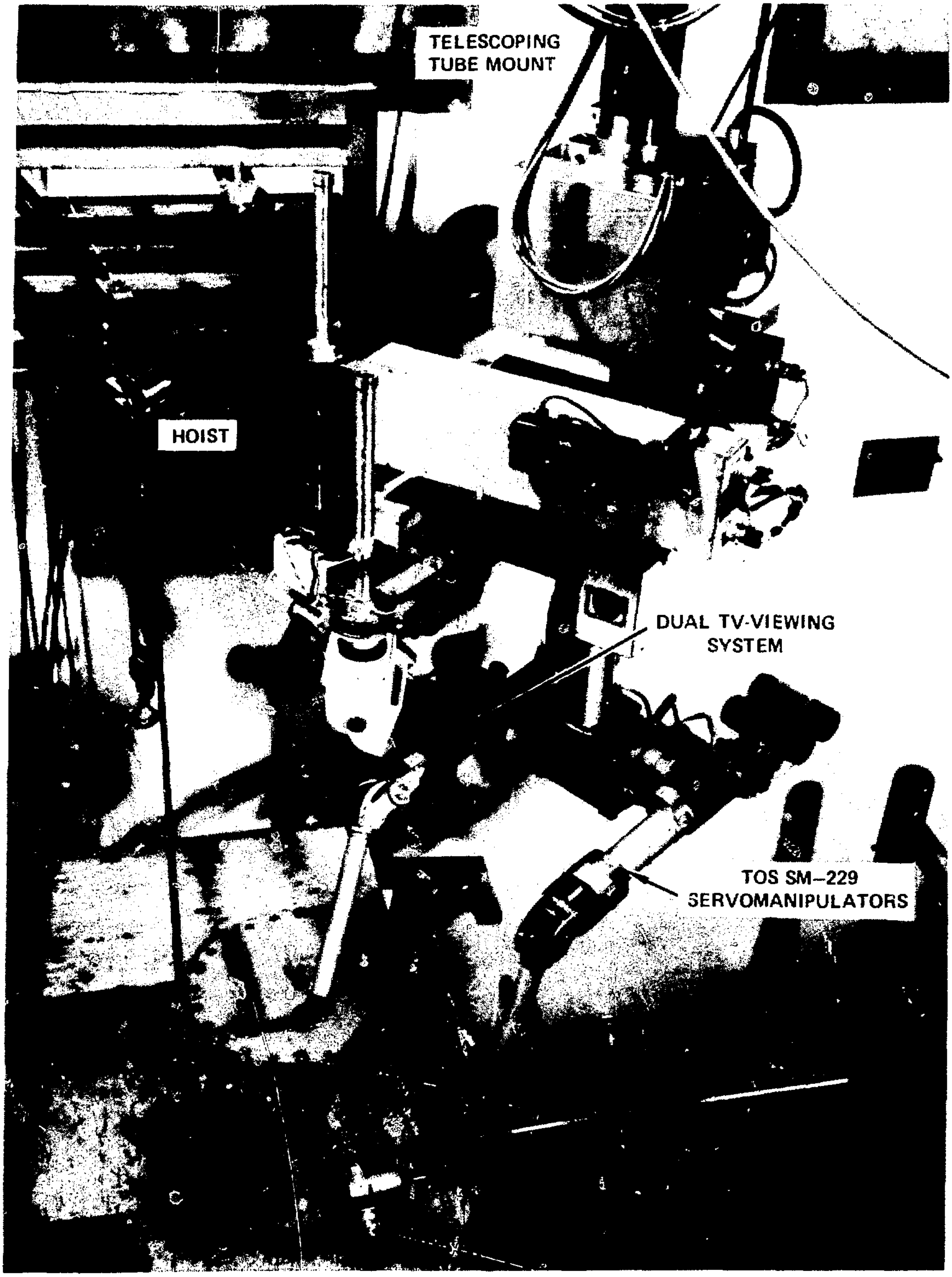

FIGURE 1 Slave as Installed in the Remote Systems Demonstration Facility

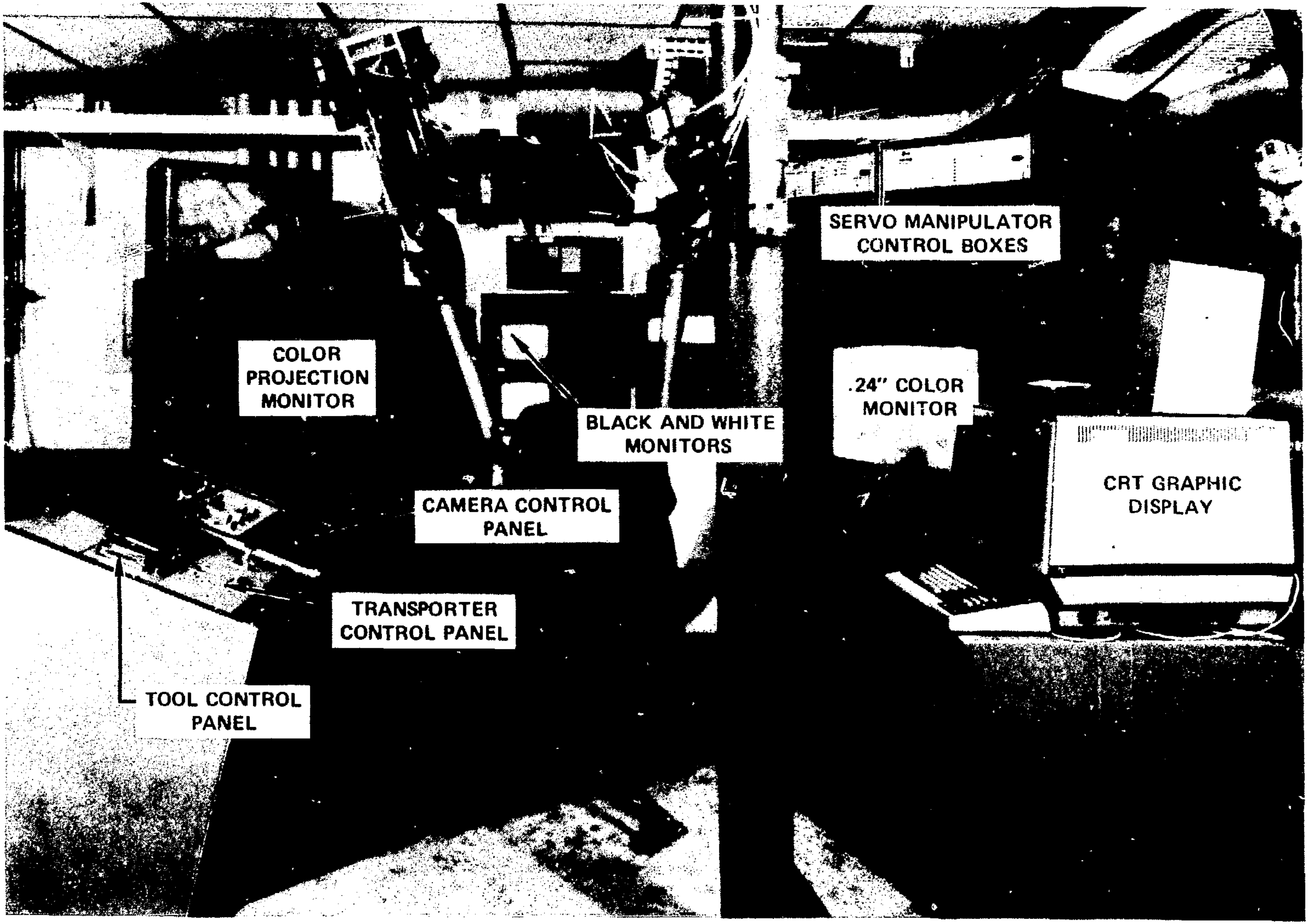

FIGURE 2 Master as Installed in the Remote Systems Demonstration Facility

FIGURE 3 M-2 Slave Manipulator as Installed in the Remote Operations and Maintenance Demonstration Facility

FIGURE 4 M-2 Master Manipulator as Installed in the Remote Operations and Maintenance Demonstration Facility

There is a third stage in our present development program and one in which we have a great deal of pride. For the application of reprocessing or waste solidification, we felt that improvement in two attributes of the servomanipulator were necessary. The first is increased reliability and the second is improved maintainability. To that end, we have developed and manufactured a gear and torque tube driven servomanipulator.[5]

Replacing the tape and cable tendon drives with gears and drive shafts provided us with a solution to our goal of increased reliability and improved maintainability. These mechanisms are theoretically more reliable and the gear and spline interfaces provide a manipulator that is separable into removable and replaceable modules. These modules were designed to be within the lifting capacity and dexterity of another manipulator arm.

