HUMAN FACTORS AND SAFETY ISSUES ASSOCIATED WITH ACTINIDE RETRIEVAL FROM SPENT LIGHT WATER REACTOR FUEL ASSEMBLIES*

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Human Factors and Safety Issues Associated With Actinide Retrieval from Spent Light Water Reactor Fuel Assemblies*

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A major problem in environmental restoration and waste management is the disposition of used fuel assemblies from the many light water reactors in the United States, which present a radiation hazard to those whose job is to dispose of them, with a similar threat to the general environment associated with long-term storage in fuel repositories around the country. Actinides resident in the fuel pins as a result of their use in reactor cores constitute a significant component of this hazard. Recently, the Department of Energy has initiated an Actinide Recycle Program to study the feasibility of using pyrochemical (molten salt) processes to recover actinides from the spent fuel assemblies of commercial reactors. This project concerns the application of robotics technology to the operation and maintenance functions of a plant whose objective is to recover actinides from spent fuel assemblies, and to dispose of the resulting hardware and chemical components from this process. Such a procedure involves a number of safety and human factors issues. The purpose of the project is to explore the use of robotics and artificial intelligence to facilitate accomplishment of the program goals while maintaining the safety of the humans doing the work and the integrity of the environment. This project will result in a graphic simulation on a Silicon Graphics workstation as a proof of principle demonstration of the feasibility of using robotics along with an intelligent operator interface. A major component of the operator-system interface is a hybrid artificial intelligence system developed at Oak Ridge National Laboratory, which combines artificial neural networks and an expert system into a hybrid, self-improving computer-based system interface.

One of the major concerns of the present attention to environmental restoration and waste management centers on the disposition of used fuel assemblies from the many light water reactors (LWRs) in the United States. These spent assemblies present a radiation hazard to those whose job is to dispose of them, as well as a potential radiation hazard to the general environment associated with long-term storage in fuel repositories around the country. A significant source of this hazard lies in the actinides resident in the fuel pins as a result of their use in reactor cores. Actinides are heavy, radioactive metals of increasing atomic number ranging between actinium (89) and lawrencium (103). Only the four transuranic of the 15 elements are of concern in spent LWR fuel assemblies: neptunium (93), plutonium (94), americium (95), and curium (96). In this paper, the term "actinides" is used to refer to these four elements, collectively. These actinides have long half-lives, and decay by alpha emission. Thus, they present a problem due to their potential health risk. During FY 1991, the Department of Energy initiated an Actinide Recycle Program (ARP), to study the feasibility of using pyrochemical (molten salt) processes to recover actinides from the spent fuel assemblies of commercial LWRs. The project which is the subject of this paper concerns the application of robotics technology to the operation and maintenance functions of a plant whose objective is to recover actinides from spent fuel assemblies, and to dispose of the resulting hardware and chemical components from this process. Such a procedure involves a number of safety related human factors issues.

ACTINIDE RECOVERY

Actinide recovery involves a number of steps, some mechanical and some chemical. LWR fuel assemblies consist of a large number of fuel pins about three meters long and 3-5 mm in diameter. The first step in the ARP process is to disassemble the fuel assembly and dispose of the resulting excess irradiated hardware. Each pin has a metallic shell, or clad, around it which must be removed to obtain the used uranium fuel and its associated impurities, including the actinides. Several mechanical procedures exist for this decladding process. Once the assembly hardware and pin cladding have been separated from the fuel, these hardware items must be disposed of safely. A complicating factor is that some fuel pins are not spent, due to uneven burning in the LWR, and can be economically reassembled, with other unburned pins, into new fuel assemblies. In addition, safety and inventory considerations require that the final disposition of each fuel pin be recorded -- whether it was diverted from the process for reassembly or was decladded and the spent fuel processed. Once the decladding process is completed, the actinides can be recovered.

The purpose of this project is to explore the use of robotics and artificial intelligence (AI) to facilitate accomplishment of the ARP goals while maintaining both the safety of the humans doing the work and the integrity of the environment. Robot assemblies consisting to two arms mounted on a crane have been built for pool-side handling of fuel assemblies during on-site storage. These assemblies are teleoperated, but can be adapted for (largely) automated handling of fuel assemblies for disassembly and decladding. In addition, each time material must move from step to step in the pyrochemical treatment process, either human or robot labor is required to accomplish the move. The project described in this paper involves an analysis of the tasks to determine the extent to which the task can be fully automated, be assigned to a telerobot, or requires a human to perform the task. Additional human factors efforts are directed to the application of AI to help the operators monitor the overall process, and to assess and record the uranium levels and final destination of the fuel pins that are recovered from the assemblies.

