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CONCEPTUAL DESIGN OF A SYSTEM FOR DETECTING NATIONAL DIVERSION OF LWR SPENT FUEL*

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ABSTRACT

A conceptual design for detecting the national diversion of light water reactor spent fuel in water basin storage or in transit between facilities is described. This is the third in a series of reports dealing with this topic. The first report provides the spent fuel facilities and operations baseline description; the second report discusses cost and performance tradeoffs for three inspection and surveillance concepts for the detection of a national diversion of spent fuel. The conceptual design presented herein will provide a basis for future feasibility investigations and tradeoff analyses of hardware configurations and inspection options.

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EXECUTIVE SUMMARY

A principle safeguards concern is that a nonweapons state operating a commercial light water reactor (LWR) could attempt to divert the LWR spent fuel and extract the plutonium for non-peaceful uses. Presently, LWR spent fuel is routinely being removed from reactors, stored and transported internationally. In response to this concern, Sandia has been tasked by the U.S. Department of Energy, Office of Safeguards and Security (DOE/OSS) to develop advanced technology to allow an international inspection agency to maintain a continuity of knowledge of LWR spent fuel assemblies within participating states.

This report presents an initial conceptual design of a system for detecting the national diversion of LWR spent fuel. The three sections of the report describe: (1) the basic procedures and rationale used to develop the design, (2) the fuel storage facilities and transportation modes that are being considered for the initial system, and (3) the containment and surveillance (C&S) equipment that is being developed for initial operational test and evaluation at spent fuel storage facilities and during interfacility transportation. Included in the latter section is a discussion of the analytical techniques that have been employed to assist in the initial selection of C&S safeguards equipment.

This report is the third in a series of three reports dealing with spent fuel safeguards. The first report[1] describes the facilities and transportation activities being considered in the storage and handling of the LWR spent fuel. The second report[2] describes three options that could be used to detect attempts at national diversion. These options vary according to timeliness of detection, cost, the number of on-site inspections required, and the amount and type of C&S equipment needed to support or supplement the inspectors' activities.

The concept presented herein is based upon the third option. This option utilizes two concurrent techniques of detecting diversion attempts: (1) remote collection of data from on-site C&S instruments with periodic readouts provided either at the facility or at a central monitoring and display module, and (2) occasional facility inspections. This option was selected because it provides the best balance of timeliness of detection capability and hardware development cost, while still maintaining compatibility with the other two options should one of these ultimately be selected.

This report describes the general design principles and the basic performance requirements which were developed for the C&S system. In brief, these principles and requirements dictated that the system be capable of rapid detection of unreported fuel movements with the capability of timely data readout both on-site and remotely.

Fuel cycle storage facilities and transportation modes to which these system principles and requirements apply were limited in this report to light water reactors, away-from-reactor storage facilities, and road or rail interfacility transportation vehicles. A brief description of these facilities and transportation vehicles, including the spent fuel shipping casks used during interfacility transportation, is included.

A generic analysis of the fuel cycle storage facilities and transportation methods was used as a basis for the selection of the C&S equipment. The analytical techniques used were adapted from fault tree methodology wherein the events related to a specific safeguards concern are connected using logic gates to show their interdependencies. This analysis technique provides a systematic approach to the problem solution, visibility of logic, and traceability. The objective of the analysis is to identify basic activities which must be detected to prevent the occurrence of national diversion. This, in turn, leads to the choice of C&S elements required to detect these activities.

Results of preliminary logic tree analysis provided the initial basis for the system description. Other factors that governed the choice of system elements were availability of off-the-shelf hardware and guidelines developed from facility constraints and performance requirements.

For spent fuel storage facilities, the following system elements were initially specified:

SENSORS	Includes radiation and crane-monitors for sensing the presence, location, and change in location of spent fuel when out of the storage pool; and acoustic monitors for sensing spent fuel activities within the storage pools.
TAMPER-INDICATING SENSOR MODULE (TISM)	Data from each sensor is collected, processed and formatted in a TISM for transmission to the data collection module (DCM). The TISM contains a microprocessor, a power supply, tamper indicating hardware, a communications interface and, in some cases, the sensor. (Some sensors are external to the TISM.)

CLOSED CIRCUIT TV (CCTV)	Provides TV pictures for storage when: (1) anomalous conditions are identified in the sensor data by the DCM, and (2) upon command by the central monitoring and display module (CMDM).
FUEL ASSEMBLY IDENTIFICATION DEVICE (FAID)	A device which has a unique ultrasonic signature and is attached to the fuel assembly to provide a positive identification.
DATA COLLECTION MODULE (DCM)	Collects, correlates, and stores data from the various instruments located in the facilities, and communicates the information to the local display module (LDM) and the CMDM.
LOCAL DISPLAY MODULE (LDM)	Provides the inspector with a means of obtaining on-site data for assessment.
CENTRAL MONITORING AND DISPLAY MODULE (CMDM)	Receives, interprets, stores, and displays data gathered from DCM's and transportation vehicles.

The overall system is being designed with the capability of indicating tampering attempts. A tamper-indicating fiber optics data transmission link will be used between each TISM and the DCM. All hardware modules will include tamper-indicating features, such as microswitches on access doors and vibration sensors. Data transmitted between DCM's and CMDM will use authentication techniques.

The CMDM interrogates the stored data in the DCMs approximately once each day and gathers the stored information. The CMDM then analyzes the data, further interprets it (if necessary), and quickly reports any unusual operations, or diversion attempts.

Subsequent analytical and operational test and evaluation activities for the C&S equipment elements will be used to identify additional requirements, and provide a more realistic basis for subsequent trade-off analyses of possible hardware configurations and inspection options. In operation, a minimum configuration can be installed to provide basic surveillance. As requirements change, capability can be added without the need for eliminating any of the basic hardware, because of the modular nature of the C&S hardware which allows it to be easily configured to simulate various hardware options.

CONCEPTUAL DESIGN OF A
SYSTEM FOR DETECTING NATIONAL DIVERSION OF
LWR SPENT FUEL

I. INTRODUCTION

The safeguarding of reactor spent fuel against acts of national diversion aimed at establishing a nuclear explosive capability is a principal international concern. This concern spans all modes of spent fuel storage, handling, and transportation. Water basin storage at power reactors and at away-from-reactor storage facilities, and the related interfacility transportation are currently practiced internationally. Development concepts for interim dry storage, deep seabed, and deep geologic storage are already underway.

Studies describing the various facilities and transportation modes[1] and concept options for detecting national diversion[2] were essential to the development of this report. The three concept options presented are as follows:

Option 1	Periodic inspection of each facility to obtain and review data acquired by C & S instruments and to verify the spent fuel inventory.
Option 2	Continuous inspection aided by C & S instruments.
Option 3	Collection of data from C & S instruments with periodic readouts either at the facility or at a remote CMDM. Only occasional inspection is required.

Containment and surveillance instruments are included in each option to assure a sufficiently high probability of detection. Timely reporting of any diversion is critical to all three options in order to provide adequate time for verification and response. To make an effective choice of the possible options available, a tradeoff analysis of hardware configurations and inspection options must be completed. The following procedures are required for this analysis:

- Develop preliminary concepts for detecting national diversion of LWR spent fuel.
- Perform preliminary analysis of LWR spent fuel storage, handling, and transportation operations.
- Develop a preliminary C & S concept which contains elements which hold potential promise for future applications.
- Develop a test capability which will allow the elements to be evaluated in a realistic environment.
- Determine the feasibility of the various system elements by operational test and evaluation.
- Complete the tradeoff analysis of hardware configurations and inspection options.

This tradeoff analysis will provide data on the effectiveness of various hardware configurations in detecting the unreported movement of spent fuel. This data will allow comparisons of relative effectiveness and cost of inspectors versus hardware in these tested configurations.

All three options presented in Reference 2 require the use of some C & S hardware to assure an acceptable probability of detection. Option 3 incorporates remote monitoring of C & S equipment and only occasional on-site inspections; as a result, it would probably require a somewhat more comprehensive hardware development program than Options 1 and 2. Yet, although the operational cost estimates for option 3 are competitive with options 1 and 2, Option 3 has the advantage of an improved timeliness of detection[2]. It is believed that the relatively small additional hardware development costs for Option 3 would therefore be worthwhile to allow consideration of the overall concept.

Based upon the selection of Option 3 as the primary system concept to be developed, the following general principles are required for developing hardware to implement Option 3:

- Assure high probability of detecting significant, unreported movement of spent fuel, including tamper indication.
- Allow timely reporting of detections.
- Minimize need for on-site inspectors and other personnel requirements of the inspection agency.
- Minimize cost and operational impact on the facility.

Similarly, the basic performance requirements for the operating system were defined as follows:

- Verify in a timely manner reported spent fuel movements and detect unreported movements.
- Provide capability for assessing alarms.
- Provide capability for rapid inventory verification.

From the preceding, the common element of any national diversion is the unreported movement of spent fuel. At fixed sites, this includes such items as:

- Unreported transfers of fuel between a reactor and the storage pool.
- Unreported transfers of fuel between the storage pool and a reprocessing area.

- Unreported transfers on or off site.
- Nonarrival of reported transfers.

Diversion of spent fuel can also occur during interfacility transportation (section IIIA, Figure 8). The fact that the fuel is already prepackaged and mobile and that the transport time may extend to days or weeks may be, to the potential diverter, a significant advantage over removing the fuel from a fixed facility.

During interfacility transportation, the safeguards concerns include:

- Unreported removal of the fuel from the transportation vehicle.
- Delivery of the fuel to an unreported location.

The conceptual design described herein is based on near real time detection of unreported fuel movements with the capability of both on-site and remote data readout. Figure 1 shows a conceptual overview of the system. The particular elements represented by the various blocks was chosen based on the above principles. The sensors were chosen as a result of a generic analysis of the C & S requirements in water basin storage facilities. The analysis technique used is a logic tree development which breaks each concern into a set of basic activities, connected by logic gates. This technique provides a systematic approach to defining a necessary subset of activities which must be detected to prevent the occurrence of a given concern. (Details of this technique and the logic trees developed for water basin storage of spent fuel are given in Section III.) As a result of this analysis, the following set of sensors was identified as useful for fixed site, water basin storage facilities:

- Radiation Monitors, which sense radiation level changes associated with spent fuel handling operations outside the storage pool.
- Crane Monitors, which detect crane activities associated with spent fuel handling operations.

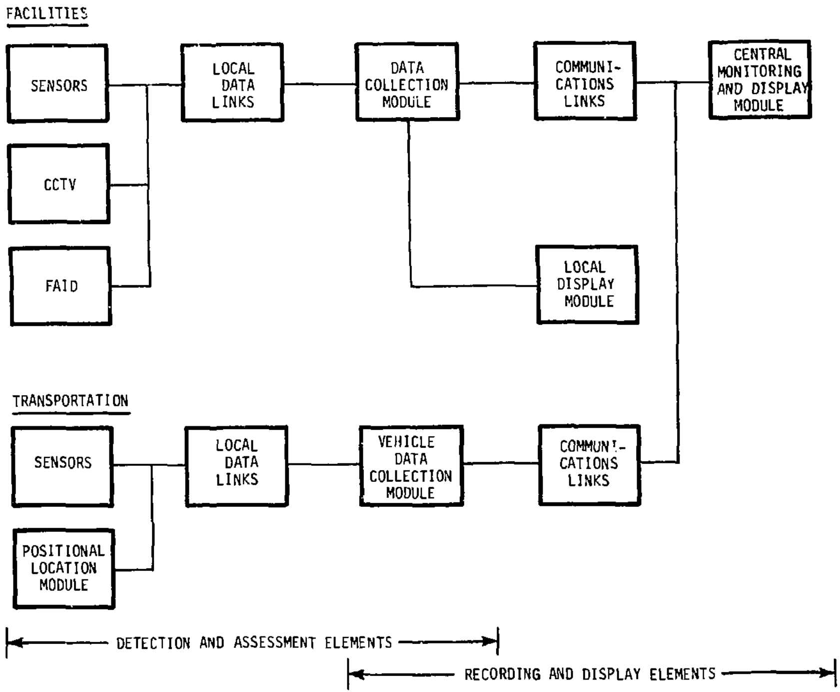


Figure 1. Conceptual Overview of Spent Fuel Containment and Surveillance System

- Spent Fuel Pool Acoustic Monitors, which detect underwater acoustic signals associated with spent fuel handling.
- Video Motion Monitors, which detect changes within a scene.
- Portal Monitors, which detect door openings.
- Electrical Power Monitors, which detect activities of motor operated equipment.

