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A LASER SURVEILLANCE SYSTEM FOR SPENT FUEL *

S. Fiarman, M.S. Zucker, A.M. Bieber, Jr.

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Abstract

A laser surveillance system installed at spent fuel storage pools (SFSP's) 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 full size laser system operating in air and have used an array of 6 zircaloy BWR tubes to simulate an assembly. The reflective signal from the zircaloy rods is a strong function of position of the assembly, but in all cases is easily discernable from the reference scan of the background with no assembly. A design for a SFSP laser surveillance system incorporating laser ranging will be discussed.

1. Introduction

By the year 2000 it is estimated that there will be 1 million spent fuel assemblies in storage at-reactor (AR) or away-from-reactor (AFR) spent fuel storage pools (SFSP). Safeguarding these assemblies will impose an increasing burden on the IAEA inspectorate. Presently, the IAEA safeguards spent fuel assemblies by a combination of item counting and containment and surveillance (C/S) systems such as seals and TV or movie cameras. For the future, new C/S systems will undoubtedly be introduced to improve the efficiency and effectiveness of the periodic inspections at reactors. The actual routine inspection effort (ARIE) for power reactors is only 9-15 man-days per year[1] with a maximum

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routine inspection effort (MRIE) of 1/6 of a man-year.[2]

Some of the new systems being developed include Cerenkov glow detectors, NDA scanning of spent fuel, radiation and motion detection in the pool,[3] and a laser surveillance system. The laser system, described in this paper, records the specific information of storage rack location and times of spent fuel movement during the inspector's absence. The inspector can use this information to divide the assemblies in the pool into two populations -- those that have been moved and those that haven't -- and direct the appropriate safeguard system at his disposal toward each population. The assumption being made is that any credible diversion scenario involves movement of the spent fuel.

NDA scanning of spent fuel will probably be too slow to scan the hundreds of assemblies in the pool necessary to achieve high detection probability. 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. Only where sampling plans are based on solely those assemblies which have been moved can high detection probabilities be achieved.

The inspector spends many hours watching TV or movie frames of poolside activity. If he had a knowledge of the times and locations of fuel movement, he can focus his attention on the important frames and not waste time with frames showing irrelevant poolside activity such as the maintenance and testing of fuel handling equipment or the training of bridge operators. The time spent reviewing irrelevant occurrences in the pool area decreases safeguards effectiveness by numbing alertness to genuine suspicious activity.

2. The Laser Concept

The laser system extracts the fuel movement information by creating a sheet of light $\sim$ 25' below the surface of the pool and directly over the assemblies in the storage racks. The light is generated by two separate laser beams sweeping 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 does not intercept the laser beams. Laser light reflected from the stainless steel sides of the pool (the reference scan) is detected by two photomultiplier (PM) tubes. The laser scanning signals from the PM tubes are amplified and processed by a small computer. The laser, PM tubes, electronics and minicomputer are housed in a tamper-indicating container at poolside while the scanning and receiving mirrors and stepping motor are located below water.

A raised assembly will slowly break through the covering sheet of light causing a change in the reflective signal when the laser beams are at specific angles. The response anomaly in both PM tubes is interpreted by the computer as assembly movement and the location of the assembly is determined by triangulation and perhaps by laser ranging as well.

3. A Laser System Prototype

A prototype laser system has been designed and constructed to operate 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. Tests were run using a mock assembly of six BWR zircaloy fuel rods. The details of the system are shown in Figures 2 through 6 and are described below.

Figure 1. A PWR SFSP Showing the Placement of Two Laser Systems, the Beam Scanning Housings and the Laser Beams.

