BNL-28054
CONF-800655--29

A LASER SURVEILLANCE SYSTEM FOR SPENT FUEL*

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ABSTRACT

A laser surveillance system installed at spent fuel storage pools will provide the safeguard inspector with specific knowledge of spent fuel movement that cannot be obtained with current surveillance systems. The laser system will allow for the division of the pool's spent fuel inventory into two populations - those assemblies which have been moved and those which haven't - which is essential for maximizing the efficiency and effectiveness of the inspection effort. We have designed, constructed, and tested a laser system and have used it with a simulated BWR assembly. The reflected signal from the zircaloy rods depends on the position of the assembly, but in all cases is easily discernable from the reference scan of background with no assembly.

1. INTRODUCTION

The Laser Surveillance System (LSS) is as an active spent fuel pool surveillance system which continually scans a plane just above the assemblies with two sweeping laser beams. In the sense that it is an active surveillance system, it is similar to the TV/movie camera systems now installed at many safeguarded spent fuel storage pools (SFSP's). However, in contrast to the TV/movie systems which are focussed at poolside indiscriminantly recording every frame, the LSS will compare successive scans and only record significant changes from the normal background reflective response, such as caused by an assembly being raised.

Although comparison of scans is also planned for TV/movie systems(1), it is not as efficient as comparison of underwater scans because of the many non-fuel movement activities occurring at poolside, e.g., operator training on the fuel handling equipment, maintenance and repair of the fuel handling equipment, deliveries of equipment, most of the poolside activities during refuelling, tours of visitors, etc.

Furthermore, the LSS, again in contrast to TV/movie systems, provides the inspector with a chronological listing of specific fuel assembly locations where reflection anomalies have been detected. The inspector can use the time information to focus his attention more closely on the corresponding TV/movie frames, and he can use the anomaly location information to concentrate other safeguard systems on just those assemblies which presumably have been moved, i.e., the Cerenkov viewer(2), the spent fuel radiation scanners(3), and/or fuel identification scanners(4) can be directed at the few assemblies that have been moved rather than at a sample of hun-

*Research carried out under the auspices of the United States Department of Energy under Contract No. DE-AC02-76-CH00016.

dreds of assemblies most of which have not been moved.*

A Laser Surveillance System has been constructed and successfully tested in air with beam path lengths typical of SFSP's. The system uses off-the-shelf components (laser, stepping motor, mirrors, etc.) with well-established records of reliability. It is planned to test the system at the GE Morris, Ill. away-from-reactor pool in August. The water absorption at blue-green wavelengths results in about a factor of 6 loss in intensity for the longest path lengths, however, this should pose no problem[5].

II. HISTORY OF THE LSS CONCEPT

Sealing of spent fuel assemblies was the focus of the study that eventually led to the LSS concept[6]. During the study, it was realized that a substantial safeguard advantage could be gained by tieing several assemblies together. Once tied together, the facility operator could not move an assembly with the normal single-assembly fuel-handling equipment. All the assemblies could be tied together, or equivalently, a sealed, tamper-indicating cover could be placed over the assemblies. The SFSP and cover is then a sealed tamper-indicating container for the assemblies, much like a sealed shipping cask. For facility acceptance of the SFSP "cover" concept, it was necessary to replace the objectionable solid cover with an "electronic" cover. The closer the electronic cover is to the the assemblies, the more it functions as a solid cover and the less manuverability it provides a diverter. Hence, the LSS[7], TV/movie systems, ultrasonic surveillance[8], etc., are all electronic covers; they differ only in the scanning methods and the type of information generated.

III. SYSTEMS OPERATION

The LSS system extracts fuel movement information by use of a covering "sheet" of light, i.e., by scanning the region of the pool ~ 25' below the surface and directly over the assemblies in the storage racks with laser beams. Two separate laser beams sweep in a horizontal plane (see Figure 1) just below the bottom of the fuel transfer mechanism. Movement of the fuel transfer mechanism alone without an assembly attached therefore does not intercept the laser beams. Laser light reflected from the stainless steel sides of the pool (the reference scan) is detected by a photomultiplier (PM) tube associated with each laser. The laser scanning signals from the PM tubes are amplified and processed by a small computer. The laser, PM tubes, electronics and mini-computer are housed in a tamper-indicating container at poolside while the scanning and receiving mirrors and stepping motor are located below water.