The first three of the above sensors were initially selected to demonstrate the feasibility of and develop hardware techniques for the spent fuel remote surveillance system. Since several options exist for each sensor, further selections had to be made on the basis of those options in each sensor that were compatible with the preliminary measurements and analysis of data taken from fuel handling and storage facilities.

In addition to the sensors, the initial conceptual design includes the Fuel Assembly Identification Devices (FAIDs), which could be installed on fuel assemblies to provide unique identification and integrity information, and closed circuit television (CCTV), which assists in assessment activities.

Communication between the sensor modules and the DCM takes place over fiber optics local data links. The fiber optics system coupled with tamper-indicating enclosures around the various on-site modules will allow detection of any tampering attempt on the system. The DCM collects sensor data and tamper-indicator status from the various sensor modules. It correlates the sensor data and checks for unusual or inconsistent operations.

As an example of such a correlation process, the relative radiation levels as seen by several spatially separated radiation monitors should correlate in a predictable manner to a radiation source, such as a cask containing spent fuel, being moved through the area. The monitor outputs can be used to generate source strength and position location solutions by a process called deconvolution, or simply, unfolding[3]. An unusual condition could then be a solution which shows the radiation source (presumed to be spent fuel) moving in a direction opposite the normal one for a given facility or operation. An inconsistent condition could be one in which the unfolding process does not converge to a unique solution. This may be due to an attempt to mask or fool the system by the introduction of shielding around the sensors and/or the introduction of extraneous radiation sources within the area. Such unfolding techniques further enhance the tamper-indicating capability of the system, reduce false alarms, and increase the probability of detection of an unreported spent fuel movement. The exact data base of normal operations will have to be generated on the basis of observations and data obtained from each facility during the initial installation and checkout phase.

In operation, the data collection module will poll the sensors and tamper status indicators every few seconds and perform the unfolding calculations. Whenever an abnormal solution is obtained, sensor data will be stored, and when required, a closed circuit TV picture will be stored by the DCM. This sequence could also be initiated at random times or upon interrogation from the local or remote display module as shown in Figure 1. Approximately 24 hours of data can be stored by the DCM for later interrogation by the LDM and/or the CMDM.

The system elements which allow timely reporting of any detected diversion are the DCM, LDM, the communication links, and the CMDM. It should be noted that the DCM is an element of both the detection and the recording and display subsystems. The data links to the CMDM can be either satellite, hardwire, or ground station RF links. Data authentication will be required on these links to detect tamper attempts.

The CMDM may be located many miles from the spent fuel site. It contains the necessary equipment to communicate with the DCM's, to record, to process and to display data. It also provides the capability to accommodate inputs from system operators and aid them in assessing spent fuel status via any of the system DCM's.

A simplified, although functionally similar, system concept is used for the interfacility transportation. The sensors consist of tamper indicators and sensors to detect whether or not the cask has been displaced from the transporter. In addition, the interfacility transportation concept includes a location calculator, based on a system of ground-based transmitters, which can calculate the approximate location of the transportation vehicle. An RF data link is required between the mobile DCM and the CMDM.

II. SPENT FUEL STORAGE AND TRANSPORTATION

This section provides a brief description of the fuel storage facilities and transportation modes which are being considered for the initial surveillance concepts. A more complete description of these and other storage and transportation modes is given in Reference 1. Although deep seabed and dry storage are being considered by the United States and other countries, only water basin storage facilities will be addressed in this report. The other storage modes will be covered as they are more fully defined.

A. Storage Facilities

1. Light Water Reactors

Light water reactors have facilities for water basin storage of spent fuel. These basins are used for temporarily storing reactor fuel prior to the time it is shipped to an AFR storage or reprocessing facility. Figure 2 shows a typical pressurized water reactor facility. A typical boiling water reactor facility is shown in Figure 3.

Spent fuel is removed from the reactor and transferred to the storage basin entirely under water. This requires flooding the reactor refueling basin to a depth sufficient to shield against radiation from the spent fuel as it is lifted from the reactor and transported to the storage basin.

Fuel storage racks contain the fuel assemblies. A fuel handling crane is used to move the fuel assemblies within the basin and into the cask loading area where the shipping casks are loaded with spent fuel. The cask loading area is isolated from the fuel storage area to prevent damage to stored fuel in case of a cask tipover accident.

A cask-handling crane is used to move the casks between the cask loading area, the decontamination area, and the shipping vehicle. A decontamination area is used to flush, clean, and check the casks

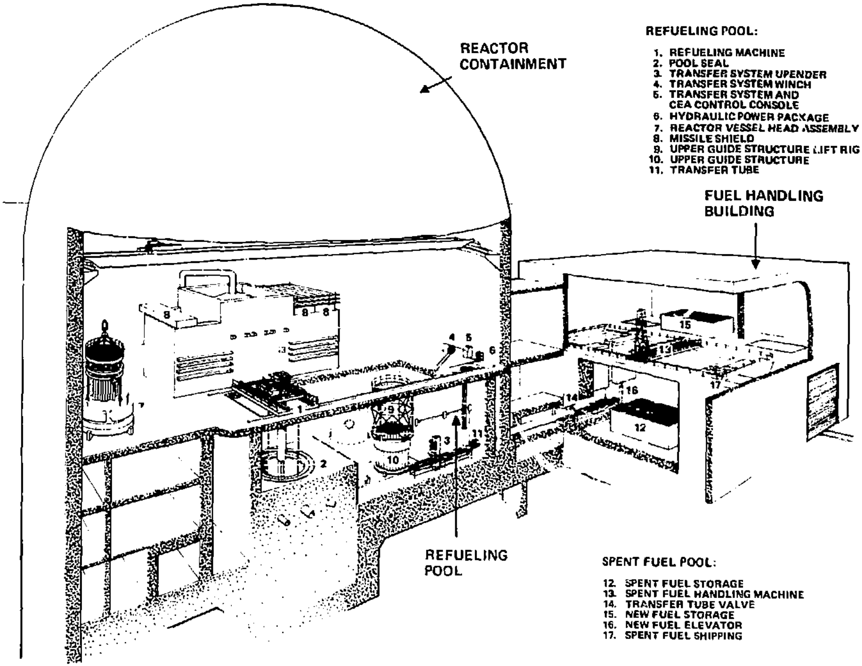


Figure 2. Fuel Handling and Storage at a PWR Facility

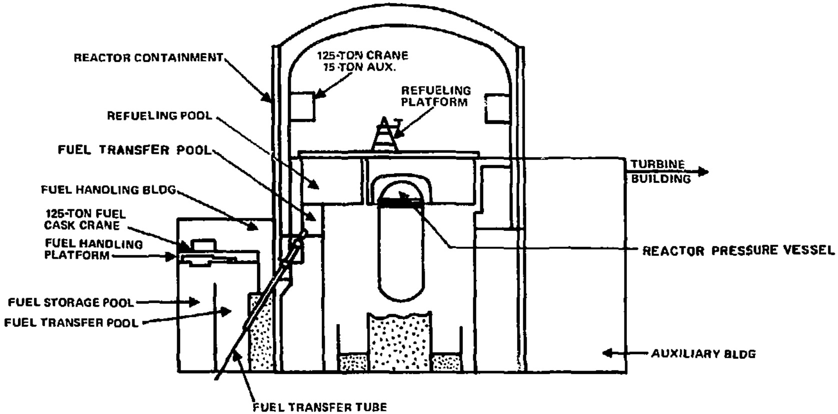


Figure 3. Fuel Handling and Storage at a BWR Facility

for contamination prior to loading the cask onto the shipping vehicle or placing the cask into the cask loading area of the storage basin.

The baseline reactor facility being considered is a pressurized water reactor. The fuel storage basin outside the containment building is connected to the refueling basin by a fuel transfer tunnel. The basin is divided into three connected areas which are approximately 6 by 20 m overall and about 12 m deep. The largest area, approximately 6 by 12 m, is used for spent fuel storage. The remainder is divided into a fuel transfer area and a shipping cask loading area.

2. Away-From-Reactor Storage Facilities

Existing Away-From-Reactor (AFR) storage sites are of the water basin type. The baseline AFR facility chosen has a water basin which is divided into three connected areas which are approximately 12 x 21 m overall and together contain about 2500 m^3 of water. A large section of the basin area is about 9 m deep; however, one 4 x 5 m section used for unloading casks underwater is 15 m deep. Figure 4 shows an AFR concept using dry unloading of the cask. The cask and fuel handling operations are similar to wet unloading. The similarity in facilities is shown in Figure 5.

The fuel assemblies presently stored in the fuel storage basin are in open-top metal baskets. The baskets are made to accommodate either nine BWR assemblies or four PWR assemblies.

Fuel handling operations within the AFR facilities are functionally similar to those described for the reactor pool.

3. Reprocessing Facilities

The differences between the AFR facilities described in the previous section, and the system of receiving-and-storage pools in reprocessing facilities are as follows:

- The amount of spent fuel stored in the reprocessing facility is considerably less than in AFR facilities.

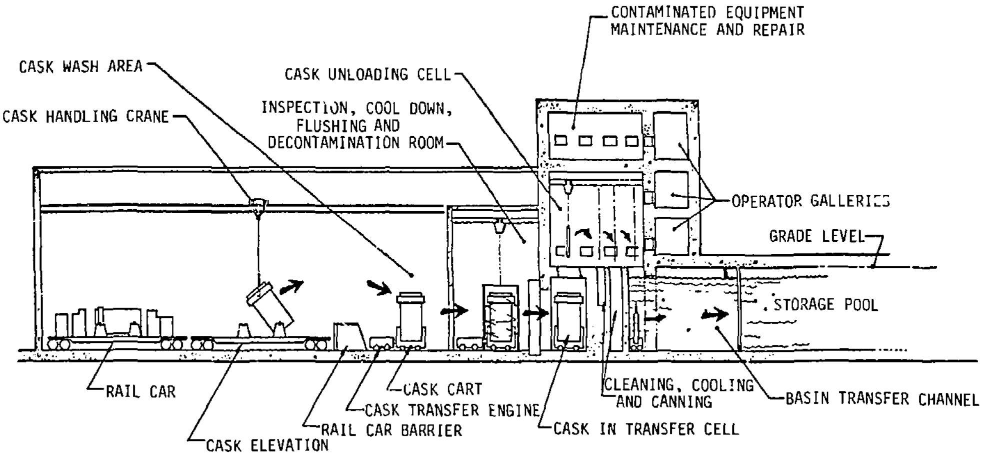


Figure 4. Spent Fuel AFR Storage Facility Receiving and Handling

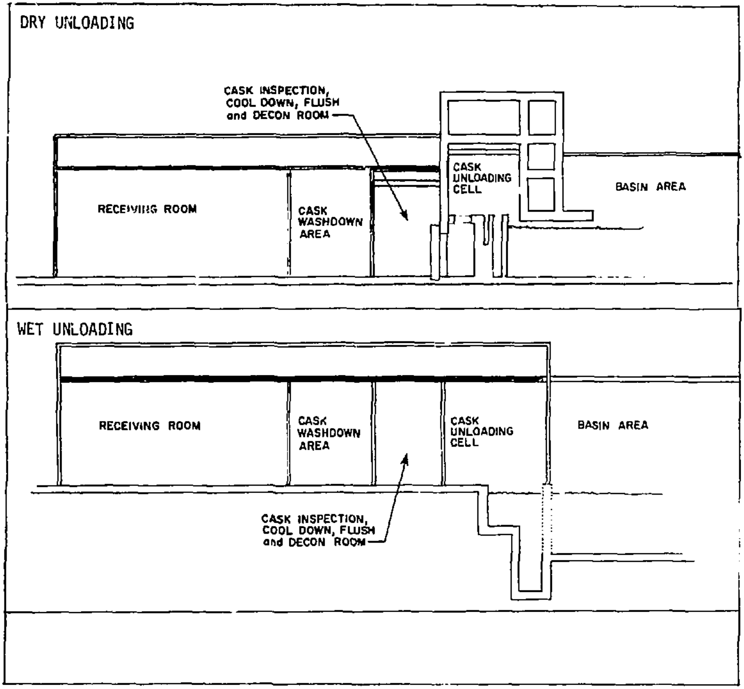


Figure 5. Cask Unloading Variations
Spent Fuel AFR Storage Facility

- The fuel will remain in the storage pool for a shorter duration of time than it does in the AFR facility storage pool.
- The fuel will normally be transferred to a hot cell for shearing and is not likely to be transported out of the facility.

