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Assessment of Current Onsite Inspection Techniques for Light-Water Reactor Fuel Systems

Executive Summary

Prepared by W. J. Bailey, C. J. Morris, F. R. Reich, K. L. Swinth

Pacific Northwest Laboratory

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CONTENTS-VOLUME 1, EXECUTIVE SUMMARY

CONTENTS-VOLUME 2, DISCUSSION OF INSPECTION TECHNIQUES

FIGURES

TABLES

1. SUMMARY

Onsite inspections of nuclear reactor fuel systems yield important evidence of the actual performance of the fuel. At domestic commercial light water reactors, these onsite inspections are generally performed in the spent fuel storage pools either during an outage or during reactor operation; however, when the reactor is shutdown (e.g., for refueling), some inspections are performed on fuel while it is still in the core. The assessment of current onsite inspection techniques for fuel systems is one objective of the Fuel Operational Performance Program at Pacific Northwest Laboratory, sponsored by the Division of Operating Reactors of the Nuclear Regulatory Commission. This report contains the results of the assessment of those onsite inspection techniques presently used on fuel system components. These inspection techniques include visual, gamma scanning, sipping, mensural, eddy current, and ultrasonic. The assessment consisted of a literature survey, meetings with all five reactor fuel suppliers, and visits to three reactor sites. The purpose of the meetings was to discuss the approach used by suppliers at reactor sites.

2. INTRODUCTION

Pacific Northwest Laboratory (PNL) is assessing the quality of onsite (i.e., poolside) examination techniques currently used for fuel systems associated with domestic commercial light water reactors (LWRs) for the Nuclear Regulatory Commission's (NRC) Division of Operating Reactors (DOR).

The immediate purpose for poolside fuel inspections is to obtain data on the actual performance of the fuel and to monitor whether abnormal distortion or corrosion (e.g., of the type that might endanger either fuel rod integrity or reactor core thermal hydraulics) is occurring (Ref. 1). Such inspections are performed on fuel systems that have completed their intended service life and those that are yet to complete their service life. For fuel that is scheduled to be returned to the core, the inspections generally must be performed during a refueling outage in the spent fuel pool. Examples of spent fuel pools and fuel handling facilities at a boiling water reactor (BWR) and a pressurized water reactor (PWR) are shown in Figures 2.1-2.4 (Ref. 2). With spent fuel, the inspections can be conducted during reactor operation in the spent fuel storage pool.

Actual fuel performance can be indicated by many observable parameters. With poolside inspection techniques, the observable fuel performance parameters include those shown in Table 2.1. Each of these fuel performance parameters can be observed by more than one poolside inspection technique.

The NRC staff has studied the general background of onsite fuel inspections and made several observations (Ref. 3). In general, the reactor fuel community recognizes the usefulness of poolside inspection techniques and the enhancement of the national power generation capacity resulting from the identification (localization) and removal of failed (and only failed) fuel system components. These techniques apply to spent fuel and to fuel examined during interim reloading outages. Unanticipated problems at operating reactors (e.g., hydride failures, fuel column gaps, channel box wear, fuel rod bowing, control element guide tube wear, and torn spacer grids) have been identified using these poolside inspection techniques. In the current complex reactor fuel systems, not

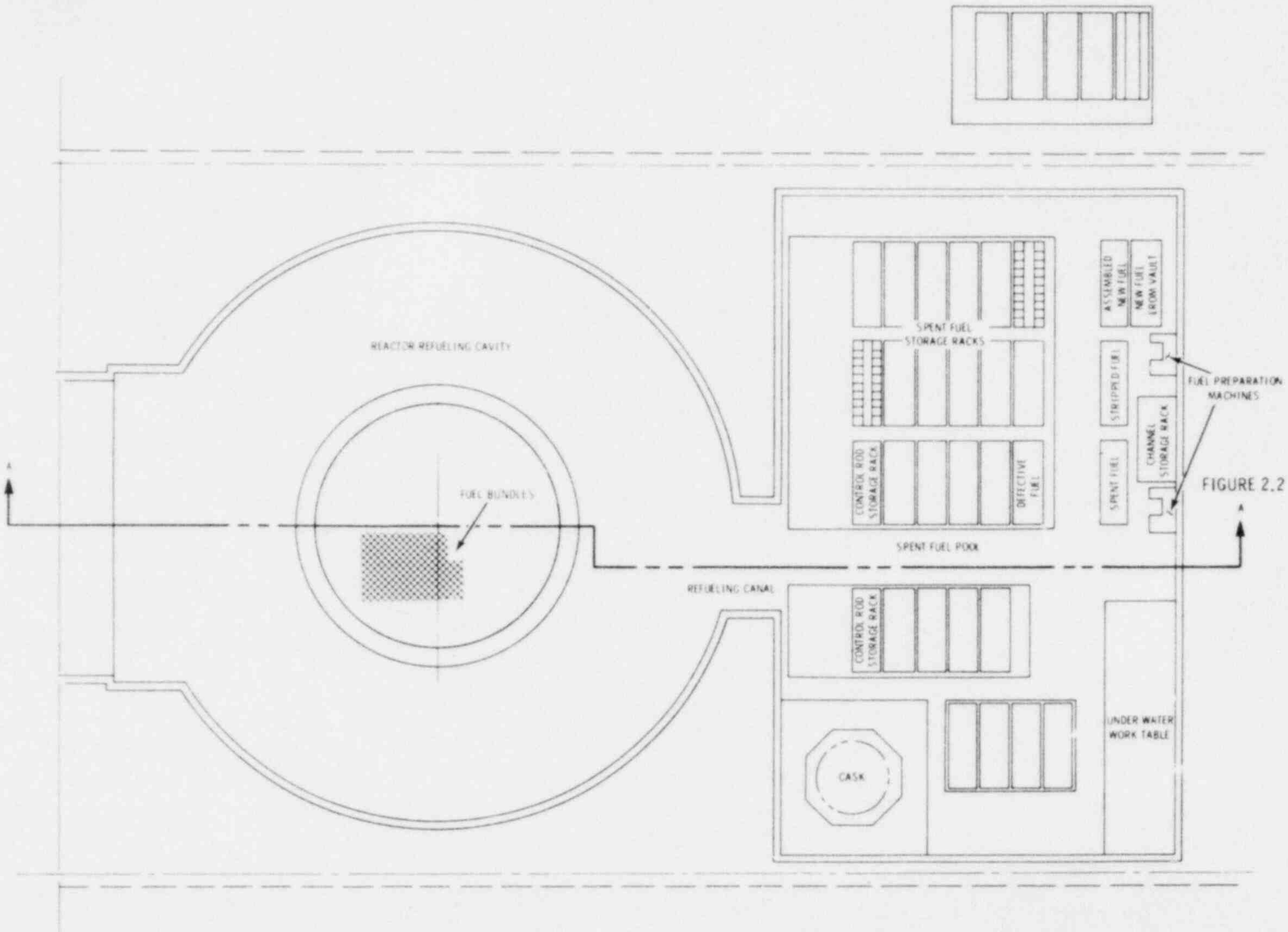


FIGURE 2.1. Example of BWR Spent Fuel Pool and Fuel Handling Facilities (plan view)

