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On Current U.S. Strategy and Technologies For Spent Fuel Handling

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Abstract

The United States Department of Energy has recently completed a topical safety analysis report outlining the design and operation of a Centralized Interim Storage Facility for spent commercial nuclear fuel. During the course of the design, dose assessments indicated the need for remote operation of many of the cask handling operations. Use of robotic equipment was identified as a desirable handling solution that is capable of automating many of the operations to maintain throughput, and sufficiently flexible to handle five or more different storage cask designs in varying numbers on a given day. This paper discusses the facility and the dose assessment leading to this choice, and reviews factors to be considered when choosing robotics or automation. Further, a new computer simulation tool to quantify dose to humans working in radiological environments, the Radiological Environment Modeling System (REMS), is introduced. REMS has been developed to produce a more accurate estimate of dose to radiation workers in new activities with radiological hazards.

1.0 Introduction

The United States Department of Energy has recently completed a topical safety analysis report outlining the design and operation of a Centralized Interim Storage Facility for spent commercial nuclear fuel[a]. During the course of the design, dose assessments indicated the need for remote operation of many of the cask handling operations. Use of robotic equipment was identified as a desirable handling solution that is capable of providing remote operations to maintain throughput, and sufficiently flexible to handle five or more different storage cask designs in varying numbers on a given day. This paper discusses the facility and the dose assessment leading to this choice, and reviews factors to be considered when choosing robotics or automation. Further, a new computer simulation tool to quantify dose to humans working in radiological environments, the Radiological Environment Modeling System (REMS), is introduced. REMS has been developed to produce a more accurate estimate of dose to radiation workers in new activities with radiological hazards.

2.0 The Centralized Interim Storage Facility

The United States Department of Energy (DOE) has the responsibility to develop and operate a Civilian Radioactive Waste Management System (CRWMS) that will remove spent nuclear fuel (SNF) from commercial reactors in the United States and dispose of the fuel in a permanent geologic repository. Elements of the CRWMS include temporary storage facilities, transport capabilities, and the long-term repository facilities.

The Centralized Interim Storage Facility, or CISF, provides the temporary federal storage capability for Spent Nuclear Fuel (SNF) under the oversight of the DOE. The DOE Office of Civilian Radioactive Waste Management (OCRWM), and the CRWMS Management and Operating Contractor, recently completed a Topical Safety Analysis Report (TSAR) for the CISF. The TSAR was submitted to the U.S. Nuclear Regulatory Commission (NRC) on May 1, 1997 and is currently under review, having been docketed on June 10, 1997.

The purpose of the CISF is to provide safe temporary storage of commercial SNF. The CISF will receive, handle, and store SNF in a manner that protects the health and safety of the public and workers, and maintains the quality of the environment in compliance with federal regulations[b].

The storage of spent nuclear fuel at the CISF will be based on the use of cask systems certified by the NRC. These cask systems include transportable storage casks and dual-purpose canister-based storage and transport systems. Facility design capacity is 40,000 metric tons of uranium, translating to approximately 5,300 to 7,800 storage casks depending on the vendor systems. For the preparation of the CISF design, cask systems were utilized that were either docketed by the NRC or under development by the DOE as of June 1, 1996. These cask systems are:

- VECTRA MP187 System
- Holtec HI-STAR 100 System
- Sierra TranStor™ System
- Westinghouse Large/Small MPC System
- NAC STC System

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[a] U.S. Nuclear Regulatory Commission Docket # 7221

[b] Title 10 Code of Federal Regulations Part 72

3.0 CISF Radiation Dose Assessment and Reduction

Initial design and operations of the CISF were based on experience at utility reactor facilities. Utilities perform manual operations for fuel transfer and storage system closure at nuclear power plants, but not on a continuous basis. As the CISF design and dose assessment progressed, it became apparent that the high volume of casks to be handled would result in undesirably high cumulative occupational radiation doses. Table I shows the estimated average annual individual exposure for each of the fuel storage systems. The preliminary values represent the doses expected using manual handling methods, based on information provided by each cask vendor's Safety Analysis Report and utility experience with independent spent fuel storage installations. Clearly traditional hands-on operational doses could be improved using remote-manual or automatic operations.