A rising assembly will slowly break through the scanning laser cover causing a change in the reflected signal when the beams are at the specific angles (θ_1, θ_2) corresponding to that assembly. The response anomaly in both

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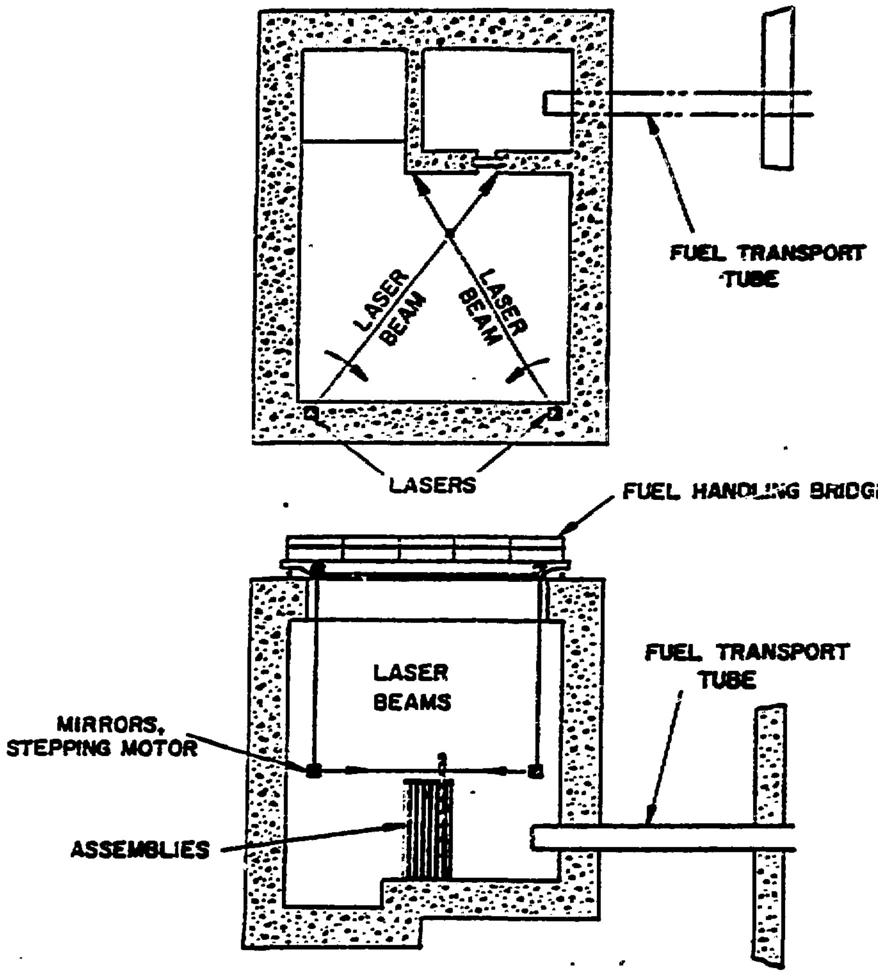
* For PWR's where two spent fuel assemblies contains a goal quantity of plutonium, 95% detection probability is achieved by assaying 77% of the assemblies.

Figure 1. A PWR SFSP Showing the Placement of Two Laser Systems and the Laser Beams.



PM tubes is interpreted by the computer as assembly movement and the location of the assembly is determined by triangulation. The dual beams would be necessary even if laser ranging were employed to determine assembly location since the diverter could attempt to raise a second assembly in the shadow of the first.

IV. A LASER SYSTEM PROTOTYPE

A prototype laser system has been designed and constructed and a similar system will shortly undergo tests at the GE Morris, Ill. away-from-reactor, spent fuel storage facility. The system has been tested in air with approximately the same geometry as exists in a SFSP. Only one laser beam and PM tube were assembled to demonstrate the engineering principles of the system. The tests in air were run using at first a set of 6 zircaloy rods and later a 13.7 cm long, 8x8 BWR zircaloy assembly. The details of the system are shown in Figures 2 through 5 and are described below.

Figure 2. Detailed Diagram of the Laser System Constructed at BNL.

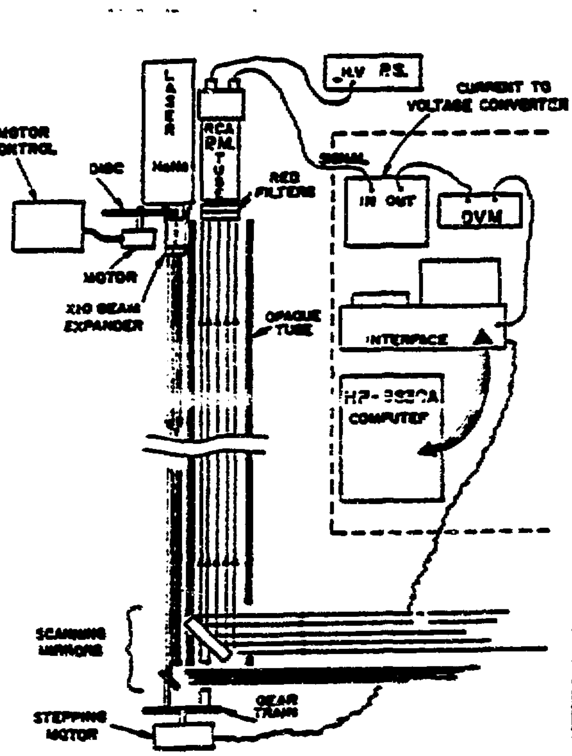


Figure 3. The BNL Laser System.