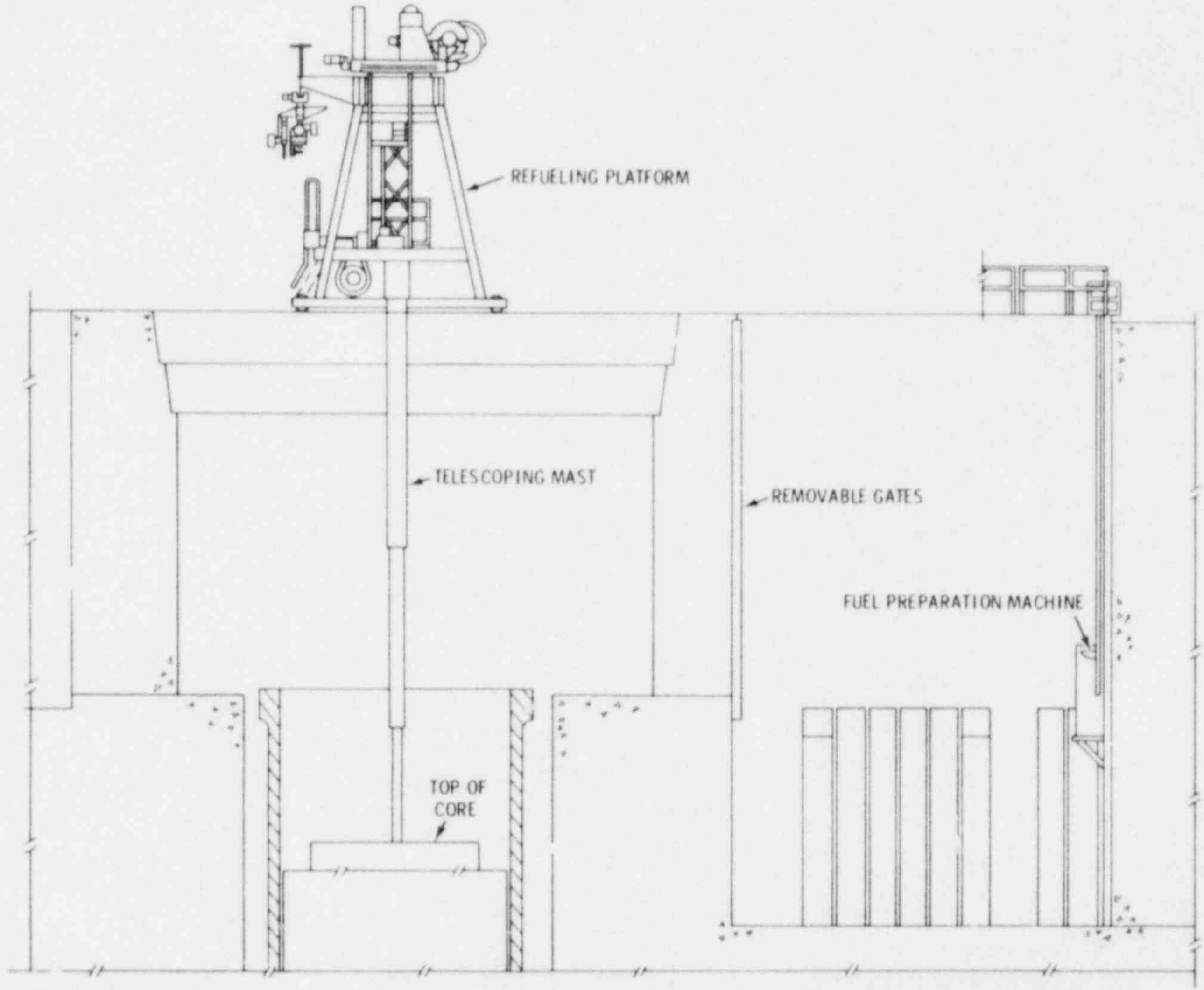


FIGURE 2.2. Example of BWR Spent Fuel Pool and Fuel Handling Facilities (cross-sectional view)

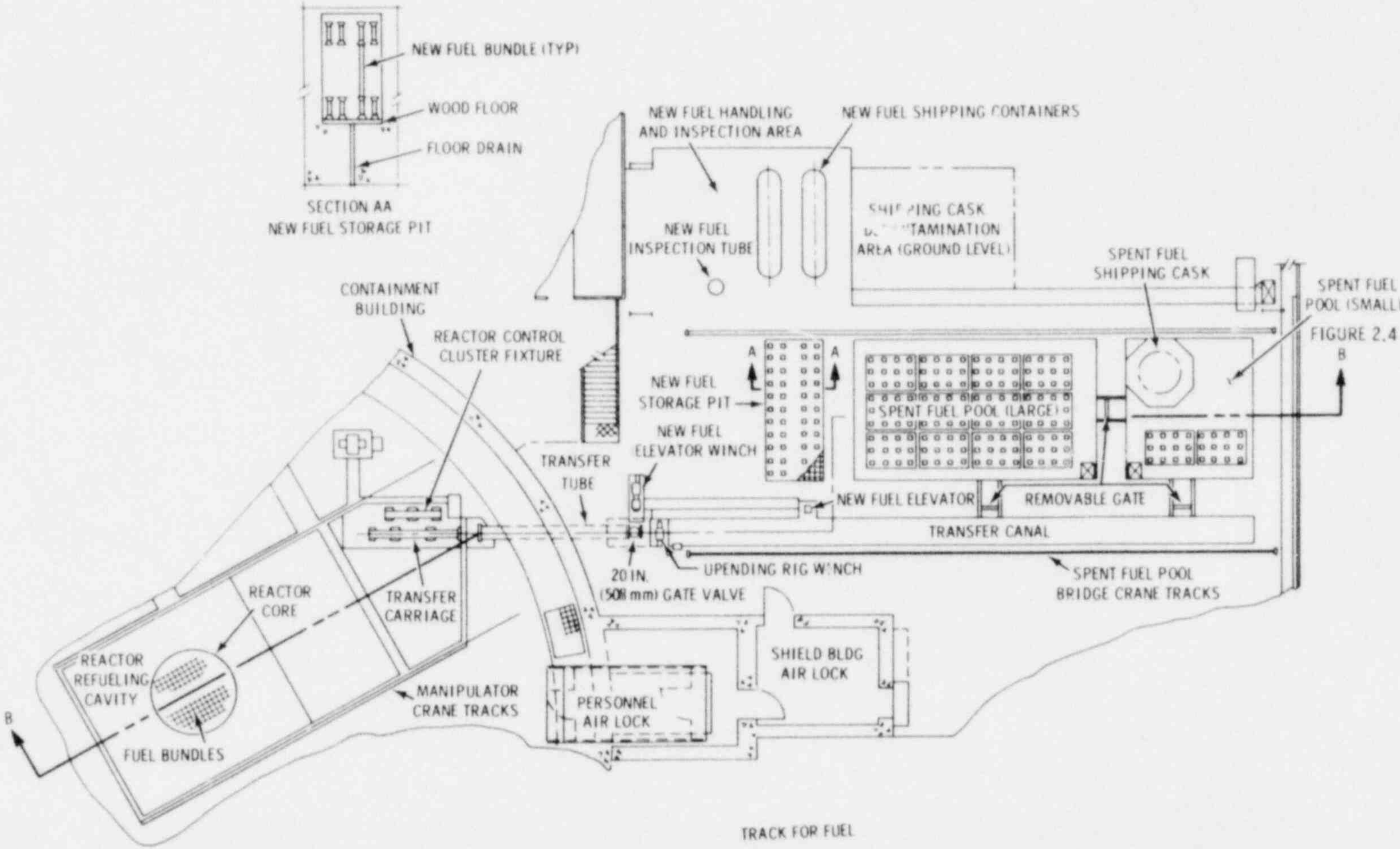


FIGURE 2.3. Example of PWR Spent Fuel Pool and Fuel Handling Facilities (plan view)

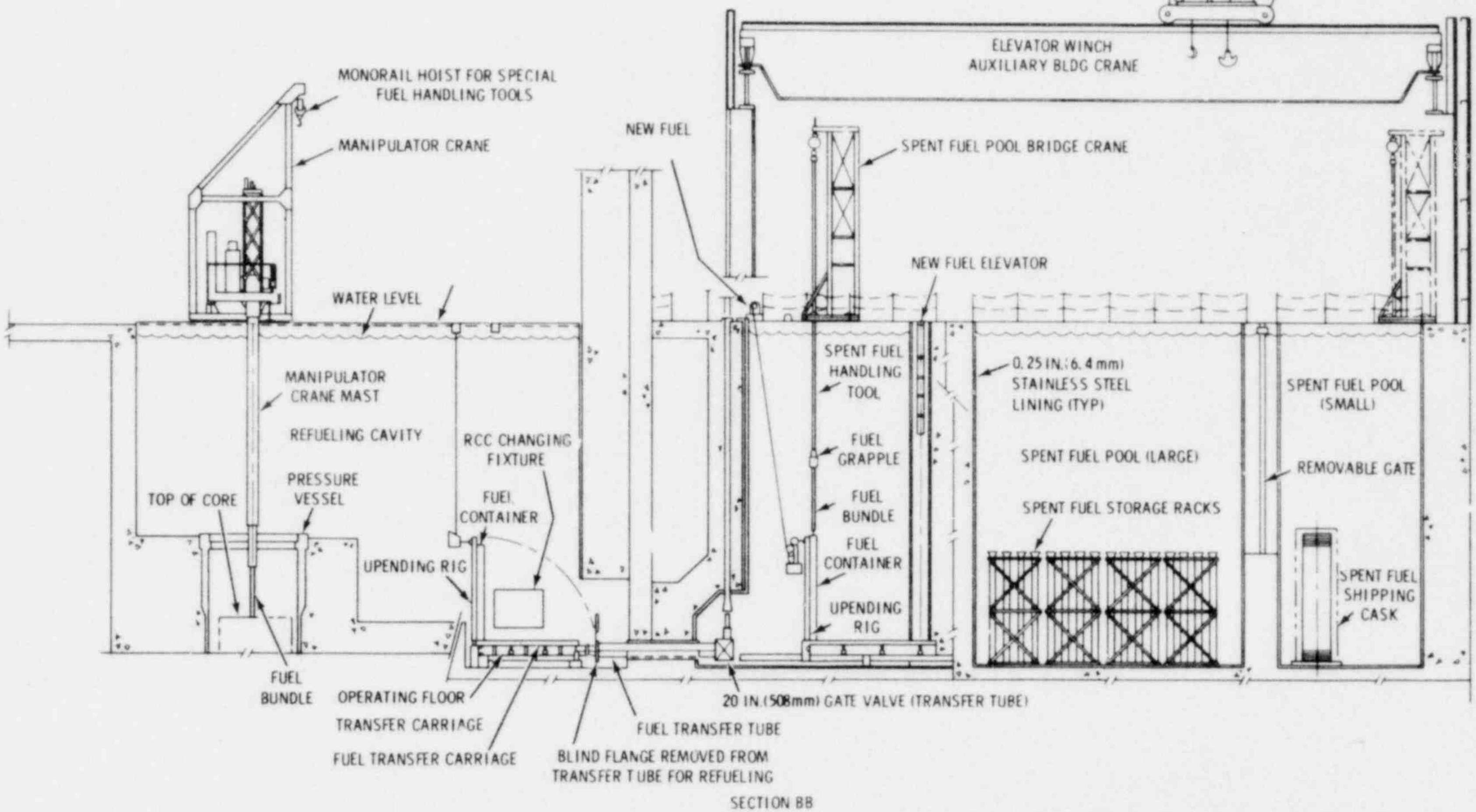


FIGURE 2.4. Example of PWR Spent Fuel Pool and Fuel Handling Facilities (cross-sectional view)