In addition to designing the manipulator for greater reliability and for ease of repair, we accomplished an additional and needed design change. All of the existing servomanipulator designs paralleled the through-the-wall master-slave design in configuration, The "elbows up" configuration is best suited for table-top work. Designing a manipulator in the anthropomorphic (manlike - elbows down) configuration required that we solve a different design problem - that of eliminating a mid-range singularity in the standard hot cell roll-pitch-roll wrist. We have successfully met that design challenge.

To expedite our development program, we produced the two slave arms on a fast track schedule and are using one of the slaves as a master while we are completing the design of the master arms. We are presently checking out the digital control system - hardware and software - with the pseudo (two slaves - one is a master) master-slave pair. Recognizing that we have much higher friction and backlash when using the slave as a master as compared to the final system, the tests to date indicate we have been successful.

For the next few months we will be operating the pseudo master-slave system. Following that period, we will add the master arms[6] (presently in design and fabrication) and begin operation of the complete system. The digital control system to be utilized is the next step in our development program after the digital control system described for the M-2 manipulator.[4,7] It is, in fact, a transition to the use of all commercially available hardware for control implementation. The system is based on the use of the IEEE-796 bus structure and Motorola 68000 micro processors for joint control. Software is written in FORTH. Figure 5 is a schematic of the manipulator. Figure 6 shows the slave manipulator as it appears today, and Figure 7 is the system control room presently under construction.

Our present demonstration schedule indicates that by the end of 1986 we will have adequate information to produce through industry a marketable system that will be available in about 1988. That schedule could be expedited if a need were shown.

Technical details of the material presented today are contained in a series of nine papers presented at the ANS National Topical Meeting on Robotics and Remote Handling in Hostile Environments held in Gatlinburg, Tennessee, in April 1984.[3-11]