To maintain minimal radiation doses, the CISF design reflects consideration of the "As Low As Reasonably Achievable" (ALARA) principles given in NRC Regulatory Guide 8.8 and the applicable criteria of Title 10 of the US Code of Federal Regulations Part 72. To reach the ALARA goal of an average dose of 10 person-mSv per year or less, specific measures are adopted to improve CISF operations. These are:

- Design structures, systems, and components (SSCs) that require maintenance or repair such that maintenance frequency and personnel stay times in radiation areas are minimized.
- Utilize robotic and remotely operated equipment and video systems to the extent practical to minimize personnel exposure to radiation sources.
- Place operations personnel in shielded, remote operating stations.
- Use dedicated, shielded transporters for moving casks to the storage area.
- Place administrative, security and radiation protection activities away from radiation areas.
- Use permanent and temporary radiation shielding.
- Monitor area radiation with local and remote readouts in the transfer facility.
- Monitor casks in the storage area continuously and remotely.
- Be capable of restricting access in radiation areas.
- Improve ventilation systems for the transfer facility radiation areas, including monitoring of all effluents and filtration systems to reduce possible human exposures and releases of radiation to the environment if accident-level events occur.
- Connect cask venting systems directly to the transfer facility ventilation system to reduce radiological release concentrations and to allow release monitoring.
- Improve decontamination facilities for transportation casks to reduce radiological contamination of other SSCs and personnel during cask handling.

After these measures were applied, a final dose assessment was made, indicating substantially lower average doses. Table I shows a comparison between the preliminary and final dose assessments for receipt and transfer operations for each occupation category, in terms of average milli-Sievert (mSv) per person per year.

Another goal of the ALARA review is to reduce the total occupational doses. Table II shows a comparison between the preliminary and final dose assessment in terms of total person-mSv per year. This table clearly shows that the dose reductions made in the final dose assessment are effective from an ALARA standpoint. From 20% to 50% of the reduction is attributable to the use of robotic manipulators specified in the TSAR.

In order to achieve ALARA design goals for the transfer facility, it is necessary to provide facility operations with handling equipment that is automated or remote-controlled. Up to half of the dose reductions in Table I and Table II are attributable to remote/automated equipment. Such handling equipment provides the ability to remotely manipulate objects and safely perform repetitive work operations, which minimizes the annual radioactive dose for operating personnel while maintaining cask throughput rates.

The improved handling procedures resulting in the final dose estimates of Tables I and II were the result of general concept specifications. The following describes remote and automated equipment assumed in the improved CISF design.

The CISF utilizes a gantry-mounted robot in the shipping/receiving area, with a support frame for the manipulators spanning three rail/truck lanes. The gantry frame can travel the width of the shipping/receiving area. Two robotic arms (manipulators) are supported on a platform to perform precise and accurate tasks. Cameras are used to aid operators in observing tasks performed by the gantry-mounted robot via closed-circuit television (CCTV) monitors located in the crane operating room. In addition, monitors are provided in a room below the crane operating room so that workers in the shipping/receiving area can both observe operations from a low radiation dose area, and have convenient access to the work area when hands-on operations are required.

Stationary-mounted manipulators are provided in the canister transfer area for performing activities on both the Westinghouse and TranStor™ transportation casks. The transportation casks are placed on indexed locations on the canister transfer area floor, such that the manipulators can access necessary areas of the casks. The manipulators are used in conjunction with cameras located in the canister transfer area. CCTV monitors are provided in the shielded remote console rooms located along the walkways at the end of the canister transfer area. Control consoles for operating the manipulators and other automated equipment are located in the remote console rooms.