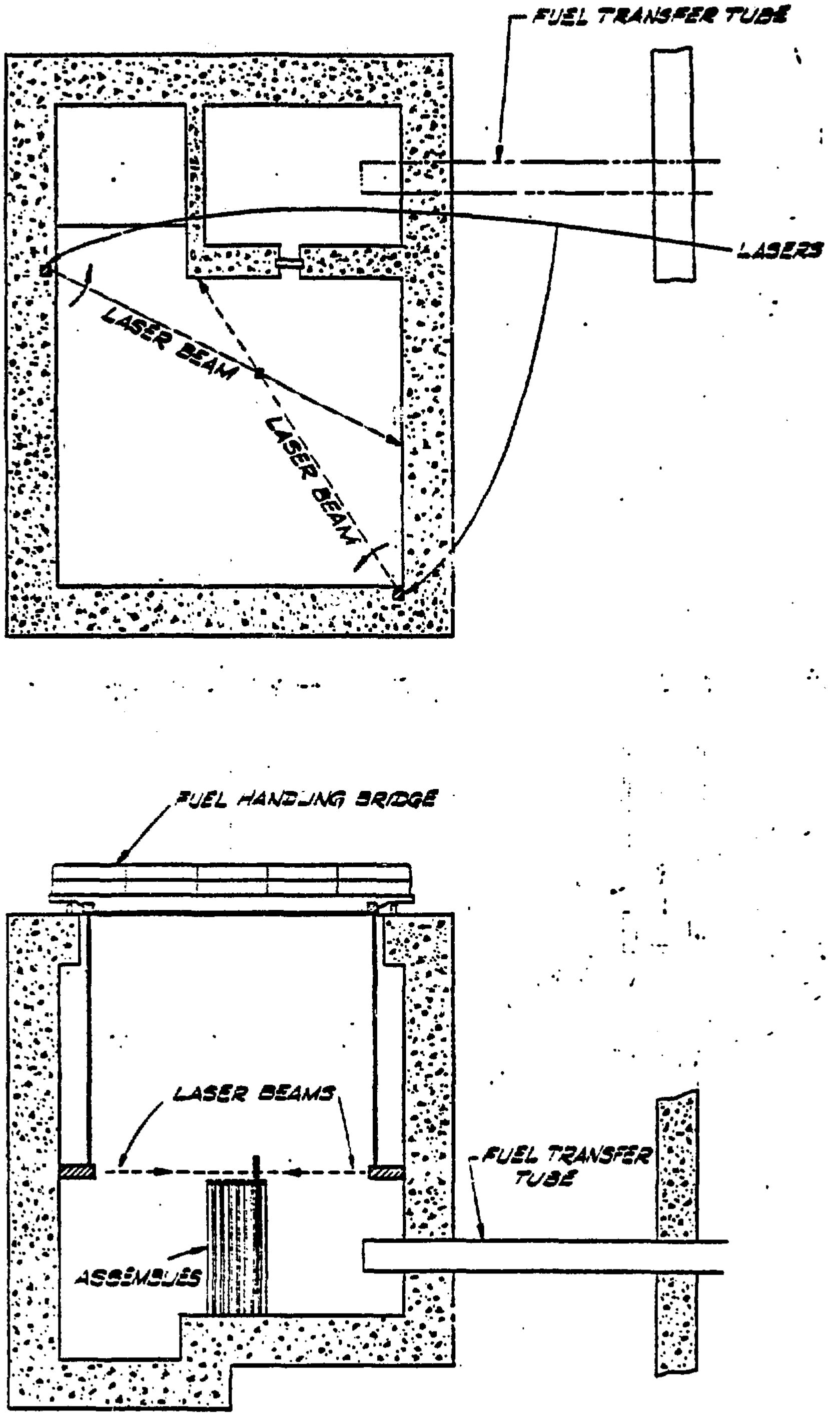


Figure 2. Detailed Diagram of the Laser System Constructed at BNL.

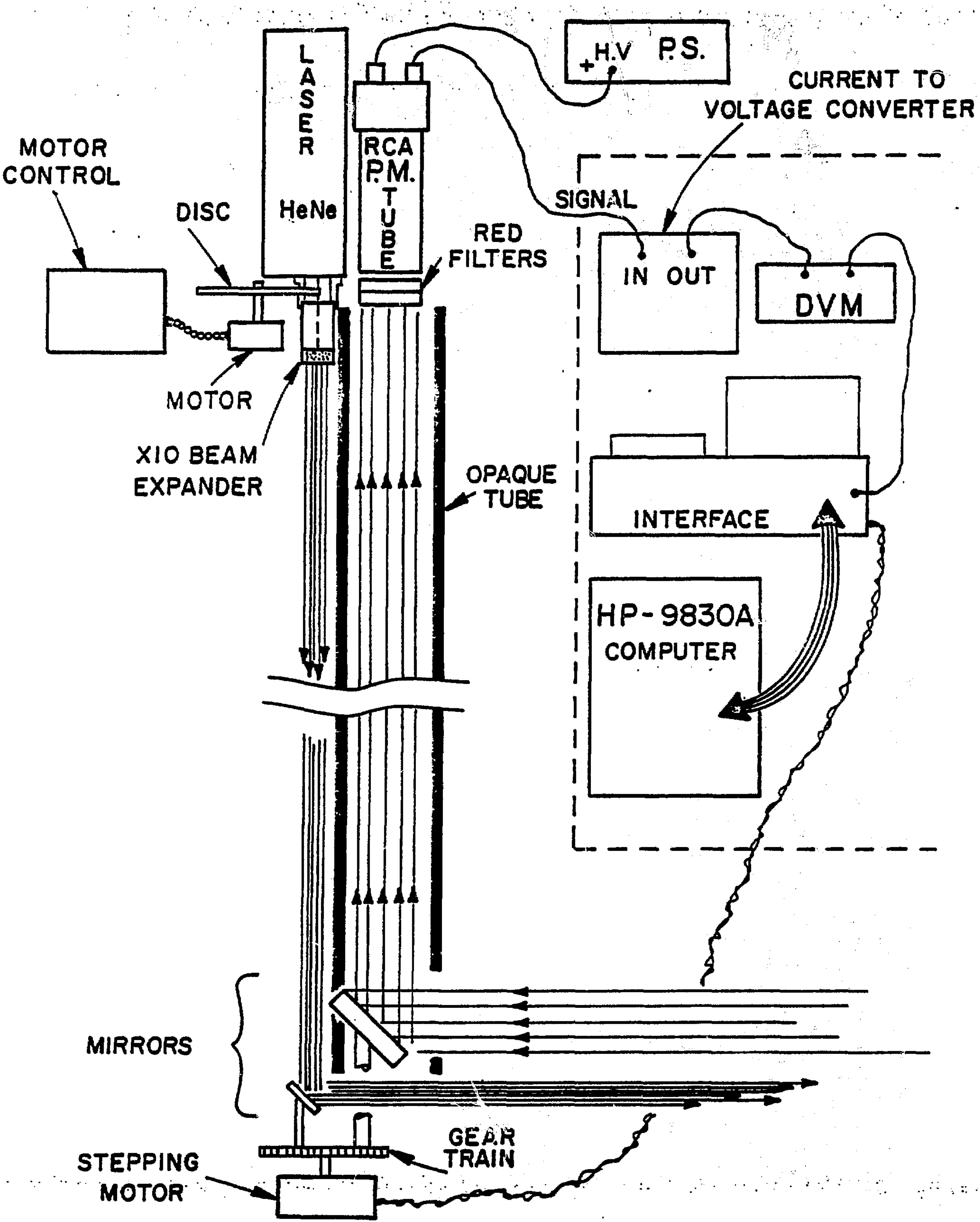


Figure 3. Photograph of the BNL Laser System.