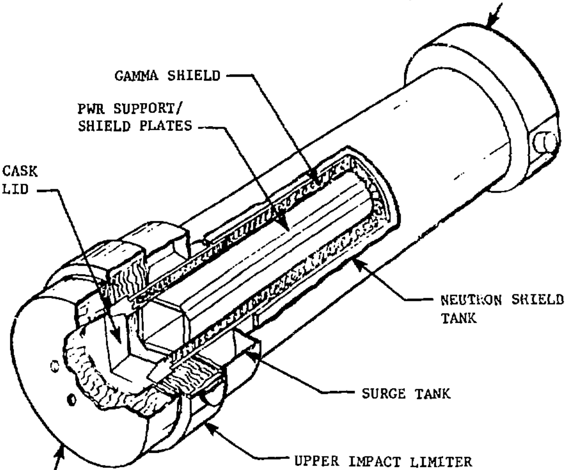
B. Interfacility Transportation

Spent fuel assemblies, loaded into heavily shielded transportation casks, are shipped between nuclear reactor sites and storage facilities, and potentially to reprocessing facilities. The quantities currently transported are relatively small but are expected to increase rapidly as shipments increase in and among the United States and foreign countries.

Reference 1 describes the spent fuel transportation operations, including the shipping casks, land and water transportation vehicles, and typical transportation modes. A typical fuel shipping cask is shown in Figure 6. Figure 7 shows a representative road transport configuration with the cask loaded on a truck trailer.

The information of interest in the transportation of spent reactor fuel is the location and status of the shipping cask. Location data can be computed by onboard equipment that receives radio signals from an existing network of radio transmitters. Cask integrity can be determined by electronic seals, displacement transducers, radiation detectors, and possibly direct contact or infrared sensitive temperature transducers.

Transportation methods being considered by the United States and other countries are road, rail, ship and barge. Air transportation is not being considered. Road and rail transportation are the principal interests for the conceptual design system, but the instrumentation will be applicable to any of the vehicles under consideration.



Capacity	1 PWR Type Fuel Assembly	or	2 BWR Type Fuel Assemblies
<u>Fuel Data</u>	<u>1 PWR</u>		<u>2 BWR</u>
Envelope Section, m	0.22 x 0.022		0.14 x 0.14
Envelope Length, m	4.50		4.50
Enrichment, % U-235	3.6		2.6
Weight Uranium, kg	447		358
Maximum decay heat, kW	11.5		11.5
Cask weight (loaded), tonnes	24		
Cask Envelope, m	1.2 diameter 6.0 length		

Figure 6. Baseline Spent Fuel Shipping Cask - Road Transport

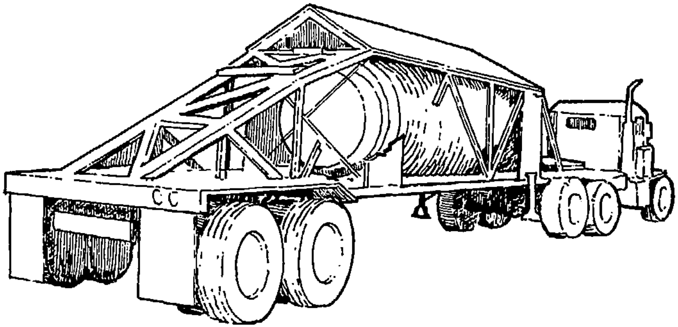


Figure 7. Road Transport Configuration

III. SAFEGUARDS EQUIPMENT

A. Analysis Technique

This section discusses the initial set of safeguards equipment which was chosen to allow spent fuel monitoring elements to be developed and evaluated for water basin facilities and interfacility transportation. The choice of equipment is based on a generic analysis of spent fuel transportation and water basin storage facilities. The analysis used is adapted from fault tree methodology where the events related to a specific concern are connected together using logic gates to show their interdependencies. This approach, called logic trees, has the following features:

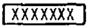
- Systematic Approach
- Visibility of Logic
- Traceability

The object of this analysis is to identify the basic activity which must be detected to prevent the occurrence of a national diversion. This, in turn, leads to the choice of C & S elements required to detect this set of activities. By following the methodology of the logic tree (Figure 8) along any desired set of branches, a set of basic activities is reached which must be accomplished before fuel diversion can take place along that particular path. Where these activities are inputs to an OR gate, the detection of all the activities is required to block that diversion path. For activities grouped as inputs to an AND gate, the detection of any one will theoretically block that path. In order to achieve reasonable reliability, however, a C & S system should be capable of detecting more than one activity along any diversion path. Three activities may be a practical goal because it allows for single failures and still provides for some redundancy.

The basic activities or events which are to be detected in Figure 8 are designated by circles. Every activity that is an input to an OR gate is to be detected. At least two activities that input into each AND gate are to be detected. Figure 9 shows a table of activities to be detected along

FUEL TRANSFER ACTIVITIES/LOGIC TREE SYMBOLOGY*

BOX: AN ACTIVITY WHOSE CAUSES ARE DEVELOPEO THROUGH LOGICAL GATES TO OTHER ACTIVITIES.



NUMERICAL CODE FOR THE ACTIVITY IN THE BOX.

CIRCLE: PRIMARY BASIC ACTIVITY WHICH IS TO BE DETECTED.

DIAMOND: SECONDARY ACTIVITY; A COMPOSITE OF DISTINCT ACTIVITIES NOT TO BE RESOLVED IN THE FAULT TREE.

LOGICAL GATE: "OR" GATE, I.E., EITHER THE ACTIVITY A OR B OR C......CAN OCCUR INDEPENDENTLY

LOGICAL GATE: "AND" GATE; I.E., ACTIVITY A AND B AND C......MUST OCCUR.

TRANSFER IN: THE SUBTREE BELONGING HERE IS DRAWN ELSEWHERE.

TRANSFER OUT: THE SUBTREE DRAWN TO THE SIDE OF THE TRIANGLE BELONGS ELSEWHERE. AN INDEX IN THE TRIANGLE INDICATES THE CORRECT MATCH.

*ADAPTED FROM FAULT TREE METHODOLOGY.