Fuel Pin Decladding

A wide variety of fuel pin decladding processes have been investigated (Bond, et al, 1992), including electrical, mechanical and chemical. Requirements of the pyrochemical process for separating the actinides from the spent fuel demands a process which recovers greater than 99.9% of the actinides, leaves the fuel in an oxide state (UO_2), and cladding wastes which are compatible with other wastes of the ARP process. The method finally selected was the roller-straightener (rod straightener) process (Heestand, 1991), in which the fuel pins are passed through a roller-straightener which mechanically crumbles the fuel and separates it from the zircaloy cladding (Abdel-Rassoul et al, 1968; Takashima, no date; Forsberg, 1991).

Actinide Recovery

Pyrochemical processes have been developed which are capable of extracting actinides from spent reactor fuels using molten metal extractants and molten salt solvents. Recently, one of the pyrochemical processes was modified to produce extraction of the actinide elements from spent LWR fuels by partitioning the spent fuel, after reduction to metal, into three components: 1) a copper-uranium fraction containing many of the noble metal fission products; 2) a salt component containing the alkali and alkaline earth fission products; and 3) a metal fraction containing the separated actinides. Each of these radioactive components must be handled and disposed of in a safe and environmentally sound manner. Because of the high temperatures and high radioactivity involved, all processing steps must be done in a shielded area (a hot cell) with a non-volatile atmosphere such as argon.

Engineering Issues

A number of problems are associated with the decladding process, some of a mechanical and some of a human factors engineering nature. The mechanical problems derive from the particular shape of the fuel pins, and the fact that their curvature and brittleness can vary considerably from one pin to the next. Thus, fully automated handling (robotic arm pick-and-place) may be precluded, requiring at least some intervention by human operators. This set of problems is exacerbated by the behavior of the pins as they pass through the roller-straightener. A typical roller-straightener has two pairs of driven rollers with either one or two pairs of idler rollers in between, the whole machine spanning about a meter. As the pin passes through, it not only passes along its length axis, it also rotates about this same axis. This causes the free end(s) of the fuel pin to oscillate around this axis, potentially causing damage to either the pin itself or to nearby equipment in the hot cell. The Silicon Graphics workstation simulation of this process is expected to help determine the extent to which human intervention will be required to safely accomplish this and other steps in the process.

Human factors engineering issues relate primarily to the level of robotic automation achievable, given the fuel pin characteristics discussed above, and given that the safety of personnel and the environment are ensured by the hot cell work context of the ARP process. Variations in the bent and/or brittle condition among pins indicates a need for human intervention and guidance of the manipulator arm doing the pin pick-and-place task to insert the pins into the roller-straightener and collect them on the output side. In addition, each pin needs to be tracked through the system, so that records exist which indicate whether a pin was processed through the decladding and actinide recovery process or was diverted for reassembly into a fuel assembly. Moreover, information display for the operator(s) concerning the status of various stages in the fuel pin processing system must be displayed in a manner which aids those operators in managing the entire ARP process. Finally, training and skill maintenance of the operators must be considered as major components of the entire actinide recovery system. These latter human factors engineering concerns (pin tracking, information display and embedded training) can be greatly aided by use of embedded AI as both an aid to process control and decision-making, and for training. The Nuclear Regulatory Commission has recently indicated an openness to embedded training (Rogers, 1991), and such an AI system has been previously described (Spelt et al, 1991).