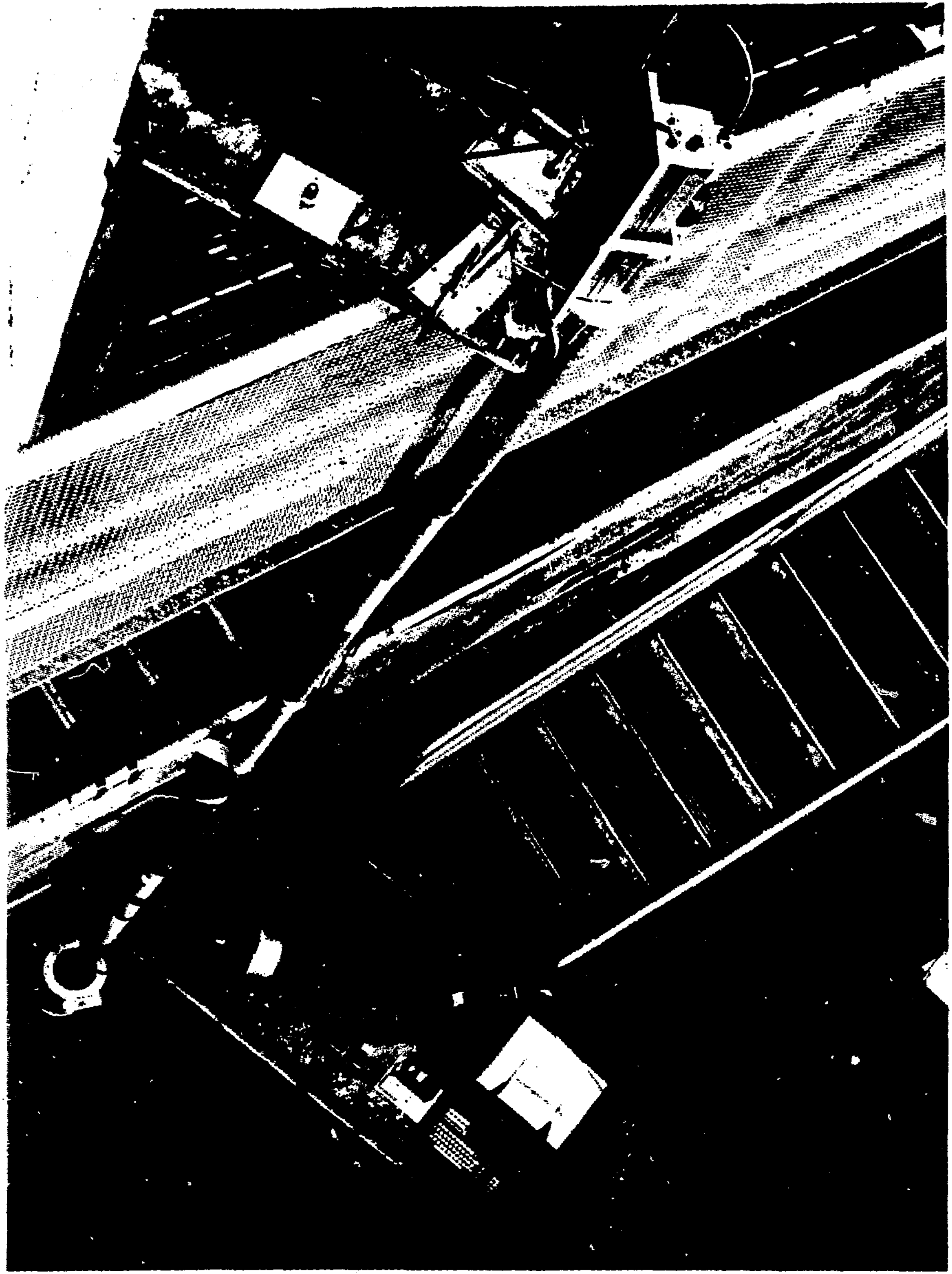


Figure 4. Photograph of the Electronics and HP Computer Used for Controlling the Laser System.