TABLE 2.1. Fuel Performance Parameters Observable by Poolside Inspection Techniques

Fuel System Component	Parameter	Inspection Technique
BWR Fuel Channel Box	• Bowing	Mensural, Visual
	• Corner Wear	Mensural, Visual
	• Displacement	Mensural
	• Flatness	Mensural
	• Twist	Mensural
Crud On Fuel Bundle, Fuel Rod, and BWR Channel Box	• Composition	Sampling and Analysis
	• Condition and Pattern	Visual
	• Thickness	Eddy Current, Mensural
Fuel Bundle	• Bowing	Mensural, Visual
	• Corner Fuel Rods:	
	- Active Fuel Column:	
	- Axial Gaps	Gamma Scanning
	- Height	Gamma Scanning
	- Relative Power	Gamma Scanning
	- Profile (OD)	Mensural
	• Fuel Rod-to-Fuel Bundle Upper End Fitting Gap	Mensural
	• Fuel Rod Cladding, End Plug, and Weld Integrity[a,b]	Sipping, Visual
	• Fuel Rod-to-Fuel Rod[a] Spacing (i.e., water channel width)	Mensural, Visual
	• Fuel Rod[a]-to-Guide Tube Spacing (i.e., water channel width)	Mensural, Visual
	• Fuel Rod[a] Withdrawal Force	Mensural
	• Holddown Spring Force	Mensural
	• Identification	Visual
	• Length	Mensural
	• Weight	Mensural
Fuel Rod	• Active Fuel Column:	
	- Axial Gaps	Gamma Scanning
	- Height	Gamma Scanning
	- Relative Power	Gamma Scanning
	• Cladding:	
	- Corrosion Variations[a]	Eddy Current, Mensural, Ultrasonic, Visual
	- Degradation[a]	Eddy Current, Mensural, Ultrasonic, Visual
	- Diameter[a]	Eddy Current, Mensural, Visual
	- Fretting Wear[a]	Eddy Current, Mensural, Visual
	- Fuel-to-Cladding Bonding	Ultrasonic
	- Hydriding[a]	Eddy Current, Ultrasonic, Visual
	- Incipient Defects[a]	Eddy Current, Ultrasonic
	- Integrity[a,b]	Eddy Current, Ultrasonic, Visual
	- Ovality[a]	Mensural
	- Ridge Height[a]	Mensural
	• End Plug:	
	- Identification[a] (for enrichment in fuel rods)	Visual
	- Integrity[a,b]	Visual
	• Identification[a]	Visual
	• Length[a]	Mensural
	• Moisture Inside Fuel Rod[a]	Ultrasonic
Guide Tube	• Structural Integrity	Eddy Current, Visual
	• Inside Diameter	Eddy Current, Mensural (only on part of tube)
	• Wear	Eddy Current, Mensural, Visual
Spacer Grid	• Structural Integrity	Visual
	• Position	Mensural, Visual
	• Spring Force	Mensural

(a) Also applies to burnable poison rods.
(b) Specifically leak-tight integrity to fluids and structural integrity.

all the latent vulnerabilities can be eliminated through design and safety reviews. Thus, the NRC considers the continued use of poolside inspection techniques a prudent measure.

The DOR noted six problems in the NRC staff's understanding of the current status of poolside inspection techniques for fuel systems. Those six problems are:

1. Whether or not the fuel is failed can depend on how closely the fuel is inspected and on the capability of the inspection technique being used. It can also depend on the time the inspection takes place.
2. The control over the quality of each technique is neither systematic nor uniform. There is limited calibration both among techniques at the same site and between the same technique at different sites. There is no calibration to a consensus standard.
3. The threshold for what constitutes abnormal degradation is not uniform and remains a matter of opinion. Therefore, the degree of reported degradation is not uniform.
4. There is no definitive answer to the following question: Is there a safety need to enhance the detection of defective fuel during interim examinations?
5. It is not clear whether nondestructive examinations have a detrimental effect on fuel behavior in subsequent operations. In other words, how nondestructive is nondestructive testing?
6. When reviewing proposed spent fuel storage pool modifications, there also remains a question about what effects of future fuel inspections should be considered. That is, will or should there be room in the pool area for inspection to be performed?

The program at PNL was outlined to aid in solving these problems by providing a report that assesses the quality of current poolside examination techniques. The objectives are:

- to characterize poolside inspection techniques for reactor fuel by description and design (principle of operation), range of parameters measured, sensitivity within range, precision (repeatability and reproducibility), accuracy (correlated with other techniques and absolute standards), response time and test frequency, and environmental limits (e.g., pressure, temperature, relative humidity, neutron fluence, impact load, vibration)
- to objectively determine the quality of fuel performance
- to enhance the detection of defective fuels during interim examinations
- to correlate poolside inspection results with responses from on-line monitors.

The scope and content of the report are summarized in Table 2.2.

The initial work at PNL involved a search and review of available literature on poolside fuel inspection techniques. As indicated to NRC by PNL during the early stages of the study, the search and review yielded only a limited amount of information on the design and operation of the inspection equipment, on the experience with such equipment, and on the criteria used to discriminate between defective, suspect, and intact fuel. That review also showed that there was a genuine paucity of meaningful information on the quality of poolside fuel inspection techniques. It was apparent that the data from publicly available sources were insufficient for the assessment. PNL stated that there was a need to either obtain proprietary documents on the various fuel inspection techniques employed and/or have discussions with fuel inspection engineers.

NRC arranged for NRC-PNL meetings with five fuel vendors and at three reactor sites, as shown in Table 2.3.

TABLE 2.2. Current Poolside Inspection Techniques That Are To Be Quantitatively Assessed for NRC

Poolside Inspection Techniques[(a)]	Components Being Inspected: Fuel Rods	Fuel Bundles	Channel Boxes	Effects Sensed by Technique
1. Visual				
a. Optical	X	X	X	Integrity, Crud, Bowing
b. Photography	X	X	X	Integrity, Crud, Bowing
c. Television	X	X	X	Integrity, Crud, Bowing
2. Gamma Scan	X			Relative Power (Recent) Fuel Column Height, Fuel Column Axial Gaps
3. Sipping (Core Also)				
a. Wet		X		Integrity
b. Dry		X		Integrity
c. Hybrid		X		Integrity
d. Vacuum		X		Integrity
4. Mensural				
a. Profile	X		X	Creep, Bowing, Growth
b. Gaps		X		Creep, Bowing
c. Lengths/Widths	X	X	X	Creep, Growth
5. Eddy Current	X			Integrity, Incipient Defects
6. Ultrasonic	X			Integrity, Incipient Defects, Fuel-Cladding Bonding

(a) NRC is interested in these characteristics of the poolside inspection techniques:

- Description and design (principle of operation)
- Range of parameters measured
- Sensitivity within range
- Precision (repeatibility and reproducibility)
- Accuracy (correlation with other techniques and absolute standards)
- Response time and test frequency
- Milieu limits (e.g., pressure, temperature, relative humidity, neutron fluence, impact load, vibration)

TABLE 2.3. Chronological Order of Meetings with Fuel Vendors and Utilities

Fuel Vendor	Utility	Place of Meeting
	Commonwealth Edison Company	Dresden Nuclear Power Station
	Commonwealth Edison Company	Zion Nuclear Power Station
Westinghouse Electric Corp.		Westinghouse Nuclear Center in Monroeville, PA
Babcock and Wilcox Company		Babcock and Wilcox Research Center in Lynchburg, VA
General Electric Company		General Electric Company in San Jose, CA
	Portland General Electric Company	Trojan Nuclear Plant
Exxon Nuclear Company		Exxon Nuclear Company's Plant Site on Horn Rapids Road in Richland, WA
Combustion Engineering, Inc.		Combustion Engineering, Inc. in Windsor, CT

In conducting the assessment of the visual, gamma scanning, mensural, eddy-current, and ultrasonic inspection techniques, two cases were considered where possible:

Case	Comments
(1) Inspection of irradiated fuel system components that are located in the spent fuel storage pool of a commercial LWR.	This is the case of prime interest to NRC; hence, of the two cases, it carried the highest priority in this study.
(2) Inspection of irradiated fuel system components that are located in a hot cell.[a]	This case is of limited interest to this study, but it aids in understanding how well we can inspect irradiated fuel system components under the best conditions.

