Carderock Division
Naval Surface Warfare Center
Bethesda, Md. 20084–5000

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Machinery Research and Development Directorate
Technical Report

Fiber Optic Hatch and Door Closure Sensors for Damage Control Monitoring

by
Henry K. Whitesel
John K. Overby

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Annapolis, Maryland 21402

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FIBER OPTIC HATCH AND DOOR CLOSURE SENSORS FOR DAMAGE CONTROL MONITORING

ABSTRACT

In general fiber optic sensor technology offers instrumentation solutions to monitoring damage control for all the damage control parameters on Navy ships. In particular fiber optic technology offers inexpensive designs for hatch and door closure sensors in forms that will ultimately help reduce shipboard man-power. The application of closure sensors to all hatches and doors makes it possible to very quickly estimate the spread of fire and flooding during emergency situations. These sensors need to be robust, meaning capable of operating during high temperatures to provide information even when compartments are on fire. Hatch and door closure sensors have been developed using light blockage and microbend techniques. Two types of position sensors were designed and evaluated. Each utilized a plunger mounted under a tab welded to the door. In one sensor the light beam between transmitting and receiving fibers was interrupted with the plunger. In the other the plunger induced microbend losses in the fiber. Sensors were operated in temperatures up to 300 degrees Centigrade during an evaluation on the ex-USS SHADWELL. Costs are presently competitive with electrical equivalents and can even be drastically reduced by development and application of multiplexing and integrated optic technologies.

INTRODUCTION

Fiber optic damage control sensors that detect the status of fires and flooding have been developed and demonstrated on the ex-USS SHADWELL over the last 5 years. Fires are detected by measuring smoke density and temperatures in individual compartments. Flooding is detected by measuring the liquid level. When combined with optical multiplexing technology being developed in the Fiber Optic Sensor Specifications and Standards Program, and with integrated optics technology, the total sensor package cost can be sufficiently reduced to enable direct competition with electrical sensors and to warrant installation in every compartment onboard ship.

The Advanced Damage Control Sensor Subtask of the Damage Control Task is developing sensors for hatch and door closure status, fire main pressure and flow rate, size and location of holes in the ship's hull and interior decks and bulkheads, and air flow in the ventilation ducts for smoke removal systems. This report documents our development and evaluation of fiber optic hatch and door closure sensors. Reports to be issued later will document development and evaluation of the other sensors.

Developing inexpensive damage control status sensors that can be installed in every compartment and in every system as needed, provides the required information input to systems that can automatically calculate fire spread and progressive flooding. This combined capability will allow for rapid response to damage situations. When fully developed and operational, these systems will aid manning reduction on surface ships by minimizing the effort required to fight fires and control flooding.

MEASUREMENT REQUIREMENTS FOR HATCH AND DOOR CLOSURE STATUS SENSORS

The closure status of the hatches and doors is very important to damage control because fires and flooding spreads rapidly through openings. Knowledge of the hatch and door closure condition will allow the ships officers and automatic systems to rapidly and reliability predict fire spread and progressive flooding and will aid the formulation of damage control strategies.

The performance goals of a hatch and door closure sensor system were determined by assessing the usefulness of the information for shipboard control and monitoring systems. To be effective at monitoring battle conditions we need to monitor every hatch and door. A count of the total numbers of hatches and doors was not done during this study but the number is estimated to be between 1000 and 2000 for a typical destroyer size ship.

The performance goals of hatch and door closure sensors are summarized in Table I[1]. The sensors must tolerate the shipboard environment of varying temperature, humidity, shock, and vibration. Size and weight must be sufficiently small to not impact the ship or the spaces within the ship. Cost is given as $500 but should even be lower, as this would further encourage the application of the technology in new construction ships.

Maximum operating temperature could have been listed as 1200°C to survive the vast majority of any fires that will be encountered onboard ship. There are mitigating circumstances that lead to a lower required operating temperature. Sensors might be mounted low or near the mid point of height on a door to avoid the high temperatures near the overhead and to keep flames from direct contact with the sensor until the fire becomes very hot. A maximum operating temperature of 800°C is relatively easily achievable with a moderately priced sensor and will enable monitoring all hatches and doors except in those compartments that have been burning for a few minutes, meaning we will at least know the initial closure state immediately after damage occurs. For the above reasons, we set the maximum operating temperature to be 800°C.

If we do not require operating temperatures of at least 800°C for hatch and door closure sensors, we may endanger not only the ship's mission but the ship itself because fires and flooding can spread rapidly through open doors and hatches. However, a lower operating temperature requirement might be 350°C. Most of the compartments adjoining those actually on fire do not experience temperatures above 350°C except those compartments immediately above the fire.

Measuring three states of door and hatch closure is required because they may be inadequately dogged down in emergency situations. A door on a ship is either open, shut with 1 or more lugs partially dogged, or completely dogged down.

Water tight doors on ships have compound hinges. Closing an open door results in two types of movement. The initial movement is angular rotation until the door moves into the plane of the bulkhead. Final movement, as the door is dogged, is linear as the plane of the door is shoved into the seal. Total linear movement to be measured between the open state and the dogged down state is about 1 centimeter (0.375 inches).

Table 1 - Performance Goals for Damage Control Hatch and Door Closure Sensors

PARAMETER	HATCH AND DOOR CLOSURE SENSOR PROPERTIES
Input Range	Open, shut, or dogged down (Total change in position is 1cm (3/8"))
Accuracy	No leaks
Resolution	No leaks
Desired Unit Production Cost (per measurement)	< $500
Size	< 325 cubic centimeters (20 cubic inches)
Weight	< 0.5 kilograms (1 pound)
Output Signal	0 to 20 milliampere, 0 to +10 volts, and/or compatible with FODMS, SAFENET or ATM
Response Time	< 3 seconds
Mean Time Between Failure	> 100,000 hours
Mean Time Between False Alarm	< 1 per 50,000 hours
Mean Time to Repair	< 1 hour
Operating Life	40 years
Environmental Temperature	Sensing Element and Cable: $0^{o}C$ to $800^{o}C$; Electronics: $0^{o}C$ to $65^{o}C$
Environmental Relative Humidity	5% to 95%
Environmental Vibration	MIL-STD-167-1, Level 1
Environmental Shock	MIL-STD-901
Electromagnetic Interference	MIL-STD-461
Environmental Atmosphere	Salt spray, dust, and smoke
Input Power	< 100 milliwatts per sensor (115 VAC, 60 Hz)
Calibration	Daily self calibration, Otherwise 6 months
Blast	Not specified

Special Considerations: Sensors will be addressable. Sensing element and cable must also withstand water spray from fire hoses. Measurements can be accomplished with position or force sensors.

HATCH AND DOOR CLOSURE SENSORS BASED ON ELECTRICAL TECHNOLOGY

Electrical position sensors have been available for many years and could be purchased off the shelf for application onboard ship. In general operation is restricted to low temperatures but the technology is mature and must be considered if the high temperature performance goals, listed above are reduced.

Non-optic displacement and position sensors come in several types including, inductive position sensors, eddy current probes, linear variable differential transformers (LVDTs), slide wire potentiometers, ultrasonics, and magnetostriction devices. Inductive position sensors measure the change in inductance of a coil as magnetic material moves relative to the coil; inductive position sensors can be both linear and rotational.[1] Eddy current probes operate by inducing electrical currents in nearby nonmagnetic materials; the power load varies as a function of the distance between the probe and the nearby material.[2] Linear variable differential transformers contain a movable core attached to the test object; as the core is moved the coupling coefficient changes.[2] Slide wire potentiometers have the tap of the potentiometer mechanically connected to the test object; as the tap moves with the test object, the tap voltage varies.[2] Ultrasonic and acoustic distance detectors emit an acoustic wave that reflects off the test object; distance is measured by detecting the transit time between transmitted and received acoustic pulses. Magnetostriction probes utilize the production of an acoustic pulse in magnetostrictive wires when movable position magnets are energized with pulses.[3]

HATCH AND DOOR CLOSURE SENSORS BASED ON OPTICAL TECHNOLOGY

Optical technology was chosen for measuring shipboard door position because of the possibility of designing high temperature sensors and the high probability of achieving an inexpensive multiplexed sensor network. Within the field of optical technology, there are many possible design solutions for measuring position as reflected in the following list:

Optical position encoder[4,5,6]
Lossy waveguides[7,8]
Reflection from a surface[9,10,11,12,13,14,15]
Bend Induced Losses[16,17,18]
Diffraction Grating[19,20]
Light Blockage[21]

There are also several application papers that review the many different techniques of using fiber optic technology to measure position.[22,23,24]

The optical position encoder consists of a reflective code plate attached to the movable object, whose position is being measured.[4,5,6] The code plate contains a digitally inscribed code that varies with linear position such that each new position reflects a unique digital code directly into the optical receiver. The code plate operates over temperatures of -48°C (-55°F) to 51°C (125°F). The code plate has been designed to measure both linear and rotational position.[5] The code plate has been tested for helicopter applications and is available commercially.[6] It was designed for input ranges extending up to 12.5 cm (5 inches).

Lossy waveguides have been used in the design of contactless position sensors.[7,8] A light source is attached to the moving object and injects light into an adjacent lossy waveguide. As light propagates down the lossy waveguide in both directions, it looses energy in proportion to the distance traveled. Detecting the light emitted from the ends of the lossy waveguide and taking the ratio gives a monotonic signal proportion to the position of the light source along the lossy waveguide. Resolutions of ±0.5 mm have been achieved over an input range of 100mm.[7]

Measuring the amplitude of reflection of an optical signal from a surface with a single fiber or a fiber bundle yields a simple straight forward design for a position sensor that has been reported on many times in the literature.[9,10,11,12,13,14,15] The usual implementation of this technique is to start with a bundle of fibers of which one half are energized and the other half function as passive optical receivers. When the end of the fiber bundle is placed in contact with a movable object and then moved away, the signal reflected into the receiving fibers initially increases to a maximum and then gradually drops toward zero. A choice is made to operate on the rising or falling slope of the response curve. The rising curve is chosen for small ranges of distance, under a millimeter.[14] The falling curve is used to measure distances from about 1 mm to 2.5 mm.[14] (This does not fit our requirement of 0 to 10 mm.)

It is well known that bending a multimode fiber causes absorption of the higher order modes. This effect has been used to design position sensors by monitoring the change in the optical amplitude.[16,18] (We investigated this position sensor in our laboratory and found that it is preferable to measure the spectrum shift because this signal varies less with ambient temperature, as explained below.) The microbending effect can be used to design position sensors for a range extending from 10^{-9} meters[16] to about 1 cm.

Diffraction gratings have been used to measure linear position over a range of about 2.5 cm (1 inch),[19] and angular displacement over 360 degrees.[20] The diffraction grating is designed to have variable line spacing with linear distance and is mounted on the movable object. When the diffraction grating is illuminated with a broadband source and the reflected light is viewed at a fixed angle, the reflected light wavelength varies with position.[19] Accuracy demonstrated was 0.1% over a range of 2.5 cm (1 inch).

Light blockage has been used to measure position in 2 dimensions to an accuracy of ±3 micrometers, over a range of 1.4 mm.[21] The principle could be adapted to the larger range measurement that we need for measuring hatch and door closure status onboard ship.

Each of these optical position measuring techniques were reviewed for application to shipboard hatch and door closure monitoring. We decided to develop our own measurement techniques as discussed in the next section.

DEVELOPMENT OF FIBER OPTIC HATCH AND DOOR CLOSURE SENSORS

Several techniques were instrumented in bench top models for consideration for the shipboard design of the hatch and door closure sensor; these included light blockage, microbending, polarimetric reflective, and Bragg-grating sensors. We eventually decided to design two types of sensors for shipboard application using light blockage and microbending operating principles.

LIGHT BLOCKAGE SENSORS

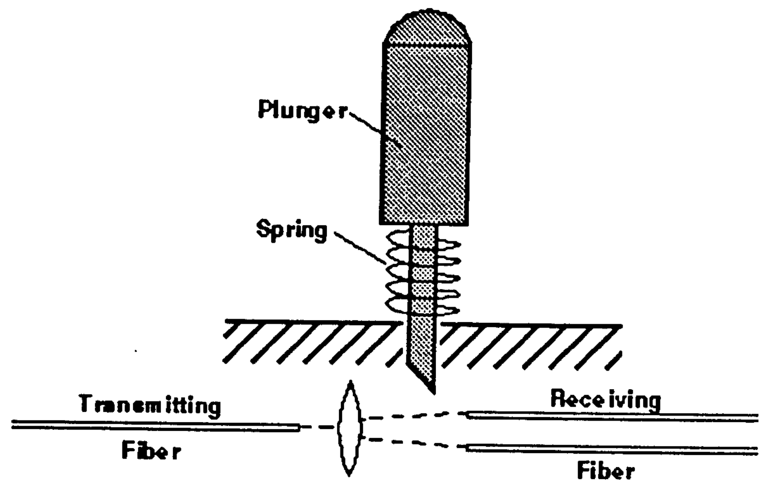

Figure 1 - Operating Principle of Hatch and Door Closure Sensor Designed by Pro-Optical Technologies.