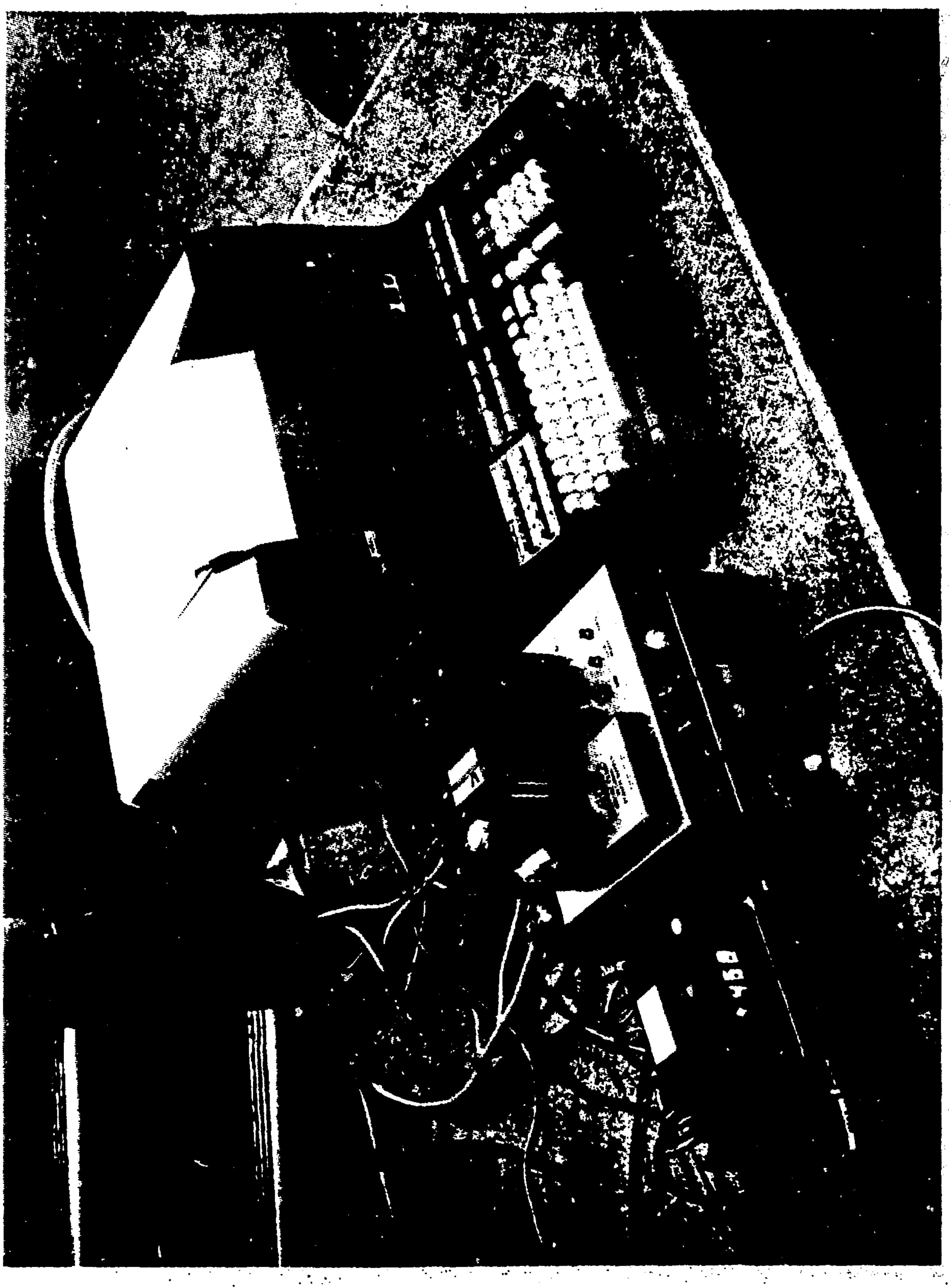


Figure 5. Photograph of the Housing for the Mirror System Showing Laser Beam Being Bent 90°.