Figure 8a. Spent Fuel Diversion Logic Tree

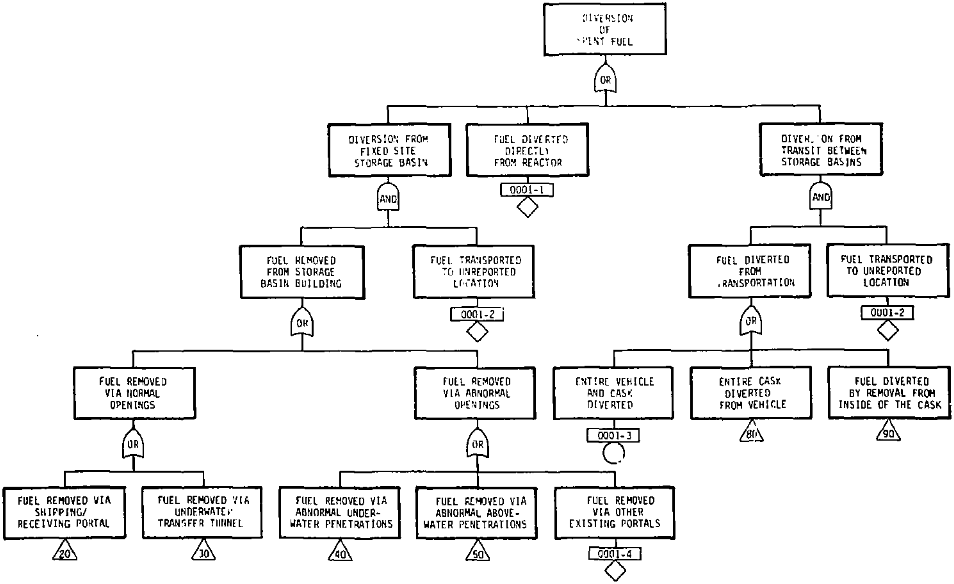


Figure 8b. Spent Fuel Diversion Logic Tree

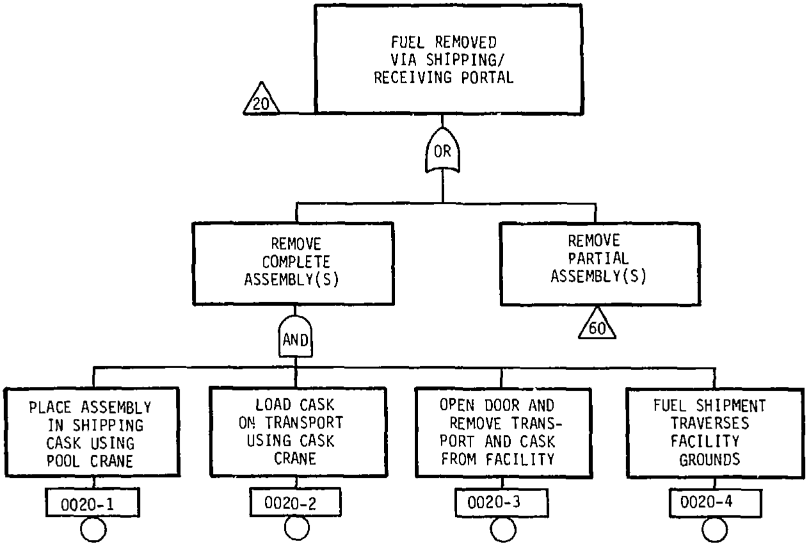


Figure 3c. Spent Fuel Diversion Logic Tree

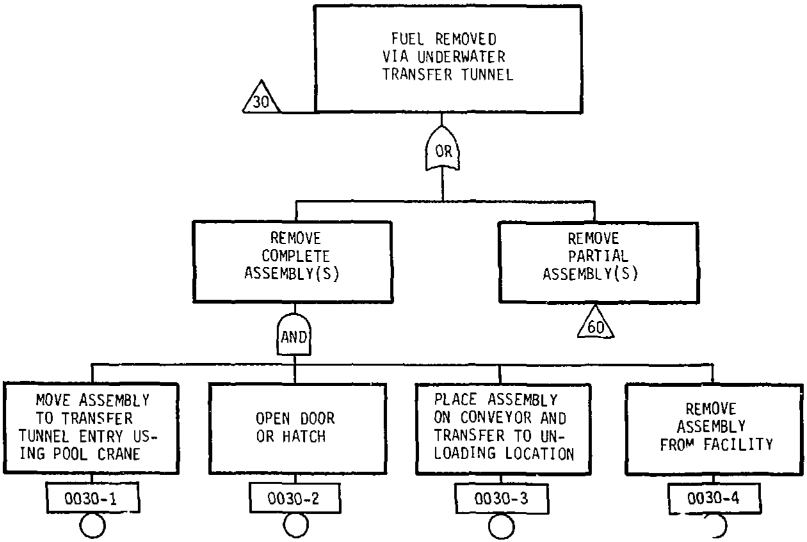


Figure 8d. Spent Fuel Diversion Logic Tree

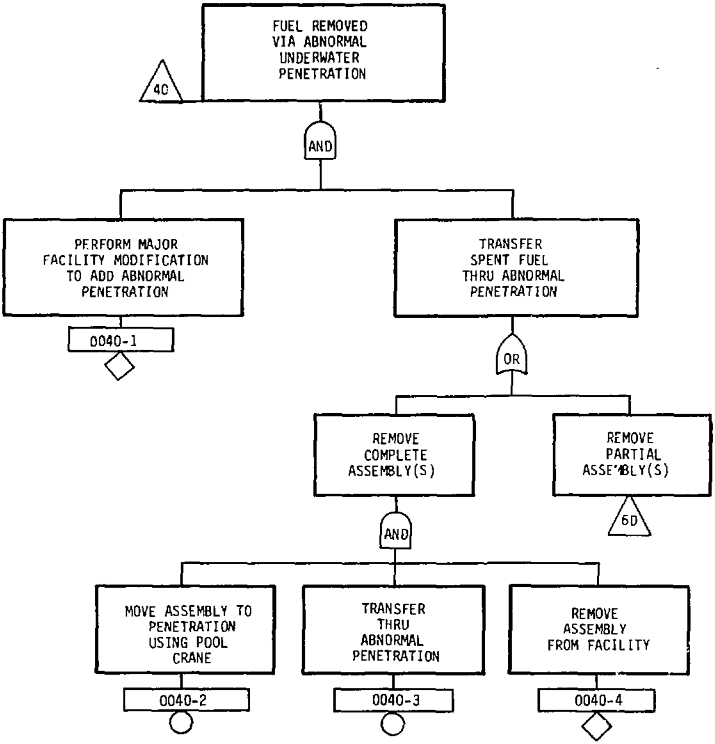


Figure 8e. Spent Fuel Diversion Logic Tree

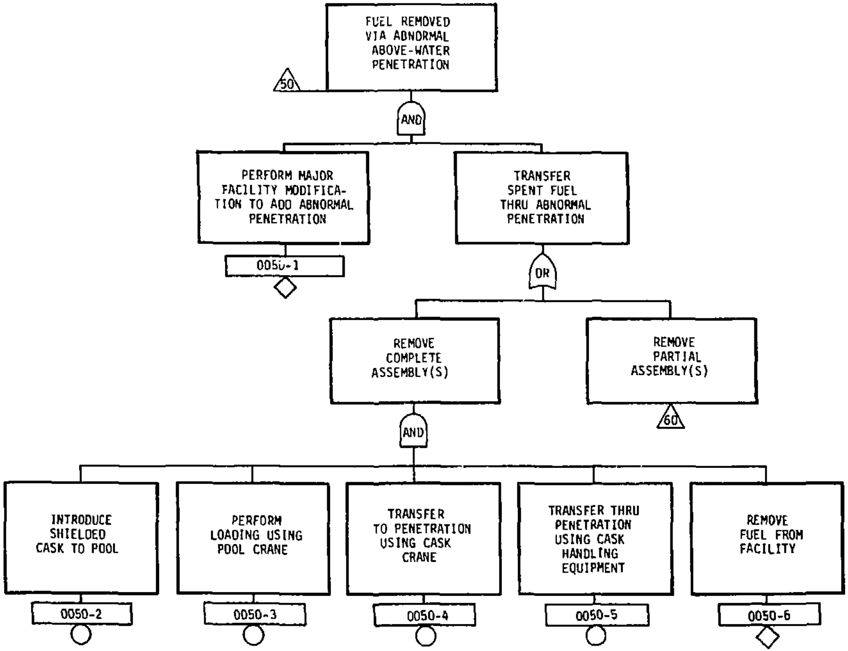


Figure 8f. Spent Fuel Diversion Logic Tree

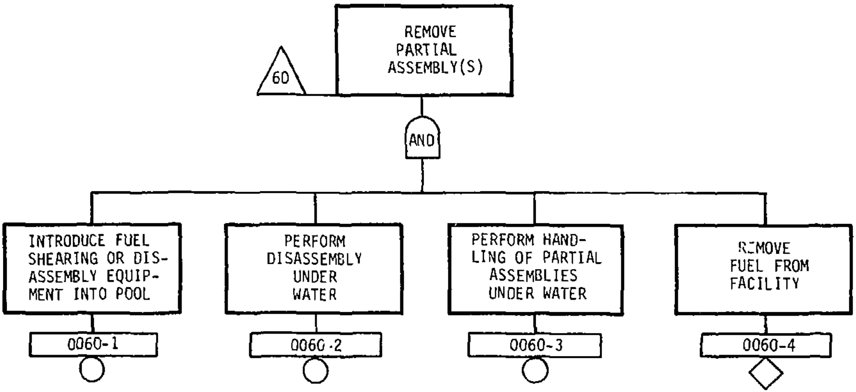


Figure 8g. Spent Fuel Diversion Logic Tree

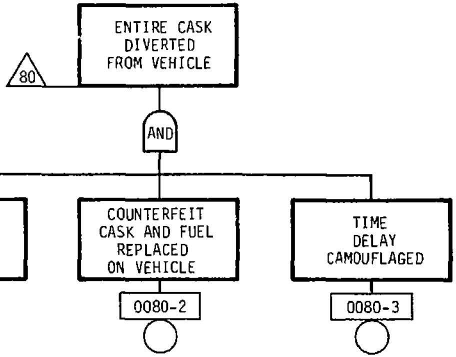


Figure 8h. Spent Fuel Diversion Logic Tree

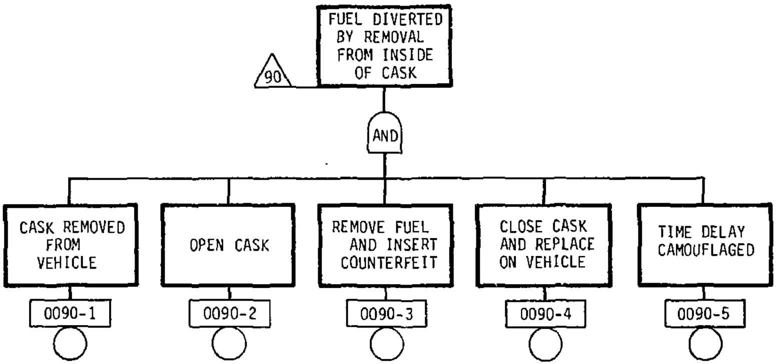


Figure 8i. Spent Fuel Diversion Logic Tree

ACTIVITY	SURVEILLANCE MONITOR(S)	COMMENTS
0001-1	None	This activity is covered by administrative safeguards and will not be developed further in this logic tree.
0001-2	None	
0001-3	Vehicle Monitor	
0001-4	See Comments	This activity closely resembles the development of 50 except that no major modification to the facility is required.
0020-1	Pool Acoustic Monitor	
0020-2	Crane Monitor	Closed circuit television will provide assessment data for these activities.
0020-3	Radiation Monitor and Portal Monitor	
0020-4	Radiation Monitor	
0030-1	Pool Acoustic Monitor	
0030-2	Pool Acoustic Monitor and Portal Monitor	
0030-3	Video Motion Detector and Pool Acoustic Monitor and Conveyor Power Monitor	
0030-4	See Comments	This activity not developed because preceding required activities are blocked.
0040-1	See Comments	Any major modification to the facility can be detected by seismic sensors, closed circuit television and/or by occasional inspection.
0040-2	Pool Acoustic Monitor	
0040-3	Pool Acoustic Monitor	Same as 0020-2
0040-4	See Comments	Same as 0030-4
0050-1	See Comments	Same as 0040-1
0050-2	Pool Acoustic Monitor	Same as 0020-2
0050-3	Pool Acoustic Monitor	
0050-4	Radiation Monitor	Same as 0020-2
0050-5	Radiation Monitor	Same as 0020-2
0050-6	See Comments	Same as 0030-4
0060-1	Pool Acoustic Monitor	Same as 0020-2

Figure 9a. Surveillance Elements

ACTIVITY	SURVEILLANCE MONITOR(S)	COMMENTS
0060-2	Pool Acoustic Monitor	Same as 0020-2
0060-3	Pool Acoustic Monitor	Same as 0020-2
0060-4	See Comments	Same as 0030-4
0080-1	Vehicle Monitor	Verification data provided by seals
0080-2	Vehicle Monitor	Same as 0080-1. Also, the arrival of a counterfeit fuel assembly at the fuel storage basin will fail to cause the proper response from the radiation monitors.
0080-3	Vehicle Monitor	Verification data provided by monitors at facility which respond to arrival of fuel shipment.
0090-1	Vehicle Monitor	Same as 0080-1
0090-2	None	Detected by cask seal.
0090-3	Radiation Monitor	This is an after-the-fact detection when the counterfeit fuel fails to generate the expected response from the radiation monitor when it arrives at the storage facility.
0090-4	Vehicle Monitor	
0090-5	Vehicle Monitor	Same as 0080-3

Figure 9b. Surveillance Elements

with a possible C & S system monitor and/or inspector verification procedure which could be used for the detection of each activity. The system elements identified in Figure 9 include Radiation Monitor, Crane Monitor, Fuel Assembly Identification Device, Underwater Acoustic Monitor, Vehicle Integrity Monitor, Vehicle Position Monitor, Portal Monitor, Electrical Power Monitor.

A closed circuit television (CCTV) system was selected to provide assessment information at storage facilities. The CCTV system will be tied into a video processor which will digitize and store selected video pictures for storage, processing and replay at low digital rates over voice-grade communication links and/or video playback for local video monitors.

Factors which govern the choice of C & S hardware are (1) the availability of off-the-shelf hardware for each monitor and (2) guidelines developed from facility constraints and performance requirements. The capabilities of the C & S system include the following:

- Detect both reported and unreported movements of spent fuel.
- Provide assessment information for both reported and unreported movements.
- Provide inventory verification data.
- Operate with a high degree of reliability.
- Allow timely reporting of data.
- Provide tamper-indicating capability throughout the system.
- Operate as simply and cost effectively as possible within preceding constraints.
- Minimize the impact on facility and transportation operations.
- Minimize the required number of inspectors and inspections.

B. Water Basin Facilities

The monitors are all interfaced to a DCM which interrogates the monitors, and collects and processes the data for subsequent local display or transmission to a CMDM.

As fuel handling operations take place inside the pool to prepare the fuel for removal from the site, the spent fuel pool acoustic detector system will detect the resulting acoustic signals. If analysis of these signals indicates they are not "normal" background, a TV picture may be taken to be used for later assessment of the activity.

Whenever the fuel is removed from the pool, the radiation detectors will respond to its presence. The radiation detector data will be processed by the DCM to solve for the source strength, position and direction of travel by a deconvolution process, called "unfolding." Unfolding is an iterative process which converges to a solution of source strength and position that satisfies the radiation data conditions. Physical constraints and other information such as crane position information will be included, where possible, to enhance the ability of the unfold process to converge to a unique solution. As the fuel is "tracked" in the facility by the unfold process, any abnormal or inconsistent solutions will cause the DCM to obtain a TV picture and store that picture along with the sensor data pertinent to the abnormality. When the fuel is tracked out of the facility, it will be assumed that the fuel has been removed from the site. This condition will cause the DCM to acquire and store TV pictures and pertinent sensor data for later interrogation by the LDM and/or CMDM.

Figure 10 shows an artist view of how the system elements might look inside a typical water basin storage facility. Figure 11 is a simplified block diagram of the spent fuel surveillance system elements. The remainder of this section gives the details of these system elements.

1. Data Collection Module

The data collection module has the responsiblity of communicating with and correlating data from the various sensors located in the facility and transmitting, on request, any data required by the CMDM or LDM (Figure 12).

The sensors interface with the DCM by a combination of software and hardware. The software will interrogate the sensors at two different rates. One rate -- about once per second -- will determine the sensor and data link