Light blockage sensors were designed and fabricated by Pro-Optical Technologies[a] in the configuration shown in Figure 1. This technique used a plunger to block the light path from a single transmitting fiber to two receiving fibers as shown in Figure 1. The sensor was mounted under a tab welded to the door. When the door was closed the plunger moved down to block the light first in the upper fiber and then in the lower fiber. The receiving fibers were separated at the proper distance to correspond to the following conditions: Presence of light in both receiving fibers indicates and open door. Absence of light in the upper fiber constitutes the door being simply closed and lightly attached, but not dogged down. Absence of light in both receiving fibers corresponded to the door position of being fully dogged. Total movement of the plunger was 1 cm (3/8 inch).

The enclosure was made of aluminum and was machined into the part pictured in Figure 2 with mounting feet designed to bolt the sensor directly to steel bulkheads. The fiber cable was armored with a corrugated stainless steel jacket for the first 30 feet from the sensor to protect from flames licking the cable during the evaluation. There were three fibers in the cable, one transmitting and two receiving. Fiber used was 200/230 micrometers.

Epoxy was used to mount the fibers in the sensor enclosure thereby limiting the maximum operating temperatures to about 350°C. Using mechanical mounting of the fibers would extend operating temperatures to slightly above 800°C. This limit is driven by the fact that glass fibers start to anneal at about 835°C, causing increased attenuation of the transmitted light. Actually the sensor might operate for a short period of time up to 1200°C if the fibers were of special design, had a metallic coating, and the section of the heated fiber was kept short.

Unit production cost of the sensor design for 350°C might be $100 while the 800°C sensor might be several hundreds of dollars. It is expected that a cost benefit study of the high temperature design would be done before the high temperature design was applied in a massive way.

Three models of the light blockage hatch and door closure sensor were made for operation up to 350°C. One model of the light blockage sensor was evaluated in the laboratory

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a. Use of Pro-Optical Technologies sensor in this development program does not constitute a government endorsement of this product and does not preclude future competitive procurements.

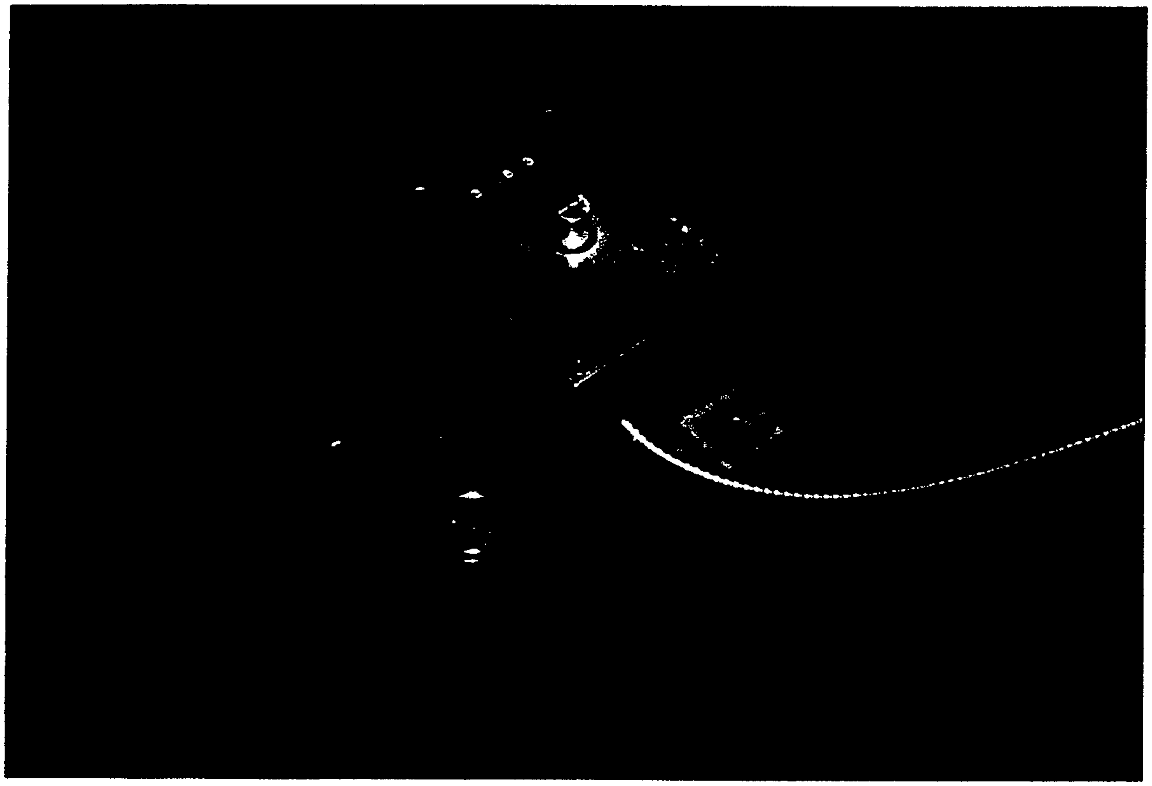

Figure 2a - Hatch and Door Closure Sensor Designed by Pro-Optical Technologies.

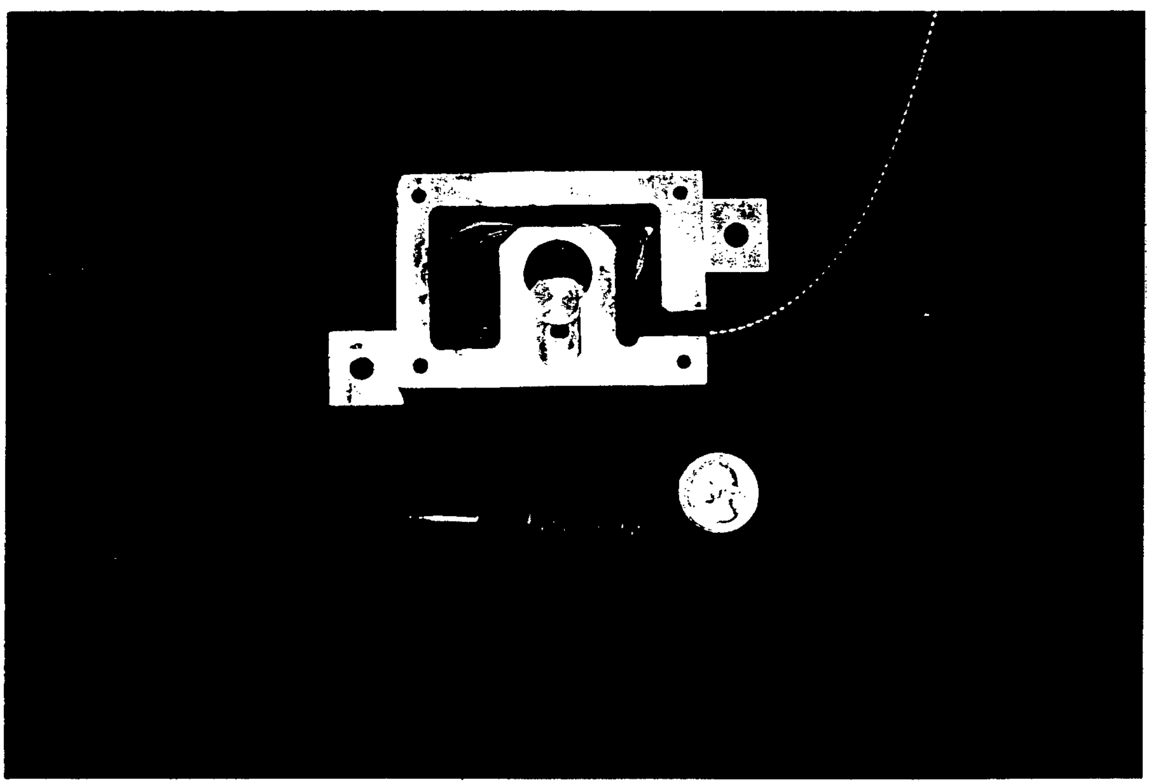

Figure 2b - Pro-Optical Technologies Hatch and Door Closure Sensor With Top Plate Removed.

for operation in the shipboard environment. The ambient temperature was elevated to 300°C and held for one hour with no change in the operation in any discernable way. The relative humidity was varied from 5 to 95 percent at 25°C with no change in operation. The sensing cavity shown in Figure 2b was also filled with tap water and the switching point did not change significantly.

MICROBEND SENSORS

A microbend sensor was designed to measure the three states of hatch and door open/close cycle as shown in Figure 3.[b] It utilizes a metal plunger to bend the fiber as the door is closed. The sensor is enclosed in a metal case for protection from heat and smoke. The light never leaves the fiber meaning it is relatively insensitive to dirt, dust and humidity. The sensor was successfully tested for life time operation of the switching cycle. The test was discontinued after 1.2 million cycles with no deleterious effects.

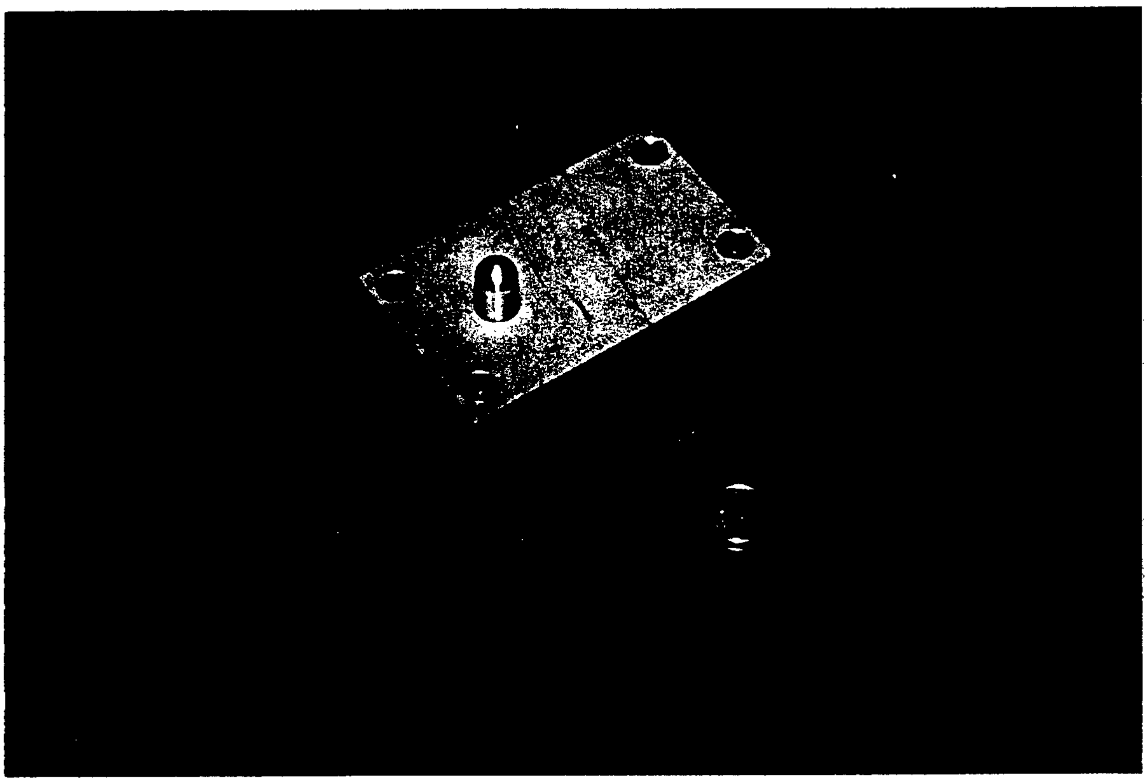

Figure 3 - The Microbend Hatch and Door Closure Sensor Designed at NSWCCD Annapolis.

Several models of this sensor were made using glues and a composite plate. High temperature operation can be achieved with the use of all metal materials and mechanical attachments of the fiber within the sensor.

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b. Details of the operating principle will not be disclosed here in as a patent has been applied for but has not been issued.

EX-USS SHADWELL EVALUATION

Four sensors were evaluated on the ex-USS SHADWELL to demonstrate their operation onboard ship. The sensors were installed according to the layout diagram shown in Figure 4. The opto-electronics packages were installed in the control room and connected to the optical sensors through a 76 meter (250 feet) fiber optic cable. Three sensors of the light blockage design, fabricated by Pro-Optical Technologies, were mounted on doors at 3-17-2 and 3-18-1 and on the hatch at 1-19-2. One sensor of the microbend design, fabricated at NSWCCD, Annapolis, was mounted on the door at 3-18-1, with the suffix N to indicate the Navy fabricated sensor. The sensors are shown in the mounted position in Figure 5a, 5b, and 5c.