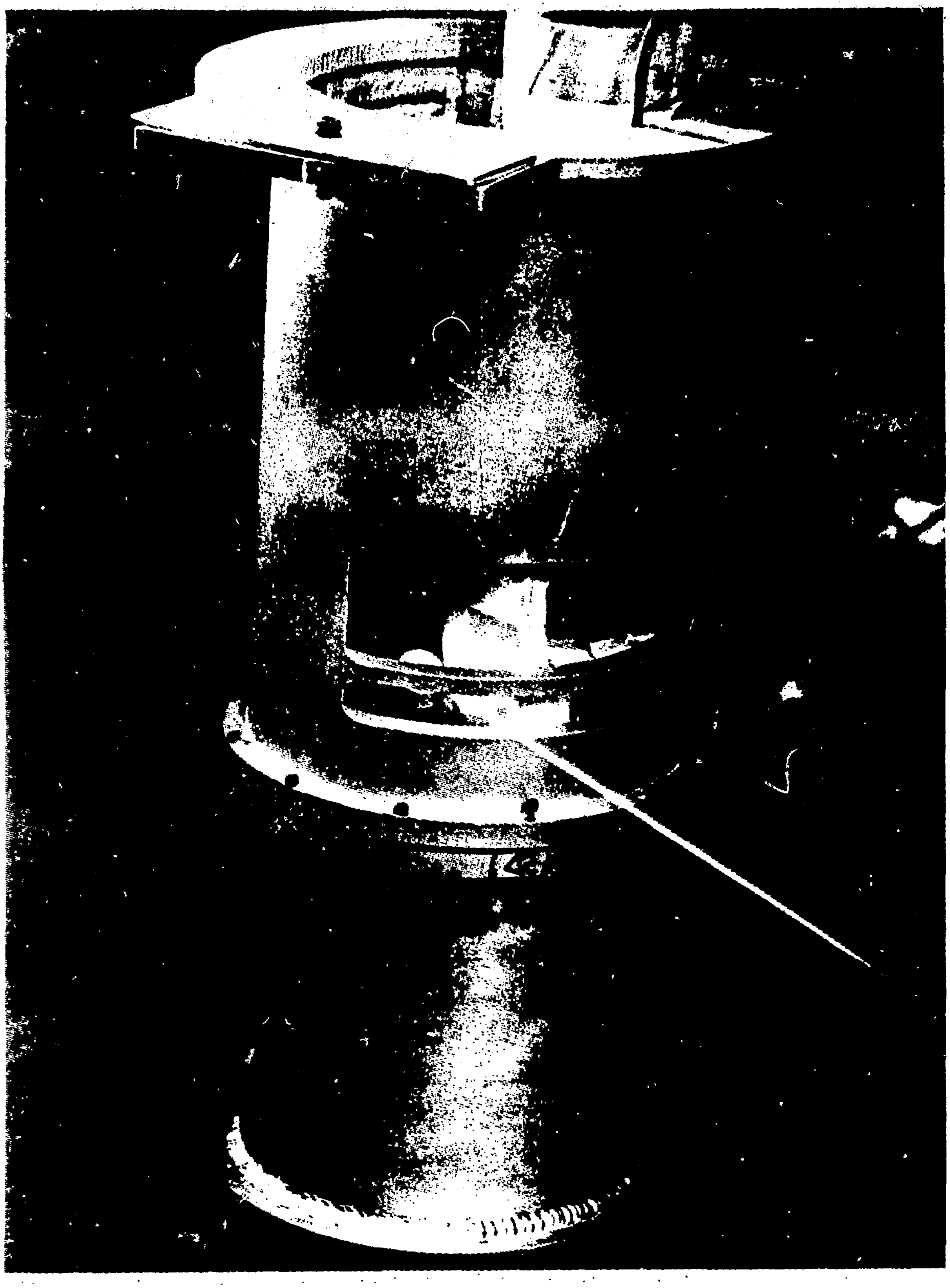
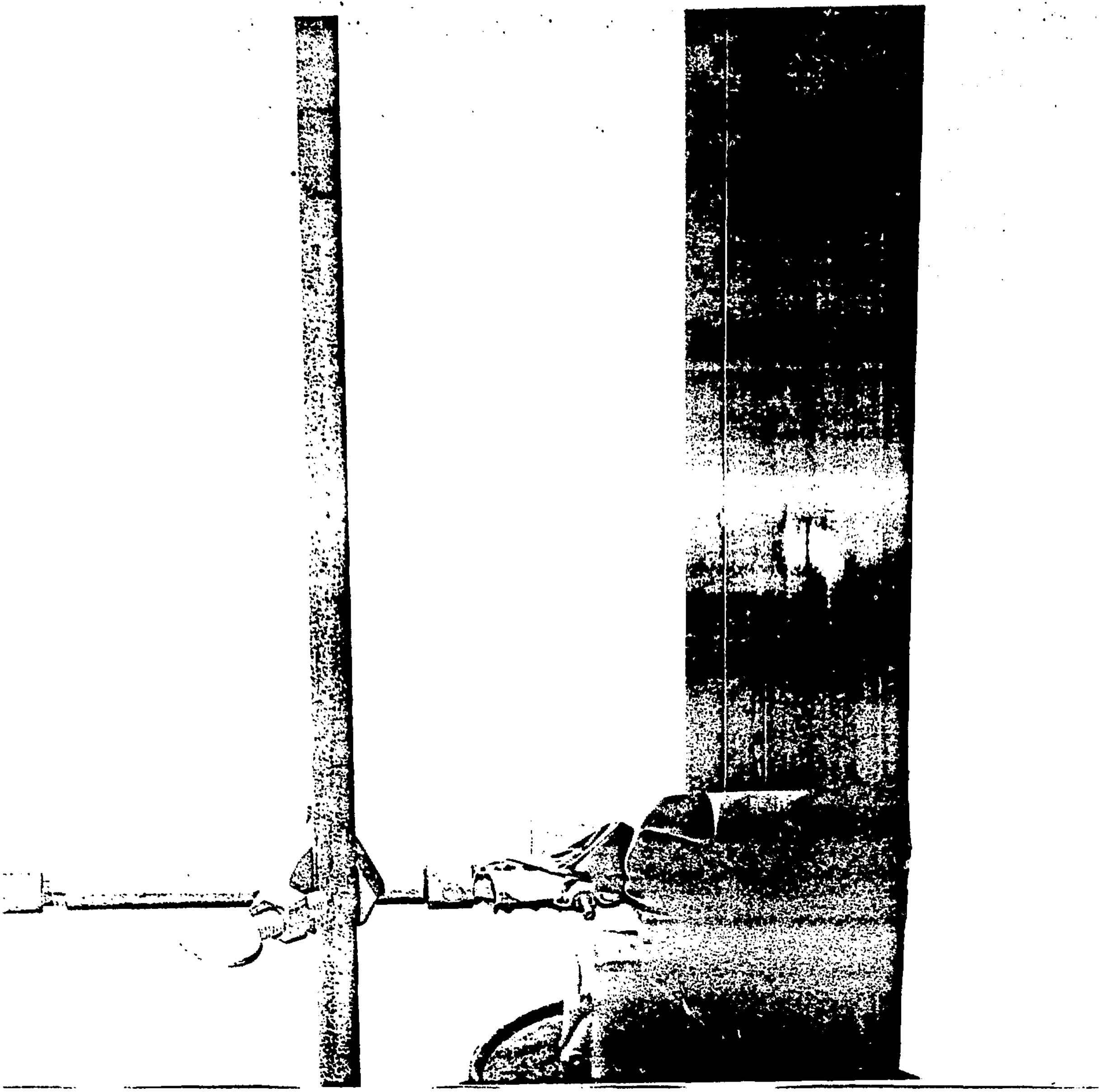


Figure 6. Photograph of the Simulated BWR Assembly Using 6 Zircaloy Rods. The Bright Spot is the Laser Beam.



