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Robotics and Nuclear Power

Report by the Technology Transfer
Robotics Task Team

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SUMMARY AND NEEDED ACTIVITIES

A. Summary

A task team was formed at the request of the Department of Energy to evaluate and assess technology development needed for advanced robotics in the nuclear industry. The mission of these technologies is to provide the nuclear industry with the support for the application of advanced robotics to reduce nuclear power generating costs and enhance the safety of the personnel in the industry.

The investigation included robotic and teleoperated systems. A robotic system is defined as a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. A teleoperated system includes an operator who remotely controls the system by direct viewing or through a vision system.

Major economic benefits will be achieved through the use of advanced robotic systems in maintenance of the current generation of power reactors resulting from:

- o Reduction in man-rem exposure (estimated to cost from \$1,000 to \$10,000 per man-rem)
- o Reduction in plant downtime (estimated to be \$500,000 to \$1,000,000 per day for a 1000 MWe plant)

Based on a 90% reduction in personnel exposure, a factor of two reduction in plant downtime, and 120 operating plants by 1995, the estimated total national annual savings will range from \$2.8B to \$6.0B.

Significant cost savings and reduction of personnel exposure in decommissioning nuclear facilities can be achieved through the use of robotics. Estimated actual costs have not been estimated for decommissioning activities since there is no data base for the decommissioning of large nuclear power plants.

Safety and Licensing is enhanced by the application of robotics in the nuclear industry. This benefit is achieved primarily by reduction of man-rem exposure, hazardous material control, in-service inspections and automated data acquisition.

The technical approach used by the Task Team in this study included the evaluation of the major sectors of the nuclear industry: construction, reactor operations, reactor maintenance, fuel fabrication, fuel reprocessing, waste management, and decommissioning. For each of these, the following information and data were obtained by personal knowledge, review of publications, and discussions with cognizant personnel:

- o Identification of elements of current practice with potential for robotic applications
- o Identification of inspection and quality assurance activities that can be improved with robotic technology
- o Identification of existing and planned robotic systems and development programs to accomplish these functions
- o Identification of non-routine applications
- o Recommendations for plant design changes to accommodate robotic systems
- o Recommendations for development of advanced technologies necessary to implement advanced robotic applications

Universities with strong robotics programs and staffs identified by the task team are:

- o Carnegie-Mellon University - Robotics Institute consists of a staff of more than 200 affiliated faculty, research scientists, engineers, programmers, and graduate students.

- o University of Florida - Center for Intelligent Machines and Robotics is active in robotic kinematics, control, computer graphics, and human/machine interfaces.
- o Stanford University - Institute for Manufacturing and Automation is an interdisciplinary organization with about 25 sponsors, including industry and government agencies.
- o Massachusetts Institute of Technology - Many diverse robotics programs underway in several departments. Effort is not centralized.
- o University of Texas - Center for Robotics, Manufacturing and Logistics was established in 1985 and is developing basic science for intelligent machines in manufacturing and military logistics.

Significant programs in robotics are in progress or planned by other agencies. The National Aeronautics and Space Administration is planning a 10 year program for the development of robotics for space applications with proposed funding of \$100M to \$200M per year. The Department of Defense has many individual robotic programs either in place or planned for automated battlefield systems, manufacturing, and hazardous materials handling. The Department of Energy has established programs on robotics at several national laboratories. EPRI is also sponsoring development of robotics for reactor operations and maintenance.

Japan has a national robotics program for all industries, including nuclear. This program is funded at \$150M over an eight year period. The objective for the nuclear industry is to provide a high performance robot with the capability to use a variety of instruments and tools in reactor maintenance.

The major near term economic benefit to the nuclear industry results from the application of robotics to the operation and maintenance of power plants. The mission of the development program is to support industry in the development of an untethered, autonomous decision-making robotic system with flexible manipulator capability for nuclear plant operation and maintenance.

The technology needs required to provide the advanced robotics for this application are summarized in the following Table A-1. These needs are ranked in three categories:

- o Category 1: Unique to the nuclear industry (the Department of Energy must lead these programs).
- o Category 2: Common to other applications, but critical for the use in nuclear facilities (the Department of Energy must apply leverage to other programs).
- o Category 3: Common to other applications, but not critical for use in the nuclear facilities (the Department of Energy can exploit other programs).

These technologies will also be applicable to robotic systems in other major sectors of the nuclear industry and future nuclear power plants.

Specific needs are ranked in priority from left to right in this table. The technology needs with the highest priority are:

- o Robots with vertical access (to provide mobility and reach required for maintenance in the current plants).
- o Sensors for spatial location and object recognition.
- o Domain specific intelligence for on-board decision making.
- o Operator/machine interface

In addition, all components for nuclear application require environmental hardening (radiation, temperature, and humidity) and the capability for decontamination.

B. Needed Activities

A team consisting of university, national laboratory, and industry participants should be established to carry out the necessary development of

the identified technologies and to interact with other programs sponsored both by other agencies and DOE to exchange data for the leveraged programs. This development team should be centered at a single facility, as consistent with cost and contractual considerations. Collaboration with the Department of Defense, the National Aeronautics and Space Administration, and the National Bureau of Standards is recommended because of the advanced status of robotics and artificial intelligence programs sponsored by these agencies and the large investments that the Government is committing to these programs. Collaboration with foreign programs is not recommended since the foreign programs are less comprehensive compared to other U.S. programs. In addition, leakage of sensitive data from Department of Defense and National Aeronautics and Space Administration sources can be minimized by avoidance of foreign collaborative programs.

A nine-year development plan has been prepared to provide technology modules which can be selectively assembled to provide a wide range of robotic systems for nuclear applications. Field testing of these technology modules can be performed in Government-owned facilities, such as FFTF. FFTF for example is an ideal test facility to provide the information required by utilities to allow them to use advanced technology in commercial nuclear plants.

The tasks and objectives of this plan are:

- | | | |
|----------|-----------------------------|--|
| Task 1.0 | Fluid Flow Detection System | Provides an integrated sensor/expert system to determine flow of hot fluid through components. |
| Task 2.0 | Mobility/Access Technology | Provides a nuclear-grade portable power supply for in-containment operation, vertical access capability, and a flexible manipulator ("snake"). |

Task 3.0 Sensors

Provides thermal imaging and vision sensors for Fluid Flow Detection System; spatial location sensors for navigation and mapping.

Task 4.0 Domain Specific Intelligence

Provides expert systems and software for navigation, mapping, and maintenance operations. Also, will provide demonstration of radiation-resistant, on-board computer hardware.

Key milestones for this activity, assuming an October 1, 1985 starting date, are:

Test of integrated Thermal Imaging, Vision, and Expert System	April 1, 1986
Complete Simulation of Flexible Manipulator	April 1, 1987
Test Improved Integrated Thermal Imaging, Vision, and Expert System	July 1, 1987
Demonstrate Radiation-Hardened, On-Board Computer System	October 1, 1985
Test Advanced Joint for Flexible Manipulator	April 1, 1989
Complete Testing and Reliability Assessment of all Technology Modules	October 1, 1993

Robotics Technology Needs

<u>Category</u>	<u>Priority</u>	<u>Mobility</u>	<u>Sensors</u>	<u>On-board Decision Making</u>	<u>Human Factors</u>	<u>Reliability Availability Maintainability</u>	<u>Environmental Hardening</u>	<u>Standards</u>	<u>Mechanical Systems</u>	<u>Payload Control Systems</u>	<u>Smart Tools</u>
1	DOE must lead	vertical access	spatial location, object recognition	domain specific intelligence	operator control console interface	modularization & interface standards	radiation	equipment decontamination			
2	DOE applies leverage	obstruction avoidance	force feedback tactile	Expert systems	mobile platform-environment interface		inert atmosphere	Equipment & facility standards thru ANSI & other organizations	higher strength to weight ratio, multi-intersecting degrees of freedom	multi-arm & multi axis	inspection
3	DOE can exploit	cableless power & data transmission	vision, viewing & lighting	adaptive learning		maintainability system manuals	temperature humidity, chemical		higher specific power motors	end effectors	cutting welding & grinding

Definition of Categories

1. Unique to nuclear facilities
2. Common to other applications, but critical for use in nuclear facilities
3. Common to other applications; important but not critical for use in nuclear facilities

II. TASK TEAM ON ROBOTICS CHARTER AND MEMBERSHIP

A. Charter

The task force will study the following sectors of the nuclear industry:

- Construction
- Operations
- Maintenance
- Decommissioning

The task team will perform the following for each of the above sectors:

- Identify elements of current practice with potential for robotic applications
- Identify inspection and quality assurance activities that can be improved with robotic technology
- Identify existing and planned robotic systems to accomplish these functions
- Identify non-routine aspects/problems
- Identify plant design changes to accommodate robotic systems
- Identify advanced technologies necessary to permit robotic applications

The economic advantages of the recommended technologies will be assessed.

B. Membership of Robotics Task Team

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III. TECHNOLOGY EVALUATION

A. Technical Approach

Each of the following major sectors of the nuclear industry were evaluated:

- o Construction
- o Reactor Operations
- o Reactor Maintenance
- o Fuel Fabrication
- o Reprocessing
- o Waste Handling
- o Decommissioning

For the maintenance and operations sectors, nuclear reactors including Pressurized Water Reactors (PWR), Boiling Water Reactors (BWR), Gas-Cooled Reactors (GCR), and Liquid Metal Reactors (LMR) fuel reprocessing/fabrication, decommissioning, and waste management facilities were considered. Fusion power was not included in this investigation because implementation of this power technology is beyond the ten-year time frame for deployment of the advanced robotics systems considered in this study.

For each sector, the following information and data were obtained by review of published documents and discussions with cognizant personnel:

- o Identification of elements of current practice and potential for robotic applications.
- o Identification of inspection and quality assurance activities that can be improved with robotic technology.
- o Identification of existing and planned robotic systems and development programs to accomplish these functions.
- o Identification of non-routine applications.

- o Identification of plant design changes to accommodate robotic systems.
- o Identification of advanced technologies necessary to implement advanced robotic applications.

The data were then assessed and evaluated to determine the technology required to permit the applications. The needs were categorized as follows:

- o Unique needs for nuclear applications.
- o Needs common to other robotic systems and critical to nuclear applications.
- o Needs common to other robotics, but not critical to nuclear applications.

Development programs were identified to satisfy these needs.

B. Construction

The discussion contained in this section assumes that future nuclear industry facility construction will be done in the field using operations of the same nature as those performed in today's construction projects. However, it will be necessary for future plant designs to be compatible with the use of robotics. This will require placement of components so they can be reached, manipulated and worked on by robots.