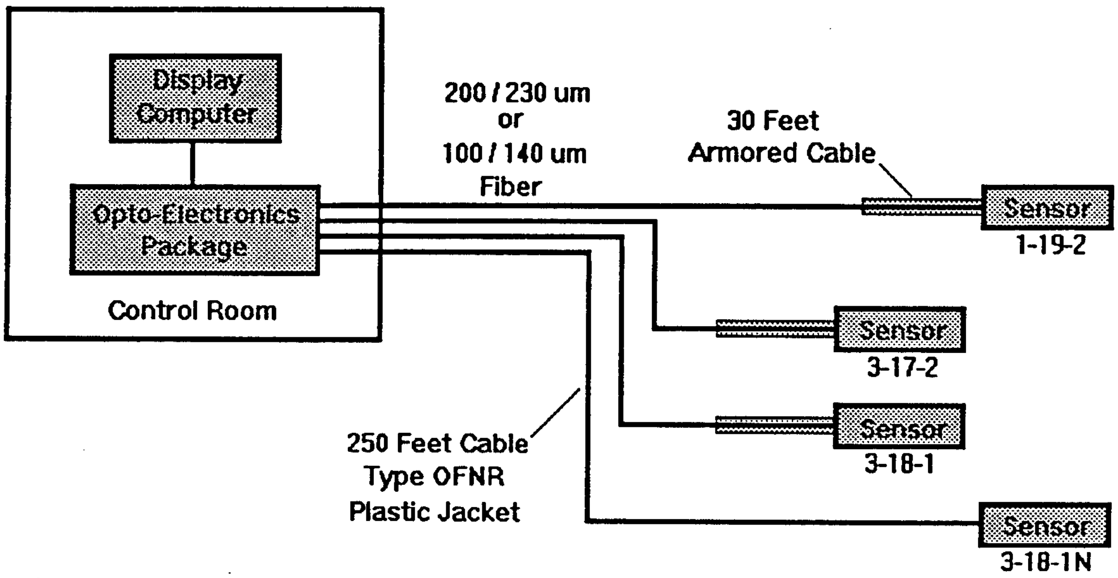


Figure 4 - Instrument Layout for the Hatch and Door Closure Sensor on the Ex-USS SHADWELL.

Each sensor was simply bolted to the bulkhead. A metal tab was welded onto the door and hatch that pushed down the plunger as the door was closed. The metal tab is clearly visible in Figures 5a and 5c.

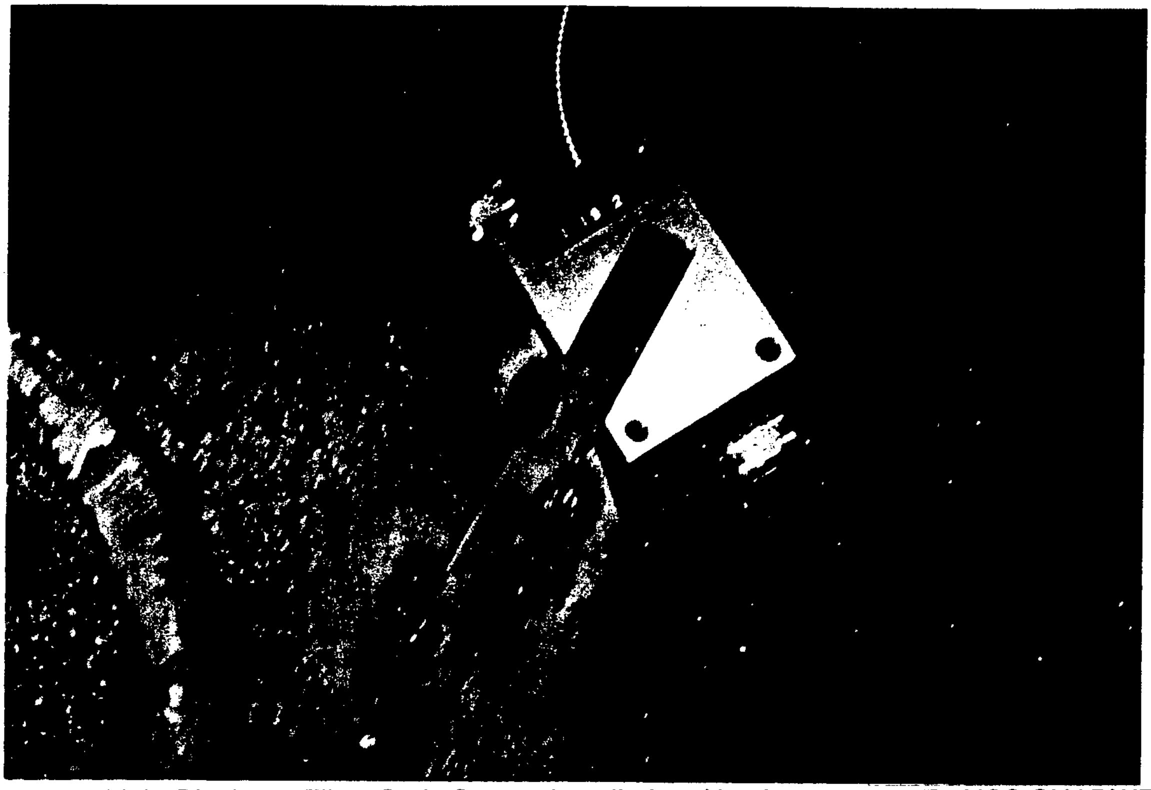


Figure 5a - Light Blockage Fiber Optic Sensor Installed on Hatch 1-19-2 on Ex-USS SHADWELL.

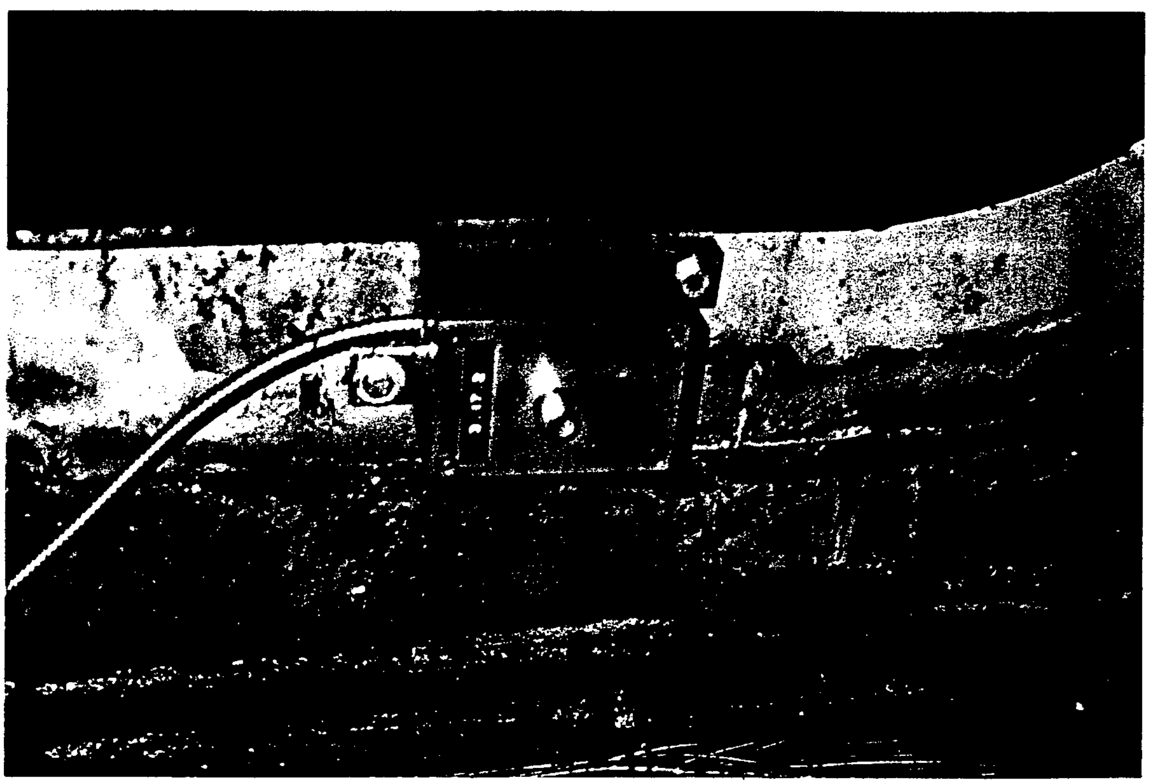


Figure 5b - Light Blockage Fiber Optic Sensor Installed on Door 3-17-2 on Ex-USS SHADWELL.

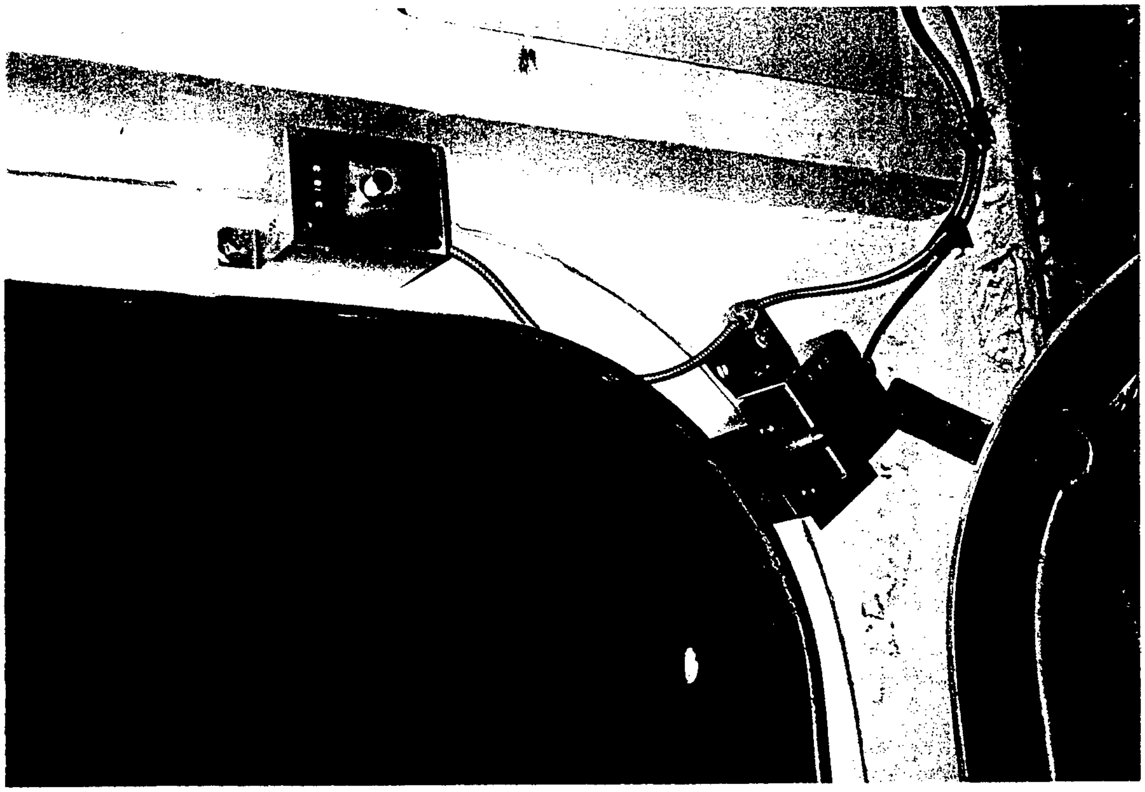
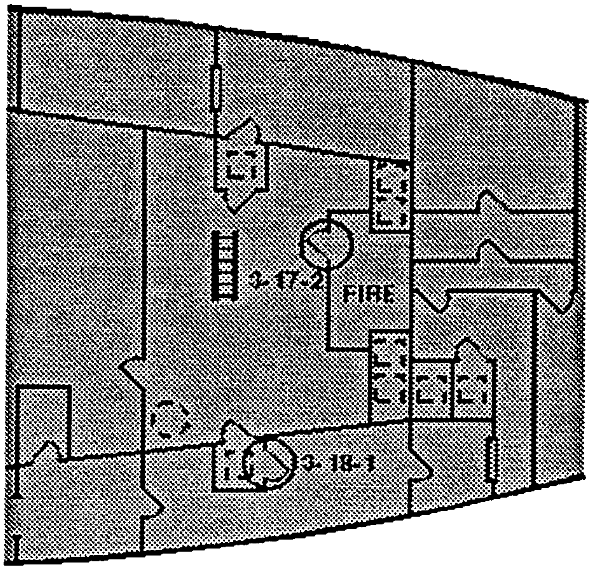


Figure 5c - Fiber Optic Sensors Installed on Door 3-18-1 on Ex-USS SHADWELL.