HYBRID AI INTERFACE

A major component of the operator-system interface is a hybrid AI system developed at Oak Ridge National Laboratory (ORNL). This hybrid AI system combines artificial neural networks (ANNs) and an expert system (ES) into a hybrid, self-improving computer-based system interface (Spelt et al 1991). ANNs and ESs have different strengths and weaknesses, which can be exploited in such a way that they are complementary to each other: Strengths in one system make up for weaknesses in the other, and vice versa. There is presently considerable interest in the AI community in ways to exploit the strengths of these methodologies to produce an intelligent system which is more robust and flexible than one using either technology alone. Any process which involves both data-driven (bottom-up) and concept-driven (top-down) processing is especially well-suited to displaying the capabilities of such a hybrid system. The system can take an incoming pattern of signals, as from various points in an automated manufacturing process, and make intelligent process control decisions on the basis of the pattern as preprocessed by the ANNs, with rule-based heuristic help or corroboration from the ES. Patterns of data from the environment which can be classified by either the ES or a human consultant can result in a high-level ANN being created and trained to recognize that pattern on future occurrences. In subsequent cases in which the ANNs and the ES fail to agree on a decision concerning the environmental situation, the system can resolve those differences and retrain the networks and/or modify the models of the environment stored in the ES. Work on a hybrid system for perception in machine vision was funded initially by an ORNL seed grant, with most of the system components operating in a parallel distributed computer environment (Glover & Spelt, 1990).

In the application of this architecture to the ARP, a low-level network hierarchy serves as a monitor of the changing patterns arising in the sensors located in the ARP environment. Most of the changes in these patterns should be within the "normal" range of operations for the system. However, some transient changes may be momentarily outside this range, returning within range spontaneously, and these transients should be filtered out. Other outliers will occur which do not spontaneously return to within the normal range, and these outliers must be learned as predictors of off-normal system events that might require human intervention into an automated task. When this happens, the hybrid AI system would notify the operator, and perhaps, through knowledge contained in the ES, provide a remedial procedure. This important function of the low-level network enables it to become able to recognize a sensor signal pattern which immediately precedes an alarm event. To do this, the feedback loop between the ES and this network must be able to tell the network to "remember that sensor pattern" when one of the alarm networks recognizes an alarm pattern. In addition, the sensor annunciator patterns which follow an off-normal ARP system event serve to confirm the occurrence of the event, thus reinforcing the decision by the high-level network that a real problem exists. The low-level network must also learn this subsequent signal pattern. This feedback function is indicated by the broad dashed arrow between the low-level A NN and the ES in Figure 1.

To accomplish these complex functions, the low-level network must be capable of monitoring and temporarily remembering annunciator patterns for a relatively short period of time (short-term memory, or STM), and also learning and retaining for longer periods of time the patterns surrounding critical off-normal plant events (long-term memory, or LTM). Adaptive resonance theory (ART, Carpenter and Grossberg, 1987) provides a network design which meets these requirements, when it is modified to include masking fields as discussed by Cohen and Grossberg (1987). As these authors indicate, an ART network is capable of monitoring data patterns which change temporally, and can provide the filtering required.

The function of the ES in this hybrid application is also considerably different than in the original machine perception application. Here, the ES serves primarily as a supervisor for the ANN activity, and as an interface between the system and a human operator. The ES models of external events consist of rules which express the relationships between alarm patterns and the learned sensor signal patterns. Any known correlations between alarm and signal patterns can be written into the ES as an a priori set of rules. As the system gains experience, additional rules linking a particular sensor pattern and the associated off-normal event can be learned, which would prime the ES to anticipate an off-normal ARP system event when its signal pattern is detected by the ART network. This ability, coupled with the human-system interface in the ES, permits warning the operator of an impending event, thus preparing the human to take appropriate corrective action.

The nature and function of the feedback loop is also changed from that used in the machine perception project. Rather than creating and training high-level ANNs, the loop here monitors and trains a single ANN which is used to recognize complex annunciator patterns associated with (impending) off-normal events. In doing so, it performs the same monitoring function of the low-level ANN learning as for the high-level ANNs of the perception system. To the extent that sensor patterns can be associated with impending off-normal events, they can be used to alert or warn the human operator of such potential