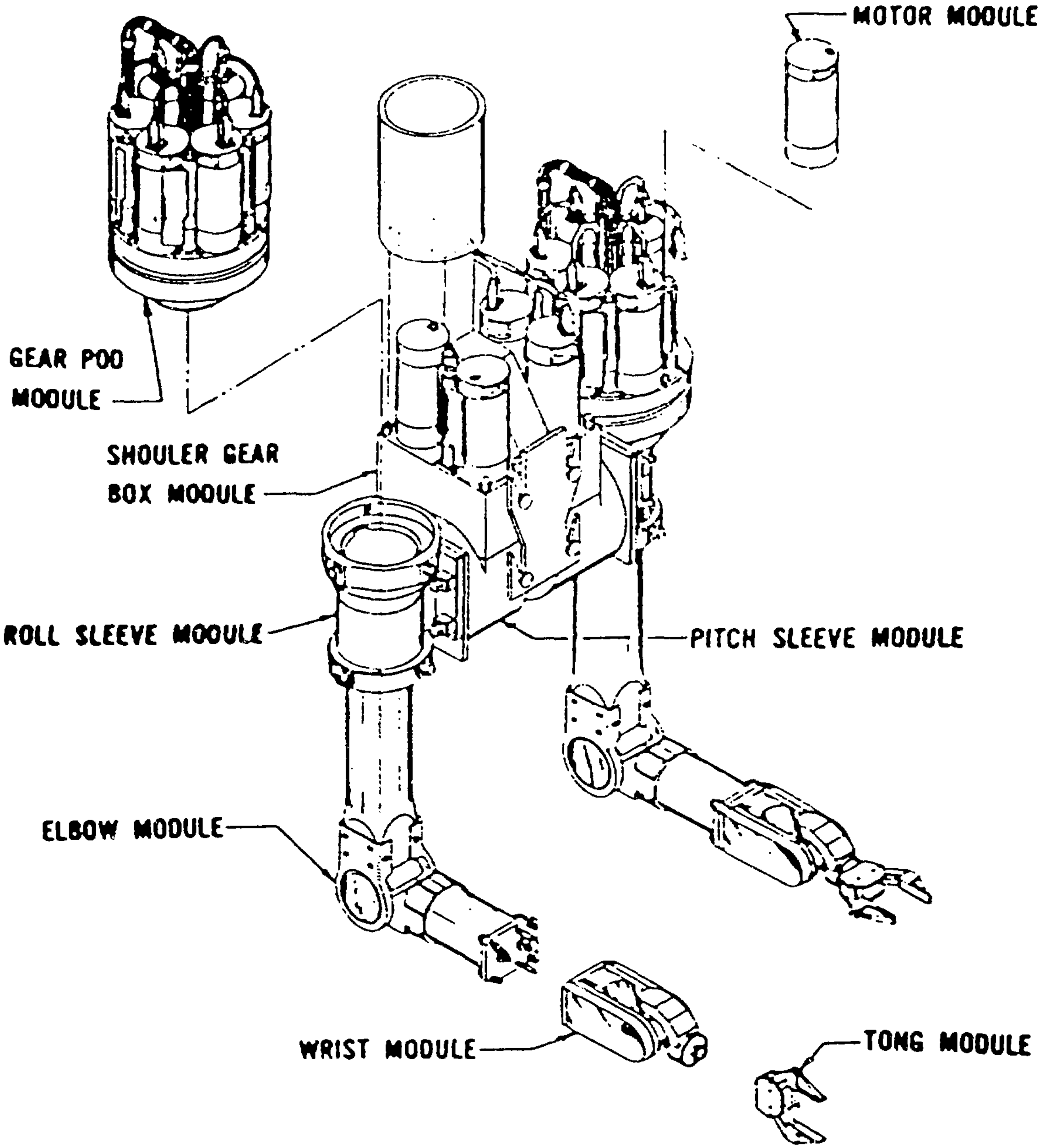

FIGURE 5 Schematic of the ASM Manipulator Slave Arm

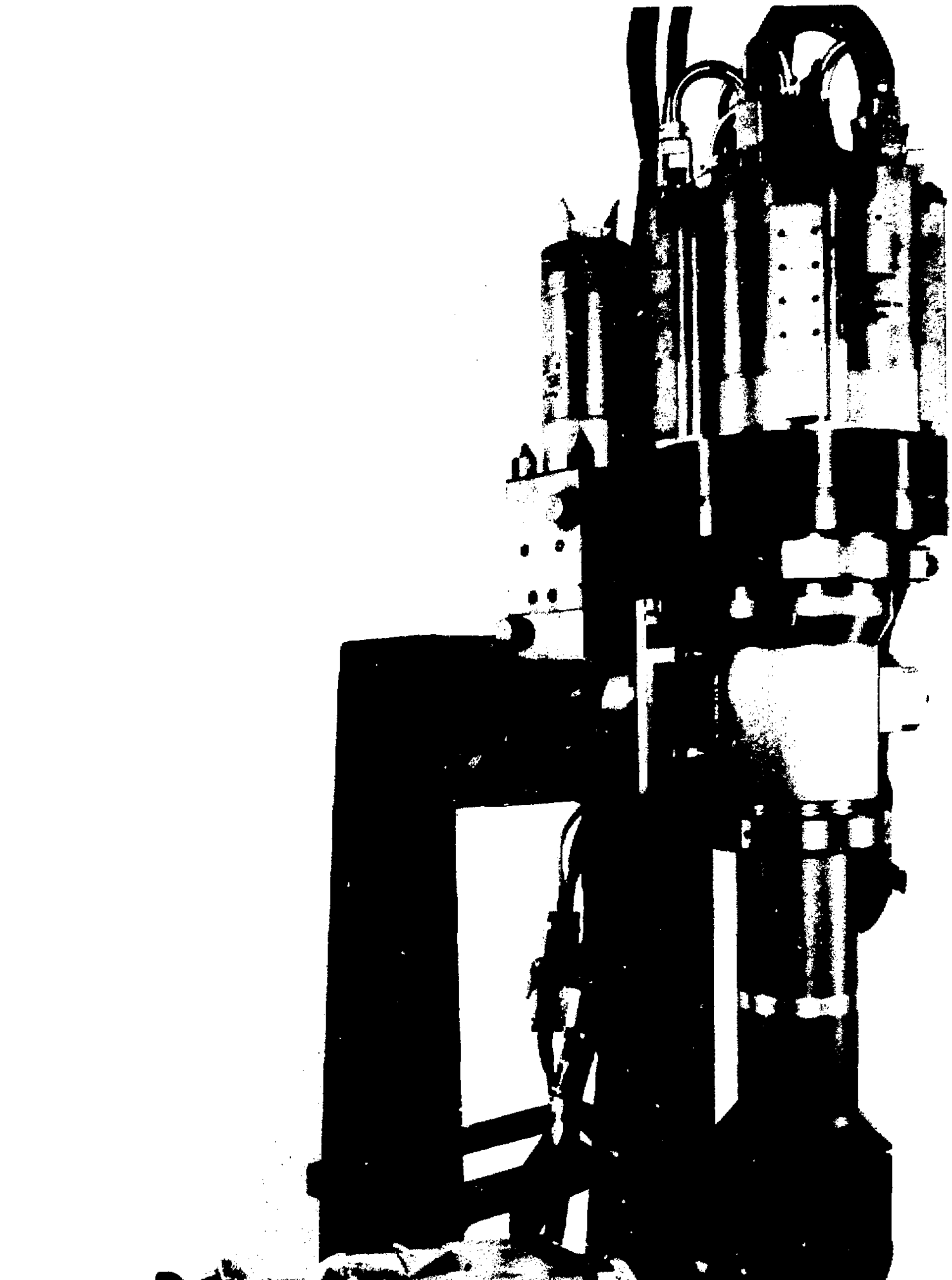

FIGURE 6 ASM Slave Manipulator as It Appears Today

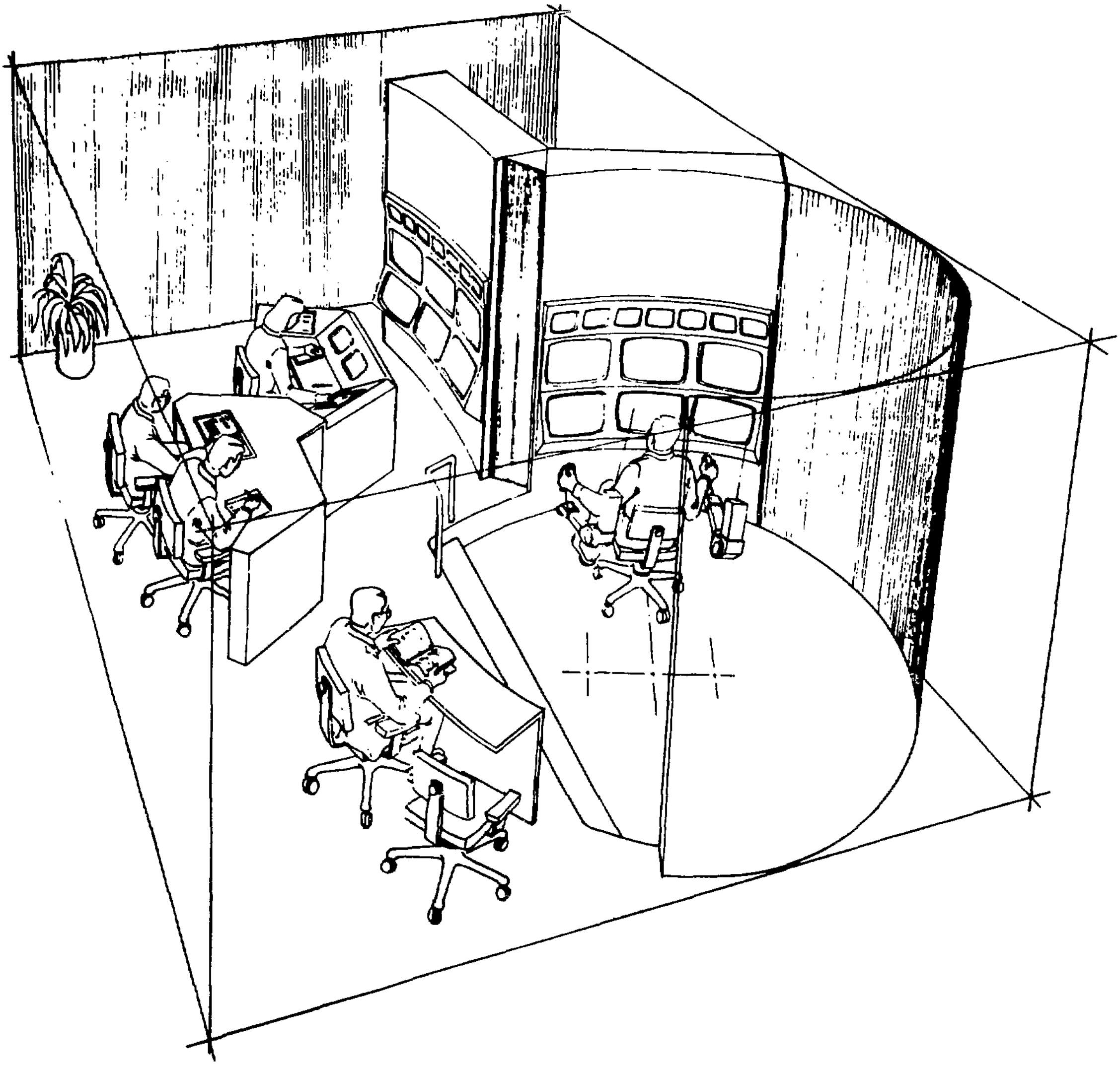

FIGURE 7 System Control Room Presently Under Construction

SYSTEM OPTIONS

Having established the availability of force reflecting manipulators and indicated the availability of nonforce reflecting manipulators, one is faced with the decisions necessary to choose the correct manipulator for the application.

One Arm or Two Arms

In general, the greater the structural definition of the work place, the higher the probability that one arm (or one hand) manipulation will be satisfactory. We can design an environment where all normal operations can be done with one hand (where normal describes the fact that we have considered the operation in the design). Our observations indicate that about 70% of the things we do with a manipulator can be done with one hand, albeit more slowly. We tend to use two-armed systems for two reasons. The first is the 30% of the operations that benefit from a holding hand and an operating hand, and the second is the fact that the redundancy provided by the second hand in case of failure of the first hand appears advantageous to completing the tasks. In the unstructured environment of an emergency situation, these authors favor the two-hand approach.

System Dynamics

For teleoperated systems using replica masters, we have observed that the operator's control is at its maximum when the system speed matches human hand speed (30 to 50 inches per second) and the speed with which operations are executed are at their maximum with replica masters. We have tested both force-reflecting and nonforce reflecting systems and the system's dynamic performance appears to be one of the major factors in controlling the time it takes to complete an operation. One factor we believe is affecting the operator is that when the slave doesn't track with the master in real time, the human operator is required to make an abnormal adjustment in his command process and a confusion results. There is no human analog to the delay feature and the operator is required to readjust his control thinking. We believe this increases both the time to complete a series of motions and the number of errors in the required sequence.

Man-Machine Interface

There are a number of attributes that fall within this category. We believe that the three major attributes of concern and decision in this area are the manipulator control mechanism used, the viewing system, and the incorporation of force reflection.

In testing a number of manipulator systems at ORNL, some general conclusions can be drawn. The learning curve is more favorable and the number of errors is minimized for those manipulators that are patterned after the human arm and whose control is a replica master of the slave. In one instance of recent testing, we were able to compare an exoskeletal master and switch box control for the same manipulator and the testing indicated a large bias for the humanlike master. As expected, the bias was in both an increase in the speed of completion and a decrease in the number of errors.

In tests run at a series of five laboratories, a comparison was made of unilateral switch control and joy stick control.[12] The testing reported time to complete similar tasks and the ranges reported in a ratio of switchbox to joy stick control times were from 2:1 to 10:1 with a preponderance of the data at about 5:1. The joy stick which matches control motion to slave motion is the better control solution. Switch boxes which have been used often because they are inexpensive to build, require the operator to make joint transformations that are time consuming, error causing, and fatigue producing.