We found during these tests and other tests on the ex-USS SHADWELL that having an attractive display that gives information at a glance is extremely important. During fires, planned or otherwise, excitement runs high and the men in charge don't have time to study a display searching for information. The display in the control room consisted of a layout of decks 1 and 3 as shown in Figure 6. As implemented on the ship, the display was in color with red indicating a closed door and green indicating an open door. (The three closure states were not demonstrated during the tests on the ex-USS SHADWELL.) This display was very easy to use, giving information at a glance. It was created in a Power Point drawing and then imported into LABVIEW. The display was updated every second.

The test being run during the evaluation of the fiber optic hatch and door closure sensors was an explosive atmosphere test. A fire was started immediately inside the door 3-17-2 in the compartment labeled "FIRE" in Figure 6. Initially, it was burned with diesel fuel for about 15 minutes. The door was then closed for about 4 minutes, starving the fire for oxygen and generating high densities of hot fuel oil vapors. The door was then opened with a pull chain, allowing oxygen to mix with the vapors in the "FIRE" compartment creating "back draft" situations. The resulting deflagration would rush out over the sensor at 3-17-2, venting through the outer compartment doors. The pull chain operator was standing near door 3-18-1 and also observed the deflagration.



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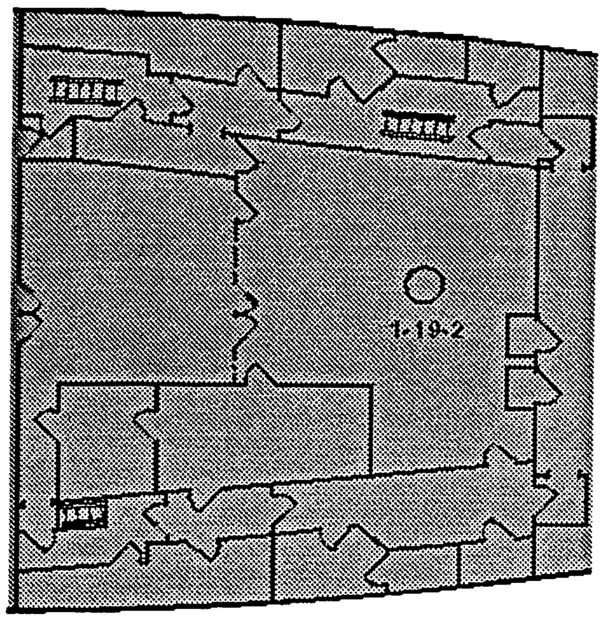


DECK - 1

Figure 6 - Hatch and Door Closure Sensor Display Located in the Control Room on the Ex-USS SHADWELL.

Pictures of the deflagration emitting from the "FIRE" compartment are shown in four photographs of Figure 7 for test SBD 59 to illustrate the conditions experienced by the sensor at door 3-17-2. In the first photograph, the deflagration is just beginning at time 13:30:37. The door closure sensor is just visible at the bottom of the door. The deflagration is maximum at 13:30:38, has started to decay at 13:30:39, and has nearly finished at 13:30:40.

The usual situation for the other three sensors was the following: Door 3-18-1 was partially dogged at the same time that the "FIRE" door 3-17-2 was closed. When the deflagration occurred, door 3-18-1 usually was blown open. Hatch 1-19-2 (2 decks up) was normally closed but not dogged down during the tests and was used as a vent for the pressure transient caused by the deflagration; sometimes it was blown open momentarily.

There would usually be 2 tests per day. Between fires, the bulkhead and door 3-17-2 to the "FIRE" compartment would be washed with water from a fire hose for cooling and cleaning purposes, also wetting down the sensor at 3-17-2 in the process. The bulkhead at 3-17-2 would sometimes glow red from the heat during the tests. Estimated maximum temperatures for the sensor at 3-17-2 were 350°C. Temperatures at 3-18-1 and 1-19-2 were not excessive.

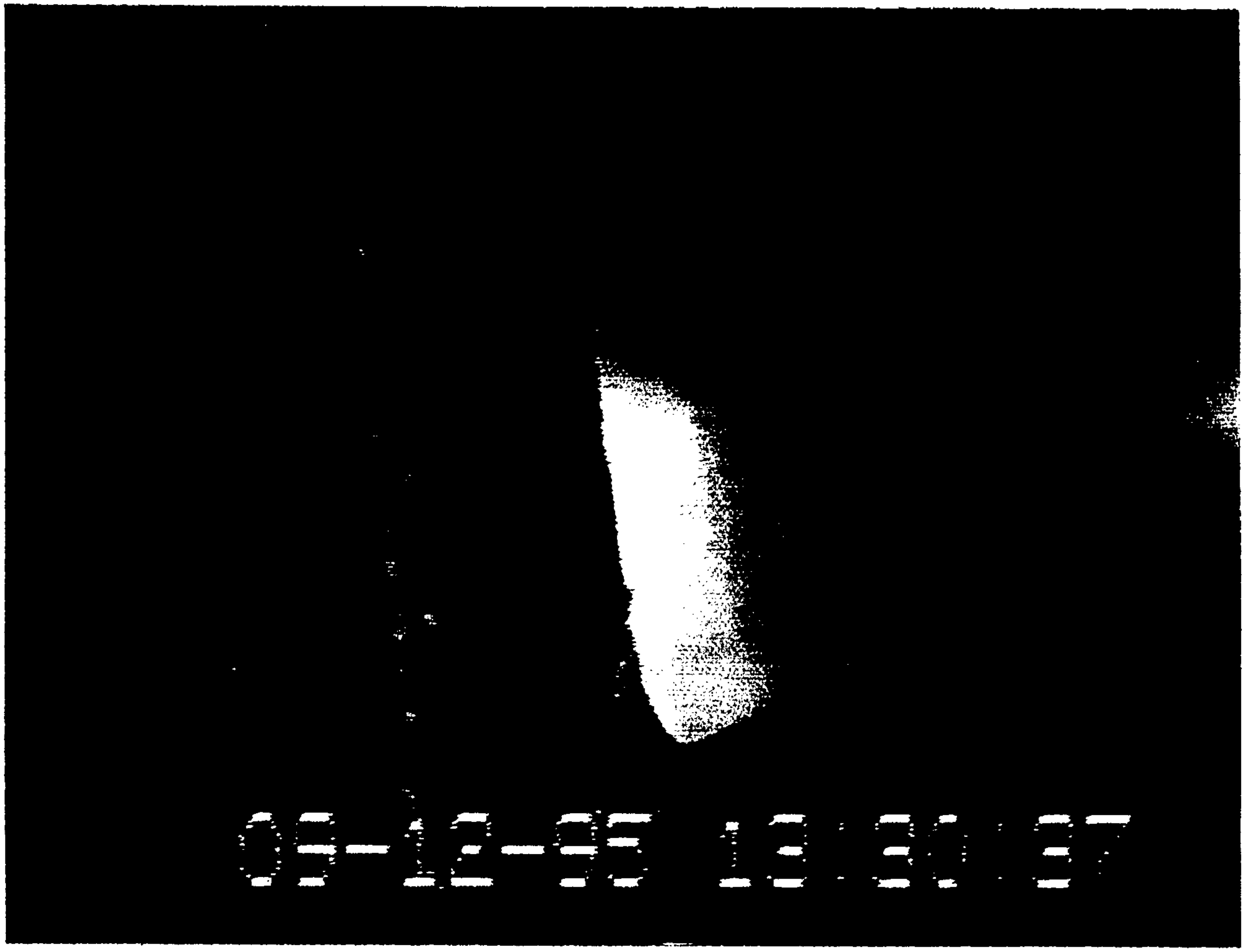


Figure 7a - Initiation of Deflagration Over Door Closure Sensor at 3-17-2.

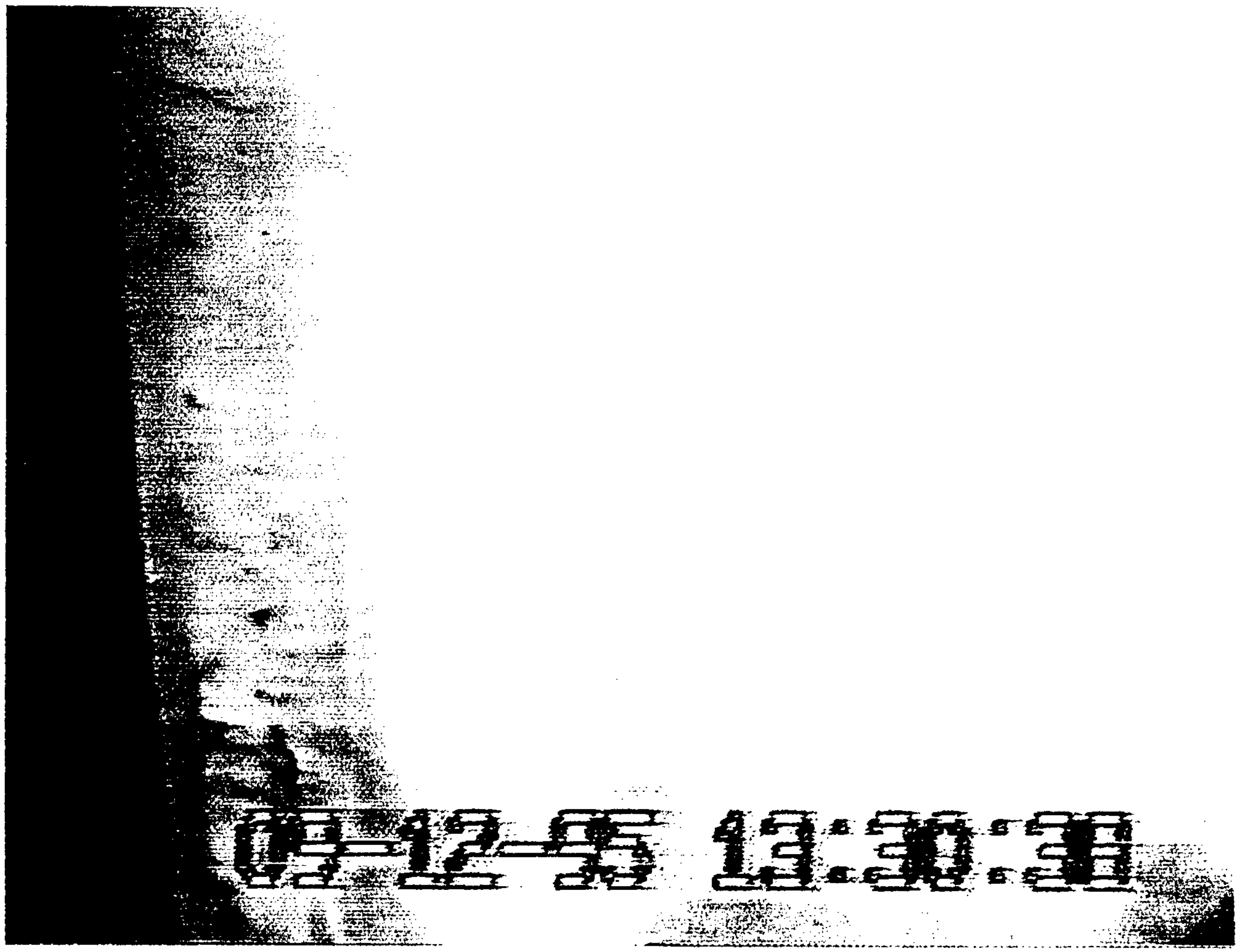


Figure 7b - Deflagration Over Door Closure Sensor at 3-17-2, One Second After Start.