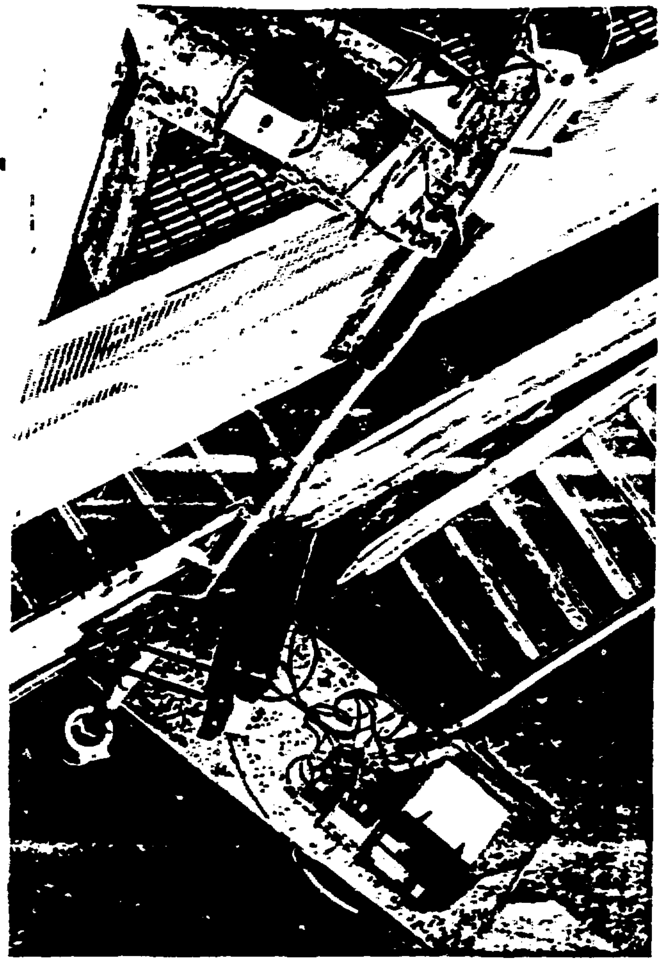


Figure 4. The Electronics and HP Computer Used for Controlling the Laser System.

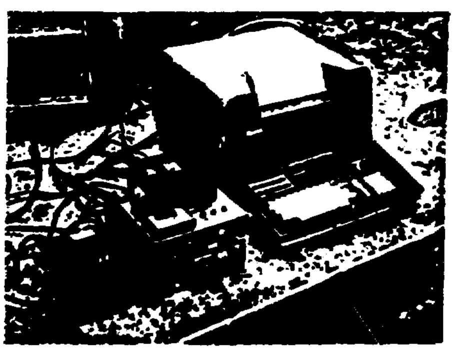


Figure 5. The Housing for the Mirror System Showing Laser Beam Being Bent 90°.