As part of the automated operations for ALARA radiation dose minimization during transfer preparation, automated bolt/stud tensioners and alignment devices are included. These devices are similar to widely used, commercially available devices with high bolt torquing capability, and will be used to remove, retain, and reinstall the transportation cask trunnions, retainer blocks, lid bolts, and venting/sampling ports with their associated bolts or studs.

Automated alignment devices are also included for operations involving removing and installing impact limiters and personnel barriers, and aligning casks for canister transfer operations. Automated equipment can be remotely controlled from the monitoring room located below the crane operating room and the remote console rooms at the end of the canister transfer area.

After NRC approval of the CISF TSAR, additional work will be required to transform the general specifications of the TSAR into detailed equipment requirements and specifications, and to assure that interface requirements for the cask systems are met. As part of this process, further consideration will be given to equipment needs, and additional dose assessments will be conducted as equipment and procedural specifications evolve. The next two sections offer considerations regarding automation and robotics, and introduce a tool that could be applied for faster and more accurate dose assessments.

4.0 Automation and Robotics

Automation and robotics have been used in some operations and considered for many others in the nuclear industry to reduce the hazards, increase work quality and provide a more rapid response to developing needs. This section discusses the topics of robotics and automation in general terms, and relative advantages of each.

To facilitate discussion, this definition of terms is offered.

> Automation - Automation may be defined as automatic control of a system by mechanical or electronic devices that replace human observation, effort and decision.
>
> Hard or fixed automation - Non-programmable, fixed tooling which is designed and dedicated for specific operations. Hard automation is cost effective for a high production rate. It is typically not easily changed to accommodate new operations.
>
> Robot - According to the Robotic Industries Association in the USA, "A robot is a reprogrammable, multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks."
>
> Flexible automation - The ability to reprogram or multi-task an automated system. Robots are considered flexible because they are capable of redirection or being used for new purposes.
>
> Teleoperation - The remote control of manipulators or other machinery by direct manual input. This is commonly seen in the nuclear industry as mechanical or electro-mechanical manipulators in hot cells. Teleoperated devices, not being programmable, are by definition not robots.
>
> Telerobotics - The control of a manipulator by direct human input is augmented by computer control. This hybrid maintains the human decision capacity while relieving the operator of many details (such as joint positioning) and increasing sensor integration opportunities (such as obstacle avoidance).

When deciding upon an automated approach, a cost-benefit analysis (CBA) should be conducted. The CBA process generally consists of the following steps: problem definition, analysis design, data collection, and option analysis with respect to the costs and benefits. One example of CBA applied to nuclear fuel cask handling is given in Reference 1[1]. Care should be taken to define the problem with the proper scope. For example, if a robot is compared to a long-handled tool to do a single task, the costs of the robot may overwhelm that of the tool, therefore precluding the use of the robot. However, the cost of the robotic system may be amortized over tens or hundreds of different operations making it a more attractive solution than it may seem.

Care should be taken to identify and consider all monetary, quantitative and qualitative non-monetary benefits. Monetary benefits include direct capital cost, operational cost, labor cost, and waste disposal costs. They also include indirect or derived costs, such as those due to throughput rates, waste generation, lawsuits, and design, approval and construction time factors. Non-monetary quantifiable benefits include the radiation dose. Some attempts have been made to assign a monetary value to a unit of dose. However, in many situations, simply stating dose units is necessary and sufficient to meet regulatory limits or design goals without a monetary transformation. Finally, non-monetary qualitative factors such as worker morale and social impact, can affect the quality of work or time to operation, and thus the technology choice.

Several differences between robots and hard automation may have an impact when deciding upon an automated approach. The case for hard automation can be made based upon throughput and simplicity. When large numbers of identical workpieces are to be manipulated at the highest possible speed, hard automation may be optimal. Costs associated with unique design can be quickly amortized. Hasegawa[2] maintains that to break even in a hard automation assembly process, approximately 200,000 products must be assembled. Special-purpose automation can also be optimized to minimize parts and subsystems. This could lead to greater reliability and lower maintenance costs.