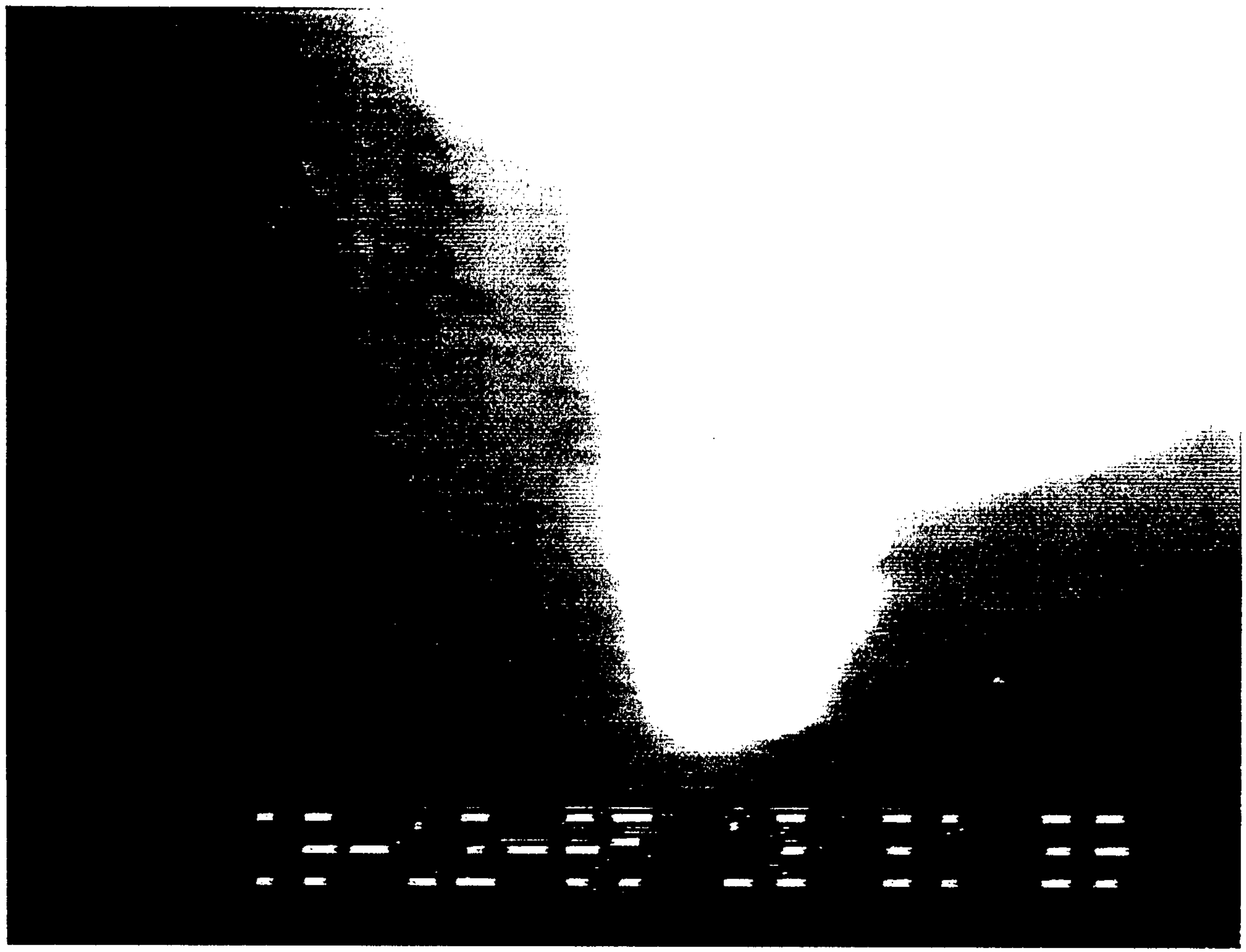


Figure 7c - Deflagration Over Door Closure Sensor at 3-17-2, Two Seconds After Start.

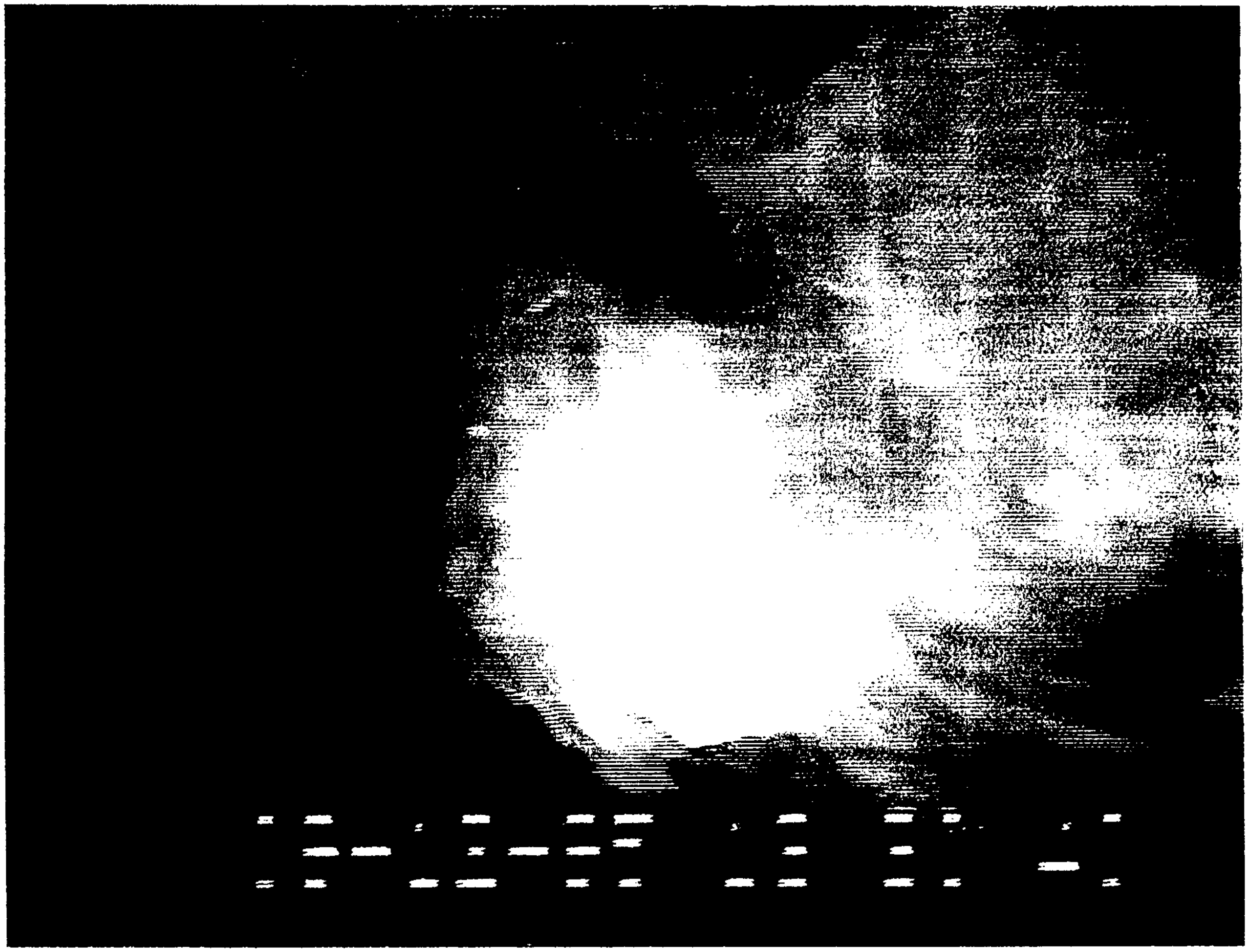


Figure 7d - Deflagration Over Door Closure Sensor at 3-17-2, Three Seconds After Start.

Records of the switching times are listed in Table II. Time traces of results of each of the tests are shown in Figures 8 through 16. There are two sets of graphs, each containing 3 or 4 time traces. The top graph shows all the data for each test. The bottom graph shows a compressed view of the data around the time that the "FIRE" door at 3-17-2 was opened and the deflagration occurred. Figures 8 through 16 indicate door and hatch closure conditions during the tests.

During the SBD 57 test, the "FIRE" door at 3-17-2 is shown as being open all the time, even though the video of the test confirms that the door was propped closed with a "2 X 4" wooden brace. However, it is clearly visible in the video that door 3-17-2 was warped and was not sealed at the bottom; the sensor thus showed the real closure condition. This illustrates an important benefit of the hatch and door closure sensors. When the deflagration occurred door 3-18-1 and hatch 1-19-2 were blown open at 14:12:56.

Test SBD 58 progressed nearly the same as SBD 57, except that this time door 3-17-2 was closed tightly for 30 seconds from 15:04:58 to 15:05:28, at which time the door warped again and pushed out at the bottom where the sensor was mounted. Hatch 1-19-2 was not blown open by the deflagration during this test.

Test SBD 59 progressed entirely as planned with all the doors being in the proper condition. The "FIRE" door 3-17-2 was closed at 13:26:22, opened at 13:30:22 with the deflagration occurring at 13:30:38, blowing open hatch 1-19-2 for one second at 13:30:39.

During test SBD 60, the bottom of door 3-17-2 again warped out about half way though the closure cycle.

The optical source (a light emitting diode), associated with the light blockage sensor on 3-18-2 overheated before test SBD 61 and was taken out of service for the duration of the testing.

During test SBD 61, the bottom of door 3-17-2 warped out 2 minutes and 40 seconds into the 4 minute closure cycle. The sensor on hatch 1-19-2 changed to indicating open at 13:19:21. This was a special test unlike the other tests. The hatch was open manually at 13:19:21 for this test only.

Test SBD 62 proceeded normally.

During test SBD 63, door 3-18-1 was not blown open when the deflagration occurred. The test had been changed and there was probably less force generated in the deflagration.

Test SBD 64 proceeded normally except that door 3-18-1 was again not blown open when the deflagration occurred. There was probably less force generated by the deflagration.

Test SBD 65 proceeded normally except that hatch 1-19-2 was not blown open during the deflagration.

Table II - Results of the Fiber Optic Hatch and Door Closure Sensor Evaluation on the Ex-USS SHADWELL (1 of 3).

TEST NO / DATE	TIME	HATCH 1-19-2	DOOR 3-17-2	DOOR 3-18-1	DOOR 3-18-1N
SBD 57 11 Sept 95	13:50:32	Close	Open	Open	Open
	14:08:40	Close	Open	Close	Close
	14:12:56	Open	Open	Open	Open
	14:15:33	Open	Open	Open	Open
SBD 58 11 Sept 95	14:47:05	Close	Open	Open	Open
	15:04:52	Close	Open	Close	Close
	15:04:58	Close	Close	Close	Close
	15:05:28	Close	Open	Close	Close
	15:09:16	Close	Open	Open	Open
	15:10:24	Close	Open	Open	Open
SBD 59 12 Sept 95	13:08:25	Close	Open	Open	Open
	13:26:19	Close	Open	Close	Close
	13:26:22	Close	Close	Close	Close
	13:30:22	Close	Open	Close	Close
	13:30:38	Close	Open	Open	Open
	13:30:39	Open	Open	Open	Open
	13:30:40	Close	Open	Open	Open
	13:33:00	Close	Open	Open	Open

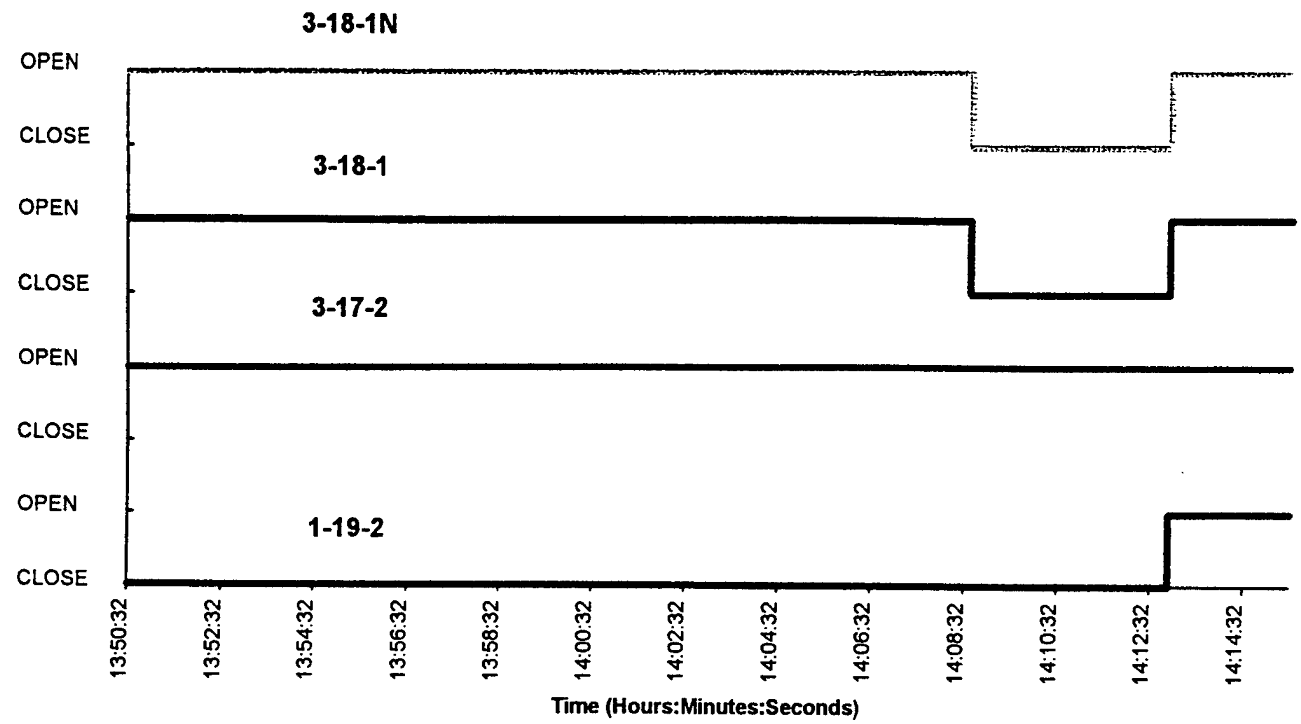
Table II - Results of the Fiber Optic Hatch and Door Closure Sensor Evaluation on the Ex-USS SHADWELL (2 of 3).