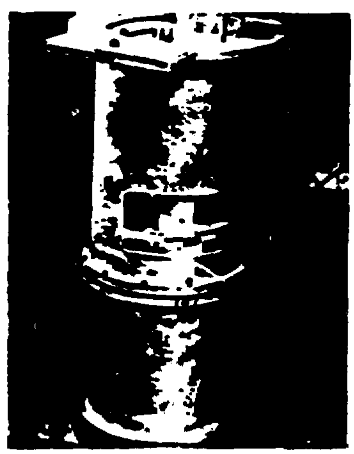
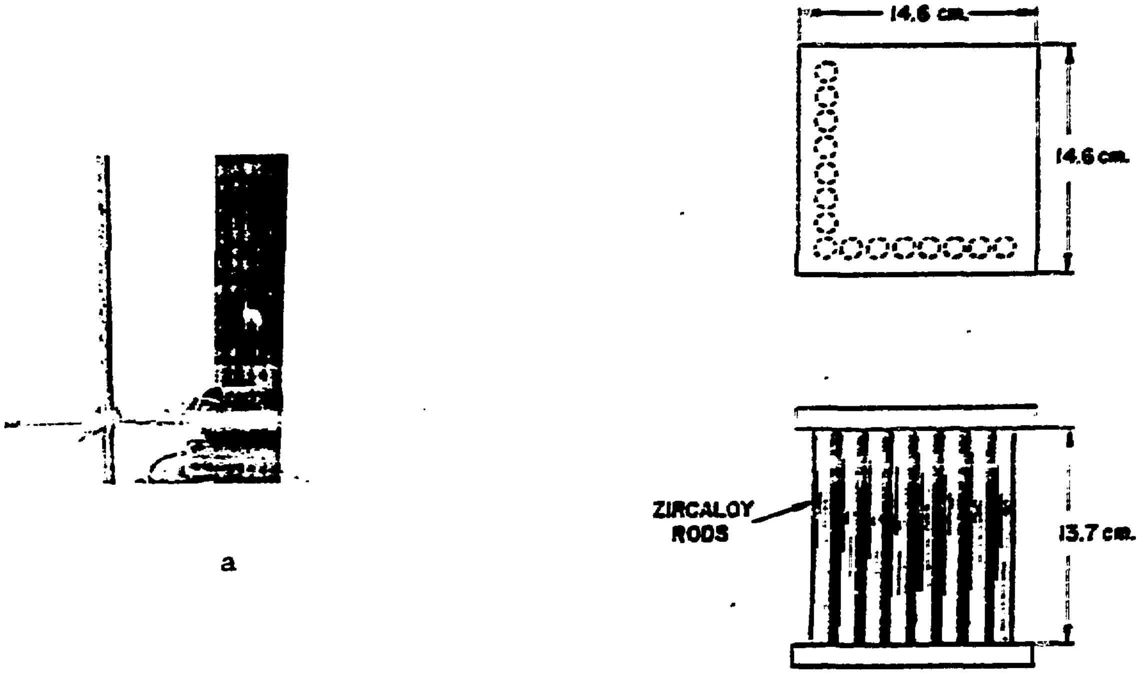


Figure 6. A Simulated BWR Assembly Using (a) 6 Zircaloy Rods and (b) a 13.7 cm long 8x8 array. The Bright Spot is the Laser Beam.



a

b

Laser and Associated Equipment

A small 0.5 milliwatt HeNe red laser (632.8 nm) emitting a 1 mm dia. laser beam was used. For the tests at GE Morris, a HeCd blue laser will be used to minimize intensity loss due to water absorption. A beam enlarger was mounted on the laser to increase the beam size, provide focussing, and to reduce beam divergence. Between the laser and beam enlarger, was placed a motor driven disc with black transparent slits to mechanically chop the beam. An a.c. synchronous motor allowed a chopping frequency of 60xN where N is the number of holes or slits on the disc. We used discs of N=30 and N=100. The purpose of the chopped beam was to generate an a.c. light signal, thereby allowing the filtering of the d.c. background lighting component.

Mirror Geometry

The laser beam was directed down 5.5 m to a 2.54 cm dia. 45° mirror and then horizontally as far away as 23 m to an assembly or a wall. The reflected light was received by a 7.6 cm mirror on an adjustable 45° mount. The two mirrors are mounted close to one another and linked by gears to a single stepping motor that allows for synchronous scanning and receiving. Scanning rates of up to 50 steps/sec were used which at 0.125° per step resulted in a 90° sweep in ~ 15 seconds. Careful partitioning of the sending and receiving signals prevented most of the background scattered laser light from entering the PM tube.

PM Detector

The PM detector was an RCA C7164R, 5 cm diameter, 10 stage head-on type tube employing a multialkali photocathode having exended red response. A more standard PM tube will be used with the blue laser. Two red filters having bandwidths of $\sim$10 nm centered at $\sim$632.8 nm were mounted on the tube. The tube was encased in an anti-magnetic shield to reduce pick-up from the synchronous motor. The light from the receiving mirror was directed to the PM tube via an opaque walled 5.5 m tube to block background lighting and scattered laser light. The PM tube was operated at 900-1200 volts.