The significant choices in television viewing are those concerning color, increased lines of definition, and stereo projection. Each of these areas offers solutions that have some specified advantage and in each case that perceived advantage is generally more expensive, more complicated, and requires greater maintenance activity than comparative standard resolution black and white. Tests conducted at ORNL[13] indicate little advantage to color for detailed maintenance activity, but did indicate a preference for color by the operators. The testing also indicated a potential advantage of color for search and location tasks or for generalized viewing. Nevertheless, the color cameras' increased complexity presents reliability problems in radiation fields. There are few radiation hard color cameras commercially available.

Testing presently being conducted at Oak Ridge, where a NHK (the Japan Broadcasting Corporation) high definition television system (HDTV) with 1125 lines of resolution is being used, indicates that some of the depth perception cues lost in monocular viewing may be offset in the high definition system. The high definition systems are more expensive and may be somewhat more susceptible to radiation damage. Our Japanese colleagues are presently conducting radiation tests on their system.

The use of stereo vision is an unsolved enigma. The human animal uses stereo vision to establish distance and create depth perception. A number of schemes are available to produce stereo vision via television cameras - our experience indicates to date none has been totally successful for continuous intense use. One of the major problems is operator fatigue - a fatigue that takes place after between 15 and 30 minutes of intense use.

Binocular vision certainly has potential advantages, particularly for degraded visual conditions, and further studies into the fatigue factors will produce useful and advantageous systems.

The mechanical master-slave manipulator gained great popularity in remote operations because it provided a true sense of feel to the operator. Of the five senses man is endowed with, two and possibly three are the effective controllers of mechanical work. Taste and smell are the aesthetic senses and make little contribution in the mechanical realm. Sound is an arguable contributor, but is generally included as it is inexpensive and a fairly simple sense to transmit to the operator. The best argument for inclusion of sound may be its contribution to telepresence. We would define telepresence as the operator having the feeling of being at the work site rather than some distance away.

That leaves us with sight and feel as the predominant senses in accomplishing useful mechanical work. There has been little argument that these are the predominant senses in the general treatment of mechanical work. There have been continuing arguments about including force reflection - feel - as a predominant requisite for projected mechanical work. The arguments begin with cost. Present force reflecting manipulators have a cost per arm that is three to five times as high as their non-force reflecting counterparts. The arguments go on to cover complexity and reliability. The force reflecting manipulator is more complex, both mechanically and electronically, but complexity is in itself only a potential measure of reliability. In the area of reliability, there is little available data. The counter argument in the reliability area is that the existence of force reflection in an operating manipulator is a built in limitation on overstressing the manipulator or the equipment being maintained. Observers of operators of non-force reflecting systems are aware that the compliance of the system is used by the operator as an indicator of applied force. Excessive system compliance, which could be used to moderate the collision force, is in itself counterproductive. In addition, the reliance on viewing the compliance as a measure of the interference was a product of the wide angle viewing provided by direct viewing (windows). Systems using television rather than direct vision may not always provide an adequate view to indicate compliance. We would suggest that the more unstructured an environment is, the greater the need for force reflection We are also impressed with the fact that the area under discussion today - radiological emergencies - is by definition the most unstructured environment a manipulator can encounter.

There are few simple solutions to the selection of the correct mechanical accessories for radiological emergencies. The technology of the last five years has added to those mechanisms to be considered, a series of improved products that we believe should be considered and utilized.

QUESTION AND ANSWER SESSION

Comment from the Audience: In general terms I support everything you said, except I feel much stronger about two arms than you do. I really feel we need two arms for that extra 30%.

Comment from the Audience: I think those data were generated on master/slave operations. If you're talking about a mobile system, the value for two arms for tool changing would be even greater.

Comment from the Audience: I'd also agree with the perspective of the talk. It's really tough in a lot of cases to get through the door and under the table and still have that second arm work. I wonder if you might comment on the adaptability of this very extended system to a mobile setting. Consider the packaging sizes, the number of components, the need to deploy those things in small packages and in hardened manners that will meet the conditions.

Mr. Feldman: Well, you get into a whole series of compromises. The kinds of manipulators, the three kinds I've talked about here, can be made in almost any size and capability that you want. The problem is, what do you need in an emergency response in the area of force and capability? We design almost all of our machines for man maintenance. So I tend to analyze the problem in terms of what man's capabilities are, and I find manipulators today about the right size. For most applications, they're about the size that can be mounted on transporters that would carry them to whatever the emergency is.

Question: Do you have any idea how you can scale down what we think of as transporter size? Does the force change in any linear way?

Mr. Feldman: I think you can drop down to a 25-pound arm, and it would fit on most transporters talked about here.

Comment from the Audience: I would add that the force reflection sensitivity is proportionate to capacity, so when you downsize you actually increase sensitivity as well.

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POWER AND SIGNAL TRANSMISSION FOR MOBILE TELEOPERATED SYSTEMS

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ABSTRACT

Appropriate means must be furnished for supplying power and for sending controlling commands to mobile teleoperated systems. Because a sizable number of possibilities are available for such applications, methods used in designing both the power and communications systems built into mobile vehicles that serve in radiological emergencies must be carefully selected. This paper describes a number of umbilical, on-board, and wireless systems used in transmitting power that are available for mobile teleoperator services. The pros and cons of selecting appropriate methods from a list of possible communication systems (wired, fiber optic, and radio frequency) are also examined. Moreover, hybrid systems combining wireless power transmissions with command-information signals are also possible.

INTRODUCTION

The design of a mobile teleoperated system must include some means of powering the vehicle and controlling its actions at the emergency site. For radiological accidents, the problems of supplying required energy and directions may become much more difficult because of possible extreme radiation exposures, the presence of corrosive gases, unpredictable excursions in ambient temperatures, and litter from damaged equipment.

All of these factors require careful considerations of the operational requirements and accident conditions an emergency teleoperated vehicle might have to manage and overcome. The judicious selection of a power supply and communications system should be based on these requirements.

Surveys indicate that there are a number of methods by which a mobile teleoperator might be powered and controlled. The purpose of this presentation is to bring to light some of these methods (including some that might be considered very "blue sky") for consideration in future conceptual/hardware designs. It is hoped that by presenting these possibilities a more open approach can be maintained when designing these interesting and important mobile emergency systems.

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POWER SOURCES FOR MOBILE TELEOPERATORS

Umbilical Systems

One means for supplying power to a remote vehicle is through a system of conductors that is continuously attached. Typical setups for accomplishing this are outlined below (Fig. 1).

Trailing Cables. All electrical power circuits are fed through a cable bundle which tracks behind the mobile device. This method is perhaps the most common and straightforward way to communicate power, but it may have serious problems from contamination in a radiologic emergency. Also, wire breakage inside a cable is possible due to cable flexing and binding when the device moves around corners. Typical cables for this service may range from $\frac{1}{2}$ to 1-$\frac{1}{2}$ in. diameter and from 50 to 200 ft long. Cable weight may become a problem. Questions dealing with the payout and collection of such cables (e.g., contamination) must have design and operating solutions.

Coiled Cords. Helical-wound cables having built-in coiled spring tension capabilities may be partially or wholly suspended by supporting devices above the floor to avoid or reduce contamination and binding problems. These cables would still be susceptible to wire-breakage problems from repeated mechanical flexing and twisting.

Folded Cables. These conductors are usually supported by mechanical extenders of zigzag shapes or by a sliding cable support. Although folded cables are held above the floor to avoid contamination, repeated flexing can produce conductor breaks.

Overhead Swivel Arm. In this arrangement, cables that provide power to the mobile unit feed down from an overhead arm that can swivel around in a full circle. A cable retractor could be used to maintain cable tension. Such an arm would be less susceptible to cable bending problems, but it would have to be preinstalled in the facility for possible use during emergency conditions. The arm usually requires a rotary electrical contractor at its turning center which adds problems relating to the operation of the contractor system. This configuration would be especially free from floor-borne contaminants.

On-Board Generation

The supply of power comes from a fueled-generator system (Fig. 2).