When throughput is lower, or when a mix of products is being processed by the same line, robots may be more desirable. First, robots are reusable. Unlike hard automation, robots are multi-purpose and can be reprogrammed for many different tasks. A large portion of equipment and experience can be applied to new tasks. Because of this, the useful life of the robotic system may be three or more times longer than that of fixed automation devices. Second, reprogramming can result in greater utilization and higher equipment efficiency. Robots have the ability to rapidly adapt from one workpiece to another, such as different container types, and the throughput rates can be scaled up or down for the different types. Third, tooling costs for robotic systems tend to be lower. This is due to the machine's dexterity, giving it the ability to move around some physical constraints. Finally, production can often be started sooner due to fewer construction and tooling constraints.

Remote automation may be considered an advantage when dealing with several thousand transport containers or nuclear fuel assemblies per year. Fixed automation may be ideal for container opening, fuel handling, packing, and closure operations, provided that there is little or no variation in the workpieces. However, in the case of the CISF, no less than five different cask systems may be used for fuel storage, each with different sets of tools and operations. In this case, the CISF will benefit from a more flexible automated system, allowing virtually instant reprogramming to manipulate each of the anticipated cask systems, and any others that may be licensed in the future. Further, the robotic system may be modified to provide a telerobotic mode, which could be of particular benefit in the recovery from off-normal conditions where pre-programming does not apply.

5.0 The Radiological Environment Modeling System (REMS)

In the nuclear industry, the decision to use remote, automated or robotic equipment is typically driven by the need to reduce radiation doses to workers. In new facility designs, dose measurements are not always available and experience with particular operations may not yet exist. Therefore, estimates of anticipated doses must be made.

A relatively new tool to quantify dose to humans working in radiological environments is the Radiological Environment Modeling System (REMS)[3] . REMS utilizes commercially available graphical simulation products, augmented with custom C code and radiation transport codes to provide radiation exposure information to, and collect radiation dose information from, graphically animated workcell simulations.

To analyze the radiation doses likely to be imparted by a set of operations, the operations are first simulated using human models in graphical simulation. An example of this is shown in Figure 1, where a neutron source is being reduced physically and chemically to separated elements. The simulation is then presented to knowledgeable operators for process validation.

REMS utilizes the IGRIP (Interactive Graphical Robot Instruction Program) simulation software and its ERGO human ergonomic assessment extension from Deneb Robotics, Inc. The human model has been modified by SNL to include 43 sensor locations at regulated and sensitive parts of the body as illustrated in Figure 2. Any combination of the sensor locations may be selected to meet the specific needs of the user.

Through the use of radiation transport codes or measured data, a radiation exposure input database may be formulated. The REMS suite of computer codes currently includes a 1-dimensional modeler and a material properties database to assist the operator in the creation of point-source geometries. Any shielding is taken into account at this stage. A transport code and selectable tissue damage databases are then used to map the radiation dose rates in the facility of interest.

The simulations utilize these maps to compute and accumulate doses to the human models operating around radiation sources. Process time, distances, shielding, and human/machine activity may be modeled accurately in the simulations. The accumulated dose is recorded in output files, and the user is able to process and view this output. The entire REMS capability can be operated from a single graphical user interface.

The REMS analytical tool provides several benefits beyond conventional spread-sheet analysis. First, the simulation is available for validation. Operators can verify that each simulated process is accurate by visual examination. Secondly, as the simulation executes, each body movement is accounted for in the distance calculations. This results in greater detail than is normally practical in spread-sheet accounting, and thus in greater accuracy of the integrated dose calculation. If measured dose rate data are used for the dose maps, REMS could result in the best dose estimation available. A third benefit of REMS is that dose calculations may be easier to defend to clients and regulatory agencies. The ability to demonstrate new processes visually lends confidence to the observer that the calculations are complete and accurate, while facilitating dialog and feed-back. Finally, REMS simulations can be used as training aids, familiarizing trainees with various equipment and processes.