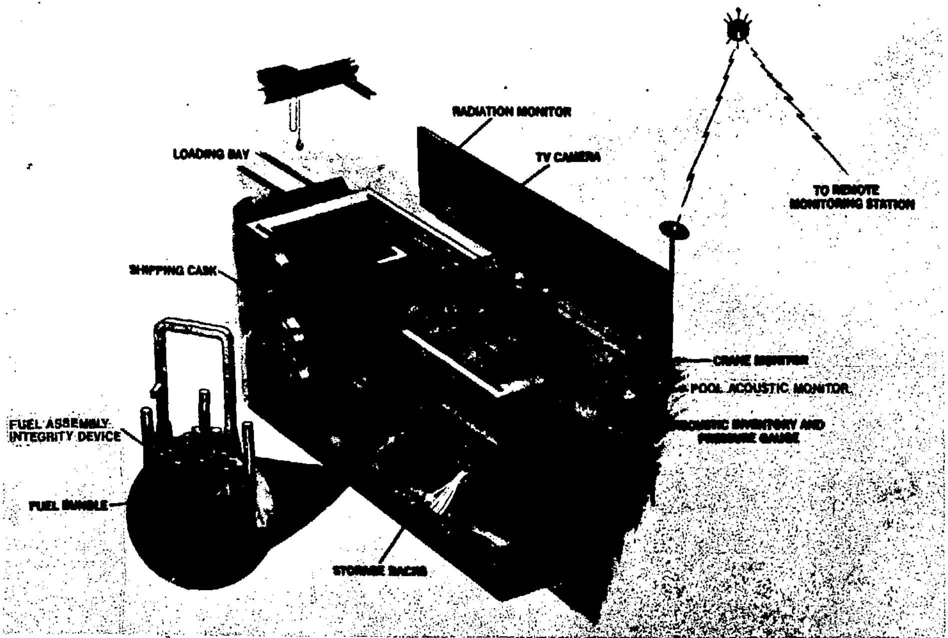


Figure 10. Spent Fuel Storage Monitoring

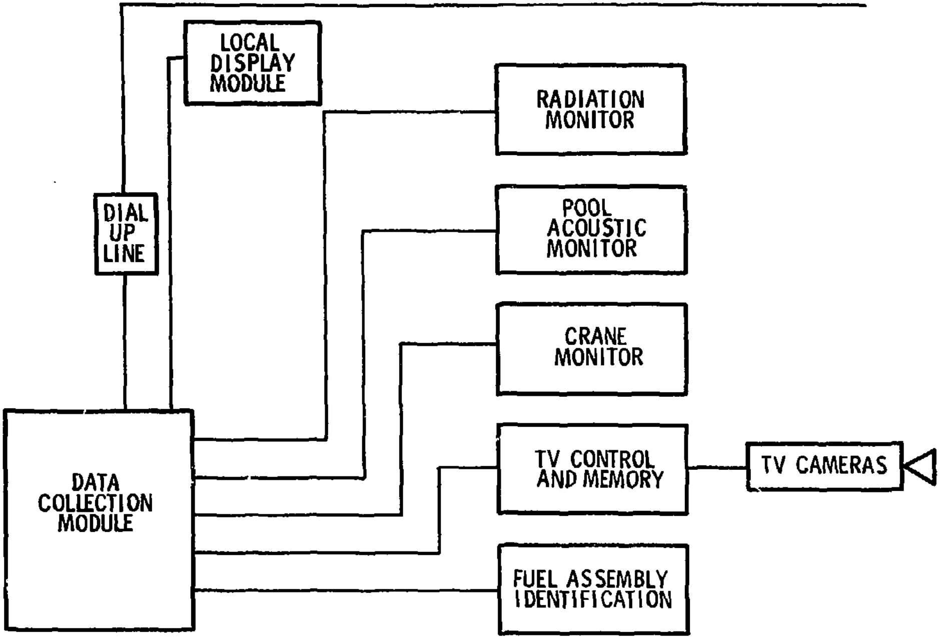


Figure 11. Facility Data Collection Module Computer System

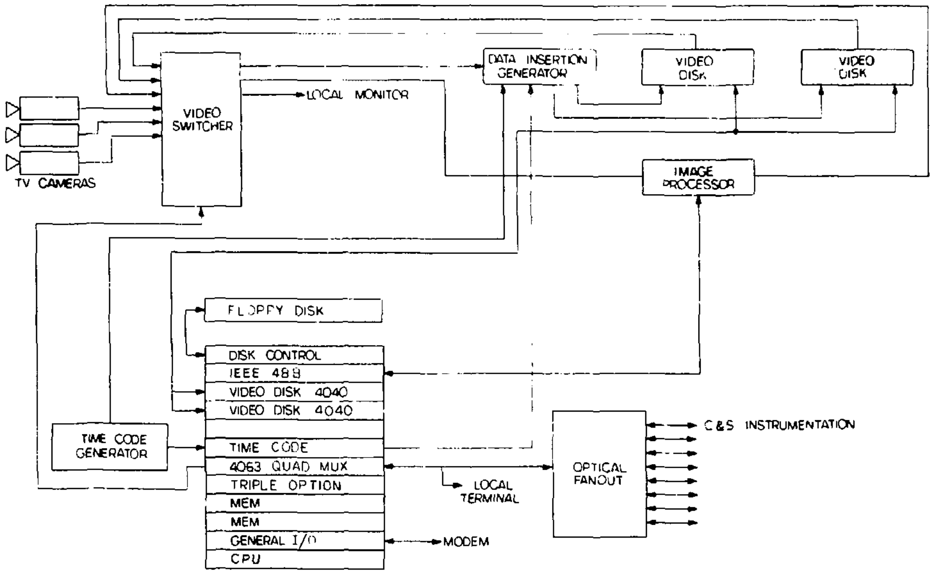


Figure 12. Data Collection Module and Interface Block Diagram

tamper status. The second rate -- about once per fifteen seconds -- will acquire the most recent data of all the sensors for use in the unfolding algorithm. A data flow diagram is given in Figure 13. The hardware portion of the interface will convert computer commands into the proper data format for transmission to the optical interface. At the optical interface, the electrical signals will be converted to light in the near infrared spectrum for transmission over fiber optics to the sensors. Signals received from the sensors will be converted back into the data format for transmission to the computer.

The DCM computer and the communication system coordinate the activities of the other subsystems and components located in the facility and communicate with the CMDM located off-site. The computer contains all of the software logic and peripheral controllers needed to issue commands and collect data from all the other subsystems. The off-site communication is initiated by the CMDM to an auto answer circuit in the DCM. Once a circuit is established the computer in the CMDM can pass commands to the DCM in the form of requests for either sensor data or CCTV data.

The DCM has enough memory capacity to store approximately 24 hours of sensor alarm and related closed-circuit television (CCTV) data. The alarm data from sensors will be stored in the main memory of a mini computer and the CCTV data will be stored on a video disk. The CCTV system will be inhibited from taking a picture more than once every 10 minutes in order to assure a minimum of 24 hours of coverage. On command from the CMDM the alarm data will be transmitted from the DCM, and if any video data is desired, it will be digitized and transmitted. The data buffers in the computer and in the video disk will allow data storage so that, at expected alarm rates, a large amount of historic data can be maintained and presented in total to an on-site inspector through the use of the LDM.

The DCM is physically housed in a 1.45 m high, tamper-indicating enclosure which can be located up to 1 km from the sensors it is controlling. Communication between the DCM and the sensors occurs over a full duplex fiber-optics link, taking advantage of its inherent tamper-indicating

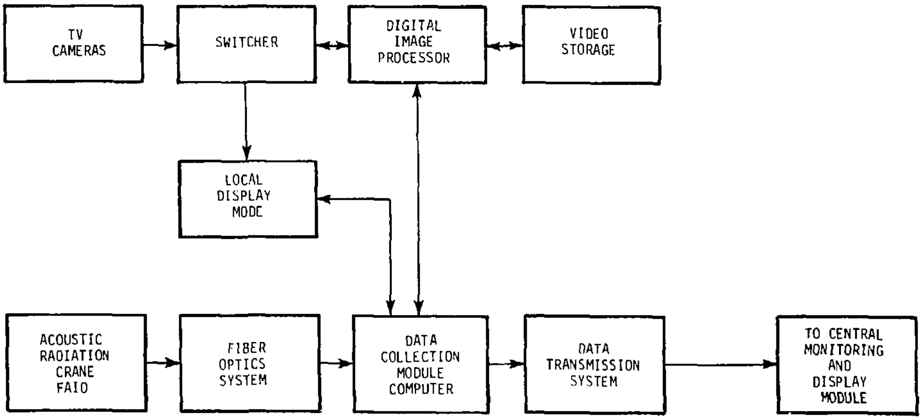


Figure 13. Data Collection Module Data Flow

properties. Communication between the DCM and the CMDM makes use of an authenticated data link which can be on land lines or by satellite (see Figure 14).

2. Closed Circuit TV

The slow scan CCTV subsystem will record a TV picture any time an anomalous condition is detected by the sensors, or upon command from the CMDM; it is used in assessing the activity involved. The sub-system consists of a video switching matrix, a data annotator, video disks, and a digital image processor -- all of which are under computer control (Figure 12).

The video switcher can transfer video from any camera or disk to either a monitor, an annotator, or the digital image processor. Likewise, it can transfer video from the digital image processor to either a monitor or an annotator. Interconnecting the video subsystem in this manner allows extremely versatile operation of all the components. For example, the video can be annotated, stored, examined, displayed, recalled, and processed for transmission. The data annotator will tag all video with world time plus 16 alphanumeric characters that will identify the parameters such as site, camera number, and reason for the picture.

The two video disks, housed in the DCM, comprise the only electromechanical component in the DCM. The two disks are provided for backup purposes because the life of the recording surface is limited. Each disk has the capability of recording 200 frames of video which can be recalled for later viewing or transmission. Only one disk will normally be powered at a time and the decisions to start, stop, record or recall are all under computer control.

The digital image processor is the key component of the slow scan TV subsystem. It allows TV data to be digitized and stored in a random access memory at video data rates. This stored data can then be selectively transferred to the computer and used to drive a communications modem at data rates compatible with phone lines and narrow bandwidth

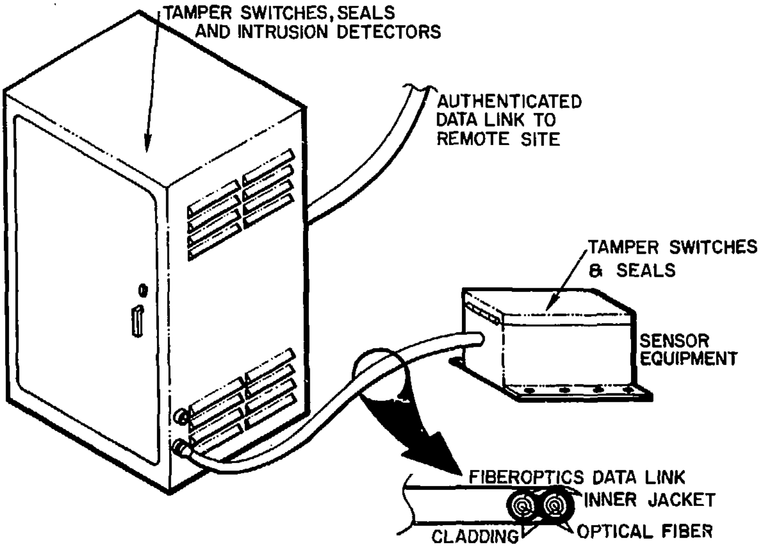


Figure 14. Tamper-Proofing Techniques

radio frequency links. Some of the functions performed by the digital image processor are as follows:

- Digitize a frame of video data
- Perform arithmetic functions on the digital video data
- Convert the digitized data back to video for storage
- Pass digital data to the computer for transmission
- Receive digitized data from the computer and convert it to video

3. Local Display Module

The local display module is a ruggedized suitcase that contains two instruments and the cables necessary to connect them to the DCM (Figure 15). One of the instruments is a standard 30-character-per-second terminal that has an alphanumeric keyboard and will provide a hard copy of significant recorded sensor data with times of occurrence. The other is a small television monitor for viewing the video that may be stored in the CCTV subsystem to allow assessment of sensor data.

The terminal may issue any commands to the DCM for data retrieval but may not be used to alter the software in the DCM. This feature will be implemented by the software in the DCM limiting the commands that will be accepted and acted upon between the LDM and the DCM.

4. Tamper-Indicating Sensor Module

Each of the various types of sensors will be integrated into a Tamper-Indicating Sensor Module (TISM) to form an individual sensor. This TISM will combine one sensor with a microprocessor, a power supply, an interface to the Data Collection Module, and several tamper-detecting devices (Figure 16).