Recent Administration deferral of reprocessing and recycling has prompted a reevaluation of fuel management strategy. Preliminary studies have shown that significant savings are possible by extending the peak fuel pellet burnup from the current 3456 GJ/kg of heavy metal (40,000 MWd/MTU[b]) to 5184 GJ/kg of heavy metal (60,000 MWd/MTU) (Refs. 4 and 5). However, the savings are contingent on maintaining fuel rod integrity[c] to prevent unscheduled outages. If extended fuel burnup is pursued, improvements in both nondestructive inspection methods and nondestructive evaluation will likely be required in

(a) Hot cells are heavily shielded examination facilities where testing operations on radioactive objects may be performed remotely. Cell environments are strictly monitored and controlled: temperature, humidity, and even atmospheric composition are regulated. Hot cell facilities are expensive, high technology installations; there are three domestic facilities (Babcock & Wilcox Company; Battelle Columbus Laboratories; and EG&G Idaho, Inc.) large and well-equipped enough to handle full-length commercial reactor size fuel.

(b) Megawatt days of thermal energy released by fuel containing one metric ton (10^6 grams) of heavy-metal atoms such as uranium (MWd/MTU).

(c) Specifically, leak-tight integrity to fluids and structural integrity.

anticipation of the potential for an increase in the number of defective fuel rods. Improvements in fuel bundle design inspectability and nondestructive testing methods could significantly decrease both the time required to locate leaking fuel bundles and the time subsequently needed to locate the defective fuel rod(s) in the bundle. Improvements in nondestructive evaluation of both qualitative and quantitative measurement data will increase measurement reliability. These improvements will also assist in the decision processes leading to criteria for fuel rod acceptance or replacement.

3. OVERVIEW

3.1 General Comments

Poolside inspection techniques do more than identify "failed" fuel bundles; many of the techniques are useful as fuel performance indicators. Utilities use poolside inspection for fuel warranty purposes and for investigating fuel bundle conditions associated with anomalous reactor operations. Nuclear fuel vendors use poolside inspection to verify new fuel performance and the predictive capability of their fuel codes. From NRC's viewpoint, detection of failed fuel (i.e., failure of the cladding to perform its safety functions) is of primary interest and detection of fuel anomalies is of secondary interest.

In general, there are four reasons for poolside inspections: to verify codes, to comply with the fuel warranty, to diagnose fuel problems, and to monitor performance of fuel design changes. Not all fuel is inspected regularly (Ref. 1). Typically, sipping is done at BWRs if on-line monitors have indicated fuel failures are present. Visual inspection is typically done at PWRs if the radioactivity in the effluents is high. An individual at one vendor organization stated that most of their success in identifying operating fuel problems other than breaches in cladding comes from cursory visual inspections and not from detailed inspection for fuel research and development purposes.

In discussing detailed poolside inspection techniques with fuel vendors and utilities, several general conclusions are evident. There is no standard poolside inspection campaign when detailed inspection data are to be obtained. The general attitude is that a detailed poolside inspection is not necessary during an outage if the reactor operation preceeding the outage has been normal (i.e., coolant radioactivity has been low). Most utilities do not have the expertise or hardware for the detailed poolside inspection of fuel. It is apparent that onsite quantitative detailed inspections of irradiated fuel are not routine, can only be performed by each fuel vendor at a few plants per year, and are very expensive in dollars and personnel (Ref. 6). Some spent fuel storage pools lack available space for detailed inspection techniques.

Generally, a fuel vendor has only one or two special fuel inspection stands (Figure 3.1) because they are precision-made apparatuses with limited use. Some stands can be transported and thus are used for approximately two inspections per year.

There is a potential hazard to fuel integrity as a result of the fuel inspection technique itself. Fortunately, only a few actual cases were noted. Mishandling of fuel has occurred during inspections (e.g., fuel bundles and fuel rods have been dropped (Ref. 7) and spacer grids have been damaged). In one case, a fuel rod hung up in an eddy current test coil. In another case, a small thermal cycle during dry sipping may have been a contributing factor in the abrupt scale spallation observed in the subsequent reactor cycle (Ref. 8).

Inspection rights are apparently not included in current fuel contracts. Poolside fuel inspection is typically covered by a separate proprietary contract that outlines responsibilities, liabilities, and costs for all involved parties. That contract also contains the complete inspection procedure. Interestingly, of the total man-hours required to plan, execute, and conclude a poolside inspection program, the onsite poolside inspection (i.e., data gathering) generally represents only about 10% of the total (Ref. 3).

In general, poolside inspection is not considered a high priority item during a reactor outage by the utility, and planned inspections may have to be deleted or modified to avoid the outage critical path. Also, the equipment frequently malfunctions, thus preventing completion of all planned inspections during refueling outages (Ref. 3).

Some fuel vendors stated that mandatory poolside inspections at more reactors would decrease the detail of the collected data. The decrease would occur because the available resources (personnel, equipment, and time) for fuel inspection would be reduced.

The definition of failed fuel is tied to the functional, legal, and detection requirements on the fuel. The designation of fuel as failed depends on which functional requirement is not met (safety, commercial, design), whether or not there is a legal contingency on that requirement (Technical Specification, fuel warranty, design basis), and which indicator is used (coolant or off-gas

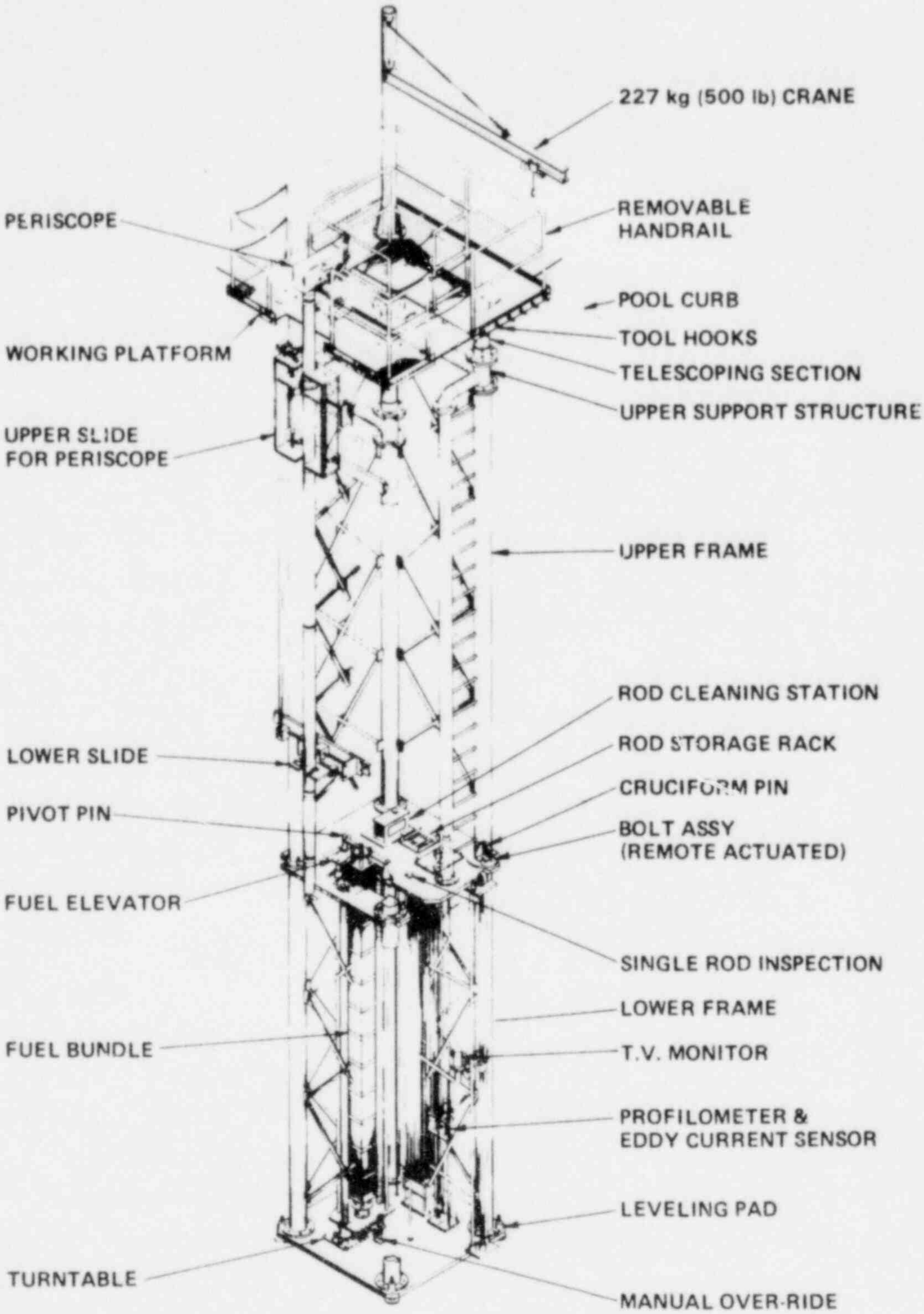


FIGURE 3.1. An Example of a Large Special Fuel Inspection Stand

activity, sipping, strain, or deflection). Thus, the definition can vary from outage to outage and from reload to reload for each utility as the considerations change. At present, it does not appear feasible to use a predetermined threshold of fuel failure with the inspection techniques assessed in this report.