To date, REMS has been used to analyze manual operations for radiation exposure, and to identify possible candidates for automation at three DOE nuclear material handling locations.

6.0 Summary

Dose assessments of CISF operations based on traditional manual operation of spent nuclear fuel storage cask systems indicate the need for substantial dose reduction measures. Robotic systems are considered a critical component of these measures, contributing 20% to 50% of the dose reduction in the final CISF dose assessment improved ALARA measures.

Robotics and automation are both useful techniques. Hard automation may be simpler and is best used when many thousands of identical operations are to be performed at high speed. However, it is difficult to quickly modify and does not lend itself well to a mix of operations or workpieces. Robotic automation is more flexible, enabling rapid changeover from one type of operation to another. This flexibility is an advantage in the case of the CISF, where five or more different fuel storage systems may be utilized.

REMS is a new dose assessment tool now being used to analyze worker doses in nuclear material processing lines. REMS combines a source geometry modeler, radiation transport codes and dose conversion standards (or measured dose maps) with computer animation for improved dose assessment resolution. The graphical simulation facilitates operations validation and training. It also accounts for body movement with high sampling rates, improving integrated dose calculations. REMS has been used in three nuclear material handling dose analyses.

REFERENCES

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[2] Hasegawa, Y., "Evaluation and Economic Justification," Handbook of Industrial Robotics, Ed. S. Y. Nof, John Wiley & Sons, 1985.

[3] Breazeal, N.L., et al., Simulation-Based Computation of Dose to Humans in Radiological Environments, Sandia National Laboratories, Albuquerque, NM USA, SAND95-3044, March 1996

Table I: Average Annual Individual Exposure Estimate Preliminary and Final Assessments (person-mSv/person-year)

Cask System	Preliminary			Final (ALARA)		
	Operators[1]	Rad. Prot.	Security	Operators[1]	Rad. Prot.	Security
Holtec HI-STAR 100	41	15	12	3	7	2
NAC STC	46	15	12	6	11	2
TranStor™	78	10	3	14	10	1
VECTRA MP187	83	09	5	27	8	1
Westinghouse Large MPC	75	11	7	6	5	1
Westinghouse Small MPC	73	11	7	6	5	1

[1]Crane operators and prime mover operators are included with general operations personnel.

Table II: Total Annual Operations Dose Assessment Comparison (person-mSv per year)

Cask System	Preliminary Dose Assessment			Final (ALARA) Dose Assessment			ALARA Dose Reduction
	Receipt[1]	Maint.[2]	Total	Receipt[1]	Maint.[2]	Total	
Holtec HI-STAR 100	510	10	520	50	10	60	460
NAC STC	570	9360	9930	80	10	90	9840
TranStor™	1660	18860	20520	260	10	270	20250
VECTRA MP 187	1210	9460	10670	440	10	450	10220
Westing-house Large MPC	1830	9460	11290	170	10	180	11110
Westing-house Small MPC	1790	9460	11250	170	10	180	11070

[1]Based on receipt of 232 casks per year. Receipt includes all operations to receive transport casks, prepare these for transfer, transfer canisters to storage casks, and place storage casks in the storage yard.

[2]Based on 20,000 metric tons uranium (MTU) in storage area. Maintenance includes all inspections of storage systems in the storage yard required as per technical specifications