It should be noted that another task team is studying modularization. The degree of modularization could range from prefabrication to large assemblies. The recommendations of that task team are likely to be in the direction of shifting many site activities to a shop. Such a change in construction practices would not eliminate the use of robotics, but would be likely to change the ways in which robotics is applied.

1. Elements of Current Practice

a. Civil

Rock and earth moving - Activities in this group include excavation of both rock and earth, trenching and filling. Most of these activities require machinery that can excavate, transport excavated material, and place and compact such material. If rock is too hard to be cut by the excavating equipment, drilling and blasting is also required.

Steel erection - Major activities include positioning of steel members and connecting them. Most connections are bolted. However, some connections are welded.

Concreting - Major activities in this group are forming, placement of rebar, actual placement of concrete, finishing and stripping of forms.

b. Mechanical

Equipment installation - Equipment installation in nuclear power plants includes major components such as the reactor pressure vessel, the turbine and the condenser, as well as a host of equipment items of various sizes. This includes pumps, heat exchangers and tanks. The latter may be shop fabricated or erected in the field.

Piping - Installation of piping includes installation of supports, as well as positioning and connecting spool pieces and valves. Piping includes small diameter instrument tubing, small bore pipe (2" diameter and less) and large bore pipe (over 2" diameter) which can range up to 30" diameter main steam piping.

Building services - The most obvious of the building services work includes the heating, ventilating and air conditioning systems which include blowers, refrigeration equipment, heating boilers, heating and cooling coils, filters, ductwork and duct supports. This area also includes fire water distribution and conventional plumbing.

c. Electrical

Equipment installation - Major electrical equipment includes the generator and the station switchgear. In addition, there are motors of all sizes, motor control centers, instruments, control components and computers.

Cabling - This area includes installation of conduits and cable trays, pulling cable and making terminations.

d. Architectural

This area involves many miscellaneous activities. These include interior walls and finishes, exterior walls and their treatment, roofing, doors, laboratory furnishings, tile setting, placement of fire-proofing, paints and coatings and floor finishes.

2. Inspection and Quality Assurance

The typical inspections described below do not include acceptance tests for equipment and system startup tests, although they may be performed in the field. These tests and inspections include only those required to verify construction that is put in place.

a. Civil

All areas of civil involve verification of dimensional quantities in some respect. Earthwork requires verifying the degree of compaction attained in placement of fill. Concreting requires conducting slump tests, taking of cylinders for compression tests and tests to verify the integrity of concrete that has been placed. Typical inspections for structural steel erection include verifying bolt torques and welding inspection.

b. Mechanical

As in the case with civil construction, verification of dimensional items is required for mechanical installation. Especially significant is the piping as-built verification required by IE Bulletin 79-14.

Weld inspection is probably the most widely performed inspection on mechanical systems. It includes visual, dye penetrant and magnetic particle inspections as well as radiography on a routine basis. Certain special welds are also inspected ultrasonically. In addition, soap bubble, halogen and helium leak testing is performed. Most fluid systems are hydrostatically tested before acceptance.

c. Electrical

Testing of electrical installations is primarily in the nature of acceptance and startup testing, and hence is not considered here.

d. Architectural

Testing of architectural features generally does not have the same significance as in the civil and mechanical areas. However, for special protective coatings, wet film thickness measurements are important. In addition, building leak rate tests are required at times. These may indicate deficiencies in sealing of joints in exterior walls.

3. Existing and Planned Systems

a. Existing Systems

Currently, automatic pipe welding and tube welding systems are available commercially and are used on construction sites. These systems are positioned and controlled by human operators.

Other applications, mostly experimental in nature, include:

- o Laser guided earthmoving and paving equipment
- o Laser guided tunnel boring machines
- o Shotcreting with gun mounted on an earth excavator
- o Concrete distribution by an arm supporting a concrete pump hose
- o Fireproofing application by an arm supporting a spray gun
- o Numerically controlled drilling in rock
- o Inspecting tiles on a vertical wall
- o Mapping concrete reinforcement placement by a carriage using electromagnetic sensors
- o Excavating robot to locate underground utility lines and uncover them.

b. Planned Systems

Due to the fact that the construction industry is so diverse, there is no focussed effort on applications of robotics. Many of the planned systems are those already listed in the previous section.

4. Non-routine Construction Operations

Plant modifications primarily involve electrical and mechanical systems and equipment, although there may be some structural or architectural modification. Thus, increased automation of pipe and tube welding would be important. This is especially true where the work is done in contaminated or high radiation areas, because of the potential for reducing personnel radiation exposure.

Typically, as-built drawings exist only for safety related piping. Thus, almost every plant modification effort involves preparation of as-built drawings of the area involved just prior to design of the modification. This usually requires personnel to enter the area to make the requisite measurements. In many cases this is a radiation area with the attendant concern of personnel exposure. It would seem that it should be possible to develop a robot that could find its way to the area. This robot would then map the area either by electronic or photogrammetric means, to produce as-built drawings. In the latter case, pairs of stereo photos could be processed by close range photogrammetric methods to yield digitized data. These data could then be processed by a CAD system to produce the as-built drawings.

5. Plant Modifications

Modifications of plant designs that would facilitate the use of robots in construction are generally design features that would enhance constructability. These would include:

- o Standardizing design features
- o Increasing uniformity in configuration and layout
- o Reducing crowding
- o Increasing accessibility to items to be installed by robotic systems

Additionally, for plants designed by CAD constructability reviews could include simulation of robotic applications to construction on the CAD system.

Other non-routine construction operations usually involve a problem in which an operation has not gone as planned, in which an object of unusual size or weight is handled, or in which there is some other deviation from the norm. It is unlikely that even a system with programmed learning could

be easily developed to cope with such a wide range of situations that cannot be anticipated in advance.

6. Technology Needs

The needs for technology development cover several areas. These are discussed below in terms of both specific applications and general areas of technology.

Future systems must be able to function in an unstructured work environment that is poorly configured and has minimal repetition. In order to develop such systems consideration must be given to the factors identified in this section on "Technology Needs." Systems described below assume that the necessary technological advances will take place.

In the civil area, additional tasks in which performance might be enhanced by improvements in robotization include:

- o Excavation of foundations for power plant structures
- o Placement of reinforcing steel in concrete slabs
- o Bolting and welding of structural steel joints
- o Inspection of bolted and welded joints
- o Use of autonomous robots to work under compressed air inside of caissons.

These operations are highlighted, because all have some degree of repetitiveness, although not to the same extent as in a factory operation. In addition it should be possible to utilize information captured in a CAD system in tasks involving rebar placement or structural bolting.

In the mechanical area, the most fruitful area for increased use of robotics is in pipe welding. Since the basic equipment already exists, the changes would primarily be in the area of reducing the degree of dependence

on human operators. Once this is done, the next appropriate step would be to adapt the concepts developed to weld inspection.

For work in a construction environment, the greatest need is in the area of mobility. Robots must be able to move around an uneven construction site and to work inside crowded buildings. To be useful in bolting joints in a steel frame, a robot should have vertical access capability.

Next in importance are sensing and expert systems. For instance, to put together bolted joints of varying patterns, the robot would need to locate an initial bolt by either tactile or visual sensing. Once this is done, data transferred from a CAD system design of the joint could be used to locate the remaining bolts. Selection of the proper rebar for placement in a slab could involve a combination of CAD data and pattern recognition.

Manipulation appears to be generally well developed for the needs of construction. However, some work on improving hand dexterity might be appropriate.

Finally, although not specifically a matter of robotics, some consideration should be given to identify those design features which make it easier to use robotics effectively in construction. Once developed, this information should be disseminated to designers.

C. Reactor Plant Operations

Reactor plant operations that can be enhanced by the application of robotics are identified in this section. Inspection and quality assurance operations suitable for robotic applications are also defined. Robotic systems for reactor operations both currently in use or being developed are described. Plant modifications to facilitate implementation of robotic systems for reactor operations are suggested. There are some overlapping areas between reactor operations and maintenance; however, an attempt was made to separate these functions.

1. Elements of Current Practice

The elements of current practice that are suitable for robotic application for the current U.S. power reactors are listed below. These elements are applicable to BWR, PWR, GCR, and LMR plants.

a. Common

- o Surveillance.
 - Environment (temperature, humidity, etc).
 - Safety including fire detection.
 - Leak detection (steam/water).
 - Pump oil levels/leaks.
 - Detector inspection.
 - Radiation levels (personnel locations).
 - Detection of loosened parts.
 - Noise/vibration detection.
 - Instrument.
 - Training.
 - Security (passive/active) - personnel location.
 - Weld inspection.
 - Airborne and surface contamination.

- o Spare parts storage.

- o Decontamination/Cleanup.

- o Material sample collection and testing.

- o Snubber testing.

- o Radwaste volume reduction handling, processing, containerizing, shipping.

- o New fuel receipt and inspection.

- o Spent fuel removal, inspection, and reconstitution

- b. Specific

The elements of current practice that are unique to current types of U.S. power reactors are summarized below.

- o BWR.

- Turbine generator inspection.
- Off-gas system inspection.
- Control rod drive (CRD) hydraulic control unit inspection.

- o PWR.

- Steam generator inspection.

- o GCR.

- Gas leak inspection.
- Steam generator inspection.
- Maintenance of primary coolant blowers.
- Stacking of graphite moderator blocks .

- o LMR.

- Spent fuel transportation in sodium.
- Sodium leak detection.

2. Inspection and Quality Assurance

Inspection and quality assurance applications that can be accomplished with robotic systems are defined below.

- a. In-service weld inspection using visual, ultrasonic or other techniques.

- b. In-service leak detection using visual, ultrasonic or other sensors.
- c. In-service pump oil levels; oil contamination.
- d. Materials testing - mechanical, chemical and radiological sample collection and testing for aging, corrosion, stress and radiological exposure.
- e. Snubber testing - hydraulic snubber testing to check bleed rates, reservoir levels and conditions of lock-up. Mechanical snubber testing via torque testing.
- f. Surveillance inside the containment - remote television to provide 3-D or holographic displays; manipulator directed camera/laser beam.
- g. Inspection/safety tours - useful for safety verification, training, instruction, identify needed repairs, problem areas, NRC inspections, security, radiation levels, etc.

3. Existing and Planned Systems

Although many automated, computerized, remotely viewed and operated systems are in existence, there are no advanced robotics per se used in current power reactor operations. Systems planned are: (1) general purpose mobile robotic surveillance; (2) mobile weld inspection robot; and (3) a decontamination robot.

4. Non-routine Operations

Nonroutine operations primarily result from the response to unexpected equipment failures. Hence, these operations are discussed in Section 4. of the Reactor Maintenance Section.

5. Plant Modifications

The major complications to robotics utilization in current plants are lack of space and the unstructured nature of the environment. Plants should be modified and future plants should be designed to incorporate space for utilization of robotics, particularly for inspections/sampling/monitoring/-viewing during operation. Specific areas of plant modifications recommended are: (1) wider door access; (2) functional elevators; (3) distributed power (4) improved lighting; and (5) easier access to containment areas.