Organic Fuel in Tank. An engine-driven generator can supply power to the remote device. It may have attending safety problems from fuel storage and/or from

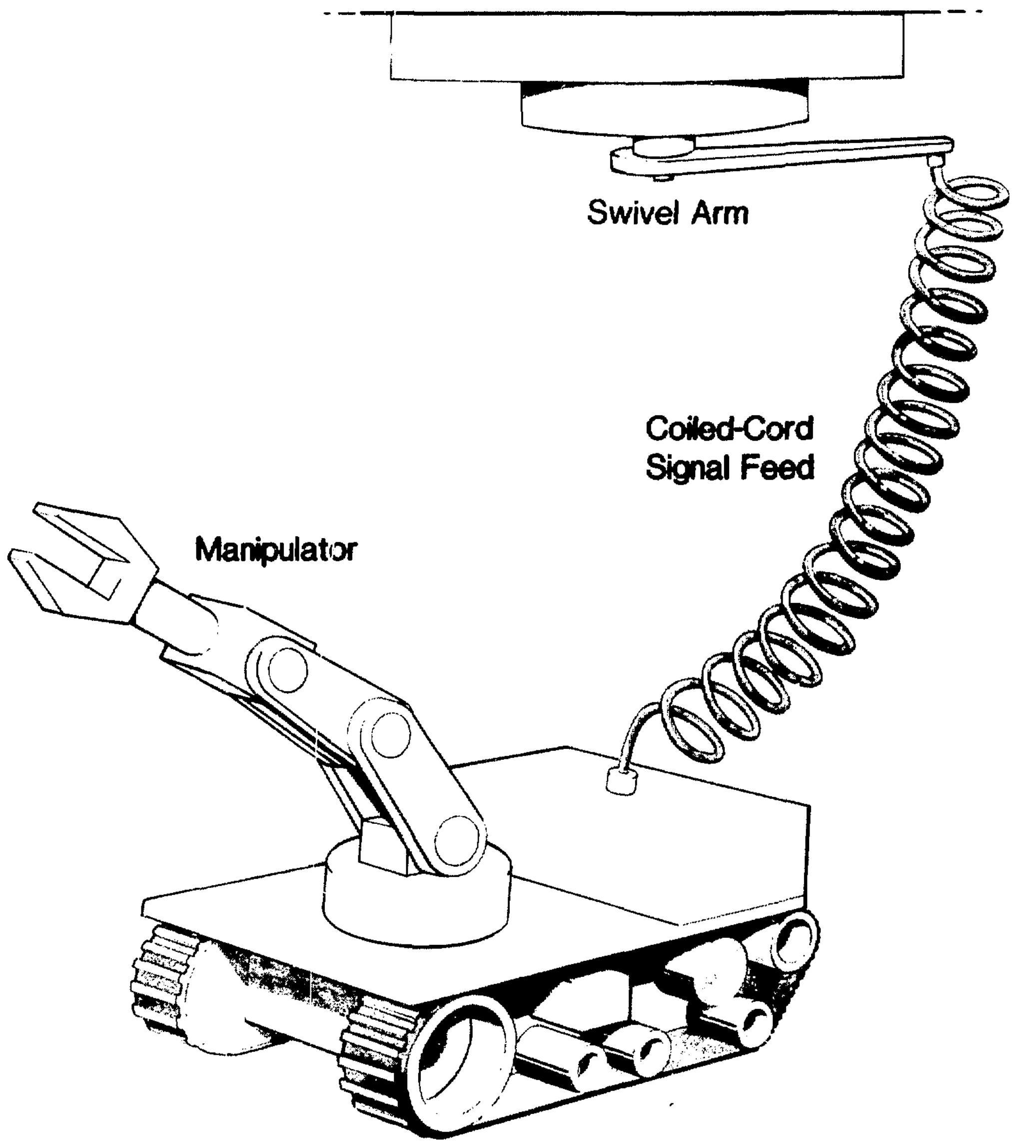

FIGURE 1 Mobile Vehicle with Coiled-Cord Umbilical Plus Swivel-Arm Feed for Command Signals

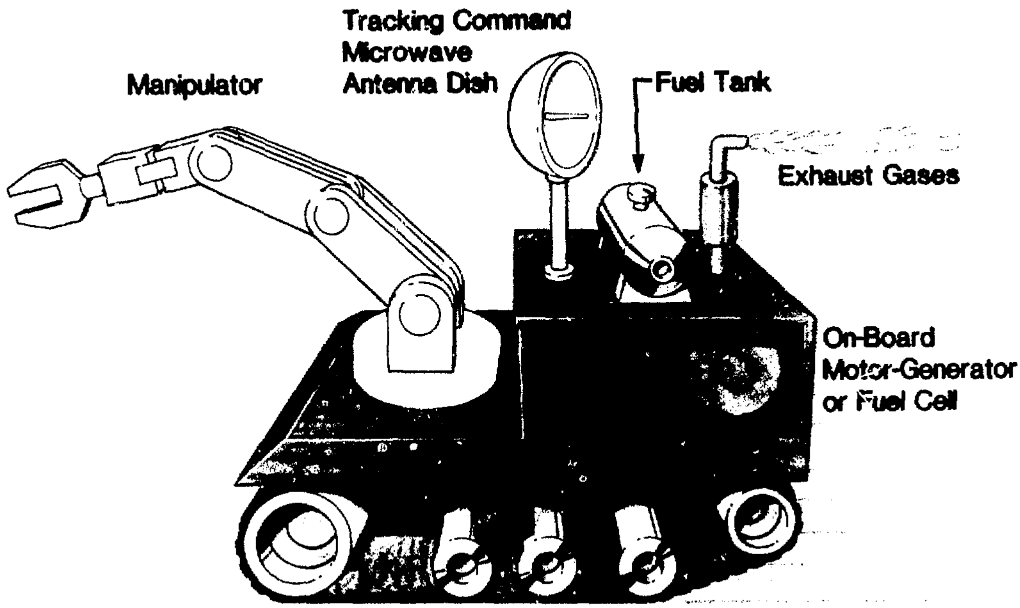

FIGURE 2 Teleoperator with On-Board Power Generator

exhaust sparks or fumes. It has the advantage of being a fairly powerful source of energy (i.e., high power-to-weight ratio) that is self-contained for mobile operations.

Compressed or Liquefied Gas. This would operate using an on-board generator or fuel cell. Like the organic fuel model, this also may have safety and exhaust problems and may possibly release unsafe gaseous fuel through an accidental tank rupture.

ENERGY STORAGE SOURCES

These vehicles rely on stored on-board power (Fig. 3).

Lead-Acid Batteries

This battery-powered unit would have the advantages of being commonly available on the marketplace, and having a fairly high power density per unit volume. Problems arise from its weight, potential acid spills, and hydrogen-release characteristics. It must be constantly trickle charged to maintain readiness. Power storage capabilities of about 600 Wh/ft^3 are typical.

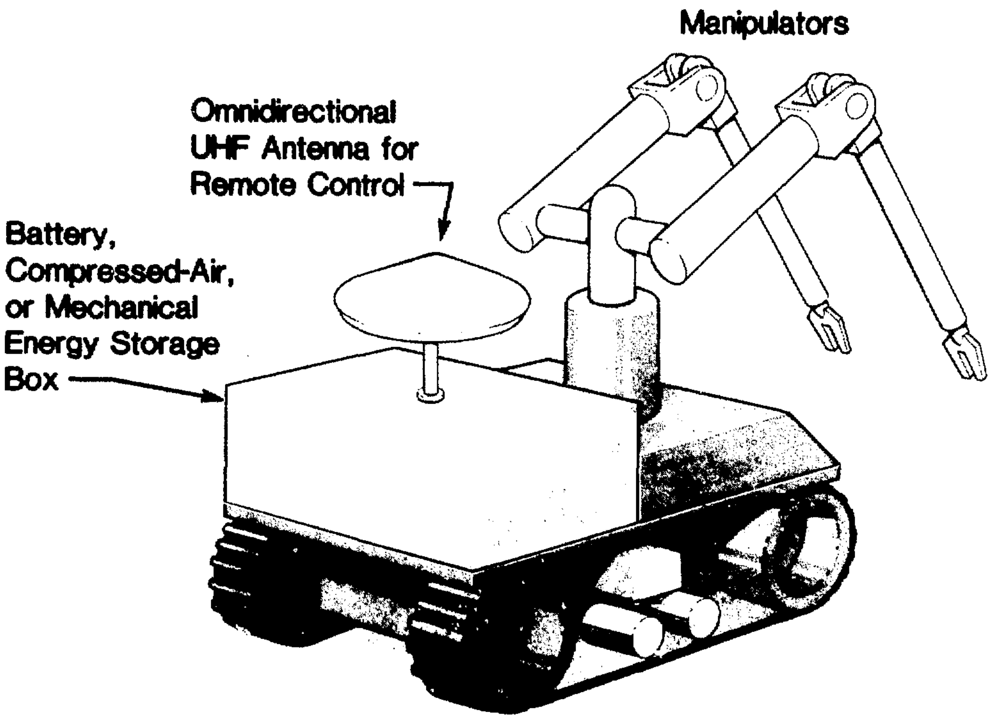

FIGURE 3 Mobile Vehicle with Energy-Storage Power Source

NiCad Batteries

NiCad batteries have somewhat higher energy density per unit volume than lead acid types (750 Wh/ft^3 typical), and have longer charge-storage lives before needing recharging. However, comparable NiCad batteries are considerably higher in initial cost, and they have a "memory" characteristic that requires periodic deep discharge followed by complete recharging cycle to maintain cell-life capabilities.