Laser and Associated Equipment

A small 0.5 milliwatt HeNe red laser (632.8nm) emitting a 1mm dia. laser beam was used. 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, discs with small holes or slits were located 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 18 feet to a 1 inch dia. 45° mirror and then horizontally 75' to a wall. The reflected light was received by a 3 inch 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 the background scattered laser light from entering the PM tube.

PM Detector

The PM detector was an RCA C7164R, 1½" diameter, 10 stage head-on type tube employing a multialkali photocathode having exended red response. Two red filters having bandwidths of ∿ 10nm centered at ∿ 632.8nm 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 18' 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.

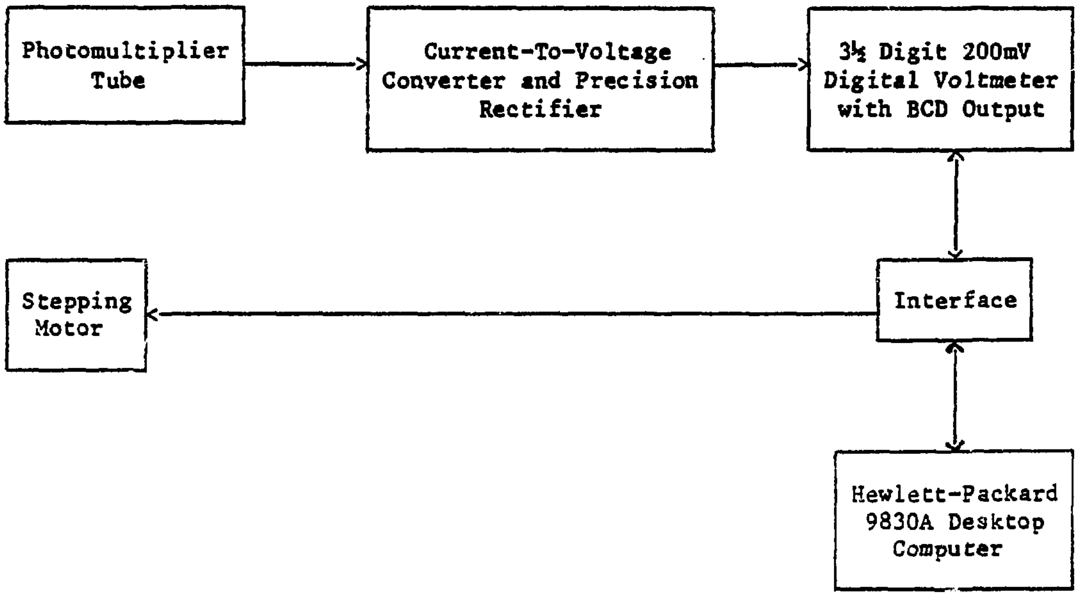


Figure 7. Electronics System Block Diagram

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. 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.

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 is programmable 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.

Simulated Fuel Assembly.

Six ½" zircaloy rods were aligned roughly into a section of a BWR assembly (see Figure 6) to obtain a realistic reflective response to the incident laser beam.