6. Technology Needs

The technology needs to implement the application of robotics to reactor plant operations are listed below:

- a. Nuclear "hardening" of robotic components to allow more exposure to robotic systems during operations.
- b. Three dimensional or holographic display and rapid scan vision systems for accurate and comparative surveillance.
- c. Robot mobility; collision avoidance; item recognition; vertical access, traversing objects.
- d. Mobile power interface with the robot.
- e. On-line repair capability to reduce downtime.
- f. Improved remote control; robot tracking.
- g. Accurate sensor feedback.

D. Reactor Plant Maintenance

Reactor plant maintenance and inspection/quality assurance operations which are or can be achieved using robotic systems are identified in this section. Existing and planned robotic systems are described. Plant modifications to enhance the application of robotics in performing both planned and unplanned maintenance are suggested. Technology needs to permit the design and application of advanced robotic systems for maintenance operations are identified.

1. Elements of Current Practice

Elements of current practice in maintenance of reactor plants suitable for robotic applications are summarized below:

a. Common

- o Weld preparation, welding and inspection
- o General activities such as drilling, sawing, tapping holes, fastening and using an assortment of tools
- o Replacing/repairing detectors
- o Control rod drives
 - Removal
 - Replacement
 - Rebuilding
 - Testing
 - Cleaning
 - Inspection
 - Hydraulic control unit refurbishment
- o Radwaste
 - Collection/sorting/compaction
 - Handling/mixing

- Sampling/analysis/mass and isotopic balance
- Container capping, handling and cleaning

- o Valves/valve seats and packing
 - Replace/repair
 - Test
 - Inspect

- o Pumps
 - Replace/repair seals, bearings & drives
 - Test
 - Inspect

- o Piping
 - Cutting
 - Aligning
 - Welding
 - Inspection (including leak detection)
 - Repair
 - Condenser tube location and cleaning

- o Refueling*
 - Head removal/replacement
 - Spent fuel removal
 - Reconstitution
 - Densification
 - Inspection

- o Surveillance
 - Safety including fire fighting
 - Leak detection (steam/water)

- Pump oil levels/leaks
- Detector and instrumentation inspection
- Radiation levels** (personnel location)
- Problem areas
- Training
- Security (personnel location)
- Weld inspection
- Damage assessment
- Environment (temperature, humidity)
- Read instruments
- Detect loosened parts
- Airborne and surface contamination

* Reference 5 indicates the mean contribution on various operations to refueling outages in BWR plants are as follows: maintenance and repair - 21 days (31%), inspection - 5 days (7%), testing - 7 days (10%), and refueling - 36 days (52%).

** Reference 6 provides the following radiation profile for a PWR (none provided for BWR): forced outage maintenance - 40%, routine maintenance - 30%, refueling - 15%, routine operations and surveillance - 6%, in-service inspection - 5%, and waste processing - 4%.

- o Spare parts storage/handling
- o Material sample collection and testing
- o Snubber testing
- o Decontamination/cleanup
- o Filter change

- o Condenser tube cleaning
- o Pressure relief valve removal/calibration/replacement

b. Specific

The elements of maintenance which can be improved by use of robotics for each of the current U.S. power reactors are summarized below. These elements are categorized according to reactor type.

- o BWR
 - Turbine components (temporary clamping or welding; leak detection and repair in valves and moisture separators)
 - Suppression pool inspection and cleaning
 - Main steam isolation valve (MSIV) maintenance
 - Condensate filter element replacement
 - Nitrogen-inerted containment special maintenance
- o PWR
 - Steam generator components (leak detection, repair, cleaning)
 - Evaporator (boric acid)
 - Cavity water cleanup/cavity cleaning
 - Pressurizer heater replacement
- o GCR
 - Gas storage, recirculation systems and leak detection and repair
- o LMR
 - Liquid metal spill detection/cleanup
 - Fuel transfer equipment maintenance (liquid metal handling)
 - Liquid metal waste handling

2. Inspection and Quality Assurance

- a. Primary system weld inspection using ultrasonic or other volumetric techniques.
- b. Leak detection using visual, ultrasonic or other sensors.
- c. Pump oil levels; oil contamination.
- d. Material testing - mechanical, chemical and radiological sample collection and testing for aging, corrosion, stress and radiological exposure.
- e. Snubber testing - hydraulic snubber testing to check bleed rates, reservoir levels and conditions of lock-up. Mechanical snubber testing via torque testing.
- f. Surveillance inside the containment - remote television to provide 3-D or holographic displays; camera/laser beam manipulation.
- g. Inspection/safety tours - useful for safety verification, training, instruction, identify needed repairs, problem areas, NRC inspections, security, radiation levels, etc.
- h. Steam generator tube inspection (except for BWRs).
- i. General purpose inspection such as holes, saw cuts, nuts tightened/untightened, detector, control rod drive, valve, pump and piping inspection.

3. Existing and Planned Systems

A remotely operated service robot has been developed and is in use for the Nuclear Steam Supply System (NSSS) maintenance. This machine is a six-degree-of-freedom arm actuated by electric motors and is controlled remotely from a portable control room up to 600 feet distant. Several parallel

microprocessors provide the logic and commands to the servo-motors. The system can be operated in a teach-and-play mode or by operator control using television. The arm which is waterproof and radiation resistant can operate submerged in the reactor vessel or in air. It may be operated from a fixed or mobile base or mounted upside down. The arm can reach from about 2.5 feet to 6 feet with a repeatability of ± 0.06 inches.

Remotely operated devices have been developed in the early 1970s for repair of steam generators. One is an arm with four degrees of freedom used to place equipment and tools remotely in the channel head of steam generators. A Master/Slave Tubesheet Indexer uses a master mounted on a half-scale replica of the steam generator head. These devices have been used in steam generator tube inspection and repair.

Several in-service inspection robots for ultrasonic inspection of reactor vessels have been developed. These computer controlled systems can operate underwater and in a high radiation field.

A multi-axis manipulator that walks on the surface of a steam generator tubesheet has been developed. This system uses eight pneumatically activated fingers and electric motor drives. It has been used for inspection of steam generator tubes.

Several industrial firms are developing versions of a pipe "walker" that will be capable of moving through the primary coolant piping. It will be used for inspection of welds and removal of debris in the piping.

A remotely teleoperated, multi-wheeled system has been developed for surveying the radiation level in the cavity of TMI-2. Several national laboratories have also supplied mobile teleoperated systems for use at TMI.

Remote handling devices are used for refueling, vessel head removal, vessel inspection, control rod drive removal and rebuilding, coolant sampling, etc., but these are primarily extensions of remote handling technology with little or no artificial intelligence or programmability.

4. Non-routine Operations

Non-routine maintenance operations, such as occur subsequent to failure of a component are summarized below. These non-routine maintenance operations will probably be performed by a remotely operated manipulator system since these operations are regularly encountered. The operations requiring many repetitive operations, however, such as steam generator inspection and repair have been automated to some degree and can be expected to become more automated as the sensor and control systems become more advanced.

- a. Surveillance/monitoring for damage.
- b. Temporary/permanent repair of damaged item.
 - o Steam generator tubing
 - o Valves
 - o Pumps
 - o Core internals
 - o Piping
 - o Pipe snubbers
 - o Pressurizer heater
- c. Decontamination/water sampling and removal/waste removal.
- d. Erection of shielding.
- e. Recovery from liquid metal spill (LMR only).

5. Plant Modifications

The recommended plant modifications or design changes to enhance the application of robotics in plant maintenance are:

- a. Accessibility.
 - o Space around components and piping
 - o Wider doors and aisles
- b. Provide tracks or rails, both vertically and horizontally for the robotic devices or elevators.
- c. Use modular construction for the plants.
- d. Use captured bolts and tapered bolts to facilitate remote operations.
- e. Provide permanently installed data transmission relay stations.
- f. Provide bar coding on components for identification; relate coding to CAD system.
- g. Provide indexing marks for absolute positioning confirmation.
- h. Improve lighting.

6. Technology Needs

The following technology advancements are needed by the designers of advanced robotic systems:

- a. Radiation and other environmental hardening: Robotic systems for nuclear applications will require resistance to radiation or other hazardous environments. While the machines have a greater radiation

resistance than man, they still must have special features to assure operation in a hostile environment. Environmental considerations should include temperature and humidity, and inert atmospheres.

- b. Vision and other sensory capabilities: The robot must have very good vision to be able to recognize not only the object it was sent to repair, but also the variables caused by equipment failures. Vision capability includes such aspects as depth perception and spatial relationships. The robot must be able to characterize the objects that it picks up using a touch capability.
- c. Mobility: Cableless power and data transmission are required to provide flexible, mobile robotic systems capable of deployment in reactor containments. Present generation systems with power cords present serious operational concerns and limitations to their use. Collision avoidance, object recognition and traversing, and vertical access are also needed for mobile systems.
- d. Non-Vision Sensors: The usefulness of manipulators is closely tied to control systems that rely on sensor feedback for adaptive behavior in an unstructured environment. Collision avoidance systems, in particular, are necessary for nuclear applications.
- e. Artificial Intelligence: Computer systems to provide expert systems logic and adaptive controls will be necessary for advanced robotic systems. These systems will require on-board computers with increased capacity or wireless data/control transmission to fixed computer/control centers. Development of the algorithms and control schemes for multi-arm systems and intersecting multi-axis robots are also required.
- f. Sensors: Sensors are required to measure forces accurately to permit use of adaptive end-effectors. Tactile sensors are essential for object identification and for adaptive control systems. Infra-red sensors are needed for thermographic scans of operating systems to detect defects such as leaks, insulation failures, and hot spots.

Miniaturization of all of these sensors is desirable to reduce the size and weight of the sensing package.

- g. Improved Mechanical/Electrical Systems: In order to provide more compact robotic systems to permit deployment of robotic systems in minimum space applications, higher strength to weight ratio mechanical components are required. Higher specific power, radiation and humidity/water-proof electric motors or other new types of actuators are needed. Multi-intersecting degrees of freedom are required to provide increased flexibility for robotic systems. Improved dexterity is required to permit the performance of more delicate tasks.
- h. Smart tools: Tools and end-effectors with integrated circuits that provide feedback and adaptive control are required. Tools for welding, cutting, grinding, and inspection are among the key tools to be considered.

E. Fuel Fabrication and Maintenance (Reference 1)

1. Elements of Current Practice

a. Common

Fuel fabrication robotic operations which are common to all processes include material handling and machine loading/unloading.

b. Specific

Specific robotic application in the Liquid Metal Reactor (LMR) process is cleaning (swabbing) clad tube ends prior to end cap welding.