Electronics System

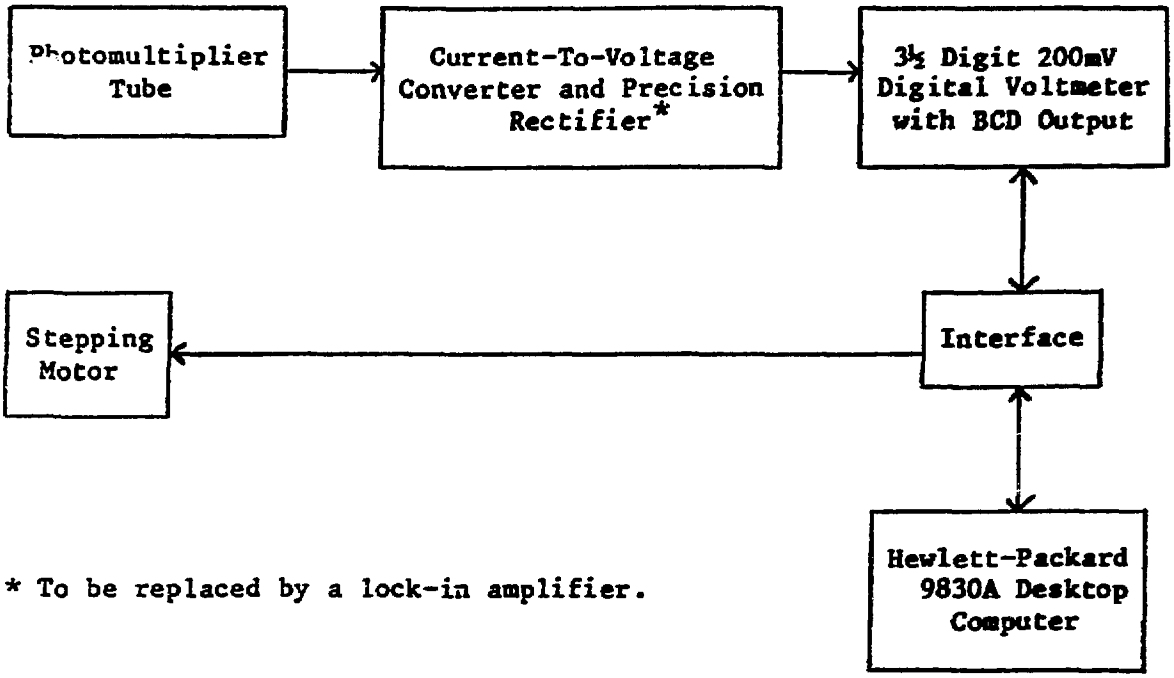
All control, data storage, and data analysis are carried out using a Hewlett-Packard 9830A desktop computer system, with suitable signal conditioning and interfacing.

Figure 7 is a block diagram of the overall system. Two major functions are performed: control of the stepping motor which drives the mirrors sweeping the laser beam and PM tube field of view; and input and storage of voltage readings from the PM tube. A single interface, designed and built at BNL, handles communications between the computer and the peripheral devices. A commercial 3½-digit 200 millivolt digital voltmeter (DVM) with BCD outputs is used for analog to digital conversion of the PM tube output. The pulsed output of the PM tube is processed through current-to-voltage conversion and precision rectification prior to being fed to the DVM. Each of the major pieces of the system is described in detail below.

Current-to-Voltage Converter and Precision Rectifier (CVCPR). Since a chopped laser beam is used, the signal from the PM tube is current pulses, the peak height of which is a function of the intensity of the reflected beam. The CVCPR simply converts these current pulses to voltage pulses and rectifies them, providing a slowly varying DC signal to the DVM. Conventional integrated operational amplifier circuitry is used. We have also tested a system in which the CVCPR was replaced by a lock-in amplifier which receives its reference frequency signal from a phototransistor mounted directly over the rotating disc. A LED mounted below the disc provides the light source for the phototransistor. The system provided much better background light suppression and its higher signal sensitivity enabled operation of the PM tube at lower voltages which reduced electronic noise.

Digital Voltmeter (DVM). A 3½ digit 200 millivolt digital voltmeter is used for analog-to-digital (A-to-D) conversion of the processed DC signal from the PM tube either from the CVCPR or from the lock-in amplifier. The output of this DVM is standard 8-4-2-1 BCD data.

Stepping Motor. A 12V DC stepping motor is used to drive the mirrors of the system. This motor requires properly phased control pulses to each of four windings to advance. The pulses are provided by a special purpose integrated circuit stepping motor controller which is part of the system interface.



* To be replaced by a lock-in amplifier.

Figure 7. Electronics System Block Diagram

Interface. The interface performs three major functions: (1) selection of the proper peripheral (DVM or stepping motor) to be addressed by the computer; (2) synthesis of proper control signals for the computer and the peripherals; and (3) provision of 12V DC power for the stepping motor. The interface also has limited capability to control the system without the computer. All interface electronics (except the stepping motor controller) are conventional TTL logic.

Hewlett-Packard 9830A Computer. The laser system is controlled by a Hewlett-Packard model 9830A desktop computer. This computer was programmed in BASIC, and has 16K words of memory, cassette tape storage for data and programs, and an X-Y plotter. All system functions are under computer control, including mirror positioning, data acquisition and storage, and data analysis. All software is modular, and data storage is handled separately from data analysis to provide maximum flexibility. It is expected that many of the safeguard systems at a SFSP will be feeding information to a central mini computer in a time sharing mode and the LSS will be one of them and not require its own computer.