To date, attempts by one fuel vendor to correlate fuel rod data and reactor coolant activity have not produced a reliable correlation, possibly due to the limited number of fuel rods evaluated.

Radionuclide escape rate coefficients from the fuel and the fuel-cladding gap are two of the most sensitive, but least understood parameters employed for evaluation of fuel rod cladding (Ref. 9). The coefficients are dependent on fuel temperature and vary by orders of magnitude from one another; experimental data are sparse. When estimating the fraction of defective fuel in the reactor core by using the fission product activity in the reactor coolant as a base, the estimate is a strong function of the values assigned to those two parameters.

An NRC study performed by Oak Ridge National Laboratory concluded that incorporation of "tags" (i.e., krypton-xenon mixtures) in normal LWR fuel does not appear to be a practical aid for identifying failed fuel rods in commercial LWRs. The study also stated that no methods currently exist for identifying the chemical forms of the fission product nuclides that are released from failed fuel rods and that data on the physical forms of released material are sparse.

Several fuel vendors indicated that there is a serious question concerning the real cost-benefit of any inspection data other than visual, dimensional, and sipping measurements. They further point out that all LWRs were designed in anticipation of some fuel rod cladding failures; therefore, the cost to detect and replace several leaking fuel rods among the many thousands of fuel rods in the core has economic disincentives. In addition, the probability of damaging the fuel bundle or individual rod(s) increases with the scope of the fuel inspection program. Other considerations include the potential for increasing the occupational exposure and the generation of significant amounts of low-level radioactive waste as more fuel inspections are performed.

Currently, there are inherent difficulties in trying to combine or directly compare data (i.e., results derived from onsite inspections of fuel systems) from fuel experience reports from different fuel vendors and utilities for a number of reasons. Those reasons are described in the subsections below, but briefly they include the following: there is nonuniform emphasis on visual examination, a subjective inspection technique; sipping is a relative measurement; standards are not generally used during poolside gamma scanning; there is no standard mensural campaign; there is a lack of standardization for poolside eddy-current and ultrasonic testing. Two other reasons, mentioned earlier, are the variations in the definition of failed fuel and the lack of uniformity in deciding what constitutes abnormal degradation.

It is possible to unintentionally overlook some fuel bundles with defective fuel rods if you depend on the results from only visual inspection (see 3.2) or from only sipping (see 3.4) of fuel bundles, the two routinely used fuel bundle inspection techniques.

If only fuel bundles are inspected (i.e., if bundles are not dissembled for individual rod inspection), there is an inherent difficulty in accurately determining the total number of failed fuel rods present.

In those cases where fuel rods are removed from the fuel bundle for inspection, the detection of failed rods (other than those obviously failed rods identified visually) is a reasonably established procedure, using either or both eddy-current and ultrasonic testing; however, the detection of incipiently failed rods is not (Ref. 1).

Reference 10 indicates that the use of coolant activity measurements (rather than inferring numbers of defective fuel rods during reactor operation) to assess fuel performance does not show the increased fuel rod failure rate occurring later in life due to pellet-cladding interaction.

Mainly because of the problems associated with fuel shipments and waste disposal, there is a trend toward larger fuel inspection programs at poolside and smaller hot cell examination programs (Ref. 1). As part of the study for

NRC, PNL compared the capabilities of inspection techniques for fuel systems at poolside and at hot cell facilities--however, this does not imply that hot cell technology should be used as standards or performance goals for fuel inspections at poolside. With visual inspection, much finer optical details can be observed and photographed in a hot cell because optical conditions are much more controllable. More emphasis is placed on color and detail in hot cell visual examinations because the typical objective is to determine the cause of fuel rod failures or anomalies. With some inspection techniques (e.g., gamma scanning, mensural), there appears to be as much as an order-of-magnitude difference between in-pool and hot cell measurements. Although improved positioning accuracy and smaller collimator slits (higher resolution) are evident with the hot cell gamma scanning equipment, the long scanning times are not compatible with poolside inspection operations. Techniques such as precision (quantitative) gamma scanning, three-dimensional reconstruction, and scans of sectioned fuel rods are performed at hot cell facilities, but they are not presently feasible as poolside. Today, the differences in gaging accuracy between hot cell and poolside measural inspection equipment are being rapidly eliminated. Poolside mensuration, which used to be more of a macroscopic analysis tool, is now becoming a microscopic area, similar to today's hot cell technology. Almost all of the mensural inspection tasks that were formerly performed in a hot cell can now be done in a spent fuel storage pool. Single-frequency eddy-current systems are currently used at poolside; however, not all fuel vendors agree that such systems are adequate for fuel rod inspection. Single-frequency, multiple-frequency, and pulsed eddy-current systems are used in hot cells; however, the last two are presenty considered by fuel vendors to be research and development techniques. Many fuel rods have been inspected at poolside using the ultrasonic leaker test (see 3.7). A limited number of fuel rods have been inspected at poolside using the ultrasonic defect test and the ultrasonic pellet-cladding bond test, two techniques that are currently under development (the reliability and sensitivity of these two tests are undetermined at this time). Ultrasonic inspection of fuel rods in hot cells has shown the potential to detect incipient defects in cladding that are less than 10% of the cladding wall thickness.

Uncanned spent fuel is now being stored in pools in the interim until policy questions concerning reprocessing and ultimate disposal are fully resolved (Ref. 11). It is also pointed out in that reference that presently there is no basis to assume that discernible degradation of spent fuel bundles is occurring; however, it is also not clear how long pool storage of spent fuel may be extended. As a result, it will be important to continue confirming by inspection that spent fuel can be satisfactorily stored for extensive periods in water. It would appear prudent to have sufficient space available to accommodate fuel inspection equipment at reactor spent fuel pools and at other spent fuel storage facility pools.

3.2 Visual Inspection

Visual inspection is normally a very tedious, subjective task. The key visual inspection tasks are bundle integrity and the identification of anomalies. However, the role of visual inspection is not uniformly emphasized. The main inspection tool for BWRs is sipping and visual inspection is used for verification. In a PWR inspection campaign, detailed visual inspection may be the only poolside inspection performed.

Standardization for visual inspections comes from trained and experienced inspectors. No "book of standards" was discovered. However, equipment and procedures for visual inspection are usually well documented.

Poolside visual inspections are limited by the visibility of fuel rod surface areas in a fuel bundle, the subjective judgement of the visual inspector, and the time available for inspection. The fuel vendors and utilities consider visual inspection a poor technique to identify leaking fuel rods from a leaker fuel bundle. Small cladding cracks and perforations are difficult to see unless bubbles are being emitted during the visual inspection. Of those fuel rods ultimately determined to be failed, one fuel vendor indicated that probably only 10% or less are detected by visual inspection of the fuel bundle; one has to disassemble the fuel bundle and inspect individual fuel rods to detect most of the failed rods.

There are varying advantages among the visual tools and equipment. Some poolside inspections are done with periscope only. Periscopes have enough resolution to see the fine detailed anomalies present in modern fuels. Color can be seen with a periscope and that can be a very important inspection factor. Although some inspection campaigns use closed-circuit television (CCTV) alone, others use CCTV with periscope backup for the finer inspection detail and for color evaluations.

3.3 Gamma Scanning Inspection

Gamma scanning is a nondestructive technique used primarily to assess new fuel designs. Poolside gamma scanning inspections sense either gross activity changes or specific isotopes. Gamma scanning is not specifically sensitive to a breach in the fuel rod cladding; hence, it is not directly useful in locating such failure sites on a fuel rod. All fuel vendors performed poolside gamma scanning during the first few years of their commercial activities. All fuel vendors have gamma scan capability (although one vendor no longer uses gamma scanning as one of their poolside nondestructive tests), and one consulting company provides a gamma scanning service. One vendor has a large Electric Power Research Institute (EPRI) program to gamma scan fuel rods for power distribution. Similarly, another fuel vendor is developing an advanced gamma scanner under EPRI sponsorship. Most of the fuel vendors have access to hot cell gamma scanning facilities, and this seems to meet their present requirements. At present, the vendors seldom gamma scan during poolside inspections; the frequency of gamma scanning is less than once per year.