The sensor can be any one of the types described in this report, such as Crane Monitor, Radiation Monitor, Pool Acoustic Monitor or Fuel Assembly Integrity Device, etc. For its protection, the sensor will be as completely contained within the module as possible. It is possible to completely

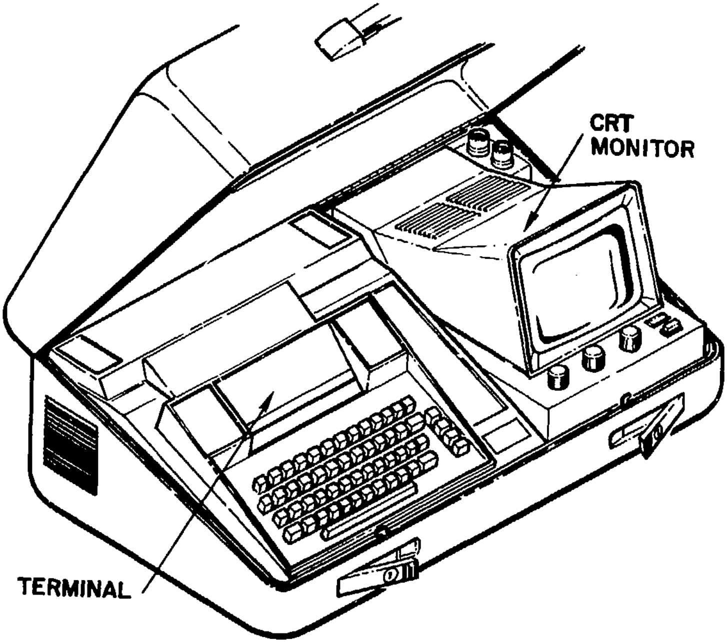


Figure 15. Local Display Module

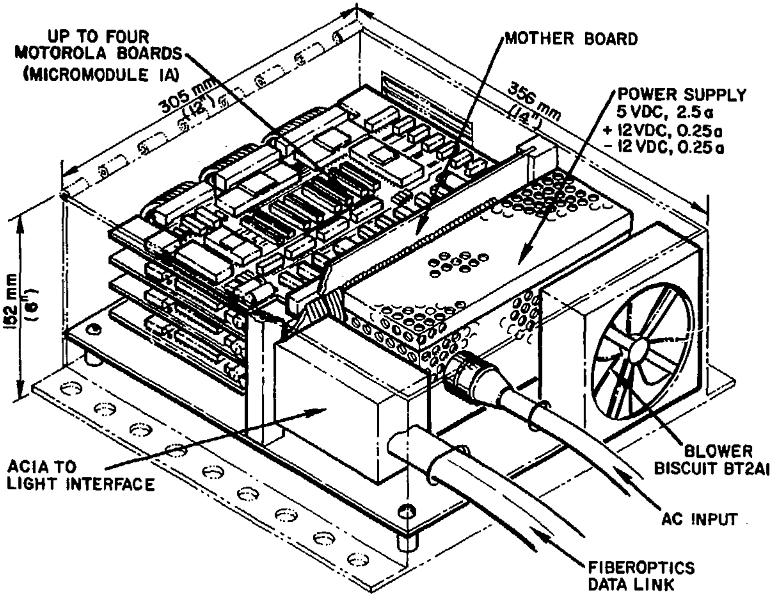


Figure 16. Tamper-Indicating Sensor Module

contain the radiation detector; however, some elements of the crane monitor and acoustic detector must be outside the module. These elements require special monitoring circuits to detect tamper attempts.

The most common tamper detectors include switches on the door of the housing and a vibration switch to detect efforts to gain access by methods other than opening the door. This would include attempts to drill or saw holes in the housing. The air flow switch is another tamper detector which functions by confirming the flow of cooling air.

The strain gauge for the crane monitor can be monitored by checking the voltage and current in the bridge-wired strain gauge configuration. Any attempt to move or modify the gauge would either initiate a response from the sensor or, if the line were cut or shorted out, be detected by the voltage and current monitor, and be reported as a tamper attempt.

The acoustic monitor feeds a charge amplifier in the TISM. Any attempt to cut or modify the circuit to the hydrophone would cause an excessive signal from the charge amplifier, which can be detected. Attempts to mask sound from the hydrophone would change the background and would also be detected.

The microprocessor housed in the TISM monitors the tamper detectors, communicates with the DCM and collects and formats the sensor data. It has a clock which times the tamper switch reading cycle and which is also used for the sensors that require timed readings.

Communication between the TISM and the DCM is via an asynchronous output from the microprocessor. The interface to the DCM changes the signal to a modulated light for transmission to the DCM over a fiber-optics link, and reformats the received light signal for the microprocessor. The fiber-optics link provides tamper protection to the communication channel.

The microprocessor collects the sensor data, either on a time cycle as the radiation monitor, or by interrupt as the strain gauge. This data is formatted and condensed as the various sensors require. When the DCM asks for data, the data is transmitted along with tamper and status information, and a module address. The module also contains power supplies as required by the electronics.

5. Radiation Monitor

Typical reactor spent fuel assemblies have a radiation source of approximately 10^5 curie. A shipping cask will not entirely shield this source, resulting in a radiation field of approximately 5 mr/hr at about 3 m from a shipping cask. Thus, a shipping cask containing fuel is readily detectable even in comparable background areas. A method is required to measure the average radiation level during a time interval and to have the information available for reading by a computer system.

The radiation emerging from the cask is essentially scattered and does not exhibit any well-defined energy lines. Thus an energy-discriminating radiation detector, such as sodium iodide (NaI), is not needed. Geiger-Mueller tubes, because of their reliability and simplicity, have therefore been chosen for the radiation detectors. For maximum flexibility, each radiation detector module is controlled by its own microprocessor (Figure 17), which is housed in the tamper-indicating sensor module. Each module has two GM tubes and two separate counting channels. The counters and also number locations in the circular buffer are all under program control. Counts from each radiation detector in the module are stored in an 8-bit counter. After a fixed interrupt time ($\sim$1/2 sec.), the counters are stopped and the count in each 8-bit counter is transferred to a memory location in a circular buffer assigned that detector (Figure 18). The counters are then reset and enabled. When a count is transferred to a memory location in the circular buffer, the count previously in that location is lost. After enabling the counters, the processor sums the counts in the memory locations for each circular buffer and calculates the standard deviation of the sum. It then determines if the two channels are within statistical tolerance. The integration time for the detectors is equal to the product of the interrupt time and the number of locations in a circular buffer ($\sim$ 1/4 minute). The microprocessor also interrogates tamper monitors. When polled by the DCM the microprocessor outputs the total counts in the circular buffers -- an error message, if appropriate -- and the tamper status.

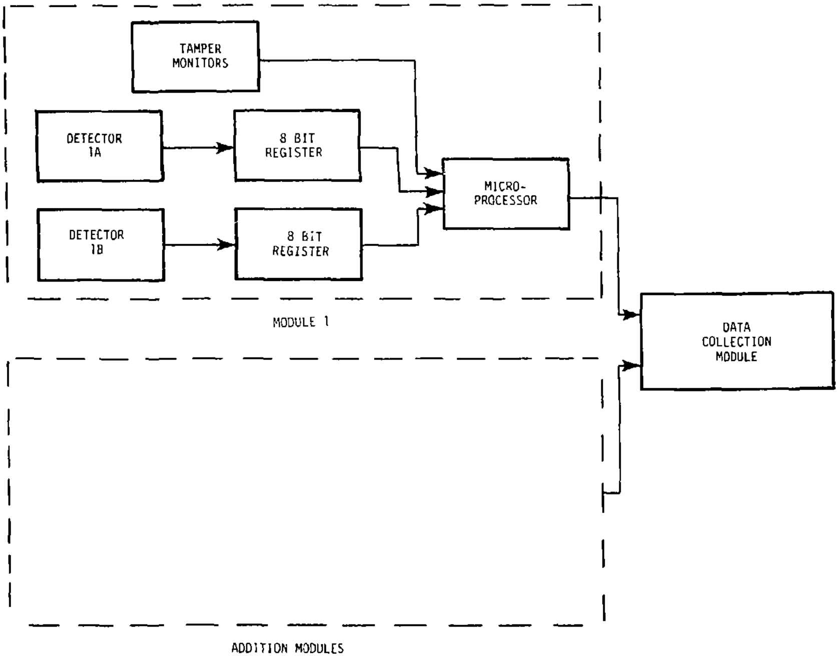


Figure 17. Radiation Monitor Hardware Configuration

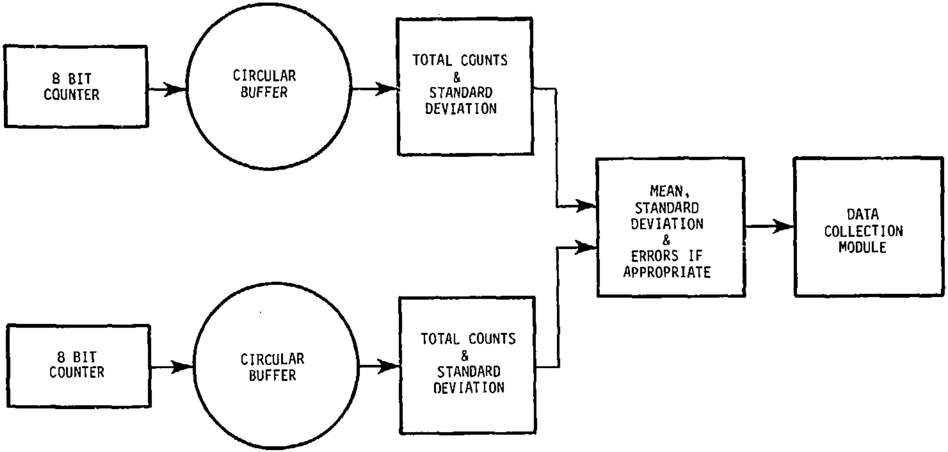


Figure 18. Radiation Monitor Data Flow Diagram

An unfolding technique is required to estimate the approximate radiation source strength, its position, and direction of travel.[3] The primary source of information for this technique is from the radiation detectors. However, there is auxiliary information which reduces the uncertainty in the unfolding algorithm. This information includes the crane position, the weight being lifted, pool activity, estimates of the source strength, and estimates of the source spatial distribution.

The radiation level measured by a detector depends both on the intensity of the source and on the spatial location of the source relative to the detector. Information concerning both the source intensity and its location can be unfolded from simultaneous measurements of the source by several detectors at different positions. This requires the implementation of accepted standard mathematical techniques to solve the system of linear equations which relate the detector signals to the radiation source's position and magnitude. A system of linear equations can normally be solved in a least-square-error sense provided the number of unknowns is at least equal to the number of equations. Auxiliary information aids in obtaining an estimated solution even for an under-determined set of equations. However, such an unfolding algorithm has to be developed for this specific application. The source's estimated position as a function of time gives its speed and direction of travel. To prevent confusion of the system, investigation of the effects of the movement of multiple sources in the monitored area is required.

6. Crane Monitor

The crane monitor system will provide information concerning crane activity at fuel storage facilities. The crane monitor instrumentation concept is to use the same basic tamper-indicating sensor module that was used for the radiation monitors with the exception that the individual sensors which monitor the basic crane functions will interface to the standard enclosure. Four basic crane functions are being considered in monitoring:

- Crane Position

- Crane Load
- Crane Activity
- Direction of Travel

A number of concepts were considered for obtaining data related to these four crane functions, including strain gauges, laser distance meters, position switches, crane hoist motor power readings, and crane hoist cable tensiometer. In reviewing these concepts against various performance criteria such as tamper-indicating capability, reliability, cost, accuracy of readings, need for local data link, etc., it became apparent that the strain gauge concept had the fewest disadvantages. In addition, by mounting the strain gauges on the non-moving bridge rail, all four basic functions could be readily monitored.

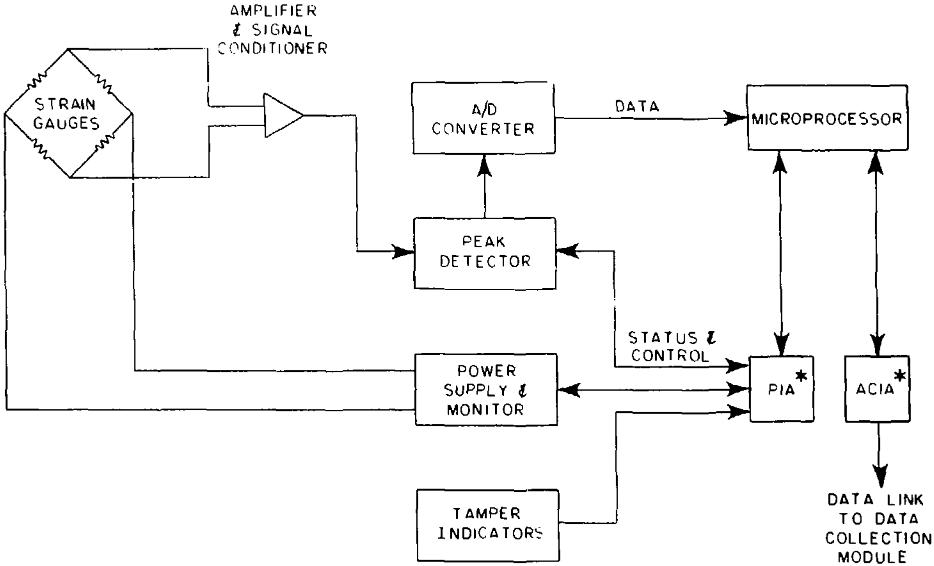
The crane sensor system concept utilizes a series of strain gauges located in pairs along the crane bridge rails. The pairing allows direction of travel to be established as the crane passes the monitor point. It is possible to determine the load on the crane as it passes over the sections of track that have been instrumented with the strain gauges. Figure 19 shows a typical strain gauge instrumentation system applicable to rail installations. All componentry, except the gauges, will be placed in tamper-indicating sensor modules. Voltage and current monitors will indicate tampering with the gauges.