4. Results

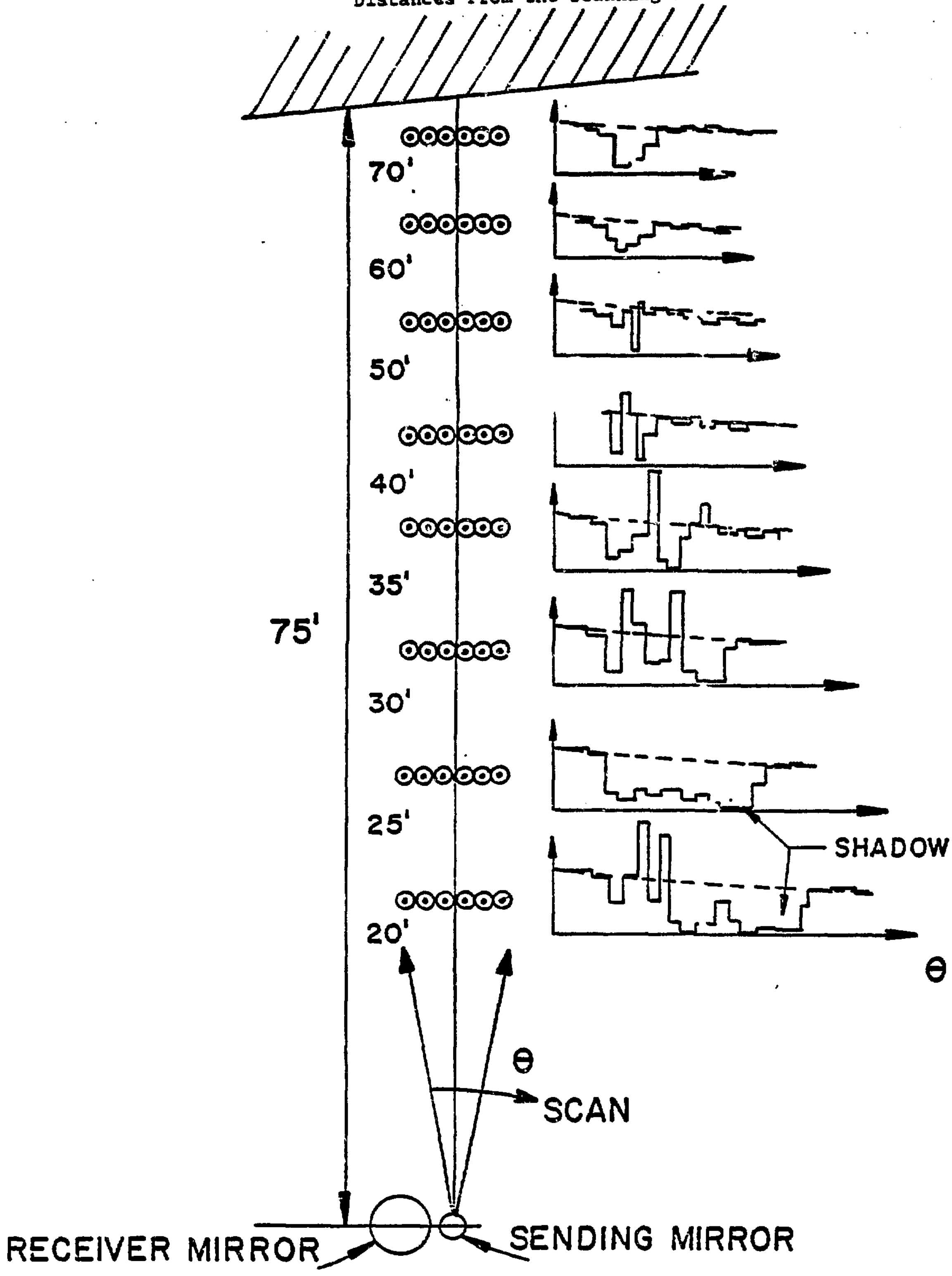
Under manual control, a 1½" dia. laser beam was scanned across the simulated BWR assembly located at various distances from the mirrors. Several of the scans shown in Figure 8 demonstrate the variety of responses possible. Besides solid angle geometric effects on the response, there is a tremendous variation in reflective 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° which translates to 2" at R=75' compared with an 8x8 BWR assembly dimension of 5". Hence, even at the furthest distances, there will be at least three anomalous points to a BWR assembly and even more for a PWR assembly. Reproducibility of a scan in all tests was very good.

At no time was there any ambiguity that an anomaly was being detected since the reference scan (either from a highly dispersive wall or from a sheet of stainless steel) with no assembly had a fairly smooth variation with angle (dotted line in Figure 8). The determination of the location of the assembly

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



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, but must be compatible with the goal of locating the assembly to within the size of one storage rack location.

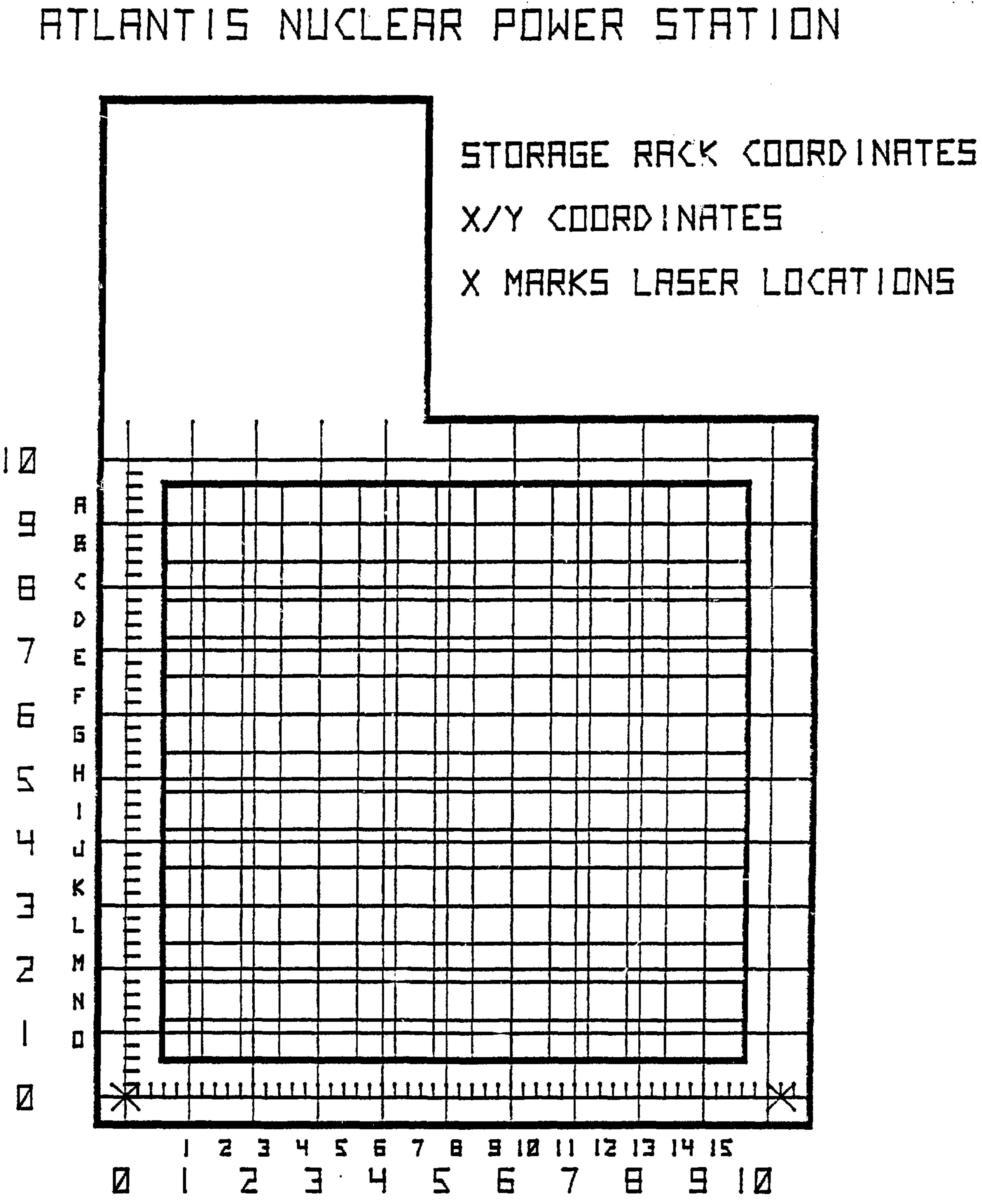
Ultimately, the computer, upon request by the inspector, will generate a table (see Table I) which will list the X-Y coordinates and times of anomalies. These coordinates can be correlated with assembly location with either an overlay map such as shown in Figure 9 or directly if the storage rack geometry is stored in the computer.