Simulated Fuel Assembly.

Originally, 6 zircaloy rods were used to simulate a BWR assembly, then a 13.7 cm length mock-up of an 8x8 BWR zircoloy assembly was constructed and scanned by the LSS system (see Figure 6).

V. RESULTS

Under manual control, a 3.8 cm dia. laser beam was scanned across the 6-rod simulated BWR assembly in various orientations and located at various distances from the mirrors. Several of the scans shown in Figure 8 demonstrate the variety of responses possible. Besides solid angle geometric effects on the response, there is a tremendous variation in reflected intensity depending on just where on the rods the laser spot fell. Some of this sensitivity may be reduced if the beam size is increased to the largest which will still allow resolution sufficient to locate precisely an assembly.

The present method of separating the two axes of the sending and receiving mirrors produces an assembly shadow effect when the light from the laser beam hitting the wall and returning to the receiving mirror is blocked by the assembly. This effect is indicated in Figure 8.

The scan step was 1/8^{o} which translates to 5 cm at R=23 m compared with an 8x8 BWR assembly dimension of 13.7 cm. Hence, even at the furthest distances, a BWR assembly and certainly a PWR assembly would be scanned with adequate resolution.

Reproducibility of a scan was investigated using the 13.7 cm long 8x8 BWR array. Under computer control, thirty scans were made on the 8x8 assembly oriented at 45^{o} with respect to the beam, 6.7 m from the scanning mirrors. A stainless steel background sheet oriented at 15^{o} was used. The laser beam was focussed to $\sim$1 cm on the rods. Figure 9a shows the very large effect of the assembly on the scan.

The laser beam diameter was then increased to 2.54 cm and the thirty scans repeated. The different reflected response is shown in Figure 9b. The stainless steel background sheet was then rotated to a 0^{o} orientation (normal to the beam) with a 2.54 cm beam size and then to a 30^{o} orientation with a 1 cm laser beam size. The results are shown in Figure 9c,d.

Two other scans are shown in Figure 10 showing the relatively smooth 0^{o} background scan compared to the assembly scan with the assembly at only 3.7 m from the mirrors, both with the 1 cm laser beam size.

The average standard deviation was a few percent for the background and as much as 30% when the beam fell on the high or low point of an assembly rod. At no time was there any ambiguity that an anomaly was being detected. The determination of the location of the assembly from a triangulation calculation based on the two angles of the laser beams and the known distance between the lasers will be performed by the computer.

The uncertainties in the determination of angle can only be found from more realistic tests at a SFSP such as the upcoming tests at the GE Morris facility, but must be compatible with the goal of locating the assembly to within the size of one storage rack location.

Ultimately, the computer, upon request by the inspector, will generate a table (see Table I) which will list the X-Y coordinates and times of anomalies. These coordinates can be correlated with assembly location with

Figure 8. Laser System Response as Beam Scans Across BWR Rods at Various Distances from the Scanning Mirror.