Direct Drive from Compressed or Liquid Gas

The working gas would directly drive the teleoperator vehicle's actions and manipulator functions through pneumatic actuators. Direct drive would avoid energy-expensive conversions. (Mechanical-electrical conversion efficiencies are typically low.)

Direct Drive from Mechanically-Stored Energy

Large industrial springs or flywheel devices can store considerable amounts of motive energy that could be directed to drive vehicle and manipulator actuators through escapements, transmissions, and electrical clutches. Low-speed operations can be very energy efficient. (The plug-in rewinding of springs could be investigated as a means of renewing the stored energy.)

WIRELESS POWER TRANSMISSION

In the following systems, energy is transmitted though free space to power the vehicle (Fig. 4).

Microwave Power Beam

Microwave energy via line-of-sight beams could be directly transmitted to directive antenna on the vehicle that would collect and rectify the beam energy to the power teleoperator and its mechanisms. Small battery capabilities may be retained to continue operations when direct beam energy became eclipsed. A large battery pack could permit charge, work, and recharge cycles in difficult locations. However, the biological hazard must be considered.

Intense Light Beam (Laser)

A high-powered laser beam can be directed to a photovoltaic array on the vehicle for conversion to electrical power. Light beams can be made exceedingly directive, so that transmitter-to-receiver efficiencies can be quite high. Again, the availability of some on-board battery capabilities would be advantageous for times of beam interruption. A biological hazard to personnel is present.

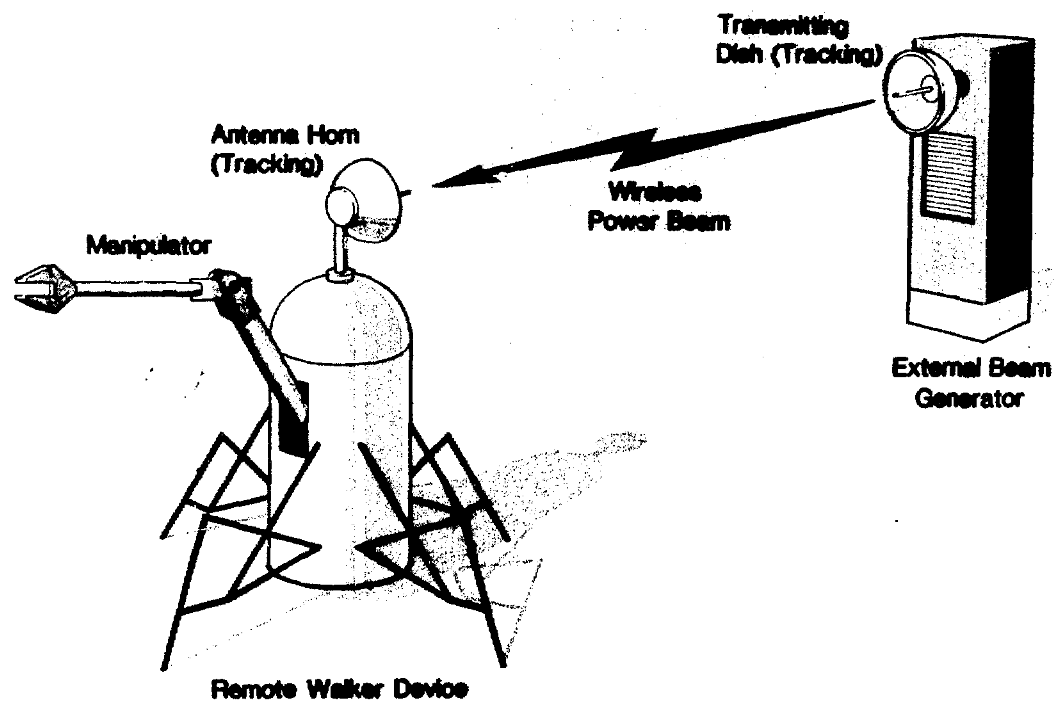

FIGURE 4 Walker-Teleoperator with Wireless Power Source

Inductive Power Loop

A loop could be installed around the inside perimeter of the facility and turned on only when power is needed or when an emergency situation exists. Although power coupling to the mobile unit is inefficient, the power sources would be present throughout the entire facility. A higher-frequency driving loop would increase its coupling efficiency, and the presence of auxiliary battery capacity would assist operations through any heavy loading periods. The vehicle might need "resting" periods while the inductive loop recharges the vehicle's internal storage batteries.

SIGNAL/CONTROL TRANSMISSION FOR MOBILE TELEOPERATORS

The following kinds of signal information may be required for remote control applications:

Signal Information

1. Mobile-vehicle drive commands.
2. Manipulator control signals.
3. Position/control feedback data for manipulators.
4. On-board TV video transmissions.
5. Temperature measurements.
6. Radiation metering (alpha, beta, gamma, and neutron levels).
7. On-board power and fuel status.
8. Vehicle location navigational coordinates.

Umbilical (Cable or Conductor) Control Signal Transmissions

Multiple, Hardwired Electrical Conductors. Such a cable bundle is trained behind or is fed out to the mobile unit and would be subject to the same flexing-breakage and contamination problems as are power umbilicals.

Coaxial Cables. These cables would carry signals either mixed or multiplexed at radio or microwave frequencies. They can be designed to be bidirectional through combiners and circulators, which would result in a cable that is much smaller in diameter than standard cable bundles for a given number of signals transmitted.

Flexible Waveguide. Signals are either mixed or multiplexed and are transmitted at microwave carrier frequencies through a specially designed pipe which is either hollow or filled with a low-loss insulating foam for additional mechanical support. Wire breakage is minimized with a waveguide system, and the cables can be very small for the number of signals transmitted. This method also can be designed for bidirectional operations.

Fiber-Optic Cables. These cables are capable of enormous signal-carrying capacities using a very small-diameter conductor. Technology is currently expanding into many such critical areas of usefulness. Fiber-optic cables are insensitive to electromagnetic interference sources over the entire length of cable run. Bidirectional signal communications are feasible using the appropriate optical systems to correct transmitter and receiver.

Wireless Signal Transmissions (wall penetrations minimized)

The control data for these systems are transmitted through space to the vehicle.

Free-Space Radio Frequency Systems.

a. VHF-UHF radio systems may be operated using directional antennas on the transmitter and omnidirectional antennas on the receiver. The technology for this is well established. The use of reflectors can help overcome blind spots within the facility.

b. Microwave signals can be used over long distances since narrow beams can be formed using dish or horn antennas. These devices have a very large signal-handling capacity, and signals can be mixed or multiplexed and may be made bidirectional. Reflectors could be used to overcome dead areas that were out of the direct beam. Many microwave semiconductor components are intrinsically radiation hardened.

Optical Communications Systems.

a. Visible light may be used for communicating control information; its advantages are that it can be seen and can use ordinary glass optical components. Blind-spot problems within a facility can be avoided by beaming signals toward the ceiling or by using optical reflectors in strategic locations.

b. Infrared (IR) light communications are possible using appropriate IR optical systems. Infrared systems have already demonstrated capabilities for excellent long-distance signal-keeping qualities through haze, fire, and smoke-filled environments. Some newer devices are intrinsically radiation hardened.