2. Existing and Planned Systems

- a. The Department of Energy's LMR fuel fabrication line, presently being installed (scheduled start-up - 1986) in Westinghouse Hanford's Fuel Cycle Plant at Richland, Washington, utilizes over 20 robots.

An electric robot is used in the Special Nuclear Material vault to load/unload containers of material from pallets, pass the container by a bar-code reader for identification and to place the container on a scale for weight verification. The robot then places the container in a dumbwaiter for transfer to the fabrication line. Current robotic applications include:

- o Nine custom-designed electric robots are used in the powder processing area for transfer of canisters of fuel material from operation to operation.
 - o A modified electric robot is used to transfer containers into and out of the pellet in-process storage area.
 - o A two-armed pneumatic robot is used in the pin loading operation to decontaminate the inside of the clad tube end (by swabbing) prior to end cap welding.
 - o Nine pneumatic robots are utilized in the close-coupled chemistry analysis area. The robots are used to load/unload pellet samples into/out of various chemistry analysis operations.
- b. An LWR fabricator is evaluating the use of a robot with vision to inspect hardware dimensions during final assembly operations.
- c. GA Technologies Gas Cooled Reactor fabrication line in San Diego utilizes a robot to remove the green rods from the press and to stack the rods into tubes for transfer to the rod carbonization operation.

3. Non-routine Operations

Replacement of process equipment modules or complete systems, e.g., pellet press, centerless grinder, rebricking continuous sintering furnace, etc. are one-of-a-kind operations.

4. Plant Modifications

The next generation LMR fuel fabrication facility will probably have to utilize remote maintenance to meet DOE's one rem/year whole body exposure (by design) criteria. This is due to the recycle (high exposure) plutonium which will be processed in the future. The present automated/remotely controlled glove box process with hands-on maintenance may have to change to a canyon-type operation to accommodate remote maintenance. As a minimum, the current glove box hands-on maintenance concept will have to change to accommodate robotics and this may impact the facility design.

5. Technology Needs

Advanced robotic technology will be needed in the future to accommodate remote maintenance of LMR fuel fabrication operations to meet anticipated personnel exposure design requirements. Smart robotic systems will be required, i.e., robots with artificial intelligence capability and advanced sensors (tactile, vision). Untethered mobile robots with multiple end effectors and 50-100 lb capacity will be needed. Homing devices, e.g., optic sensors, are needed to be an integral part of the fabrication equipment, to allow the robot (end effector) to "re-calibrate" its position in order for it to carry out its intended maintenance operation without damaging the process equipment or itself. The robotic system(s) may have to be an integral part of the process operation depending upon the fabrication concept of the future facility (canyon vs glove box).

Demonstration of typical remote maintenance operations is required.

F. Reprocessing Operations and Maintenance

1. Elements of Current Practice (Reference 2)

Existing nuclear fuel reprocessing plants have adopted one of two main maintenance philosophies. The earlier plants adopted equipment duplication in the high level (HL) radiation areas, and contact maintenance after decontamination in the medium level (ML) and low level (LL) radiation zones. Later

plants moved towards remote maintenance in the HL areas, but still relied upon contact maintenance in the ML and LL areas. The only departure from this arrangement is the Hanford reprocessing plant where all the active equipment is installed in a concrete canyon with overhead crane access. All canyon equipment is connected to process and service lines by the use of remotely demountable jumper connections to allow maintenance and replacement by the use of cranes and hook-mounted impact wrenches.

Robots as they are known today are not used in existing reprocessing facilities.

2. Existing and Planned Systems (References 3 and 4)

The Allied General Nuclear Services plant, in Barnwell, South Carolina, constructed in 1976 and never started up, was designed for maintenance using a combination of cranes, power manipulators, and mechanical master/slave manipulators in the mechanical head-end operations.

Reprocessing development activities at Oak Ridge are built around the force-reflecting bilateral servo-manipulator for use in remote maintenance operations. In conjunction with advanced state-of-the-art distributed digital control concepts, machine-manipulator interface upgrades, and remote television systems, it is expected that this manipulator will be used in the next generation reprocessing plant both for maintenance and to transfer fuel assemblies during head-end operations.

3. Nonroutine Operations

Nonroutine maintenance operations consist of equipment replacement, repair and modifications.

4. Plant Modifications

The design of a reprocessing facility is strongly influenced by the repair philosophy and if remotely maintained, by the remote maintenance equipment capabilities. The facility and all in-cell equipment must be arranged to

facilitate repair for whatever maintenance philosophy (contact or remote) is used.

5. Technology Needs

Demonstration of the remotely maintainable advanced servo-manipulator in conjunction with the advanced integrated operator station which incorporates ergonomically designed color graphics displays and standard remote TV viewing monitor is required.

G. Waste Handling

1. Elements of Current Practice

a. Common

Reactor power plants and processing facilities are constructed for manned entry for maintenance and decommissioning. Operating experience has shown some equipment installations have become too radioactive for entry, especially in light of the current requirements for keeping exposure "as low as reasonably achievable" (ALARA).

There is a need for mobile robots or automated electromechanical manipulators to assist in equipment maintenance and decommissioning of process loops where remote-controlled services were not provided in the original facility.

b. Specific

Commercial robots, modified for specific applications, can pass through most places a man could walk and perform many tasks.

Mobile equipment with closed-circuit television cameras and manipulators could perform the following operations:

- o Take video and high resolution pictures for the purposes of evaluating and planning maintenance tasks
- o Perform nondestructive examination (NDE) on pipes and vessels to determine deterioration
- o Survey for fluid leaks using closed-circuit television, radiation detectors, and leak detectors
- o Control/position tools such as wrenches, saws, calipers, drop cloths, shields, etc., to expedite the manned entry work.

Zones that are too hot for prolonged manned entry could be serviced by a mobile robot to survey an uncertain radiation field level. A robot sent into a hot zone would determine radiation field strengths and distributions to aid in developing strategic planning for limited manned entry and those operations requiring remote operation.

2. Candidate Robotic Applications

The following areas have been identified at plutonium process facilities which require special consideration in waste handling.

a. Waste Encapsulation and Storage

At the Hanford Waste Encapsulation and Storage Facilities (WESF), a large amount of very radioactive material, strontium and cesium, is stored in the WESF pool. Scenarios have been postulated (e.g., leaky capsules, cropped cover block, dislodged debris from ventilation duct) in which manned access to WESF and the appropriate controls to correct the situation would not be allowed. If a mobile robot were available, it could be sent into the pool room to observe, actuate valves, and perform numerous tasks to reduce radiation levels to allow manned entry.

At the Defense Waste Processing Plant, extraordinary, in-canyon incidents such as the damage to the Pipe Trench and Raising Cell Cover Block Out of Order have occurred. Recovering from these unusual occurrences could be simplified with the availability of a surveillance robot. The robot could be used to assist in rigging, fixturing (i.e., pipes during welding), and also record the recovery process on video tape. Commercially available robots, modified for specific applications could simplify existing maintenance operations and reduce man-rem exposure levels.

b. Change Out of Hot Filters

The changing of HEPA filters exposes workmen to unnecessary radiation levels because filters are changed only when they are radioactive. HEPA filters are intended to be replaced before they collect sufficient radioactive material to pose a risk to personnel. As a result, the usable life of a HEPA filter may be determined by the amount of man-rem exposure during replacement of the filter rather than the actual useful life of a filter. Conversely, a properly functioning filter may suddenly become very hot, due to an unusual event, resulting in an expensive changeout operation due to rate of workman burnout.

The development of a robot to change out radioactive filters would be of significant value at Hanford. With it, HEPA filters could be more efficiently utilized, and excessively hot units could be replaced with minimum personnel exposure.

For example, at the Defense Waste Processing Plant, it has been observed that a significant and undetermined amount of radioactive material has accumulated in ventilation ducts. This material is loosely adherent to the duct walls and could probably be dislodged with moderate jarring or scraping. The danger is postulated to occur if/when the material were to spontaneously dislodge and collect in the building filter system (K-3 Filter). The filter would be too hot to change-out by its usual procedure. Radiation from the

filter pit is predicted to be so intense that personnel would not be allowed in any building in the East Area. Furthermore, time would be running out. In a few months, the radiation would destroy the filter medium and contamination would be discharged from the building ventilator spreading it about the East Area.

Robots would be necessary for almost every phase of recovery from such an unusual occurrence. A mobile, radio-controlled observation robot would be sent to the filter first. A heavy-duty robot would be needed to transport shielding material to the pit. It has been suggested that a radio-controlled fork truck could cover the pit with sheets of lead or build a wall of water tanks around the pit. The tanks would be filled with a hose handled by another robot. Also, robots could be used to perform tasks such as surveying and decontaminating areas not suitable for manned access.

One technique that might be employed to change-out a very hot filter is to lower a remotely-operated device into a filter pit. A multiarmed telemanipulator device could disconnect, rig, cut, fill the cavity with foam, and perform other operations to remove the filter.

c. Automated Laundry

An important operation at Hanford is the laundry facility (200 West Area). The laundry receives dirty/contaminated coveralls, rubbers, gloves, masks, head and foot covers, and towels from all Hanford contractors and areas. The laundry cleans/decontaminates this protective clothing and returns it to service on an as-needed basis. This operation requires a staff of 14 people utilized two (2) shifts per day.

The most labor-intensive phase of the operation is sorting and folding. If an automated device were used and programmed it could be designed to fold white coveralls and handle other items. The advantaged would be to reduce man-rem exposure levels. Personnel assigned to the laundry are exposed to residual contamination left in the coveralls after washing. Although, washing reduces the radiation

level for each pair of coveralls to a safe level, the radiation level at the folding station is cumulative causing the sum of the levels from all of the whites in the pile to be higher than for a single garment.

d. Alpha Caisson Storage Containers

A material handling problem exists at the Hanford facility involving removal of waste containers from alpha caissons. The Department of Energy, Albuquerque Operations Office, Transuranic Waste Lead Site Organization (TLO), requires that technology be identified for removing the contents of these caissons for permanent burial in the National Waste Repository.

The caissons in question are 14 feet underground and are connected to the surface with an S-shaped chute. The material stored in the caissons contains transuranic material and is a strong source of gamma radiation.

A number of conceptual plans for removing the material have been attempted but none seem to be feasible, except one. The solution having the greatest potential in solving the problem is to lower a flexible robot arm down the S-shaped chute with a vacuum or gripper to remove the objects one at a time. To remove the objects, remote viewing would be employed to find and grasp each object and then withdraw it through the S-shaped chute. Pre-programmed movement of the arm would be needed to remove objects along the critical S-shaped path.