Poolside gamma scanning is used primarily to look at fuel stack height and for gaps in the fuel stack. Fuel stack height measurements can be made to ± 0.66 mm (± 0.026 in.) and gaps as small as ± 0.15 mm (± 0.006 in.) can be resolved. These numbers represent the best reported results, and typical results would be four to ten times larger. Power distributions are also measured at poolside by a few of the vendors, with an accuracy of 3% claimed by one vendor for measurements of ^{140}La. The axial position accuracy at poolside is generally larger than ± 1.27 mm (± 0.050 in.). [By comparison, the position accuracy in a hot cell is typically $\pm$0.051 mm ($\pm$0.002 in.).] Counting standards are not generally used when gamma scanning at poolside.

Poolside gamma scanning takes about one hour per fuel rod after equipment setup and fuel handling. Equipment setup takes more than one day.

Gamma scanning can measure the fission product content of reactor fuels precisely, and thus one can determine the absolute burnup of fuel. If the safeguard issue receives more attention in the future, one of the possible results could be that all inventories of fissionable material might have to be verified by measurements. Gamma scanning at poolside would be a major technique for verification of such inventories.

3.4 Sipping Inspection

Sipping is based on the principle of determining the magnitude of activity from escaping fission products from leaking fuel rods in irradiated fuel bundles that are in the sipping apparatus. Sipping provides a quantitative relative measure of fuel bundle performance, especially for fuel that is grouped according to design and performance characteristics (Ref. 12). Because sipping involves a relative measurement of the activity in the sample in comparison to the previously established background for sound fuel bundles, those fuel bundles with "abnormally" high measurements can only be identified after a number of fuel bundles have been sipped. The absolute magnitude of the sipping signals can vary for a number of reasons: fuel bundle burnup, time since reactor shutdown, and crud level.

Sipping is one of the more accurate examination techniques for determining the integrity of the fuel; however, sipping, as a means of detecting leaking fuel bundles, is not an exact diagnostic technique. It can preferentially detect fuel rod cladding perforations that occur late in the reactor cycle (Ref. 13). Two things can interfere with the detection of old leaks by sipping tests: the cladding penetration can become closed because of crud or other buildup or the entire fission product inventory may not be readily available (due to less than perfect axial communication) for release. One fuel vendor's experience has shown no correlation between sipping results and the size of the fuel rod cladding perforation. Fuel bundles with grossly failed fuel rods may not be readily identified by sipping because no volatile fission products are retained in those rods.

In theory, out-of-core sipping will be more effective than in-core sipping because of higher fuel temperature and lower environmental activity. The leaker detection efficiency of out-of-core wet sipping tends to be 90 or 95% and higher, while that of the newer in-core wet sipping techniques tends to be 80% or greater. However, out-of-core wet sipping is time-consuming (Ref. 14). In-core tests are generally less definitive than out-of-core tests (Ref. 15).

Sipping is used more at domestic BWRs than at domestic PWRs. Fuel handling can be a constraint on the fuel bundle throughput at the sipping station. At BWRs, in-core wet sipping does not involve fuel handling. At PWRs, the in-core sipping system can be a part of the fuel handling machine. All out-of-core sipping systems involve fuel handling. Because they do not have to verify each fuel move, European plants can sip faster than U.S. plants.

Fuel rod cladding temperature is not measured during sipping in any of the sipping techniques that are currently in use, although direct measurement of cladding temperature during sipping was considered preferable to indirect procedures by at least one plant (Ref. 16) in the past. One major stumbling block preventing such measurement appears to be the development of a satisfactory device for bringing thermocouples into direct contact with the cladding (Refs. 16 and 17).

In-core sipping has always been on the outage critical path for a BWR. Out-of-core sipping is not always considered a critical path item at LWRs during an outage. It may be a critical path item if sipped fuel bundles are scheduled to go back into the reactor.

Initiating a fuel bundle sipping campaign with a predetermined threshold for defining leakers does not appear to be feasible because sipping activity is interpreted only in comparisons. One of the problems is that the reactor coolant background does not remain constant, and the background in the spent fuel storage pool can vary when spent fuel is put into or moved in the pool. Furthermore, the background differs from plant to plant. The reactor coolant background is very important because it affects the leaker detection efficiency of the in-core wet sipping test and pool area accessibility.

There are some expected improvements in sipping. The newer sipping equipment, remotely operated or fully automated, reduces manpower requirements, decreases personnel exposures, and usually improves the sipping rates (the rate may depend on other factors such as whether fuel handling is a constraint). Some of the newer sipping systems are completely self-sufficient and place no burden on the plant analytical laboratories. Some of those systems also employ on-line detection, which eliminates the need for an aliquot. Out-of-core sipping at some foreign PWRs involves insulated sipping cans that allow the contained water to boil, which increases the expulsion of fission products and increases leaker detection efficiency (Ref. 18). Additional electric heating has been installed in several foreign plants to facilitate sipping of fuel bundles with very low burnup or long decay times (Ref. 18). Reduced pressure is employed in a number of sipping techniques (see Section 7.1.3.4). Reduced pressure has been demonstrated to improve the leaker detection efficiency of wet sipping (Ref. 19).

3.5 Mensural Inspection

In analyzing the current poolside mensural inspection techniques used by fuel vendors and comparing results of various published inspection campaigns, several observations can be made. There is no standard mensural inspection campaign; the effort during each inspection is unique. As a rule, utilities do not have an interest in detailed mensural inspection; they are interested in failed fuel parameters that may affect the fuel warranty. Some of the mensural data are gathered as a result of an immediate fuel performance problem while other data are used in fuel code verification. The more established fuel designs appear to have fewer critical mensural requirements than the newer fuel designs.

The trend in poolside mensural inspection hardware is toward automation, which can reduce the amount of manpower required to gather mensural data (measurements of fuel bundles rather than fuel rods) and reduce the impact on the reactor outage (avoidance of critical path).

There are significant differences in the mensural techniques in current use by the various fuel vendors and utilities doing poolside inspection. Mensural techniques and hardware are in a continual state of evolution with a general trend toward higher dimensional accuracies and a lower impact on reactor time and cost.

Because no industry-wide standard mensural inspection campaign currently exists, there is consequently no conventional approach to calibration standards. Standards are important to poolside mensural tasks but there is no uniformity in the design and use of standards. This is partially due to the fact that standards generally are designed for an optimum performance with the specific measurement technique. Because of the uniqueness of poolside inspection campaigns and the wide variation in gaging techniques, it would be very difficult to standardize poolside mensuration. Within their accuracy constraints, no specific technique is superior. However, because of potential fuel damage from handling and tool contact, emphasis should be placed on the development of noncontact gaging techniques.

3.6 Eddy-Current Inspection

Eddy-current testing is used to detect and locate defective fuel rods. Onsite eddy-current inspection is performed on individual fuel rods after the fuel bundle has been disassembled in the spent fuel storage pool; to date, nearly 44,000 rods have been tested.

In the early 1970s, extensive use of eddy-current testing of fuel rods resulted from the need to evaluate BWR fuel because of internal hydriding of the Zircaloy cladding. Eddy-current systems employed at poolside are continuous wave (sinusoid) single-frequency instruments used with a differential encircling coil probe. Recently, multiple-frequency and pulsed eddy-current systems have been used in the hot cell in an attempt to detect incipient defects thought to be caused by pellet-cladding interaction (PCI). Incipient defects of this type are extremely tight (i.e., sides of crack are in very close contact with each other), stress-corrosion type cracks and are difficult to detect with eddy currents. Presently, there are few data available to compare the capabilities of multiple-frequency and pulsed eddy-current techniques to the single-frequency eddy-current techniques employed at poolside. A review of the limited data shows that an eddy-current signal indication may result from fuel-cladding bonding, cladding ridges, or surface oxide permeability changes. Hence, use of signal data to assess the leak-tight integrity of fuel rod cladding is complicated by uncertainties in eddy-current measurement, detectability, and reliability.

Indeed, there have been several reported instances where inspection of a fuel rod produced a strong eddy-current signal, yet after detailed metallographic sectioning and study of the suspect location, no apparent cladding degradation was found. This uncertainty in measurement reliability requires the use of supplemental nondestructive techniques, including visual and ultrasonic to assist in determining fuel rod integrity.