TEST NO / DATE	TIME	HATCH 1-19-2	DOOR 3-17-2	DOOR 3-18-1	DOOR 3-18-1N
SBD 60 **12 Sept 95**	13:49:57	Close	Open	Open	Open
	14:10:27	Close	Open	Close	Close
	14:10:29	Close	Close	Close	Close
	14:12:39	Close	Open	Close	Close
	14:14:42	Close	Open	Open	Open
	14:16:14	Close	Open	Close	Open
SBD 61 **13 Sept 95**	12:56:41	Close	Open	**Bad LED**	Open
	13:18:02	Close	Close		Close
	13:19:21	Open	Close		Close
	13:22:01	Open	Open		Close
	13:23:59	Open	Open		Open
	13:24:25	Open	Open		Open
SBD 62 **13 Sept 95**	13:47:57	Close	Open		Open
	14:01:36	Close	Open		Close
	14:01:38	Close	Close		Close
	14:05:37	Close	Open		Close
	14:05:50	Close	Open		Open
	14:07:40	Close	Open		Open

Table II - Results of the Fiber Optic Hatch and Door Closure Sensor Evaluation on the Ex-USS SHADWELL (3 of 3).

TEST NO / DATE	TIME	HATCH 1-19-2	DOOR 3-17-2	DOOR 3-18-1	DOOR 3-18-1N
SBD 63 14 Sept 95	13:14:39	Close	Open		Open
	13:36:33	Close	Open		Close
	13:36:38	Close	Close		Close
	13:40:38	Close	Open		Close
	13:43:07	Close	Open		Open
	13:45:30	Close	Open		Open
SBD 64 14 Sept 95	14:04:16	Close	Open		Open
	14:29:06	Close	Close		Close
	14:33:05	Close	Open		Close
	14:34:15	Close	Open		Close
SBD 65 14 Sept 95	14:53:16	Close	Open		Open
	15:11:07	Close	Close		Close
	15:15:07	Close	Open		Close
	15:15:23	Close	Open		Open
	15:16:16	Close	Open		Open

SHADWELL TEST SBD 57



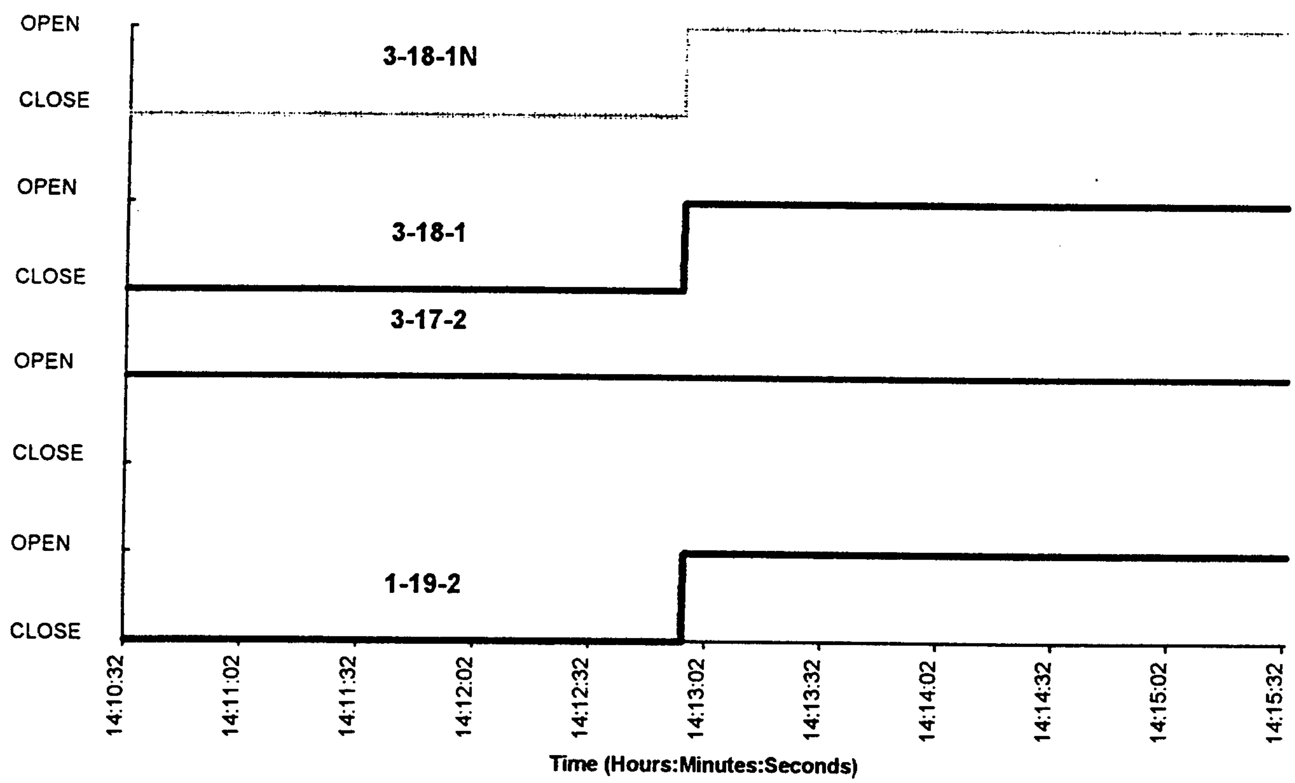
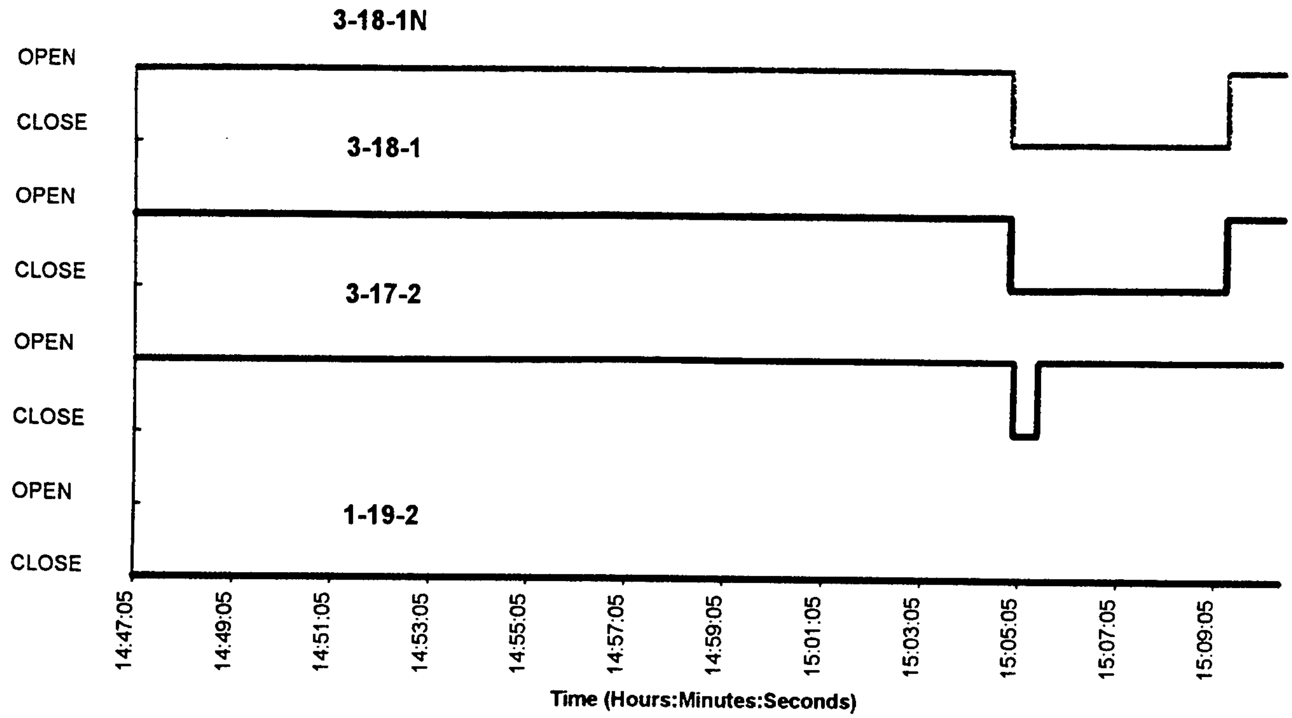


Figure 8 - Hatch and Door Closure Sensor Test Results SBD 57 11Sep95

SHADWELL TEST SBD 58



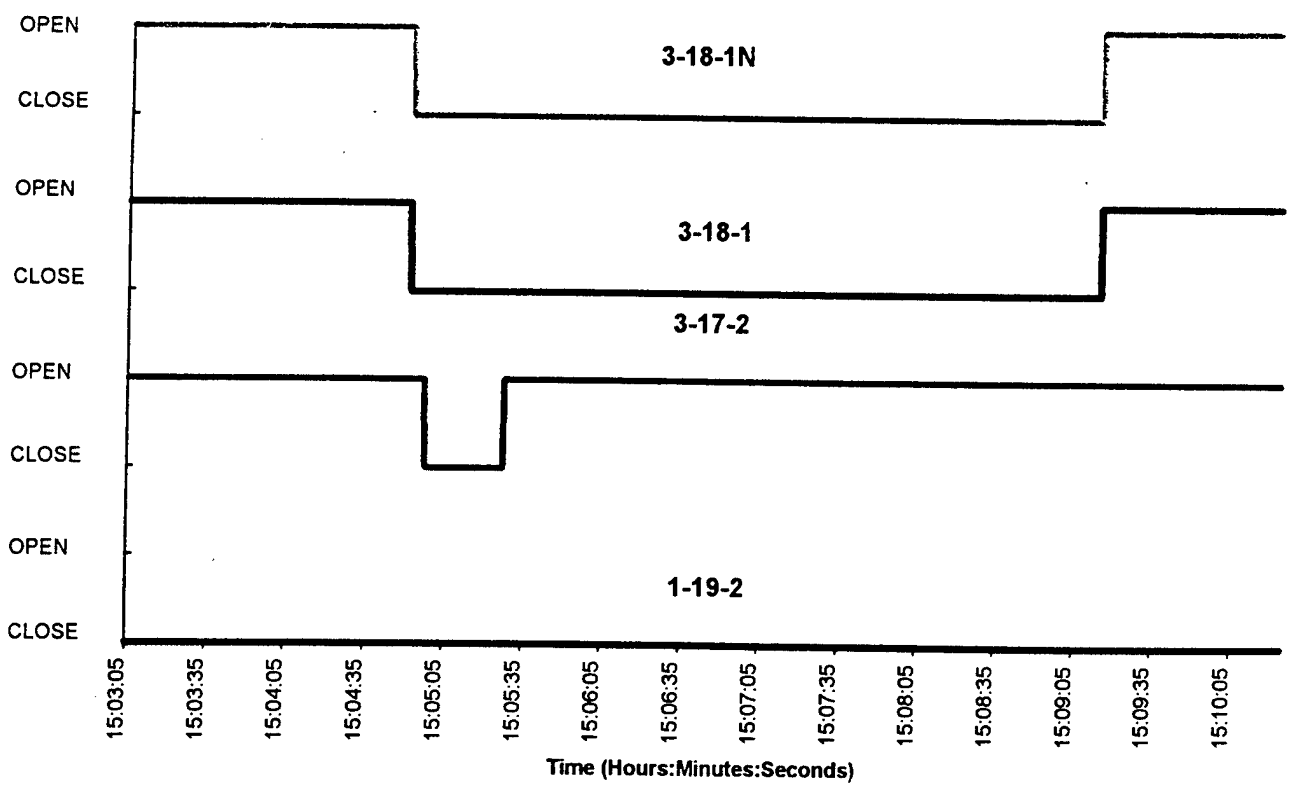
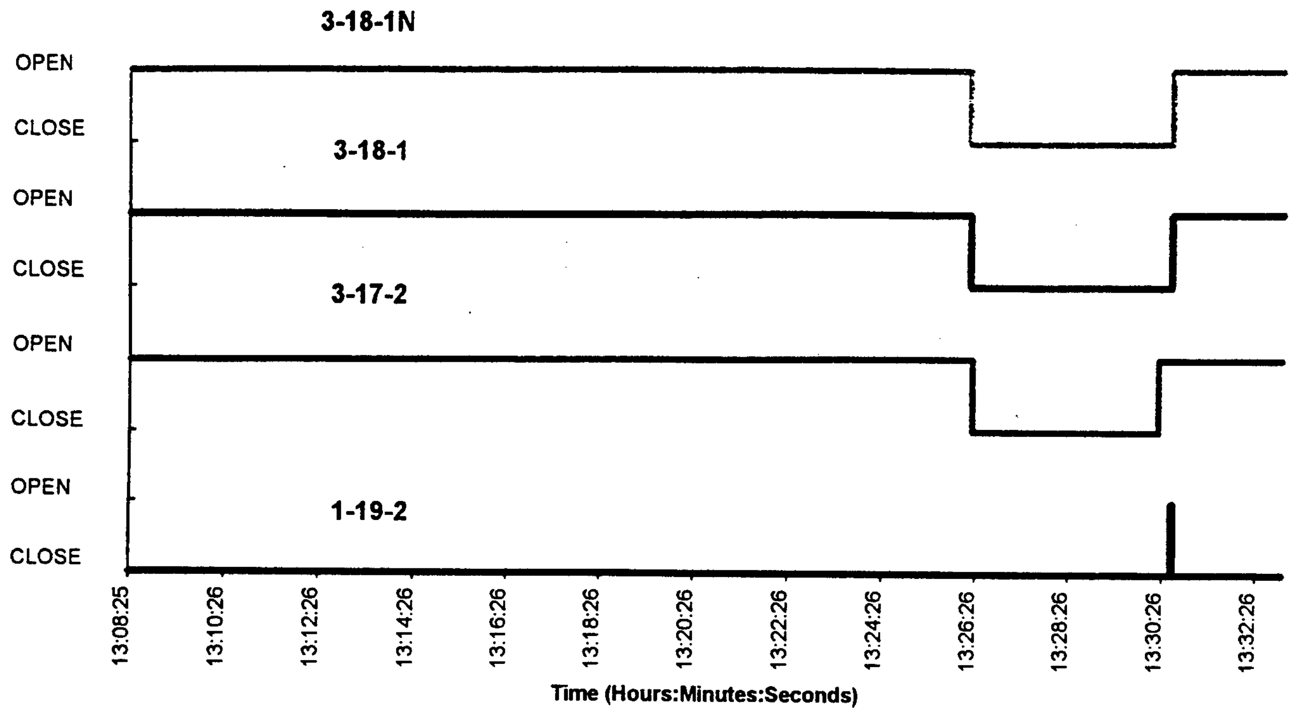