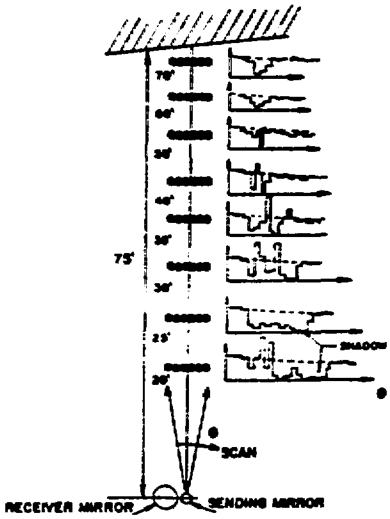


Figure 9. Average of Repeated Scans

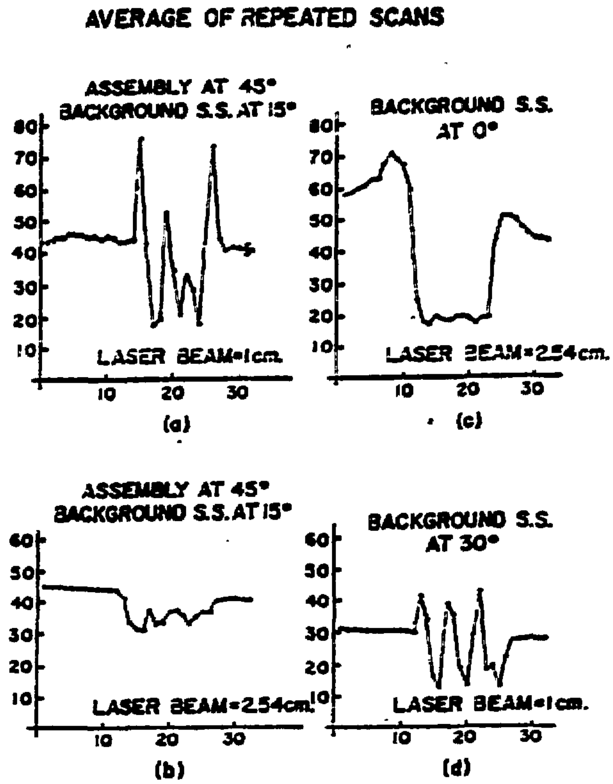


Figure 10. Average of Repeated Scans

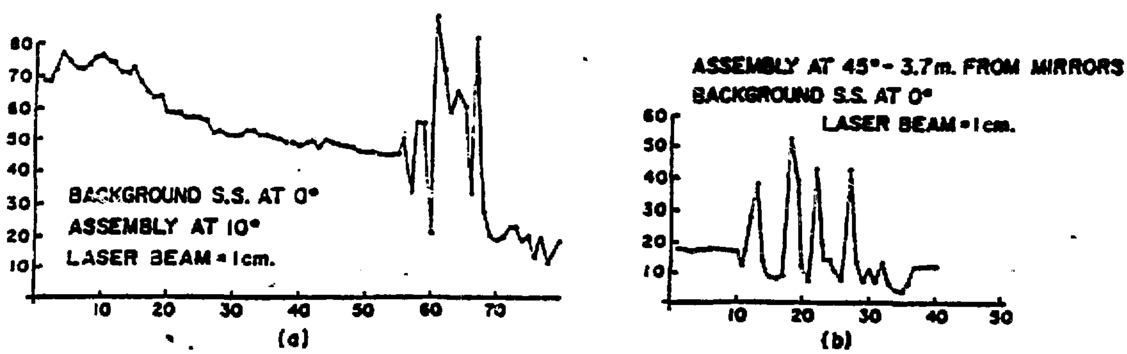


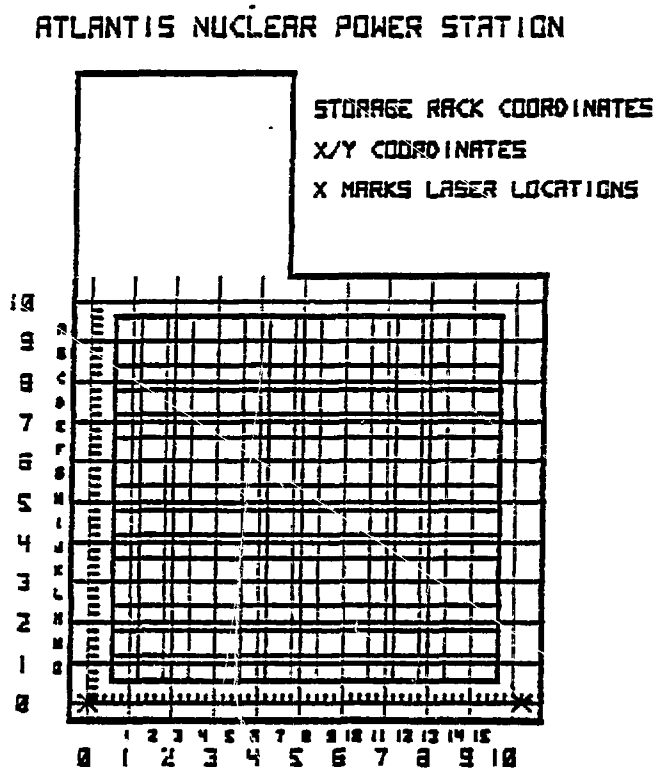
Table I

Atlantis Nuclear Power Station
Spent Fuel Pool Surveillance Anomalies

Date	Time	Scan #	X	Y
1/ 2/ 81	0: 23: 43	14	3.73	2.74
2/ 4/ 81	0: 25: 37	3	7.58	2.07
2/ 6/ 81	12: 37: 52	1	1.69	2.05
3/ 8/ 81	1: 17: 35	776	2.15	4.90
3/ 10/ 81	9: 12: 50	720	8.56	3.05
4/ 12/ 81	14: 26: 23	658	8.97	5.84
4/ 14/ 81	22: 20: 51	4	0.83	9.96
5/ 16/ 81	5: 53: 19	85	5.29	1.44
5/ 18/ 81	20: 25: 39	747	6.62	5.93
6/ 20/ 81	18: 57: 8	849	5.50	6.78

either an overlay map such as shown in Figure 11 or directly if the storage rack geometry is stored in the computer.