Acoustic Transmissions. Acoustic transmissions are sound transmissions of commands through the air from the control site to the vehicle.

a. Low-frequency audio tones can convey control information through the air to audio sensors on the vehicle. Low-frequency transmission has serious drawbacks in the limited number of channels that can be broadcast simultaneously and in the bandwidth of information transmitted. This system would be most useful in controlling sequential tasks that do not require high speeds or complex manipulator actions. Loudspeakers can be used to assert control over long ranges.

b. Ultrasonic carrier tones can be used to increase the number of control frequencies used and can facilitate making the transmitted or received signals more directional. Problems of dead spots in the audio pattern might be solved using multiple ultrasonic transducers prelocated within the facility.

c. Voice recognition equipment can be located on the mobile vehicle that would respond to the controller's voice, either unaided or projected from a loudspeaker. Although only one command can be articulated at a time, the number of stored and recognizable commands at the remote vehicle can be quite large. Although voice recognition technology is in an early stage, recent improvements are remarkable.

On-Board Control

Each vehicle has its own on-board command systems (Fig. 5).

Internally Fixed Preprogrammed Task Schedule. A prescribed group of instructions and operations would be preset. These programs may have sets of commands that help orient the teleoperator to its working site and accomplish routine required tasks; however, it would not have the capabilities for dealing with unusual situations or with conditions that do not conform with internalized plans, routes, or facility designs.

Artificial Intelligence (AI) Capabilities. Artificial Intelligence has the ability to meet the present operational needs and can also adjust and adapt to changes in the presumed plans or expected environment to obtain successful results. The degrees of this ability to adapt can be adjusted according to the difficulty of the projected damage and alterations expected from a facility emergency. AI technologies that can be utilized in

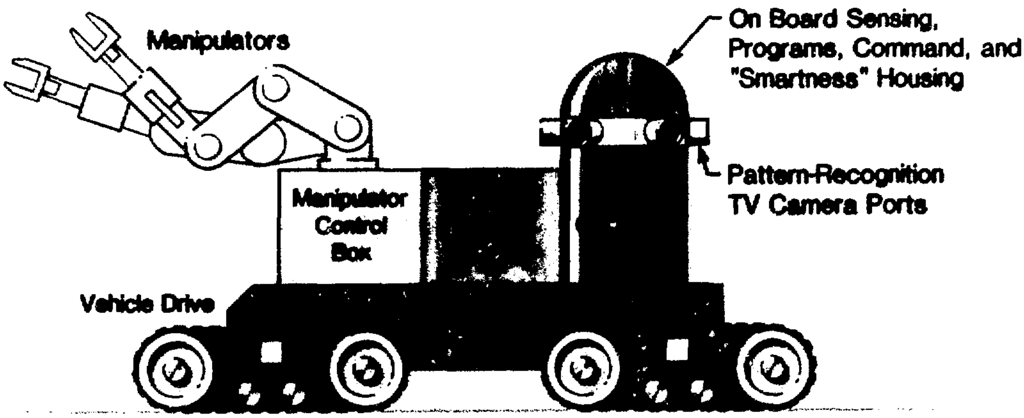

FIGURE 5 Teleoperator with Self-Contained Programs or Artificial Intelligence

this kind of vehicle control are evolving rapidly, and some systems having applicable capabilities are already commercially available.

HYBRID POWER TRANSMISSION AND COMMUNICATION SYSTEMS

Microwave-Power-Information Beams

The intense microwave beam used to power the vehicle also can be modulated with the information needed to control the actions of the mobile unit. Frequency modulation of the carrier is the preferred method to accomplish this. The information signals are separated from the power carrier at the receiving site. The average power to the vehicle does not vary, and some internal continuing programs and storage devices would be necessary to keep the vehicle operating and powered during beam eclipses. Biologic hazards are present with high-power microwave-based system (Fig. 6).

Laser-Power-Information Beams

A highly directional beam of laser energy would be continually aimed at the remote vehicle receiver. The beam would carry frequency-modulated or amplitude-modulated control information methods. Information would be isolated from the carrier beam by photoelectric devices which have very high-frequency response; these would be separate from the on-board photovoltaic generators used for producing vehicle power. Laser beams would also need some form of continuing power and control capabilities to maintain teleoperator operations during beam interruptions. Precautions would be needed for biologic hazards.

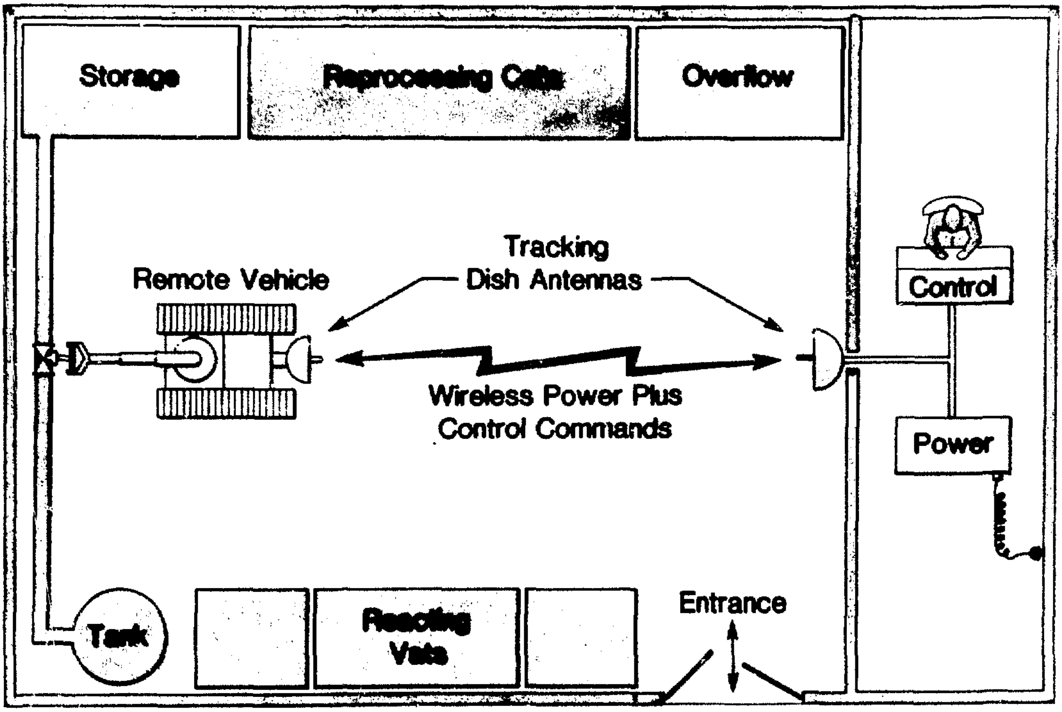

FIGURE 6 Hybrid Mobile Teleoperator with Wireless Power and Control Link

SUMMARY CONSIDERATIONS

Special Power Considerations in Remote Teleoperator Designs

1. Power source: Wired, self-contained, or wireless

2. Power feed method (power needs to be generated or supplied by facility?)

3. On-board supplementary power storage (back-up battery?)

4. Adequacy of power supply (100 W to 2 kW typical)

5. Effects of contamination and radiation

6. Methods for decontamination (hermetic seals?)

7. Effects of altered atmosphere in facility

8. Size and weight of power source (mechanical supports?)

9. Biological hazards from power source (eye, skin damage?)

Special Control Concerns in Remote Teleoperator Operations (See Table 1)

1. Command circuits: umbilical, wireless, or self-contained

2. Radiation hardness of electronics (anticipated doses?)

3. Bidirectional link needs

4. Band-width needs (1.0-200 MHz typical)

5. Control speeds required

6. Redundancy in event of circuit failure

7. Interference problems (EMI resistance?)

8. Mechanical size and weight limitations (battery weight and size?)

9. "Smartness" of on-board control circuits

Summary

It is important to match facility design requirements with available options for power and signal transmission early on, carefully considering all possible facility emergency demands and unexpected conditions. The vehicle needs to be designed with a maximum amount of flexibility, adaptability, and redundancy to cope with untoward events and crisis situations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the research in design engineering and radiation hardening of electronic controls for the Advanced Integrated Maintenance System. Especially helpful were the efforts of E.J. Kennedy (consultant from the University of Tennessee, Knoxville), D.W. Bible and H.L. Martin (ORNL Instrumentation and Controls Division), whose research has contributed to compiling current, complete information for this paper.