There appears to be one or two robots commercially available that could be modified to do this task. But some development would be necessary to develop suitable end effectors with the needed arm path control.

e. Aging Waste Management and Retrieval

Waste produced from fuel reprocessing is very radioactive and is stored in underground tanks. Current process and waste inventory control requires that waste be sampled and analyzed periodically.

Samples can be drawn from risers that communicate with the tank interior, but personnel are not allowed to remain in the neighborhood of the sample or any equipment that entered the tank.

The current proposed approach is to use a specialized hand-operated mechanism (the Aging Waste Sampler). It has several shortcomings, i.e.:

- o Hand operation exposes tank farm operators to unnecessary radiation levels.
- o Hand operation requires a complex procedure which could result in human error and subsequent contamination spread.
- o Hand operation mandates a large amount of shielding which makes the manually operated machine cumbersome and slow.

Waste sampling would be ideally suited for a pre-programmed robot. The robot could be programmed to load the sample vial to the lanyard, lower and retrieve the vial, deposit the sample in its shielded receiver, and decontaminate the used equipment. This operation could be performed as often as needed for process control and inventory without any risk of exposing personnel and subsequent spread of contamination. The robotic application would greatly reduce the man-Rem exposure and eliminate hazards to personnel.

3. Existing and Planned Systems

a. Automated Bag Out Technique

A robotic system was developed and installed at Savannah River to remotely remove and bag one-gallon waste cans from a glove box in a

Californium source processing facility. Waste cans from the facility contain sources of radiation and contamination. The process was well structured for automation, but the area suffered from severe space constraints which dictated the selection of the robot and its peripheral components. The basic sequence of the automated bag-out operation is the same as that used for manual operation. No major structural modifications were made to the process area. A special bag port, however, was installed on the glove box to enable the automated operation.

The automated system consists of an industrial robot, a pneumatic end effector and a specially designed bag gathering-clipping machine. The robot reaches through the port and grips a waste container, through the plastic sleeve, from a holding fixture attached to an existing cell transfer conveyor. A slight negative pressure inside the glove box causes the sleeve to expand around the waste can as the robot performs the gripping operations. As the robot arm is withdrawn, the bag turns inside out and envelopes the can, forming a tight protective cover. Packaged cans are deposited in a shielded drum accessible by a remote overhead crane. The robot and process components remain clean during the operation.

A control console is used to operate the waste removal system. Five television monitors, a PA system, radiation monitors, and indicator lights provide feedback to the operator. The computer program controls the process automatically but stops at various steps to allow the operator to inspect the process. Alternate routines, to stop the operation or to back the robot out of the glove box, are implemented by pushing buttons on the control console. Manual motions are not allowed during normal operations due to space constraints.

The operator-interactive control philosophy requires operators to sequence and inspect critical steps in the operation. Operators can recognize potential problems, such as damaged cans or a conveyor misalignment, and correct the problem remotely. Radiation monitors

are located outside the glove box to determine the exact quantity of material inside each can. The operator-interactive control scheme greatly reduced system installation time. A fully automatic process would have required the existing cell conveyor to be replaced and several more sensors to be implemented to perform the necessary human inspections. The entire process was mocked up in a clean area before installation. Consequently, the total personnel radiation exposure absorbed during installation was limited to 3 man-rem. Radiation exposure savings during the next year will total over 20 man-rem.

b. Radioactive Waste Shipping and Receiving

Evaluation of the use of commercial robots in conjunction with overhead cranes for truck loading/unloading high level waste shipping containers is being conducted. Anticipated future shipments (high number) dictate that remote operations be utilized to minimize personnel exposure.

4. Plant Modifications

The use of robots/overhead cranes with remote control capabilities are needed at facilities receiving waste. Casks should be unloaded and canisters removed remotely to minimize the man-Rem exposure. Preprogrammed operations need to be provided in order to assure repeatability and the overall safety of the operation. System waste handling studies are needed to identify the degree of sophistication required for existing and new facility designs.

H. Decommissioning

1. Elements of Current Practice

Decommissioning of nuclear fuel cycle facilities involves a broad range of activities requiring the ability to dismantle a major facility in the presence of radiation fields and contamination. Major elements of this effort are discussed below.

Surveys - Components to be removed must be surveyed to assess the degree to which they are contaminated. These surveys must also evaluate radiation

fields in the vicinity of these components as well as contamination levels in the potential work areas.

Decontamination - Components may be decontaminated to reduce radiation levels before work proceeds.

Dismantling - This effort includes removal of components from the facility as well as cutting oversize components into smaller pieces. During this activity appropriate steps must be taken to prevent spread of contamination.

Waste packaging - This includes moving radioactive and contaminated items to the packaging area, as well as the actual packaging. Items include components and pieces removed from the plant, decontamination wastes, tools, clothing and waste paper.

2. Inspection and Quality Assurance

The principal issues of inspection and quality assurance associated with decommissioning of nuclear facilities is monitoring of the radioactivity associated with waste material and of materials for unrestricted release. Ascertaining the background levels of contamination in the facility to be decommissioned is an important part of this process.

The issues of inspection and quality assurance extend beyond the primary facility. During removal, containerization and transport of debris and other waste, there is a critical need for inspection and QA. This responsibility continues until deposition in an approved waste disposal facility.

3. Existing and Planned Systems

There are no existing truly robotic systems that are used in decommissioning although there is a moderate amount of capability with respect to remotely operated equipment. Although, not a decommissioning operation, the recent removal of a reactor thermal shield from an operating reactor is typical of the operations that are likely to be performed in decommissioning. This operation was performed with a plasma arc torch that was remotely positioned

by an operator. Control of torch parameters was by a feedback control system.

At Three Mile Island-2 (TMI-2), decontamination of concrete has involved the use of a hydraulic lance mounted on a mobile base.

The Shippingport decommissioning will involve the use of remotely operated pipe cutters and power hacksaws. A remotely operated manipulator installed through a roof hatch is in use at the West Valley Demonstration Plant. It is used for dismantling the piping in the chemical process cells.

4. Non-routine Operations

The entire process of decommissioning is nonroutine. Limited precedent exists for this work and systems are just being developed.

5. Plant Modifications

New facilities should be designed to facilitate and accommodate decommissioning. For all practical purposes, the existing nuclear facilities have not incorporated decommissioning as a principal objective during design. Among the elements to be included are the following:

- o Access for survey and work robots
- o Utility supply for decommissioning
- o Waste and scrap handling
- o Monitoring systems to evaluate radioactive contamination levels

6. Technology Needs

Areas in which robotic technology can be beneficial to decommissioning are in conducting surveys, performing decontamination work, cutting, transporting pieces to a waste packaging area and the actual packaging operation.

Technology needs applicable to these include the following:

- o Radiation resistance of electronic materials

- o Radiation resistance of mechanical and hydraulic components
- o Robot mobility
- o Robot navigation
- o Sensing systems for construction robots
- o High force level manipulators
- o Data transmission in radioactive and dirty environments

I. Economic Impact

The major economic benefit to the nuclear industry results from the application of robotics to the operation and maintenance of power plants. This is due to the multiple units for this application compared to a very limited number of reprocessing, fuel fabrication, or waste management facilities. If there is a resumption of construction of large numbers of reactor plants, then there will be significant economic benefits in this application; however, at this time, the expected new construction is limited. When new construction is resumed, plant designs should be modified to accommodate the use of robotics.

Substantial economic benefits through the use of robotic systems can be achieved because of:

- o Reduction in man-rem exposure
- o Reduction in plant downtime

In addition, the need for rework will be reduced because of the precision and repetitive capabilities of robotic systems. The following cost values for these major improvements are:

- o Average cost per man-rem exposure is \$1,000 to \$10,000.
- o Average cost per day of downtime for a 1,000 MWe plant is \$500,000 to \$1,000,000.

The costs of personnel exposure have been estimated using the above costs and the following assumptions:

- o Average exposure per plant is 560 man-rem per year (Reference 6).
- o Number of plants in 1995 is 120.
- o Robotics will reduce personnel exposure by 90%.

The costs of plant downtime have estimated using the above costs and the following assumptions:

- o Present plant annual downtime is 90 days.
- o Number of plants in 1995 is 120.
- o Robotics will reduce the downtime by a factor of 2 by performing some tasks during plant operation and by eliminating the need to perform other tasks while wearing protective clothing.

The results of these cost estimates are summarized in the table below:

	Reduced Outage _____	Reduced Radiation Exposure _____	Total _____
Expected Annual Savings (\$B)	\$ 2.7 to 5.4	\$ 0.6 to 0.06	\$2.8 to 6.0

J. Safety and Licensing Impact

The application of robotics in the nuclear industry will have a positive impact on safety and licensing. Candidate applications would consider plant construction, reactor operation/maintenance, fuel fabrication, reprocessing, most handling and decommissioning. At the present time, robotic maintenance systems are not considered during reactor plant licensing. This could change, especially if robots are used for maintenance during plant operation.

1. Safety Considerations

The safety of construction workers, technicians and plant operating personnel will be enhanced by the use of robotic systems. Examples are:

- o Minimizing/elimination of personnel radiation exposure
- o Contamination control
- o Handling of corrosive/toxic material
- o Handling/packaging of waste
- o Decontamination activities
- o Hazardous construction activities
- o Size reduction of contaminated equipment facilities

2. Licensing Considerations

Compliance with licensing requirements involving plant operation will be enhanced by use of robotics. Examples are:

- o Enhanced service in inspection capabilities
- o Maintaining personnel exposure limits
- o Automated data acquisition and recording

K. Technology Needs

The last subsection of each of the areas covered in Sections B thru H identifies the technology needs for each of the areas discussed. These needs

are summarized in the accompanying table which lists these needs under major technical categories.

Within each technical category there is a prioritization from top to bottom. This categorization considers that robotic technology is being developed outside of the nuclear industry. For instance, category 3 is based on developments in other areas of robotics discussed under Developments Underway and Contracts. There is also a prioritization implicit in the ordering of the columns, with the columns on the left deemed to have higher priority than those on the right.

Robotics Technology Needs

Category	Priority	Mobility	Sensors	On-board Decision Making	Human Factors	Reliability Availability Maintainability	Environmental Hardening	Standards	Mechanical Systems	Payload Control Systems	Smart Tools
1	DOE must lead	vertical access	spatial location, object recognition	domain specific intelligence	operator control console interface	modularization & interface standards	radiation	equipment decontamination			
2	DOE applies leverage	obstruction avoidance	force feedback tactile	Expert systems	mobile platform-environment interface		inert atmosphere	Equipment & facility standards thru ANSI & other organizations	higher strength to weight ratio, multi-intersecting degrees of freedom	multi-arm & multi axis	inspection
3	DOE can exploit	cableless power & data transmission	vision, viewing & lighting	adaptive learning		maintainability system manuals	temperature humidity, chemical		higher specific power motors	end effectors	cutting welding & grinding

Definition of Categories

1. Unique to nuclear facilities
2. Common to other applications, but critical for use in nuclear facilities
3. Common to other applications; important but not critical for use in nuclear facilities

IV. DEVELOPMENTS UNDERWAY AND CONTACTS

Today's activity growth for robotic systems parallels the expansion experienced ten years ago in semiconductor miniaturization and computer development. Many educational institutions now offer courses relating to robotic technology, and several have established centers for the integration of computer science, mechanical engineering, and electrical engineering into robotic and automation research.