The concepts to be evaluated on the crane monitor system are:

a) The ability to determine an optimum technique for monitoring crane loads.

b) The usefulness of crane load, direction of travel, position, and activity information in assessing fuel handling operations.

c) The ability to reliably measure the above parameters in an unmanned environment under computer control for long periods of time.



*ACIA → ASYNCHRONOUS COMMUNITIONS INTERFACE ADAPTER
* PIA → PERIPHERIAL INTERFACE ADAPTER

Figure 19. Typical Strain Gauge Instrumentation

A feasibility model system is scheduled to be installed at the away-from-reactor storage facility to collect operational data. The final engineering model crane monitor system will be built based on the results of the operational tests. This engineering model will then be integrated into the overall data collection system. Subsequent operational testing will provide the data to evaluate the remaining two concepts.

7. Pool Acoustic Monitor

A Pool Acoustic Monitor (PAM) will monitor underwater acoustic activity within the fuel storage pool. At this time, no reasonable alternatives to the PAM have been identified for underwater spent fuel monitoring. However, alternatives such as underwater CCTV motion detectors, collimated radiation sensors, and microswitch type devices have been considered. Depending upon the ability of the PAM to operate as presently conceived, these alternatives may be considered for auxiliary usage with the PAM at a later date.

The primary objective of the PAM will be to provide an intrusion alert output whenever acoustic signals within the pool are characteristic of fuel assembly handling, particularly those activities associated with removal of nuclear fuel from storage locations to either the reprocessing portion of the plant or the cask loading pool. A block diagram of the conceptual PAM is shown in Figure 20.

The technology development required for the PAM consists of the following:

a) Determination of whether or not spent fuel handling operations generate unique acoustic signals in the spent fuel pool.

b) Development of hardware and software which can recognize spent fuel handling acoustic signals, with acceptable probabilities of detection and false alarms.

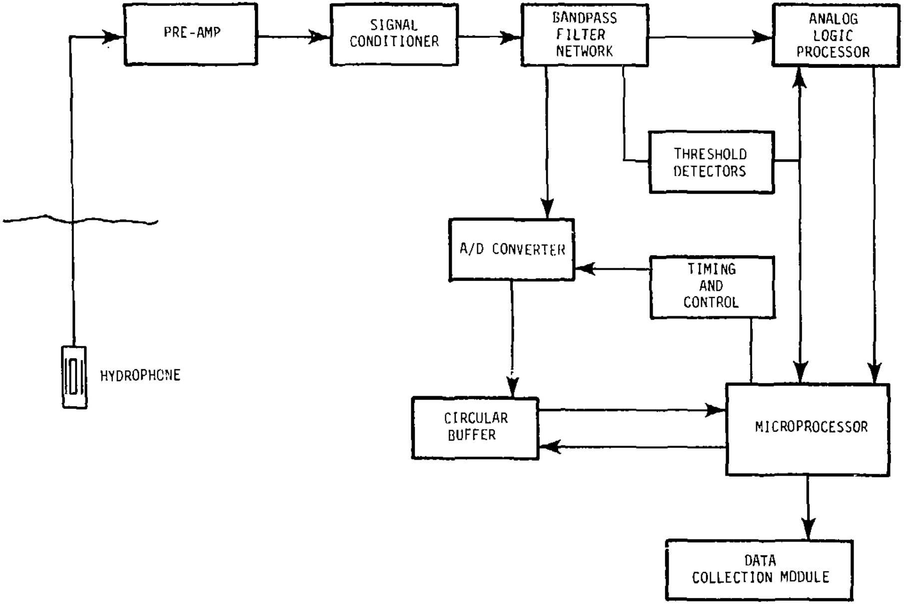


Figure 20. Pool Acoustic Monitor System

c) Development of criteria which correlate detections of fuel handling with possible fuel diversion.

Several analog signal processing techniques will be evaluated as required to minimize false alarm output from the analog logic processor. The initial design will consider the level detector approach. Amplified analog output for each filter band is level-detected with follow-on event counters monitoring the output state of each level detector. Time integration of events in each frequency band are then correlated with specific fuel handling activity to form the basis for setting an alarm threshold. Alarm output status corresponding to each input is provided for further analysis.

Digital logic processing will be used to analyze frequency domain information characteristic of acoustic signal features that correlate to specific fuel handling activities.

The preliminary design goal is to be able to distinguish between acoustic signals generated by fuel handling operations and normal or expected background signals generated by such things as water recirculating pumps. Signal attributes of amplitude, time history, and frequency content will be investigated to uniquely correlate the signals to specific activities including background noise sources.

8. Fuel Assembly Identification Devices

The purpose of the Fuel Assembly Identification system is to provide unique identification and integrity information for independent verification of each fuel bundle in the inventory. The concept that is presently being pursued is to place an ultrasonic Fuel Assembly Identification Device (FAID) on each fuel assembly that can be interrogated with an ultrasonic scanner. This method appears to hold the greatest promise for near-term development because of the considerable research and development activity that has been accomplished by the Ispra Laboratories (Euratom) over the past few years. Other concepts such as radiography or fiber optics are being considered for long-term development, pending the outcome of initial ultrasonic-based concepts. Initially, development activities will be centered on installation of FAIDs on spent fuel only; however, the long-term objective is to place the FAIDs on fresh fuel at the time of initial fabrication whereby they can be monitored throughout the lifetime of the fuel assembly. This latter effort will require certification of the seal for in-reactor use; it will also require a considerable amount of time and development effort.

In operation, FAID data will be sent from the FAID scanner to the DCM, where it is temporarily stored. The data can then be displayed on the LDM and/or transmitted to the remote data collection and display module. The displayed data can then be compared to the reference data for the particular FAID to establish its identity. A conceptual layout of the FAID system is shown in Figure 21.

A mechanical alignment fixture is required to ensure that the interrogating transducer is properly aligned with the FAID. Two scan models will be considered. A detailed focused beam scan of the X and Y axes will be used to completely characterize the FAID (Figure 22). A more general unfocused scan of the Z axis (depth) only will also be performed, giving reflected energy versus depth below the front surface of the FAID (Figure 23). It is this second scan mode which will be used for general inventory verification, if enough detail can be obtained. The detailed scan will be used (1) if the Z scan proves insufficient, (2) for random spot checking, and (3) for final accountability at the time of fuel assembly disposal.

In operation, the reflected energy versus depth information will be digitized and stored at the CMDM. As a FAID is read to verify its identity, the data is buffered into the local facility DCM and then displayed locally or transmitted to the CMDM for comparison. Transmission of the data to the CMDM greatly reduces the amount of information stored at the fuel storage facility.

The technology developments to be undertaken are listed below:

1) FAIDs which have a unique ultrasonic signature that (a) will be altered if the FAID is removed from the fuel assembly, (b) will

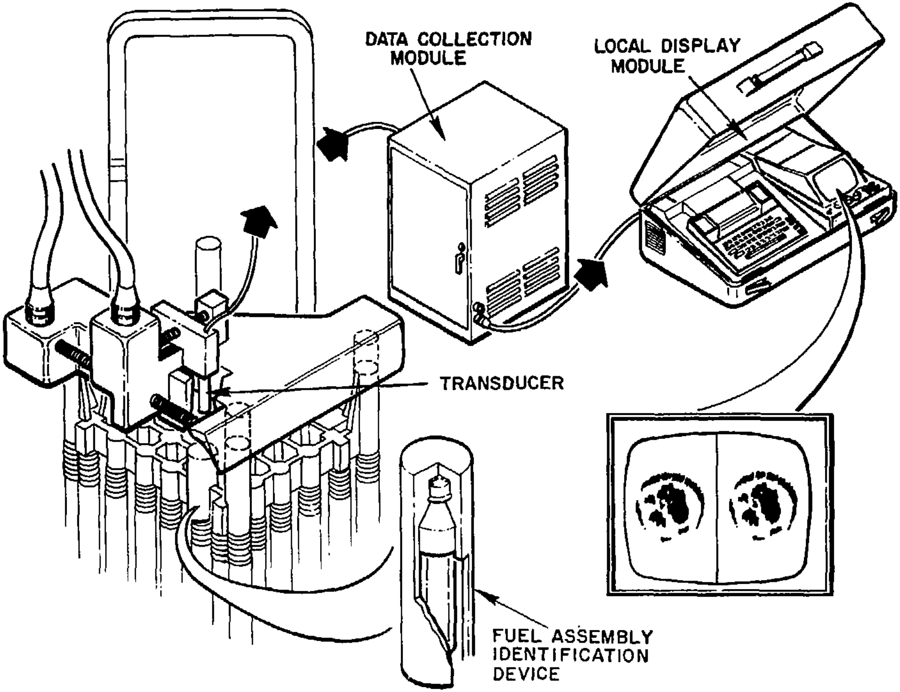
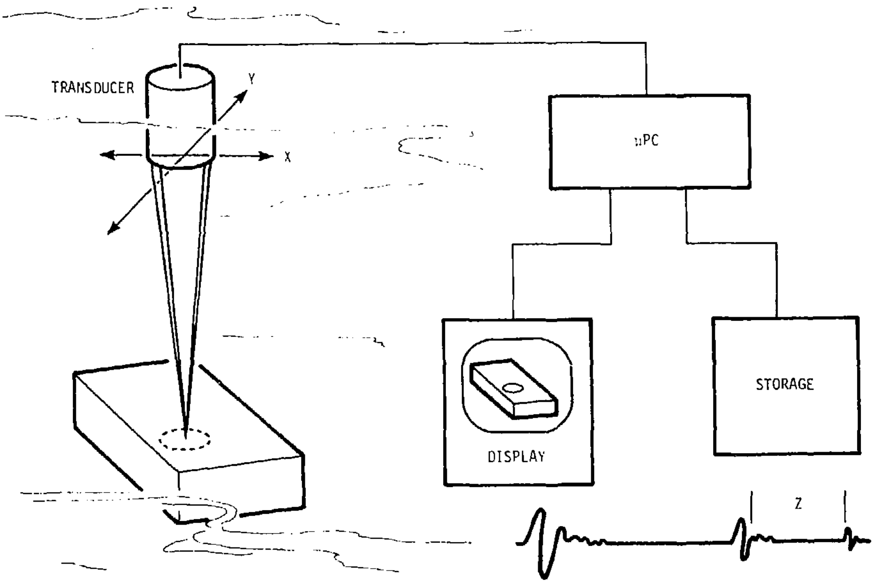


Figure 21. Fuel Assembly Identification System



1 RELATIVE AMPLITUDE
2 TIME DELAY
3 X Y POSITION
4 ULTRASONIC VELOCITY

Figure 22. High Resolution Ultrasonic Identification

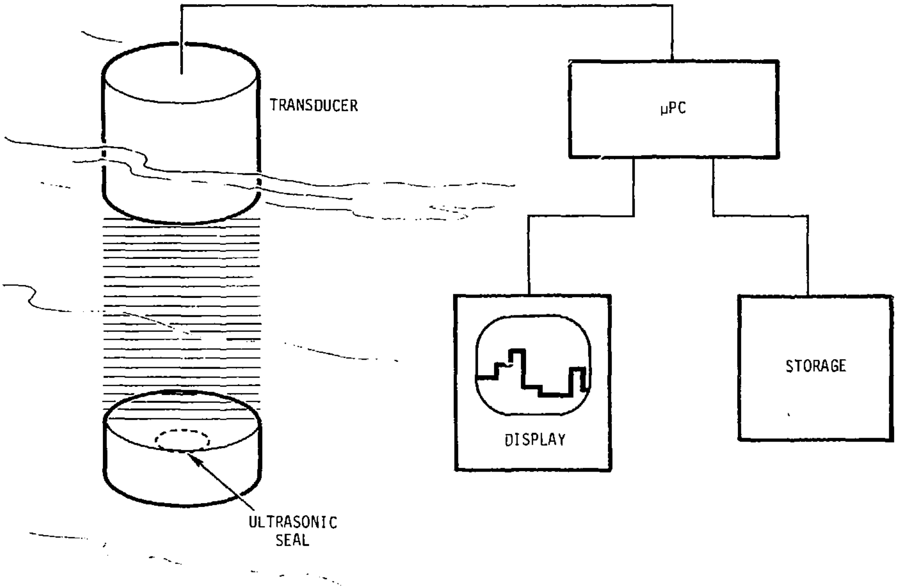


Figure 23. Information vs. Depth (Z) Ultrasonic Identification

prevent undetectable disassembly while in place, (c) can be interrogated in place, and (d) is compatible with all fuel assembly environment conditions.