TABLE 1 Signal Transmission Survey

Properties Systems	Slotted line (FM)	Lossy coax (FM)	VHF-UHF radio (FM)	Micro-wave (FM)	Visible light (AM)	Infra-red (AM)	Induct. loop (AM)
RAD-Hard	3[a]	3	2	4	1	1	4
Mechanical size	2	2	2	3	4	4	2
Bidirectional	3	3	3	4	4	4	2
Bandwidth	3	3	3	5	4	4	1
Bandwidth expand	3	3	2	5	4	4	1
Power level	3	3	2	4	4	4	1
Available technology	3	3	4	4	2	2	2
Maintenance easy	1	2	3	4	4	4	2
Multi-path	5	5	2	3	4	4	4
Bio-hazard	5	5	4	4	3	2	5
Ease of redundancy	2	2	3	4	4	4	2
Avoids interference	4	4	2	5	2	2	2
Low maintenance	3	3	3	3	2	2	4
Score	40	41	35	52	42	41	32

[a]1 = poor, 5 = very good.

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THE HUMAN-MACHINE INTERFACE IN MOBILE TELEOPERATORS*

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My subject today deals with some general problems of the human-machine interface in remote teleoperators. As Tony Foltman mentioned, I have worked for a number of years in this field at the Oak Ridge National Laboratory with Mel Feldman, Bill Hamel, and others.

The Fuel Recycle Division at the Oak Ridge National Laboratory is developing technology for the maintenance and repair of future nuclear fuel reprocessing facilities. Part of this effort requires advanced teleoperator systems, under the assumption that man will be an integral part of these systems as prime mover. In other words, a human will actually have his hands on the controls and provide the primary input for maintenance and repair procedures. My talk is therefore aimed at managing the interface for this human participation. Perhaps in the future we will move toward making man the supervisor; but in the near term, we will assume that the current arrangement will prevail.

Just what is the man/machine interface? Simply put, it is the point at which information is transmitted between the machine and the operator. It consists of several different types of displays and controls. Normally, television is the single most important source of operator information. There may also be other CRT displays for machine status, collision avoidance, and other types of information. In manipulator systems, information about forces applied in the remote area. Speakers may be included to give the operator a sense of hearing in the remote environment, and there is normally an assortment of dials, gauges, bells, etc., to relay information on machine status.

Three types of controls are used in systems that include both manipulator and transporter: (1) manipulator controls, which may be switches or master/slave controls; (2) transporter controls, which are generally joysticks; and (3) camera controls.

The ideal human/machine interface might provide something known as "telepresence," which means that the interface is fully transparent and the operator is projected into the remote environment itself. Achieving telepresence would require a full spectrum of sensory inputs and controls. The teleoperator device would have stereo

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‡Clarke Ambrose, Inc., performs work for the Fuel Recycle Division of Oak Ridge National Laboratory under Work Order AC467GAi. Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy.

vision and hearing. Such devices would have highly dexterous, human-like end-effectors and probably exoskeletal controls to provide the full array of kinesthetic and tactile feedback. In summary, telepresence would completely reproduce the remote environment and thus is a goal that we strive toward.

Although current systems cannot approach telepresence, we can still achieve an interface that makes the system effective from the human point of view. We must take a mission-oriented approach, analyzing the tasks that are required of the machine. This does not mean we must break down every task into its smallest components, but we should at least have an idea of what the machine is expected to do. Must it move through a facility while observing silt on the floor, or must it tighten clamps, remove screws, and perform other such duties? This kind of knowledge allows allocation of tasks to machine or man and definition of the optimal mix of automation and manual control.

An earlier speaker mentioned that one effective way to program a machine to carry out robotic operations was to use a sort of teach/playback mode. The operator (or teacher) goes through all the needed motions, and the machine remembers and repeats them. This can provide a very nice synthesis of robot and operator. From the operator's viewpoint, ergonomic design is important. This entails the locating of dials, gauges, switches, cameras, etc., in the right places for the operator's use. All of this contributes greatly to increased efficiency and cost effectiveness.

The typical interface in use today actually degrades the information that the operator must have about the remote environment. In the area of vision, for example, television provides degraded color, a loss of stereoscopic cues, and relatively poor resolution; in all, the result is an unnatural and generally low-quality transmission at information. Part of this problem is due to the relatively low resolution of the video system compared to that of the human eye; furthermore, the camera reduces the number of colors that can be detected in a remote area. The loss of stereo vision, of course, occurs when only one camera is used, but even a stereo television system cannot restore the full vision achieved by the eyes themselves. In any case, considerable adjustment may be needed by the operator to comprehend the relationship of the machine to its actual environment and to have the machine do what the operator wants it to do.

The sense of touch is also seriously degraded by teleoperators. Although some excellent force-reflection systems are available, none really has the sensitivity of the human touch. The minimum force that can be sensed by these systems is about one pound; anything less will not be felt by the operator. This degrades the ability to perceive weight and inertia. A related problem is the degraded sense of arm position. It is important for the operator to know where all the arm links are at any one time to avoid running into objects in the remote environment. It also allows the operator to plan the direction of the machine's next move. In some cases, it might be necessary to provide the human operator with a backup in the form of an overall television view of the teleoperator at work.

Audio information is also degraded because sound from the teleoperator is usually not transmitted by more than one microphone. Stereo sound would be especially helpful in cases where the teleoperator drops something (a tool, for example) and the operator must locate it. In any case, good-quality sound is important for monitoring the machine itself; motor whine, for example, can be a vital clue to the force being exerted by the machine.

The human/machine interface degrades the output of the human operator. Even the best teleoperator cannot approach the dexterity of a human, particularly in the end-effector. The human hand is an extremely dexterous end-effector.

For the future, a number of developing technologies will likely be beneficial to the human/machine interface. One example is the Model M-2 digital control system, developed at Oak Ridge, that improves the dexterity and force sensitivity of the manipulator; this, in turn, allows much easier force scaling. This system lets us change from a 1:1 force-reflection ratio, which means that one pound of force at the slave end is reflected as one pound of force at the manipulator, to a ratio of 8:1, meaning that eight pounds of force is felt as one pound at the master. This is helpful for the operator when heavy equipment must be moved, or when somewhat lighter pieces must be handled over a longer period of time.

The M-2 control system also allows **full master indexing.** In remote operations, the operator sometimes finds himself in an awkward or difficult position, one in which no further movement can be easily made. With full master indexing, the operator simply pushes a button on the master handle, moves the master to a different point, and resumes work. In a related area, the human/machine interface will be further improved by devices like the generic master control now under development at the Jet Propulsion Laboratory. This is essentially a single handle that transmits all the machine forces to the human operator.

In regard to vision improvements, high-definition television will provide much higher quality reproduction of the remote scene than does standard television. The video equipment we are using is an Ikegami system and has more than 1100 lines of resolution, so the image is much sharper. Stereo television is also being improved; the Naval Ocean Systems Center is examining how humans relate to such systems.

Some other areas are also being studied with a view toward improving the human/machine interface. At Oak Ridge, we have found that voice input is an effective way to control television cameras. For operator displays, investigators have learned that integrated control displays -- such as touch screens -- make the operator's job a little easier. Advanced computer graphics will be useful in showing the operator the machine's location.

To summarize, telepresence is the ideal that we should aim for in managing the interface between human and machine. However, full achievement of telepresence is probably not required to do effective work with teleoperators. The current interface degrades normal human input and output, but not to the degree that effective work is impossible. Technology now available or in development can contribute much toward improving the efficiency of the human/machine interface in remote operations.

QUESTION AND ANSWER SESSION

Question: Has stereo sound proved to be an asset?

Mr. Draper: As Mel Feldman mentioned, there is some question as to its overall effectiveness in improving a teleoperator's performance. It does not offer a quantum jump in operator performance. However, there are cases in which stereo sound can be very useful, especially in an unstructured environment when a tool or part must be located on the basis of the sound it made when it was dropped.

Question: When we speak of degraded human output and input in remote operations, especially during a radiation emergency at a power station, there are some things we should remember. If humans were to enter such an environment, they would be greatly hindered by the protective gear they would be wearing; they would have thick gloves, their field of vision would be quite narrow, their hearing would be restricted, etc. So you can see that their effectiveness would be greatly reduced. The literature suggests that a person wearing such protective gear could take eight times longer than normal to perform a given task.

Mr. Draper: That is a very good point. We should remember as we define requirements for robotic performance that duplicating human actions possible without protective gear is going far beyond the actual work that could be done by humans in the remote environment.

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