The nuclear industry's hot cell efforts at national laboratories resulted in an advanced state of development of master-slave systems and dexterous end effectors. Several companies have spun off and are beginning to focus this background of capability on robotic systems, especially those utilizing mobile platforms. Anticipating a market for robotic systems, several commercial companies are moving rapidly to develop systems for surveillance and maintenance. Specific problems (e.g. steam generator repair/removal, core barrel removal) have resulted in very specialized systems, now available from the nuclear service marketplace.

The accompanying table is a summary of the current status of robotics research and development programs including university research, national laboratories, Government agencies, private companies, and foreign programs. Each of these categories are discussed in the following paragraphs.

Universities

Among the universities, Carnegie-Mellon University has the most extensive program through its Robotics Institute, which was established in 1979. The total staff including faculty, research engineers, and students exceeds 200. The two major areas being developed are automation and computer-integrated manufacturing and robotics for hazardous environments, including underseas, space, nuclear power plants, and deep mine shafts. More than two dozen corporations and several Government agencies provide funding for the Institute.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Clemson University Engineering Center for Automated Manufacturing	Dr. Frank W. Paul 803/656-3291	Industrial DOD	The Engineering Center for Automated Manufacturing Technology was established in November 1981 to support education and research activities at Clemson University in automated machines and robotics, computer-aided design, materials for manufacturing and systems and industrial engineering. The Center works through its industry members and contractors on problems related to automated manufacturing. The Center is supported by a laboratory having robots, microcomputer and two VAX 11/780 computers for CAD activities.
California Institute of Technology, Jet Propulsion Laboratory	Dr. Carl F. Ruoff	DOD NASA Industrial	Major areas of research activity include; --Sensor-based manipulator control --Multi-fingered end effectors --Operating systems --Languages --Supervisory control --Teleoperation --Sensing and perception system --Human factors --Automatic plan generation --Machine Intelligence

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Massachussetts Institute of Technology, Charles Stock Draper Laboratory, Inc.	Dr. Edwin H. Porter, Jr., 617/258-2374	DOD NASA USBM Industry	Research in understanding manu- facturing, processes (assembly, thread mating, grinding, etc.) prior to automating them. Ex- pertise in engineering models of processes, design of instrumenta- tion for process monitoring, ex- perimental verification. Patent- ed technology includes 6 axis force/torque sensor, remote cen- ter compliances, instrumented RCC's, insertion stations for precision parts. Consulting services on identifying auto- mation targets, economic analy- sis, system configuration, pro- duct redesign. Recently built and delivered special tool-chang- ing robot with 12 tools, computer and sensors for complete docu- mented assembly of precision products.
MIT Aeronautics & Astronautics Dept.	Dr. David Aiken 617/253-7107	NASA	Research directed toward structural assembly of space stations. Currently testing two teleoperated vehicles, both master-slave machines.
Civil Engr. Dept.	Dr. Gregory Baecher 617/253-7101	U.S. Army	Developing a device to detect leaks in buried water pipes.
Mechanical Engr. Dept.	Dr. Carl Peterson 617/253-5373		Studying mechanical mining of underground coal deposits.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

ORGANIZATION

Rensselaer
Polytechnic Institute,
Manufacturing Technology
and Productivity Center

CONTACT

Dr. Leo Hanifin
518/270-6724

SPONSOR

NASA
Industry

PROGRAM DESCRIPTION

The Center's efforts are a balance of technological development and applications research and development rather than efforts directed toward course or curriculum. Funded by private capital, the Center's undertakings are project or problem driven in the area of manufacturing productivity. The Center solves real manufacturing problems on time and within a budget. Finally, the Center, through its "People Products" and short courses, transfers technology that exists and is constantly emerging from RPI and other sources, to industry. The Center is currently involved in a broad spectrum of projects. These include: the use of interactive computer graphics to create and simulate numerical control tapes to eliminate costly N/C tape verification on the machine-tool; computer graphic simulation of industrial robot arms; the adaptation of microprocessors and computers as controllers to replace manual, hardwires, or CAM controllers; the use of interactive computer graphics to optimize work station layout for robotic assembly.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
	John Reidy	Wright Patter- son AFB	Design and construction of a robotic engine repair facility for the Air Force.
		ORNL	Design of a remote-weld- repair system concept for radioactive piping.
		DARPA	Development of an adaptive suspension system for a rugged terrain vehicle, including hydraulic devices and the machine intelligence system.
Georgia Inst. of Tech, Atlanta, GA	Dr. Dickerson 404/894-2000	25 industrial Sponsors, IBM is the largest	Programs in manufacturing automation, vehicle guidance, tactile sensing, and high speed/light weight motion system.
U. of Maryland	Dr. Yang	DARPA, NSF, ORNL, industry (W-Columbia)	Vision systems and human computer interaction. Have program with EPRI (through GE) on inspection techniques.
U. of Rochester Rochester, NY	ME: Dr. Benson 716/275-7847	Gleeson Memorial Fund	One full time graduate student (ME Dept) is working on vision systems. The EE Dept. has a Production Automation Project which is directed at the software development.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
U. of Florida Center for Intelligent Machines and Robotics (CIMAR)	Dr. Jack Ohanian (904) 392-0464 Dr. Joe Duffy (904) 392-0879 Staff approx. 20 grad students- approx. 75	DOE, Self, FL State, Industry	<p>Program on-going for several years through 1984 under the direction of Dr. Del Tesar (J. Duffy now acting Director). Approximate funding level is \$3M per year. Specific - all programs on-going with emphasis toward implementation</p> <ul style="list-style-type: none"> a. Real time/man-machine systems* <ul style="list-style-type: none"> 1) Joystick controllers (essentially complete) 2) 4 degrees of freedom (DOF) planar controller 3) 6 DOF spatial controller 4) 7 DOF (1 redundant DOF) controller 5) Force feedback b. Dynamics (Robot Control) <ul style="list-style-type: none"> 1) Phase I - correct for inertial loading 2) Phase II - correct for deflection/flexible loading c. Graphics - 3D d. Multiple robot systems e. Kinematics f. Mathematics
U. of Texas Center for Robotics, Manufacturing, and Logistics	Dr. Delbert Tesar (512) 471-3039 Staff, Grad Student development underway (Expect 200 total)	Air Force Self Texas State Industry	<p>Program initiated in 1985 under the direction of Dr. Del Tesar (formerly with Univ. of Florida). Funding is approximately \$1M to \$2M for 1985 and is expected to increase to \$5M-\$7M per year.</p> <ul style="list-style-type: none"> a. Mobile robots* suitable for battlefield operations.

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* This work is particularly applicable to the nuclear industry because of the unstructured environment orientation.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

ORGANIZATION

CONTACT

SPONSOR

PROGRAM DESCRIPTION

(chemical, biological, nuclear environment)

- 1) rapid runway repair
- 2) fire-fighting on carriers
- 3) ammunition handling
- 4) maintenance/repair
- 5) riveting-deriveting
- 6) jet engine repair

b. Manufacturing robots

- 1) free-standing/database controlled

c. Advanced technology development

- 1) new computer architectures
- 2) improved man-machine interface
- 3) mathematics
- 4) dynamic modeling
- 5) advanced sensors/vision
- 6) manipulators/end effectors/materials
- 7) miniaturized systems/sensors

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Drexel Univ.	Dr. Alexander Meyestel	DOD	Developed software for a mobile system (tank) with three distinct levels of intelligence for terrain negotiation.
Stevens Inst.	Dr. John Crisp	U.S. Army	Work in telematics. Courses offered in microprocessors and one in robotics.
U. of Rhode Island	Dr. Morris Driels	Funds Others	Program directed toward industrial applications that involve fixed-position robots. e.g., to recognize and remove a part from a bin of parts.
Brigham-Young University	Dr. Edward Red (801) 378-5539 25 Faculty, 509 students, 100 grad. students	Self, Industry	Develop interdisciplinary systems including vision, CAE, CAD, and robotics for automated manufacturing. Program established a few years ago and is on-going. a. Systems development/implementation 1) robots 2) CAE/CAD 3) Vision 4) digital transmission 5) software

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
UCLA	Dr. Geo. A. Bekey 213/743-5535	Government Industry	Courses and R&D in AI, manufacturing technology, robotics, and automation.
Stanford Univ. Inst. for Manufacturing and Automation	Dr. Elliott C. Levinthal 415/497-9037	About 25 sponsors, including IBM, NSF, NASA, Mettler AG, SDF, AFOSR, DARPA, DNA, EPRI, and others.	Interdisciplinary organization with four major centers whose end-products are graduates, research results, and educational activities.
Robotics Inst. Carnegie-Mellon Univ.	Dr. Raj Reddy 412/578-2597	Government Industry (30+) DOE, DARPA, EPRI, GRI	Large, interdisciplinary research center studying autonomous systems capable of sensing, thinking and acting. Robotics Institute was established in 1979 and has more than 200 staff and students. Active in automation, computer-integrated manufacturing and robotics for hazardous environments, including nuclear and deep mine shafts. Funding is approx. \$9M per year.
U. of California LaJolla, CA CA Space Inst.	David R. Criswell 619/452-2047	NASA	Established the Automation and Robotics Panel to provide guidance on the application of advanced automation and robotics to the IOC program.
U. of Nevada-Reno	Dr. N.D. Perreria 702/784-6094	DOE	Evaluation of optic sensors for remote maintenance of reprocessing fuel fabrication equipment.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
U. of Warwick		European Atomic Energy Commission	Decommissioning studies.
Japan Advanced Robot Technology Association		Ministry of International Trade & Industry	Development of high performance robot with sufficient versatility to work in nuclear reactor maintenance.
Kansai Electric Power Company		Mitsubishi, Fuji, Hitachi, Medensha Electric Mfg. Co.	Robots for operations inside steam generator channel head, valve seal tensioning, manhole cover handling, floor decontamination, and pipe elbow inspection.
Atomic Energy of Canada, Ltd.	Dr. Clive Wood		Developing pressure tube inspection system.
Japan Power Demonstration Reactor		Four Japanese construction companies	Completing research and development on decommissioning capabilities.
United Kingdom Central Electricity Generating Board-Marchwood Eng. Lab.	D.W. Perratt	U.K.	Development of sophisticated, heavy duty manipulators with arm extensions and tools (bolting and welding) for remote repair of Magnox stations.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
FRG Kernfor- shungszentrum Karlsruhe GmbH			Robotic system for fuel handling, mobile vehicles, waste processing and decommissioning.
Westinghouse- Hanford Co.	Dr. R.E. Dahl 509/376-8724	DOE	Design, development, procurement, installation and operation of automated, remotely controlled LMR fuel fabrication line. Over 20 robots are utilized.
	J.D. Berger	Sandia	Development of High Level Waste Shipping Container handling during truck loading/unloading. Uses robot and overhead crane.
Oak Ridge Nat. Lab. Fuel Cycle Program	Dr. W.D. Hamel 615/574-5961	DOE	Development and demonstration of force-reflecting bilateral servo-manipulator for use in reprocessing system operation & maintenance, advanced digital control, man-machine upgrades & remote TV system. Funded at a multimillion dollar level.
Oak Ridge Nat. Lab. (CESAR)	C. Weisbir	DOE	Develop and test advanced control systems and AI logic for autonomous vehicles.
Savannah River Nat. Lab.	J.J. Fisher	DOE	Application of robotics in various operations such as