Figure 9 - Hatch and Door Closure Sensor Test Results SBD 58 11Sep95

SHADWELL TEST SBD 59



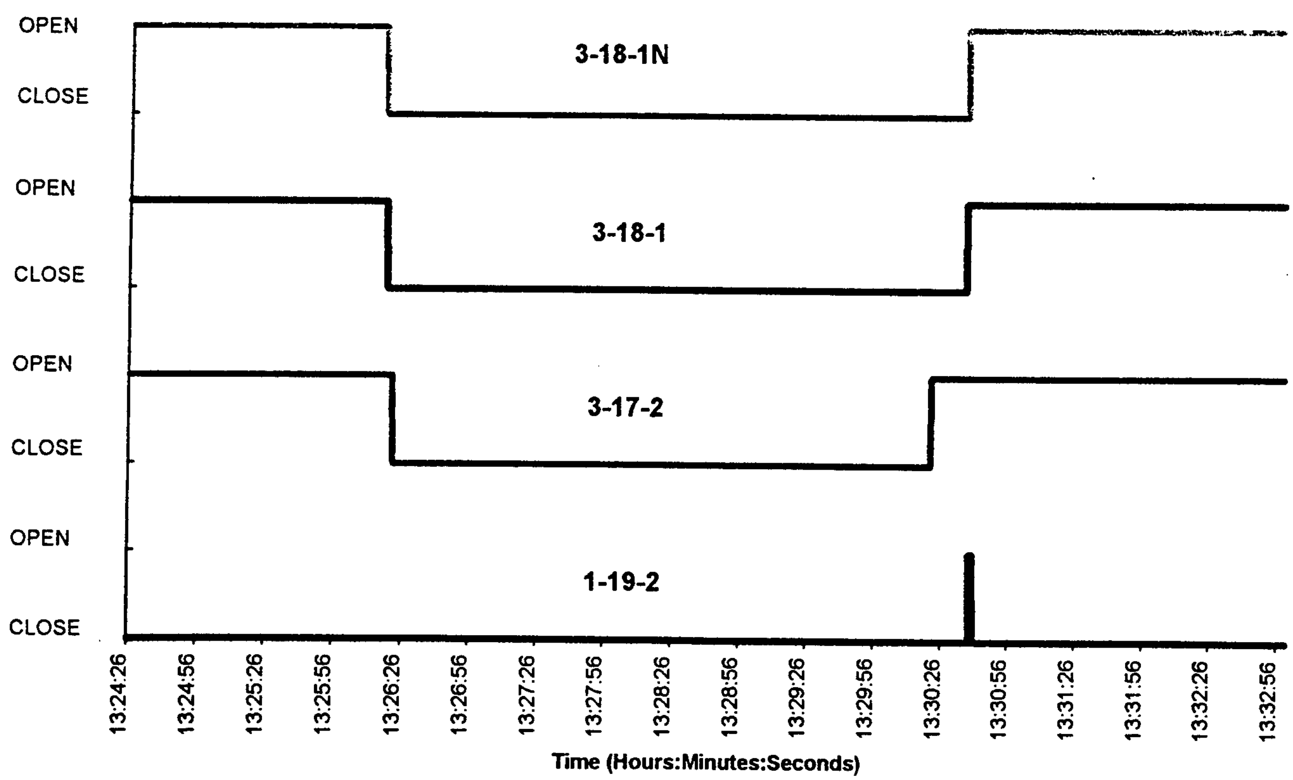
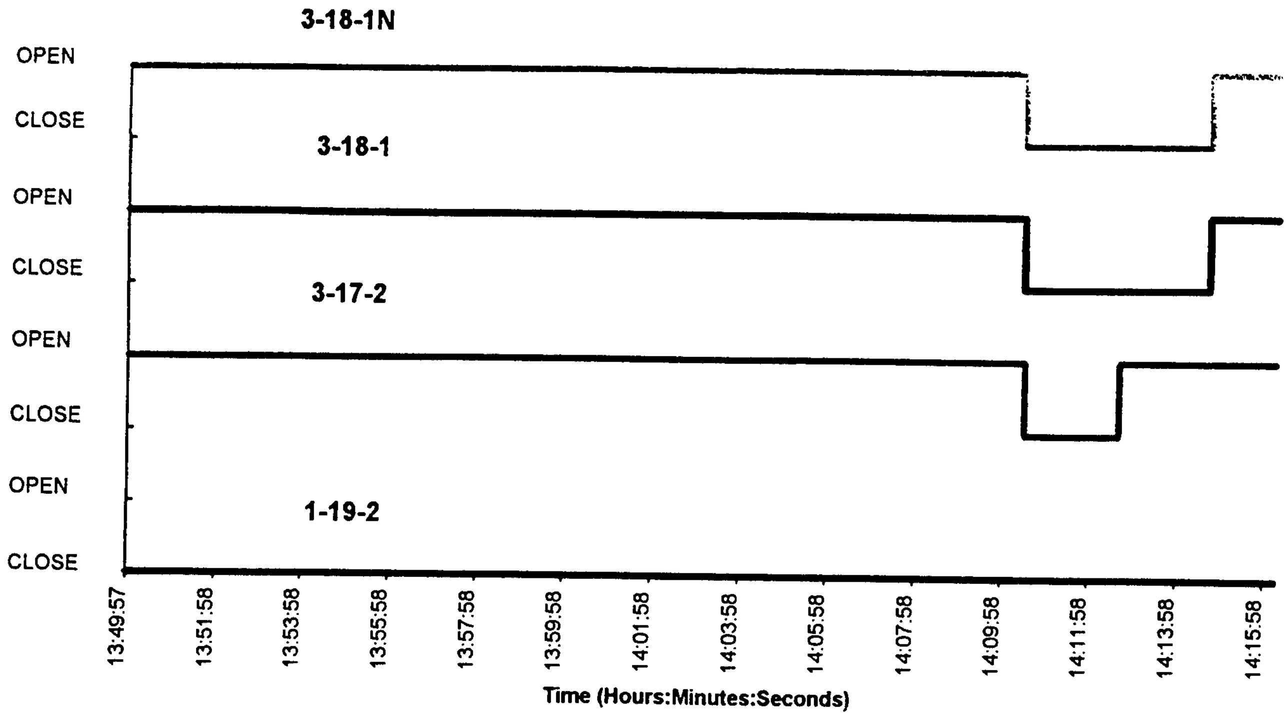