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	6.90
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

Figure 9. Overlay Map of a SFSP Showing Computer Generated Storage Rack and Laser System Coordinates and a Listing of Simulated SFSP Anomalies.



5. The Design Features for a Prototype SFSP Laser System

With the encouraging results from the first prototype laser system, we are designing a second system to be tested at a SFSP. Several changes will be made to account for the change in beam path from air to water. Foremost is the change from a red laser to either a c.w. blue laser or to a pulsed u.v. nitrogen laser.

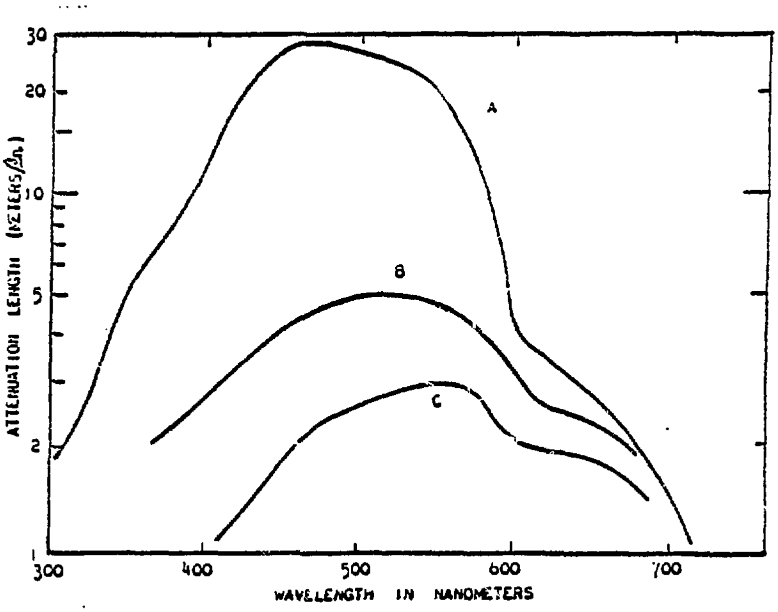
The attenuation length vs. wavelength for underwater transmission of light is a maximum for blue light (see Figure 10). At a total path length of 150' the intensity loss for blue light is only about 80% whereas for red light it is seven orders of magnitude.

If it is thought necessary to strengthen the laser system by incorporating laser ranging, a pulsed nitrogen laser will probably be used. This type of laser is known to be reliable and inexpensive and capable of producing the short pulses necessary for ranging to within a few inches in a path length of less than 75'.[4] Although u.v. light is highly attenuated in water, the narrow pulses allow for compensating high peak power.

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.

An overall improvement of the mirror design should reduce the size and complexity of the unit that is lowered in the pool. Perhaps the long tube can be eliminated if the sending and receiving beams can be transmitted to the pool's surface in water.

Figure 10. Attenuation Length vs. Wavelength for Underwater Transmission of Light in (A) Distilled Water, (B) Oceanic Coastal Water, and (C) Typical Lake Water.[5]



The electronic package will require a redesign if laser ranging is introduced. Even if a blue laser is used, the electronics may be changed to incorporate a lock-in amplifier and precision chopping of the beam. Also, the computer software will have to be revised to calculate the assembly location by both triangulation and ranging. With laser ranging, two laser beams are still necessary to detect the raising of one assembly in the shadow of another.

6. Conclusions

The laser surveillance system described above will introduce an electronic cover -- a sheet of laser light -- over the spent fuel assemblies. When an assembly is raised and intercepts the two sweeping laser beams, the altered reflective signals are processed by a small computer and the exact position of the raised assembly is calculated by triangulation, or by ranging, or both. 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 we have constructed and tested demonstrates the engineering principles involved and has provided enough information to design a system to be used at a 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 C/S devices under development. The final design should be rugged and long-lived and also relatively inexpensive.

7. Acknowledgements

We wish to thank Mike Degen for valuable assistance in testing the laser system and Tony Fabiano for his help in designing and constructing the hardware. We are indebted to Jon Sanborn for helpful discussions.

8. References

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