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
			"bag out" of waste cans from a Cf source processing facility; radioactive sample collection; transfer of nuclear sources and evaluation of walking robots.
Battelle Memorial Inst.	Matt Bartilson	Self	Developed mobile radio-controlled platform (ROCOMP) with manipulator for maintenance in nuclear power plants. Can also be used for gathering smear samples.
Westinghouse Hanford Company	W. Gajewski (509) 376-9586	DOE	Developed the equipment, systems and facilities for the maintenance, in-service inspection, and surveillance of the FFTF. Provided SISI and LOUIE mobile robots for TMI-2.
Defense Advanced Research Projects Agency (DARPA)	C. Kelly, III		Supports several university, industry and military research and development efforts encompassing most aspects of both stationary oil mobile systems.
National Bureau of Standards	Dr. James Albus (301) 921-1000	Self	Research in artificial intelligence applied to interactive/autonomous robots.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Los Alamos Nat. Lab.		DOE	Developing a robot for use in weighing and calorimetry of ²³⁸ Pu oxide for radiochemical assay of Pu and Am.
Electric Power Research Institute	J. Taylor 415/855-2030	U.S. member utilities	Mobile systems for surveillance and maintenance work. Support TMI-2 cleanup with specific remote vehicles, in conjunction with CMU.
Automated Unarmed	J. Canoe		Promoting the development oil testing of airborne and terrestrial vehicles; main focus has been on military applications.
Public Service Electric Gas of NJ	H. Roman	Self	Utility is assessing needs and for robotic systems in generating stations working with several nearby universities (e.g. NSIT)

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
GCA/PaR Systems	R. Johnston		Offer manipulators, ISI systems, robotic system control for IFA. Manufactured the Herman robot now at ORNL's Y-12 facility.
Viking Energy Corporation	J. Saluja		Developed the ROD robot for cleanup of radioactive waste at the West Valley Demonstration project.
Remote Technology Corp.	J.R. White	NRC	Developed the Surbot mobile robot under SBIR funding; other master-slave manipulation systems.
Foster-Miller, Inc.	R. Wiesman	U.S. Navy	Developed and provided three Ramrod EOD mobile systems to the sponsor.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Department of Defense (DOD)		Congress	Supports numerous AI development efforts, and several engineering application projects to develop and test specific hardware systems.
SAS R&D Services, Ltd. (I)	T.R. Sas	Self	Developed and commercially offer the Hunter remote controlled EOD vehicle.
CMS Technologies Inc. (I)	C. Stephens		U.S. representative for systems developed by Blocher in the FRG.
Tele Operator System (I)	C. Flattau		Offer the Telemac, a radio controlled, remote operating vehicle developed in Belgium by ACEC and others.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Spar Aerospace Limited	I.P. Stefou		Manipulator systems for industry and hostile environments.
Odetics, Inc.	T. Bartholet	Self	Developed the six-legged robot prototype ODEX.
Automation Technology Corporation	R. Simmons	EPRI, Gould	Developed and offer the IRIS Surveyor system for surveillance.
Hitachi Corporation	S. Kuwahara		Developed and offer the Hi-Mante remote-operated manipulator vehicle for decommissioning.
Rockwell International Science Center	J. Schoenwald		Research and development on acoustic ranging systems and robot position control.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
Babcock and Wilcox Contract Research Division	J. Kerr	Self	Remote inspection and monitoring systems, including steam generator tube repair inspection system.
Shimizu Construction Co., Ltd.	T. Yoshino		With Kobe Steel, developed and offer a robot for spraying rock wool for the fireproofing of structural steel.
Honeywell, Inc. Technology Strategy Center	R. Mostrom		Developed and promotes 3-D TV viewing systems, power-line carrier systems, range finding systems, and various communications systems technologies.
SRI International	D. Nitzan	NSF and others	Research and Artificial Intelligence and robotic manipulators.

PARTIAL SUMMARY OF ROBOTICS DEVELOPMENT PROGRAM AND CONTACTS

<u>ORGANIZATION</u>	<u>CONTACT</u>	<u>SPONSOR</u>	<u>PROGRAM DESCRIPTION</u>
General Electric Company	Mr. Vern Estes (305) 889-1401	Self	Extensive robotics hardware/software applications development. "Factory with a Future" program incorporating robots, vision, sensors and manufacturing systems. GE Corporate Research and Development Center Advanced R&D in areas such as computers, languages, assembly robots, CAE/CAD and Laser weld tracking via robotics.
Candian General Electric	Barry O'Sullivan (705) 748-7183	Self	Monitoring and intervention systems for fuel handling. Underwater robotics system with force sensor feedback.
Westinghouse Electric Corporation	C. A. Sadlow, V.P. Adv. Prod. Tech. 412/642-3811	Self	Manufacturers of Unimate robots self-funded development of advanced electric-driven robots, vision systems, laser/MIG automated welding system, artificial intelligence. Supported by Productivity Center and R&D Center. Robotic & remote operated equipment developed for nuclear applications.
	J. Gitt Oceancies Division 301/260-5804		Design studies of an autonomous underseas vehicle for DOD.

The Center for Intelligent Machines and Robotics at the University of Florida has twenty staff members and 75 graduate students. Its programs are directed at real time/man-machine systems with multiple degrees of freedom and force-feedback. The Center is also strong in 3D-graphics, kinematics, and mathematical analyses.

The University of Texas initiated a Center for Robotics, Manufacturing, and Logistics in 1985 under the direction of Dr. Del Tesar (formerly Director of the CIMAR center at the University of Florida). The planned program will focus on mobile robots for battlefield operations, manufacturing robots, and advanced technology development.

The Institute for Manufacturing and Automation at Stanford University is an interdisciplinary organization with more than 25 industrial sponsors. This Institute is exceptionally strong in artificial intelligence.

The Massachusetts Institute of Technology has several robotics programs within its departmental structure, i.e., in the Aeronautics and Astronautics Department, Civil Engineering Department, and Mechanical Engineering Department. In addition, the Charles Stark Draper Laboratory, Inc., is performing research in automated manufacturing.

An Engineering Center for Automated Manufacturing Technology was established at Clemson University in 1981. The center performs research in automated machines and robotics, computer-aided design, and materials.

Government Agencies

Robotics development programs are being performed for specific applications for individual branches of the Department of Defense and for the overall Manufacturing Technology Program (ManTech). Several U.S. Army programs are directed toward hazardous materials handling and mobile robots for battlefield operations.

The U.S. Navy is developing intelligent robots for applications that are unique to naval applications, such as shipbuilding and weapons manufacture, repair maintenance, and operations. As part of the Navy Manufacturing Technology Program, automated, adaptive robotic metal arc welding systems are being investigated. Advanced technologies include weld seam tracking, collision avoidance, and real-time weld process control. A passive three dimensional vision system is also being developed for use with this welding system. An articulated laser robotic welding system with automated weld seam tracking is also being developed by the Navy.

The Naval Surface Weapons Center has been investigating mobile robots for use in security and firefighting applications. Sonar and infra-red sensors provide the required control data. The mobile system is modular so that updated components can be substituted as improvements in technology are achieved.

The Naval Oceans Systems Center in San Diego, California has responsibility for maintenance of a Robotics and Artificial Intelligence Database (RAID) for all Department of Defense research in these areas. This on-line, computer data base can provide summaries of current programs, funding, and contractual and organizational information.

The National Aeronautics and Space Agency (NASA) has sponsored the development of remote systems for space applications, including remote surveillance and sampling systems, image enhancement software, and a remotely-operated manipulator system. A report has been prepared for NASA at the direction of Congress by an Advanced Technology Advisory Committee.

This report, which identified advanced automation and robotics technologies for the space station, recommended a 10 year development program reaching a maximum annual funding of \$100M to \$200M. This report was organized and coordinated by the California Space Institute and included participants from universities, industry, national laboratories, and NASA.

NASA-Langley Research Center has an active research program in tele-operator/robotics. This research is based on an Intelligent Systems Research Laboratory with activators, sensors, computers, and graphics display, a kinematic simulation of the robotic systems, a distributed artificial intelligence system and a reconfigurable operator control station. An integrated micro-processor controlled end effector with force, torque and position feedback is being tested.

NASA-Ames Research Laboratory is the focal point for artificial intelligence research for space applications. Research has been carried out there for both language selection and processing architecture.

The Department of Energy is sponsoring a comprehensive program for tele-operated, remote maintenance at ORNL in support of the Fuel Recycle Program. Developments include an advanced manipulator, operator/machine interface systems and a remotely operated transporter. Several mobile systems have been developed for use in radioactive environments, including early models at HEDL and ORNL, and current mobile systems for TMI developed at Carnegie-Mellon University.

Since these other Government programs will develop technologies needed for use in robotics used in the nuclear industry, it is important for DOE to reach agreements with these agencies on the sharing of data. By leveraging technologies from these Government programs, the investment in development for robotics in the nuclear industry can be minimized with the maximum benefits to the industry.