2) FAID readers which can be positioned over the FAID while it is attached to the fuel assemblies, either as fresh fuel or as irradiated fuel stored underwater.

3) The establishment of criteria and development of a system for automating the FAID identification process.

Initially, FAIDs will be attached to selected spent fuel assemblies. This will require the development of a remote attachment tool because the spent fuel is highly radioactive and is stored underwater.

The in-place FAID reader will also have to be remotely attached. This will require an alignment fixture on the reader so that the interrogation transducer can be manually placed over the FAID with sufficient accuracy to give repeatable results. The Z-axis-only reader is not expected to require a great deal of development effort. The scanning reader, however, is a much more difficult problem. An optical system may be required that will allow the operator to see down through the water to align the reader and to read the external markings on the FAID for identification cross checks. It should also be capable of allowing a general visual inspection of the top of the fuel assembly. Ideally, the optical system would be part of the remote handling device for the FAID reader.

A feasibility model for the Z-axis seal reader is scheduled to be built first. The scanning reader feasibility model is scheduled to follow, if required. Testing and evaluation of these readers will follow. As previously mentioned, the long-term goal is to develop FAIDs which can be attached to fuel assemblies at the time of manufacture and will remain in place for the life of the fuel. This will require the testing and certification for in-reactor use.

C. Interfacility Transportation

The interfacility transporation of spent nuclear fuel is assumed to include only surface vehicles such as truck, train, barge and ship. The items of interest during a fuel shipment are the status of the fuel cask containment and the geographic location of the cask. In order to adequately monitor these parameters, a RF communications link is required between the vehicle and the monitoring facility.

The fuel cask status can be instrumented with displacement transducers which are microswitch type devices that sense the displacement of the cask or its major components relative to its tied down position. Radiation and temperature sensors could be useful in detecting gross effects associated with the presence of the fuel in the shipping cask.

The vehicle position can be obtained from an existing global radio navigation system. This is a ground based system of VLF transmitters which transmit phase-locked CW signals in the 10-14 kHz range. Receivers and position computing equipment, which computes position coordinates from the received signals, is commercially available.

The system mounted on the transporter will be housed in a tamper-indicating enclosure. The main electronics will be housed in an enclosure similar to the detection systems discussed for the water basin storage facilities.

The technology development required to develop an interfacility transportation monitoring system consists of:

a) Evaluating commercially available components which could be used in the system;

b) Designing and building system elements using the most suitable components;

c) Performance-testing the elements under simulated and actual fuel transportation operations.

D. Central Monitoring and Display Module

This section provides a conceptual description of the Central Monitoring and Display Module. The purpose of the CMDM is to provide timely reporting of diversions through the receipt, interpretation, display and storage of data gathered from all spent fuel storage facilities. This data is also gathered during interfacility transporation and encompasses a specified geographical area or region en route. The data concerns containment and surveillance of spent reactor fuel at the reactor facility (AR), at away-from-reactor (AFR) storage sites, and during the related interfacility shipments. The shipments are transported in specially equipped trucks that have been adapted to send status information over High Frequency Radio or satellite data systems.

The data from the AR and AFR sites are gathered by the data collection modules where initial interpretations are made. The CMDM provides the capability for further interpretation, permanent storage, distribution and display of the data. To aid in timely detection, the DCMs are to be interrogated approximately once each day by the CMDM. This data transmission may take place over telephone lines or satellite data links. The requirement for dedicated communication links has been avoided by providing data interpretation and storage capabilities at the DCMs. For example, each DCM will initiate TV picture storage in the event that the sensor data indicates questionable operations. The exact data base of normal versus questionable operations will have to be generated on the basis of observations from each facility during the initial installation and checkout phase. In operation, the DCM will poll the sensors and tamper status indicators every few seconds and perform the calculations which determine whether or not the operation is normal. When the sensor data is transmitted to the CMDM, related TV pictures can be requested for transmission, as required.

An artist's concept of the CMDM, consisting of two rooms, is shown in Figure 24. One room contains the computer equipment and is intended for specialized computer type operations. The second room contains a local operations terminal, a video display unit and a video hard copy unit. These

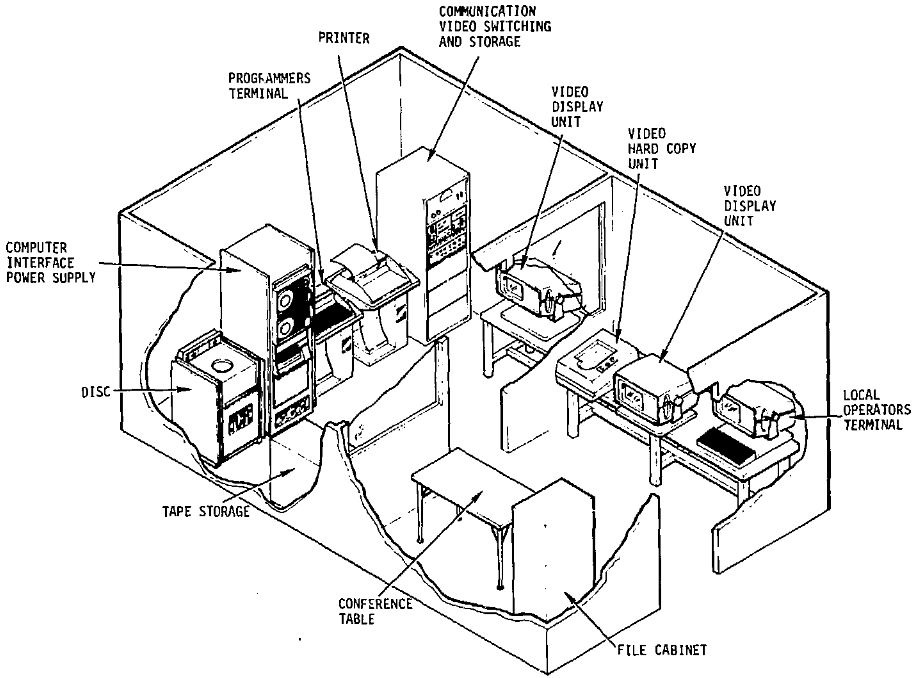


Figure 24. Central Monitoring and Display Module

devices, along with the line printer in the computer room, will enable the display of any of the recorded information in various forms. This enables detailed analysis to be made of conditions over any desired period of time.

Figure 25 shows the data flow into and through the CMDM. Data inputs are shown from only one source; however, the Prototype CMDM is designed to handle many separate sources. A simplified block diagram of the Central Monitoring and Display Module is given in Figure 26 with a more detailed diagram illustrated in Figure 27.

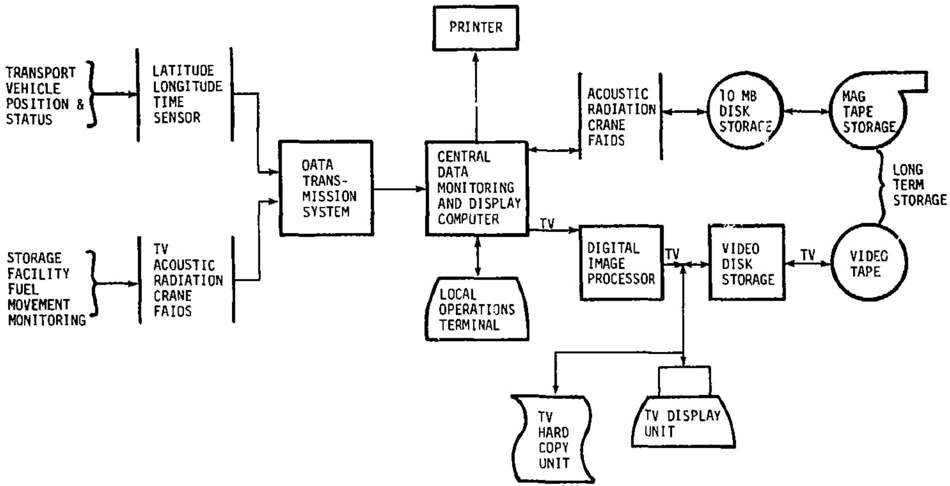


Figure 25. Central Monitoring and Display Module Data Flow

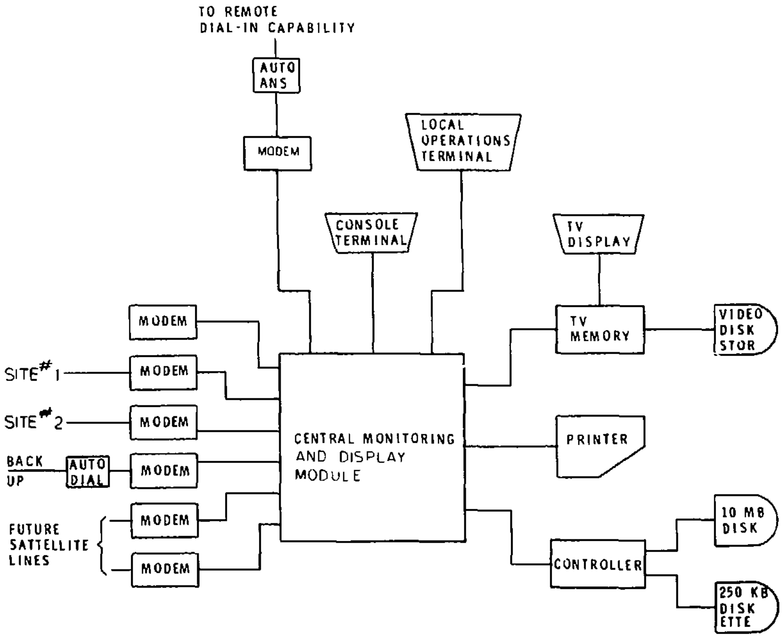


Figure 26. Central Monitoring and Display Module Computer System-Simplified Diagram

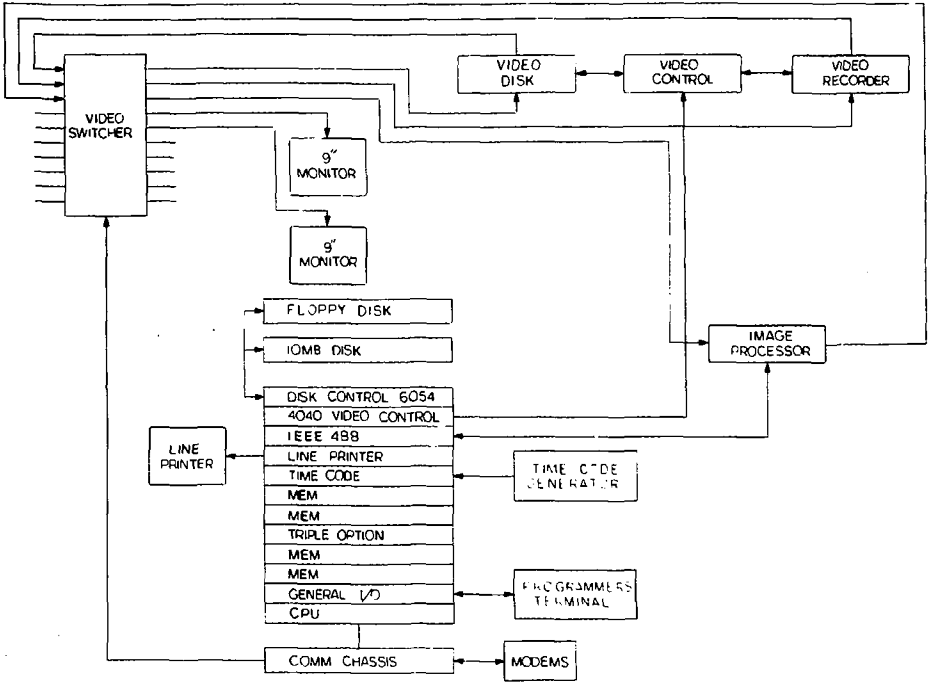


Figure 27. Central Monitoring and Display Module Block Diagram

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