The most apparent difference among fuel vendors with respect to nondestructive inspection is the lack of standardization for poolside fuel inspections. Each fuel vendor has developed its own reference standard that is typically composed of a series of through-wall and nonthrough-wall drilled holes and/or electro-discharge machined (EDM) notches, which serve as a calibration reference for eddy-current testing. The defect standard is the means of establishing a system sensitivity level and is based on the system response to artificial defects in the standard. The criteria for accepting or rejecting fuel rods is also based on the eddy-current response to the defect standard. For example, a small diameter through-wall hole provides a reference amplitude response level. Poolside eddy-current signal indications that meet or exceed this reference level are cause for rejection of the fuel rod. Signal indications that are, for example, 50% of the through-wall hole amplitude can also be cause for rejection of fuel rods. Vendors stated that eddy-current testing is not the only technique used to determine the condition of fuel rods. Data from visual, ultrasonic, and dimensional techniques are used in evaluating fuel rods. Hence, several nondestructive inspection techniques provide the means for determining the condition of the fuel.

Because equipment, probes, standards, test procedures, and evaluation criteria all vary among fuel vendors, reporting of eddy current test results will not be uniform.

3.7 Ultrasonic Inspection

Poolside ultrasonic inspection of irradiated fuel rods is performed on a limited basis by two fuel vendors. Ultrasonic inspection is considered to be a supplemental examination technique used to confirm eddy-current test results from suspect leaking or damaged fuel rods. One vendor uses ultrasonics to detect the ingress of water (leaker test) into fuel rods; another vendor has used ultrasonics to search for defects (defect test) in the cladding and for bonding of the pellets to the cladding (pellet-cladding bond test).

The substantial time and cost involved in the examination of a fuel rod limit the practicality of poolside ultrasonic testing. Eddy-current testing is somewhat more forgiving because it does not require the precision translation and alignment capability of the ultrasonic systems. On the other hand, the ultrasonic leaker test is a rapid and adequate means of determining if a fuel rod has breached cladding.

The use of ultrasonic testing for the poolside inspection of fuel rods is limited for several technical reasons. Crud buildup (generally an oxide layer buildup) causes surface interference with the incident sound field which complicates test data interpretation. Fuel rod dimensional changes create transducer positioning problems. With some fuel bundles, individual fuel rods are not removable, and ultrasonic examinations cannot be conducted.

3.8 BWR Fuel Channel Inspection

Three companies, including a fuel vendor and a utility, have recently developed and field tested BWR fuel channel measurement devices. Two systems use linear variable differential transducers (LVDTs) to dimensionally characterize each channel. The third system uses ultrasonic techniques for dimensional characterization. An eddy-current technique is used to measure the channel oxide thickness.

3.9 Miscellany

Two fission gas measurement systems that can be used on irradiated fuel rods in the spent fuel storage pool have been developed and successfully demonstrated (Ref. 5). Fission gas release data have been collected rapidly and safely. Up to now, the data have been obtained only from BWR fuel rods; however, use of such a system on PWR fuel rods is also being considered. One system does not have a means for resealing a fuel rod after it has been punctured. The other system has a resealing device; the seal is capable of withstanding a fuel rod internal pressure of at least 10.3 MPa (1500 psi).

A number of logistical factors affect fuel inspection programs by causing delays and annoyances: there is no uniform certification for access to controlled areas for both health-physics and security requirements. As a result, fuel inspection personnel are required to repeat the same health-physics courses and security clearances at different sites. Practical problems limiting inspections included: laundry and waste disposal at plant sites, parking space, and locker room space. Thefts of cameras and other personal equipment are also an annoying problem.

No overexposure of a fuel inspector during a fuel inspection program appears to have occurred to date.

4. EXPERIENCE WITH ONSITE INSPECTION OF FUEL SYSTEMS: GENERAL COMMENTS, TIME AND PERSONNEL REQUIREMENTS, AND SPACE REQUIREMENTS

4.1 General Comments

To perform poolside fuel inspections, the irradiated fuel must be transferred from the core to the spent fuel pool. At PWRs, fuel bundles from the core are typically transferred underwater in a horizontal position in a connecting tunnel to the spent fuel pool. With those BWRs under construction in 1965 or later, underwater transfer of spent fuel to the spent fuel pool eliminates the need for cask handling in this operation (Ref. 20).

Normally, the utilities do not bring all fuel bundles out of the reactor core area that may be of interest to a fuel vendor. Any additional fuel handling needed to bring out other fuel bundles is generally viewed by the utilities as representing time delays with no benefits. Refueling times at PWRs are getting shorter because most utilities are now going to a core shuffle, which requires only five to six days. Utilities, in general, do not guarantee testing time with their fuel bundles or the use of equipment required to handle bundles for inspectic other than a binocular visual examination. One fuel vendor is involved in approximately 20 refueling operations per year at PWRs and of the 20, about three or four are selected for poolside inspection operations beyond the normal binocular visual.

BWR fuel must be dechanneled before visual or physical access to any fuel surface is possible, while PWR fuel has no channel around the fuel rods. To detect most failed fuel rods, the fuel bundle has to be disassembled and individual fuel rods inspected. Fuel rods contain UO_2 pellets and have, in most cases, Zircaloy-2 or -4 cladding (fuel rods at several PWRs and at one small BWR have stainless steel cladding). Rod arrays in BWR fuel bundles are 8 x 8 in newer designs and 7 x 7 in older designs, and in PWR fuel bundles they are 17 x 17 or 16 x 16 in newer designs and 15 x 15 or 14 x 14 in older designs.

All BWR fuel bundles can be readily reconstituted [i.e., the irradiated bundle can be remotely disassembled, the fuel rods removed (e.g., for inspection) and reinserted or replaced, and the bundle reassembled for further irradiation]. Only some PWR fuel bundles can be readily reconstituted (wholly or partially). Locating defective fuel rods in a fuel bundle is the key to reconstituting that bundle (Ref. 21). The location of the failed fuel rods in a fuel bundle can be design dependent (i.e., one needs to know where the high power fuel rods are located). Peripheral fuel rods tend to have a higher duty cycle; hence, they have a greater probability of failing.

In general, there are two levels of poolside inspection capability: (1) normal or standard (for fuel warranty purposes and to support upgrading of computer codes for fuel) and (2) special (to support the analysis of fuel problems and fuel design performance changes). Most inspection procedures are carefully documented and are planned to avoid fuel inspections being on the critical path during the reactor outage. Utilities in general do not want the inspection details that a fuel vendor needs for fuel code and performance evaluation. In comparison to a utility, a fuel vendor would perhaps inspect fewer fuel bundles and rods, but in much greater detail. One fuel vendor stated that more information is obtained by conducting a detailed examination of 6-30 fuel bundles than in performing a cursory inspection of a very large number of fuel bundles. Typically, most inspection data are not analyzed at poolside but are taken back to the fuel vendor for review and examination. When fuel bundles are to be reconstituted, fuel rod data from the eddy-current and ultrasonic tests are analyzed at poolside.

A few comments regarding the use of terms such as accuracy[a], precision[a], resolution[a], and leaker detection efficiency should be made. NUREG-0650

(a) The Metals Handbook (Ref. 22) uses these definitions:
Accuracy - "The closeness of approach of a measurement to the true value of the quantity measured. Since the true value cannot actually be measured, the most probable value from the available data, critically considered for sources of error, is used as the 'truth'."
Precision - "The closeness of approach of each of a number of similar measurements to the arithmetic mean, the sources of error not necessarily being considered critically. Accuracy demands precision, but precision does not require accuracy."
Resolution - "The ability of an optical or radiation system to separate closely related form or entities; also, the degree to which they can be discriminated."

(Ref. 23) states that accuracy is the agreement between the true value and the result obtained by measurement, and precision is the agreement among repeated measurements of the same quantity. In the case of gamma scanning (see Section 6.2.4), some accuracy and precision values indicated by companies are not directly comparable. In the discussions of visual inspection (Section 5) and gamma scanning (Section 6), differences in the way resolution is defined can be noted. Leaker detection efficiency (ratio of leaking fuel detected to leaking fuel present) for sipping varies between companies and plants because relative measurements are involved (i.e., the sipping test is a relative measurement of activity in a sample in comparison to the average or background). Contributing factors (e.g., background variations, sipping signal magnitude variations) to the differences are described in Section 7.

4.2 Time and Personnel Requirements

Onsite inspections of fuel systems typically require 3 to 6 persons per shift (Table 4.1). Typical shifts are 10 to 12 hr long; two shifts are used if needed. If two shifts are used, the overall number of persons needed would probably be less. Detailed examinations tend to need the larger number of persons, one reason being eye fatique when using a periscope. The time and personnel requirements for specific fuel inspection techniques are described in the subsequent major sections of this report. In general, if a detailed examination (including fuel bundle disassembly) is to be performed, one might typically be able to have only one fuel bundle inspected in this manner per outage. For examinations other than normal and assuming 4 to 7 days are available for inspection during an outage, 6 to 8 fuel bundles (without disassembly for individual fuel rod examination) are probably the most that can be inspected.