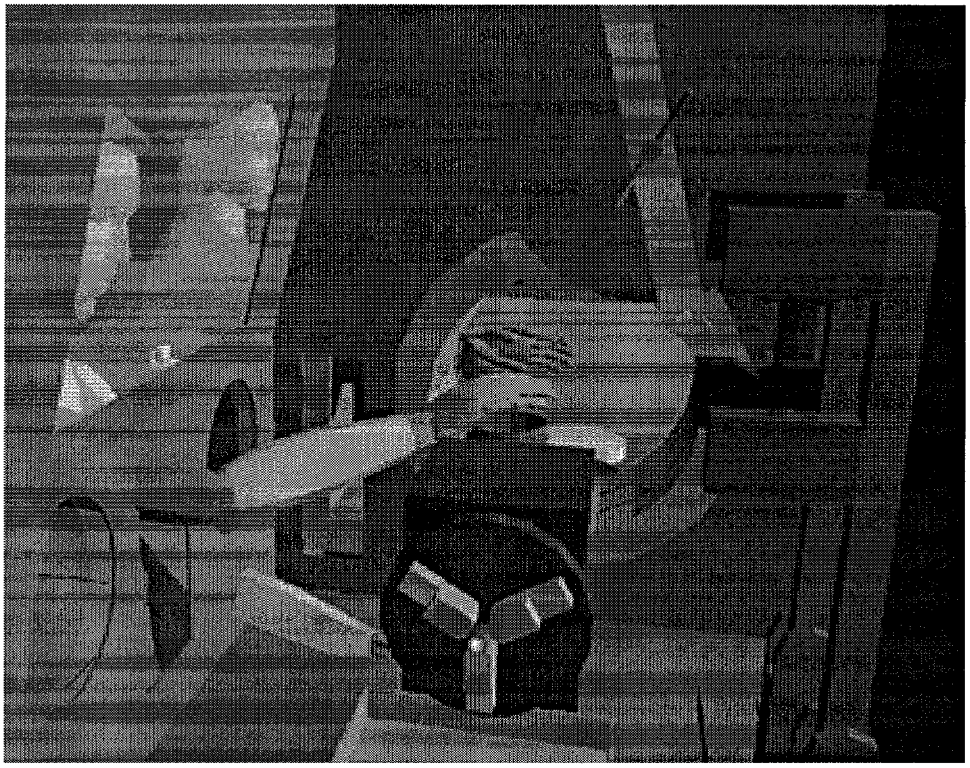

Figure 1 REMS tracks radiation doses to workers in a neutron source dismantlement operation.

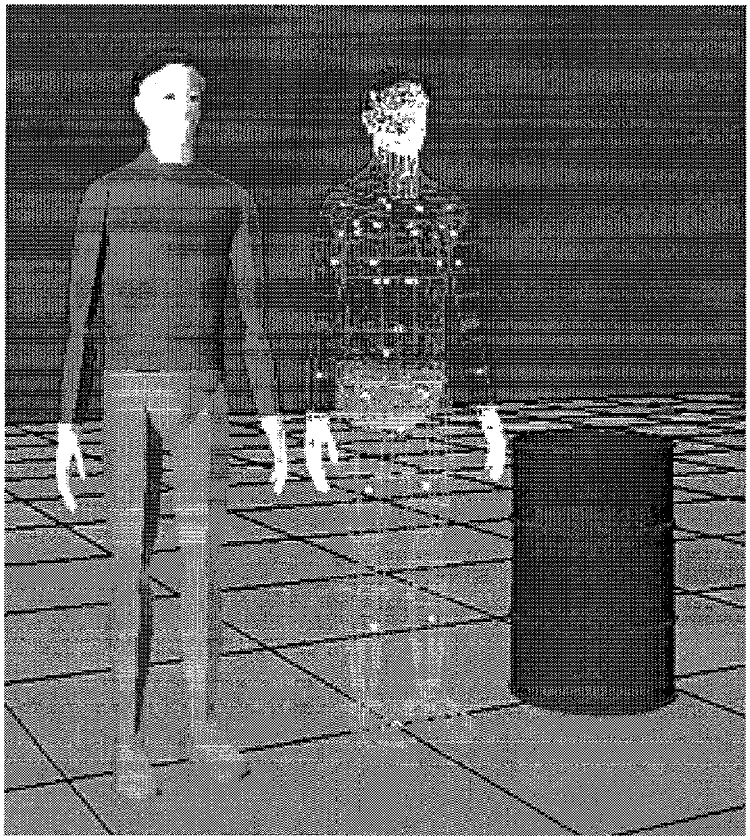

Figure 2 REMS human model instrumented with dosimeters