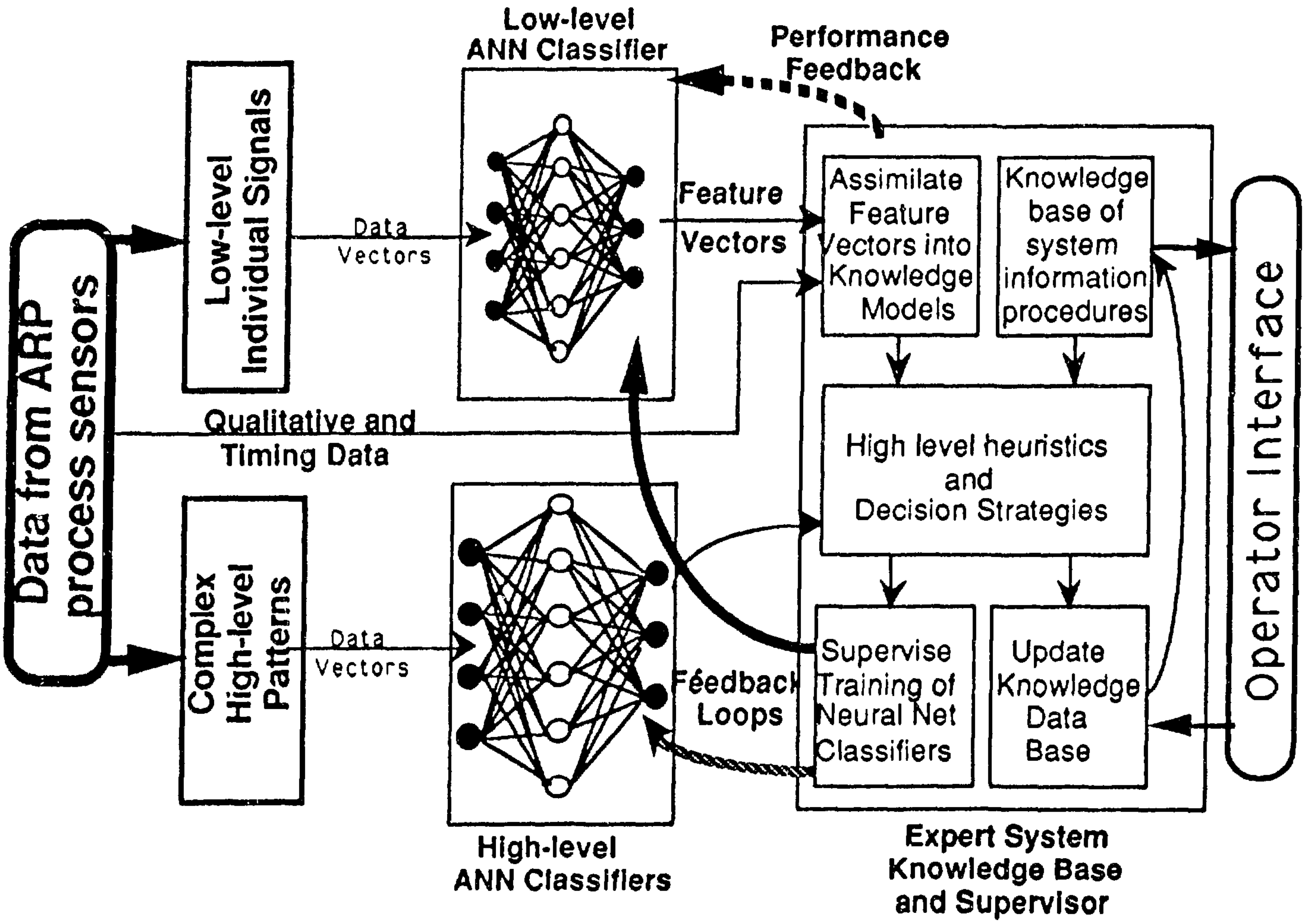

Figure 1. Diagram of the hybrid AI system as applied to the Actinide Recycle program, showing the incoming system signals at the left, and the knowledge base and operator interface at the right. The knowledge base contains system models, information and rules about sytem performance, and information display rules, as well as embedded training capabilities.

system problems, perhaps allowing the operator to preclude an accident. This function and the recognizing of unique post-event annunciator patterns are the significant components contributed by the interaction of the ANNs and the ES in this application.

The knowledge base component of the hybrid AI system will also serve as an information display manager for the operators. Intelligent display management permits tailoring the system display to the particular needs of individual operators and system status. Overall, the hybrid AI component of the ARP system operator interface permits a more efficient information display system which can be adjusted to meet the particular cognitive needs of the operators and/or the varying states of the processing system.

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