Foreign Programs

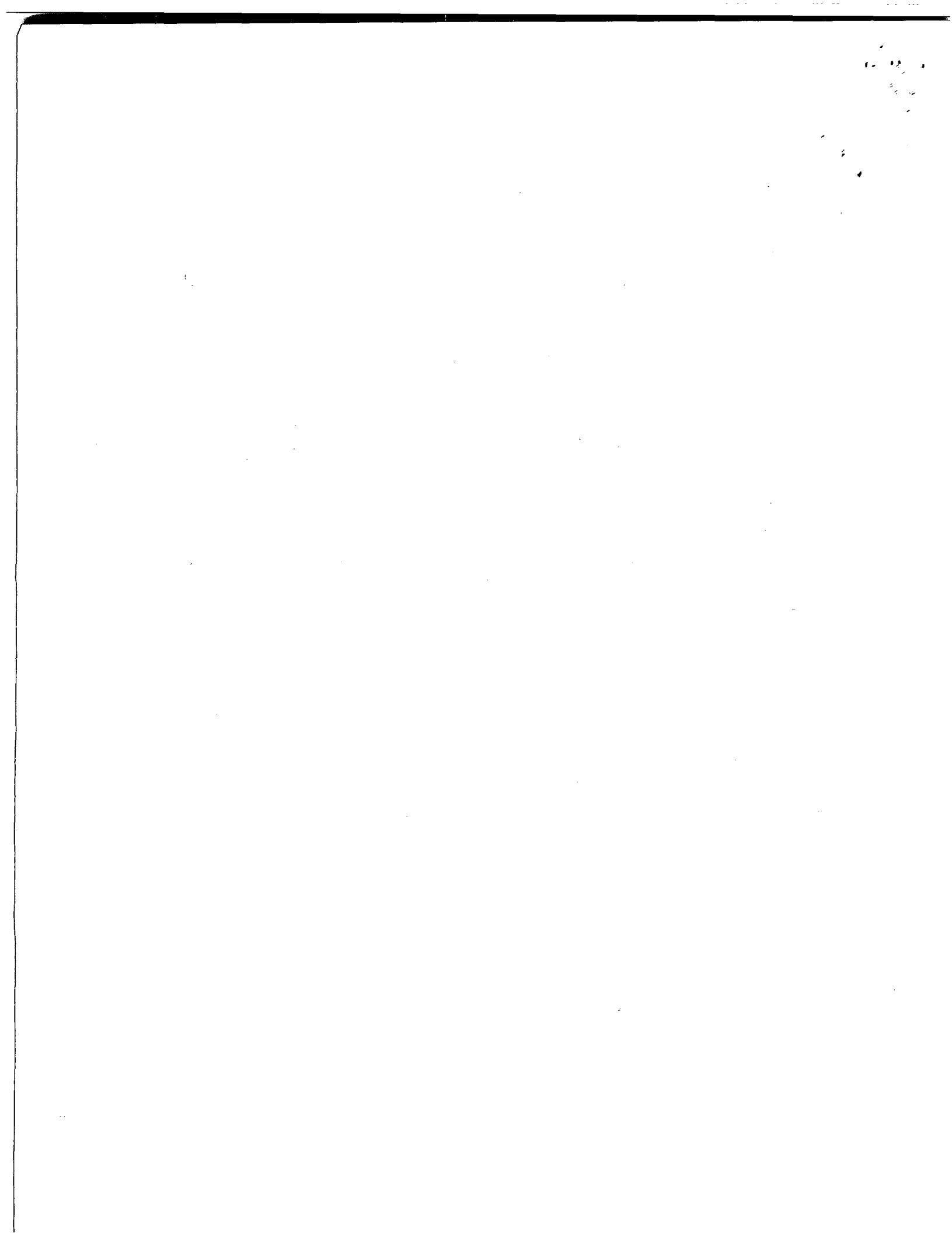
Japan initiated an eight year national robotics development program in 1984. This \$150M program includes development of maintenance robots for the nuclear industry. Appendix A is a partial translation of this plan.

The United Kingdom through the Marchwood Engineering Laboratory of the Central Electricity Generating Board has developed a robotic system for the repair of Magnox Stations (gas-cooled power reactors). These manipulators are operated over a large distance from the top of the reactor and carry tools for remote bolting and welding operations.

In France, Electricite' de France (EdF) has developed remote manipulators and special tools for the maintenance of LWR plants. These robotic systems are similar to those developed in the U.S. for maintenance of LWRs. Hispano-Suiza has provided an advanced robotic system named ISIS for EdF to perform maintenance on the CHINON A3, a gas cooled reactor. The ISIS system is mounted on a mast which can vary from 16 to 28 feet in length; the arms have a reach of 8 feet and can handle a load of 150 pounds when fully extended from the mast. The total system has eight degrees of freedom, two in the mast and six in the arm. The system is computer controlled and uses an electro-hydraulic system. Specific tooling can be attached for grinding, welding, or handling.

Industry

Most large U.S. corporations have major efforts in robotics because of the obvious need to automate manufacturing in order to remain competitive. The details of these projects are not available because of the competitive nature of the robotics industry. However, some of these corporations with large robotics efforts are: General Motors, General Electric, IBM, Westinghouse, Rockwell, Cincinnati-Millicron. In addition, there are a number of small firms specializing in robotics.



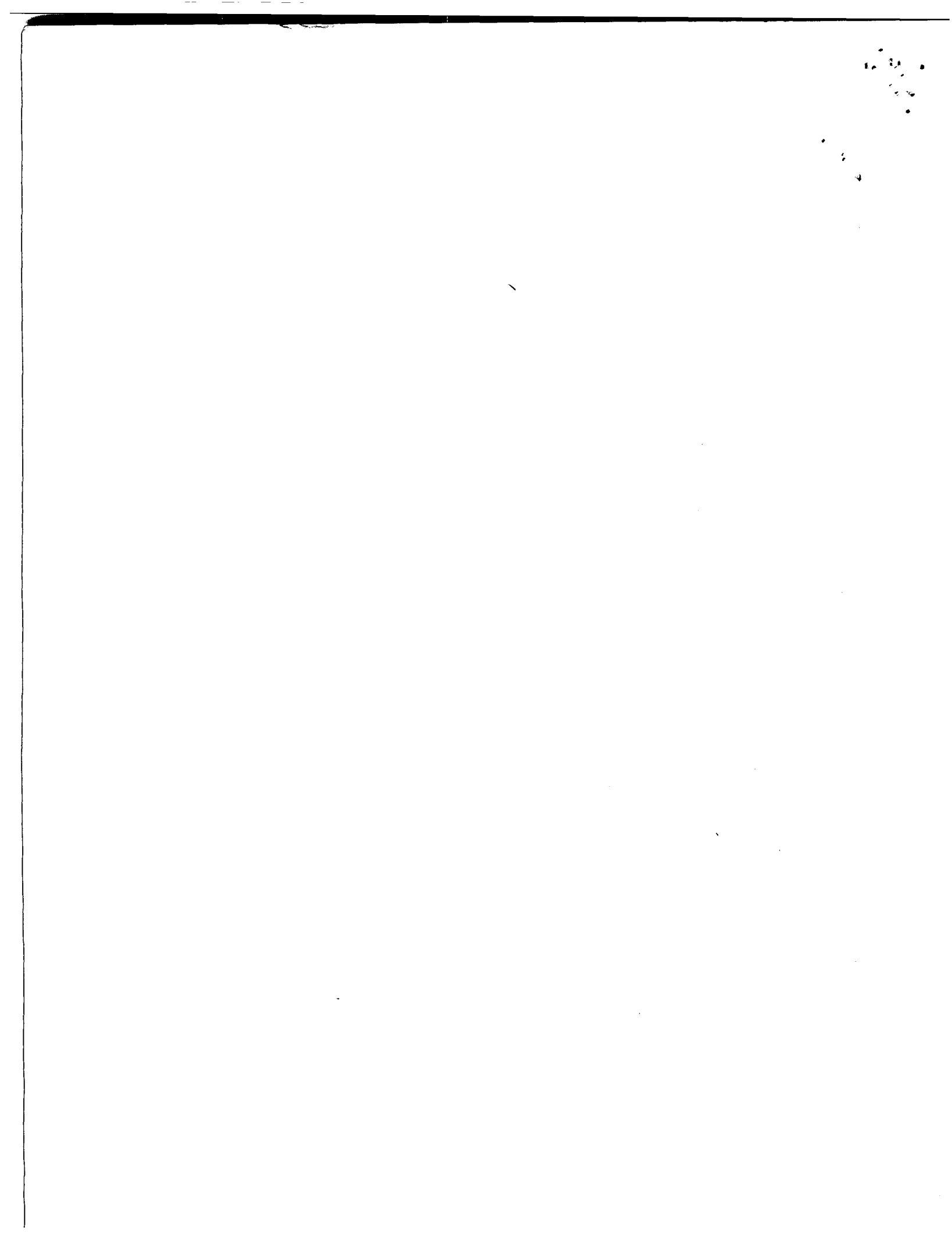
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2. "Potential Uses of Remote Handling and Robotic Techniques in the Back End of the Fuel Cycle", N. P. Reynolds, T. Tabe, N. Fenton and P. Baumgartner, *ibid.*
3. "Analysis of the Options-Rationale for Servomanipulator Maintenance in Future Reprocessing Plants", J. N. Herndon and W. R. Hamel, Proceedings of the 1984 ANS National Topical Meeting in Robotics and Remote handling in Hostile Environment". Gatlinburg, TN, April 1984.
4. "The Advancement of Remote Systems Technology: Past Perspective and Future Plans", W. R. Hamel and M. J. Feldman, *ibid.*
5. "Final Report, Nuclear Reactor Maintenance Technology Assessment", CIMAR D. Tesar, Director, University of Florida, March 1980.
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Appendix A

Translation of selected Parts of "Robotics for Nuclear Facilities," Journal of the Atomic Energy Society of Japan, Vol. 25, No. 11, p. 857-894 (1983) consisting of Table of Contents, a Summary Table and Schedule.



I. Remote Manipulation Technology in Nuclear Facilities

II. Current Status of Remote Manipulation Technology in Nuclear Facilities

1. Automation in BWR Power Plants
2. Automation in PWR Power Plants
3. Remote Manipulation Technology in Reprocessing Facilities
4. Remote Manipulation Technology in Post-Irradiation Test Facilities

III. Examples of Remote Manipulation Technology Development in Nuclear Facilities

1. BWR Power Plant Application
2. PWR Power Plant Application
3. Nuclear Fuel Recycling Facility Application

R&D of Robots for Nuclear Application

1. BWR
2. PWR
3. Power Plant Decommissioning
4. General Purpose

Robots for Extreme Conditions

(National Project of the State-of-the-Art Robotics Technology Development)

ITEM	GOAL
Nuclear Related Robots	Develop robots capable of performing complex tasks such as, inspection, maintenance and repair of equipments through remote operator's commands, in nuclear related facilities such as nuclear power plants.
Off Shore Oil Development Support Robots	
Disaster	
Systems Development	Develop systems capable of efficient mobility on irregular surface such as, stairs, and slope using legs and wheels.
	Develop systems capable of performing flexible and skillful manipulation through the use of multiple joint/finger manipulator.
Control Technology	Develop autonomous systems for robots.

1. 8 years starting at 1983.

2. 20 Bil ¥ ≈ 80 M\$

JAPANESE NATIONAL ROBOTICS PROGRAM