Figure 11. Overlay Showing SFSP Storage Rack and Laser System Coordinates.



VI. THE DESIGN FEATURES FOR A PROTOTYPE SFSP LASER SYSTEM

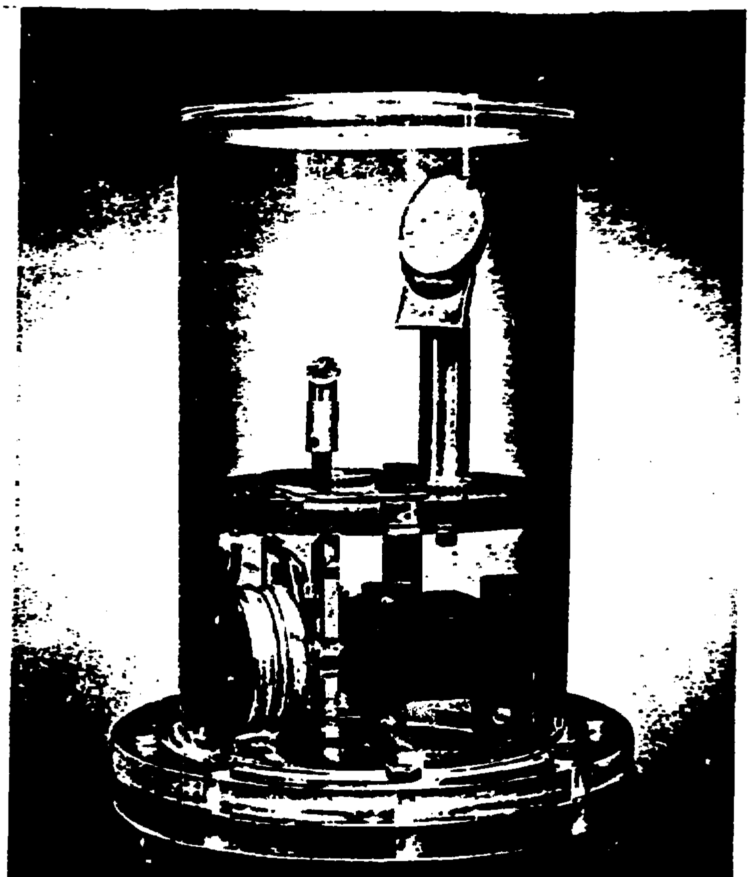
With the encouraging results from the first prototype laser system, we have constructed a more compact system to be tested at the GE Morris SFSP. Several additional changes will be made to account for the change in beam path from air to water. Foremost is the change from a 0.5 mW HeNe red laser to a 10 mW HeCd blue laser. The greater intensity of the HeCd laser more than offsets the loss of intensity going from air to water.

The attenuation length vs. wavelength for underwater transmission of light is a maximum for blue light. At a total path length of 46m the intensity loss for blue light is only about 80% whereas for red light it is seven orders of magnitude.

Besides the intensity attenuation of the water, the water temperature gradients may introduce beam bending problems that will require a larger field of view for the receiving mirror. The tests performed in air used a field of view about 20 times the laser beam spot size.

The new design has reduced the size and complexity of the unit that is lowered in the pool. The container holding the mirrors and stepping motor is made of clear lucite and is mounted at the end of a stainless steel tube which serves the dual function of supporting the lucite container and collimating the reflective signal to the PM tube. The present lucite unit is a 15 cm cylinder 41 cm long (see Figure 12). Further size reduction to ∽ 8 cm dia. and ∽ 15 cm long can be expected in a final design.

Figure 12. Luctie Housing for Scanning Mirrors and Stepping Motor



VII. CONCLUSIONS

The laser surveillance system described above will introduce a laser light cover over the spent fuel assemblies. When an assembly is raised and intercepts the two sweeping laser beams, the altered reflected signals are processed by a small computer and the exact position of the raised assembly is calculated by triangulation. If at the start of an inspection of a SFSP, the inspector could know which assemblies had been moved between inspections, then he could apportion his time so that the moved assemblies would receive the greater safeguard effort. The system constructed and tested demonstrates the engineering principles involved and has provided enough information to design a system that will shortly be used at the GE Moris SFSP. The laser system is basically a simple system consisting of a laser, some mirrors, a stepping motor, and a PM tube interfaced to a small computer. The small computer can be time-shared with other containment and surveillance devices under development. The final design will be small, rugged and long-lived and also relatively inexpensive.

VIII. ACKNOWLEDGEMENTS

We wish to thank Mike Degen for valuable assistance in testing the laser system.

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