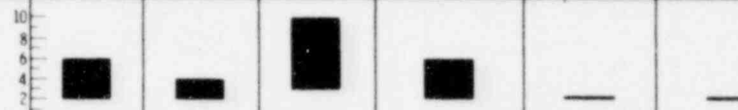
4.3 Space Requirements

Overall space requirements for onsite fuel inspection equipment and its operation were estimated. For normal inspection of fuel (e.g., routine TV/periscope visual inspection), about 0.6 m^2 (6 ft^2) of pool space plus a small amount of deck space (enough for the fuel inspectors) are used. For detailed examinations

FIGURE 4.1. Summary of the Fuel System Parameters Observed and/or Measured in Each Inspection Technique and Ranges for the Approximate Number of Persons Needed Per Shift and the Approximate Throughput of Fuel Rods, Fuel Bundles, and BWR Channel Boxes

ONSITE INSPECTION TECHNIQUE

FUEL SYSTEM COMPONENT	PARAMETER	VISUAL	GAMMA SCANNING	SIPPING	MENSURAL	EDDY CURRENT	ULTRASONIC	SAMPLING AND ANALYSIS
BWR FUEL CHANNEL BOX	BOWING							
	CORNER WEAR							
	DISPLACEMENT							
	FLATNESS							
	TWIST							
CRUD ON FUEL BUNDLE, FUEL ROD, AND BWR CHANNEL BOX	COMPOSITION							
	CONDITION AND PATTERN							
	THICKNESS							
FUEL BUNDLE	BOWING							
	CORNER FUEL RODS: ACTIVE FUEL COLUMN: AXIAL GAPS							
	CORNER FUEL RODS: ACTIVE FUEL COLUMN: HEIGHT							
	CORNER FUEL RODS: ACTIVE FUEL COLUMN: RELATIVE POWER							
	CORNER FUEL RODS: PROFILE (OD)							
	FUEL ROD-TO-FUEL BUNDLE UPPER END FITTING GAP							
	FUEL ROD CLADDING, END PLUG, AND WELD INTEGRITY (a) (b)							
	FUEL ROD-TO-FUEL ROD (a) SPACING (i.e. WATER CHANNEL WIDTH)							
	FUEL ROD(a)-TO-GUIDE TUBE SPACING (i.e. WATER CHANNEL WIDTH)							
	FUEL ROD (a) WITHDRAWAL FORCE							
	HOLDDOWN SPRING FORCE							
	IDENTIFICATION							
	LENGTH							
	WEIGHT							
FUEL ROD	ACTIVE FUEL COLUMN: AXIAL GAPS							
	ACTIVE FUEL COLUMN: HEIGHT							
	ACTIVE FUEL COLUMN: RELATIVE POWER							
	CLADDING: CORROSION VARIATIONS (a)							
	CLADDING: DEGRADATION (a)							
	CLADDING: DIAMETER (a)							
	CLADDING: FRETTING WEAR (a)							
	CLADDING: FUEL-TO-CLADDING BONDING							
	CLADDING: HYDRIDING (a)							
	CLADDING: INCIPIENT DEFECTS (a)							
	CLADDING: INTEGRITY (a) (b)							
	CLADDING: OVALITY (a)							
	CLADDING: RIDGE HEIGHT (a)							
	END PLUG: IDENTIFICATION (a) (FOR ENRICHMENT IN FUEL RODS)							
	END PLUG: INTEGRITY (a) (b)							
	IDENTIFICATION (a)							
	LENGTH (a)							
	MOISTURE INSIDE FUEL ROD (a)							
GUIDE TUBE	STRUCTURAL INTEGRITY							
	INSIDE DIAMETER				(c)			
	WEAR							
SPACER GRID	STRUCTURAL INTEGRITY							
	POSITION							
	SPRING FORCE							

		VISUAL	GAMMA SCANNING	SIPPING	MENSURAL	EDDY CURRENT	ULTRASONIC	SAMPLING AND ANALYSIS
PERSONNEL /SHIFT (d) (10-12 HR. SHIFT, TYPICAL)								
TIME FOR FUEL ROD INSPECTION		1/3 - 3 HR/ROD	~1 HR/ROD (f)	NA (g)	3-4 HR/ROD	CAN RANGE FROM ~1 MIN./ ROD(f) TO SEVERAL HOURS/ROD	~1 MIN./ROD (f) FOR LEAKER TEST; A FEW MIN./ ROD (f) FOR DEFECT AND BOND TEST	
	APPROX. MINUTES/FUEL ROD	20-180	~60 (f)	NA	180-240	~1 (f) TO ~120	~½ TO A FEW (f)	
TIME FOR FUEL BUNDLE INSPECTION (h)		2-17 HR/ BUNDLE	~4 (CORNER RODS ONLY)	0.05-1.2 HR/BUNDLE	TO 1 DAY/ BUNDLE WITH NO DISASSEMBLY; TO 10 DAYS/ BUNDLE WITH DISASSEMBLY FOR INDIVIDUAL ROD INSPECTION	NA	NA	
	APPROX. MINUTES / FUEL BUNDLE	120-1020	~240 (CORNER RODS ONLY)	3-72	TO 1440 WITH NO DISASSEMBLY; TO 10,440 WITH DISASSEMBLY	NA	NA	
TIME FOR BWR CHANNEL INSPECTION (i)		NO STANDARD TIME STATED (DEPENDS ON DETAILS)			2 HR/CHANNEL WITH OLD SYSTEM; 0.25-1 HR/CHANNEL WITH NEW SYSTEM			
	APPROX. MINUTES / CHANNEL		NA	NA	15-120	NA	NA	

(a) ALSO APPLIES TO BURNABLE POISON RODS
(b) SPECIFICALLY LEAK-TIGHT INTEGRITY TO FLUIDS AND STRUCTURAL INTEGRITY
(c) ON ONLY PART OF THE GUIDE TUBE
(d) FOR DETAILS, SEE TABLE 5.6, SECTION 7.2.3, TABLE 8.6, SECTION 9.6.8, AND SECTION 10.3.7.
(e) FOR DETAILS, SEE TABLE 5.6, SECTION 6.3, TABLE 8.6, SECTION 9.6.8, AND SECTION 10.3.7.
(f) EXCLUDES FUEL HANDLING TIME (i.e., FUEL BUNDLE DISASSEMBLY / REASSEMBLY AND FUEL ROD HANDLING TIME).
(g) NA = NOT APPLICABLE
(h) FOR DETAILS, SEE TABLE 5.6, SECTION 6.3, TABLE 7.1, AND TABLE 8.6.
(i) FOR DETAILS, SEE SECTION 11.3.4.

of fuel systems, about 2.8 to 6.5 m^2 (30 to 70 ft^2) of pool space plus 5.6 to 15 m^2 (60 to 160 ft^2) of deck space are typically used. If they were given freedom of choice, one fuel vendor indicated they would like to be able to have 28 m^2 (300 ft^2) of deck space available when conducting detailed fuel examinations. Space needs for sipping and other specific inspection techniques are described in the associated sections of this report.

One fuel vendor has two special fuel inspection stands for PWR fuel, a small one that can be attached to a spent fuel storage rack and a large one (Figure 3.1). The large stand is ~12 m (~40 ft) high, ~1.83 m (~6 ft) square, and weighs 6350 kg (7 tons). Three trailers are needed to haul it. The large stand is designed to go either in the cask lay-down area or in the spent fuel pool storage area. This stand is actually set up in the cask area so no poolside storage space is used by it during operations. About two weeks (24-hour day type effort) are needed to install (align) and remove (including decontamination) the large stand. The time is about equally split between the two operations.

Another fuel vendor has two special fuel inspection stands, one for fuel bundles (the stand has storage positions for four fuel bundles) and one for fuel rods. Each has approximately the same dimensions: ~1.2 m (~4 ft) wide, ~2.1 m (~7ft) long, and ~3.7 m (~12 ft) high. This fuel vendor indicated that some PWRs are very short on pool space and do not have room at the present time to accommodate the two stands.

Poolside space for inspection is usually very restricted at BWRs, especially for channel inspection. Older channel inspection systems, where the channel (with fuel bundle removed) is held horizontally, require 4.3 m (14 ft) of pool wall space. Newer systems, where the channel (while still on the fuel bundle) is held vertically, require 1 m (3 ft) of pool wall space. The systems extend about 1 m (3 ft) from the pool wall.

Seismic bracing for fuel system inspection equipment gives one fuel vendor an interface problem with the spent fuel pool.

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Onsite inspection techniques currently used on fuel systems at domestic commercial light water reactors were assessed. Those techniques are visual, gamma scanning, sipping, mensural, eddy current, and ultrasonic inspections. The assessment involved a literature survey, meetings with all five reactor fuel suppliers, and visits to three reactor sites.

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