Figure 10 - Hatch and Door Closure Sensor Test Results SBD 59 12Sep95

SHADWELL TEST SBD 60



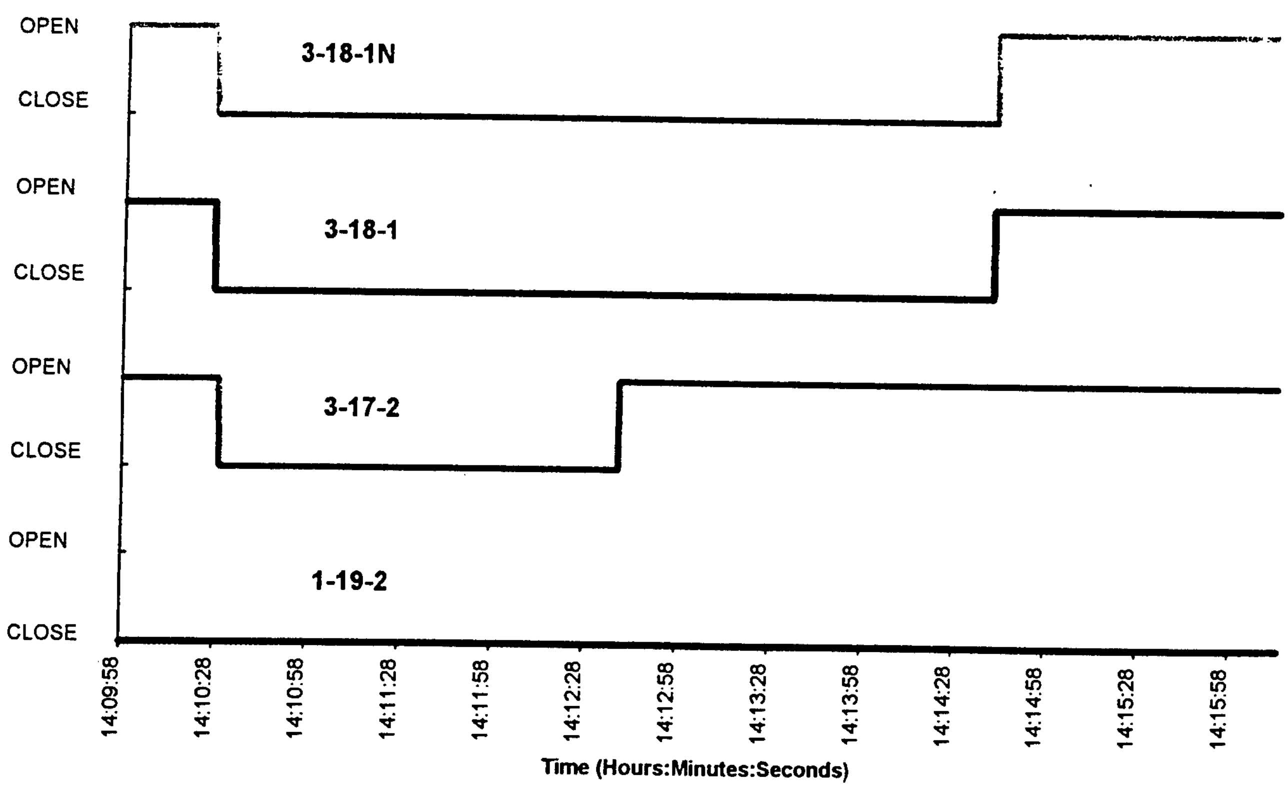


Figure 11 - Hatch and Door Closure Sensor Test Results SBD 60 12Sep95

SHADWELL TEST SBD 61

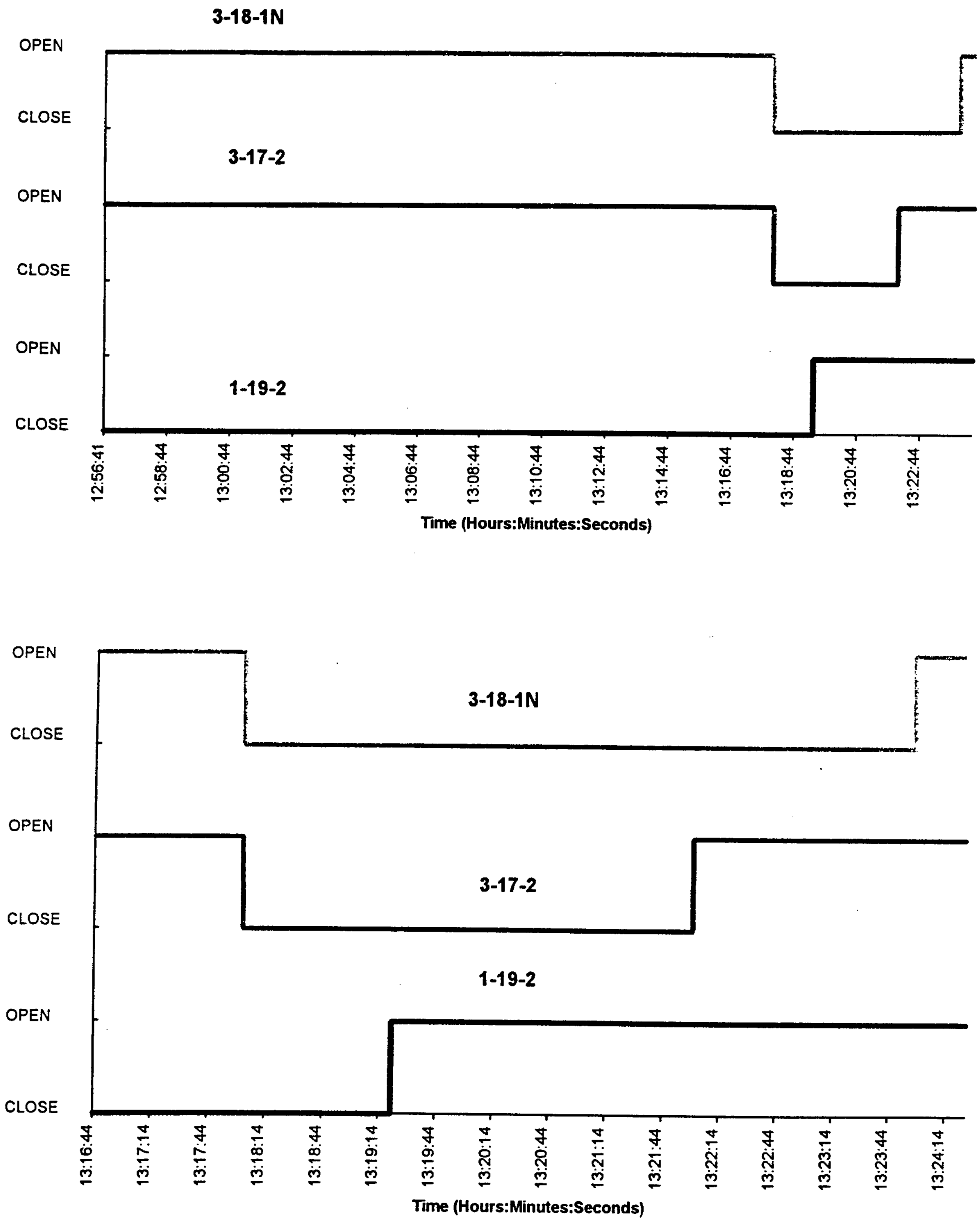
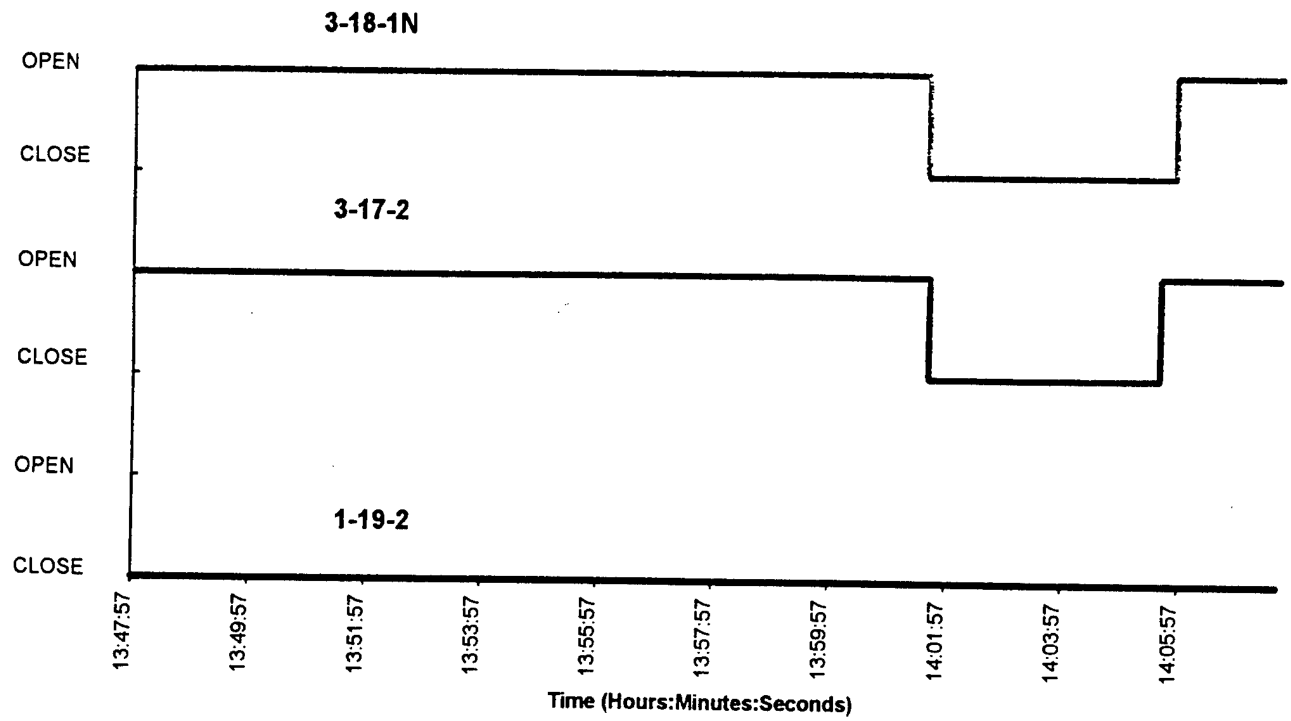


Figure 12 - Hatch and Door Closure Sensor Test Results SBD 61 13Sept95

SHADWELL TEST SBD 62



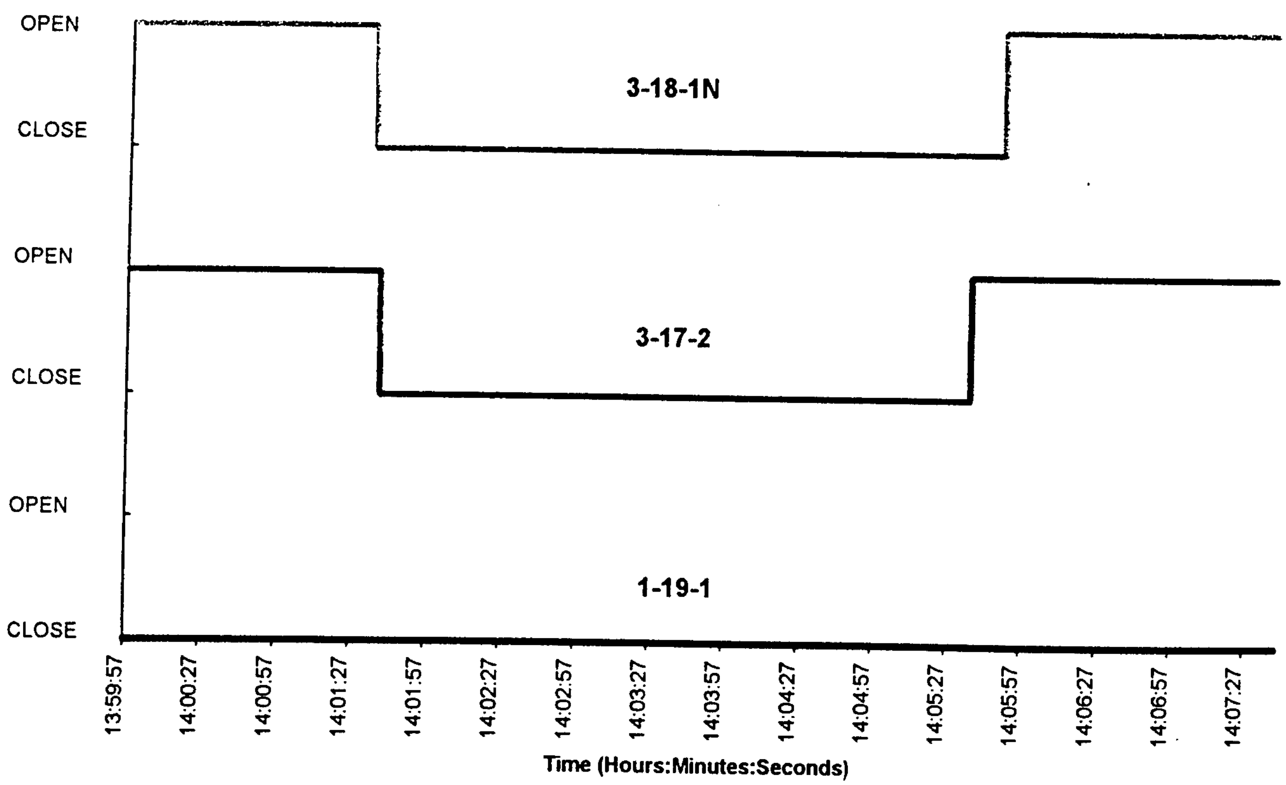
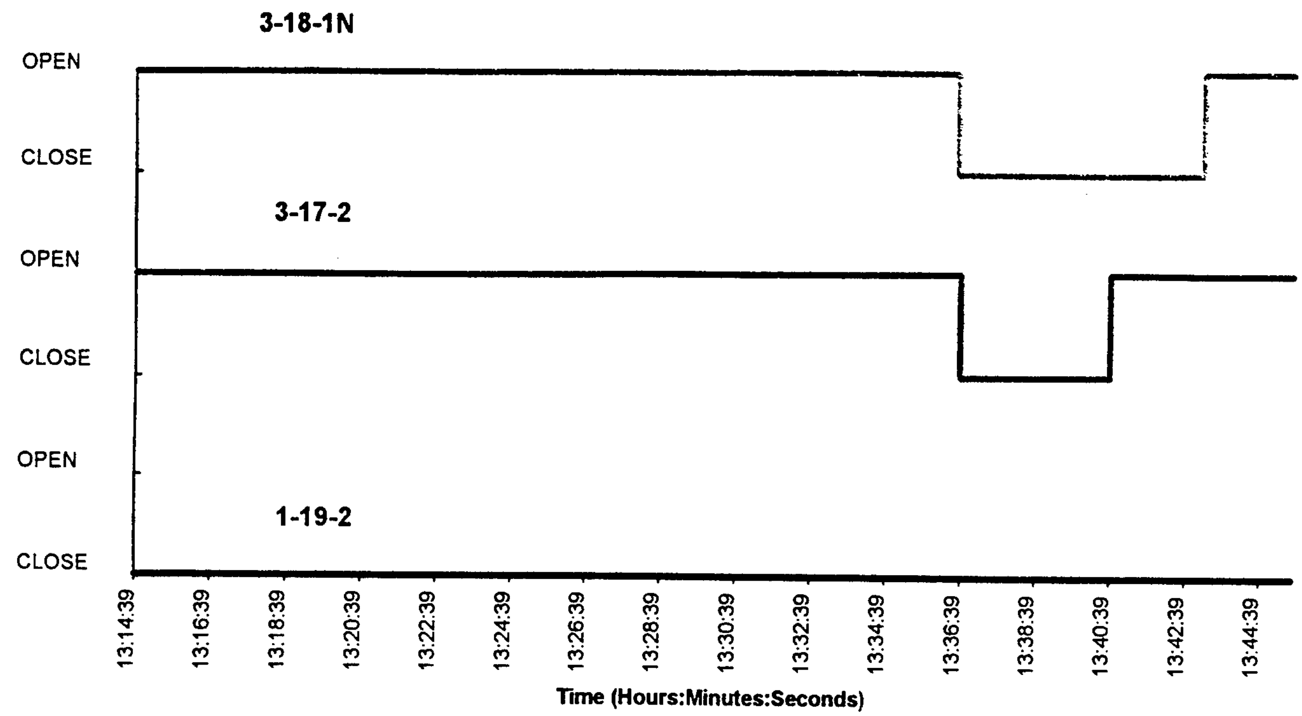


Figure 13 - Hatch and Door Closure Sensor Test Results SBD 62 13Sep95

SHADWELL TEST SBD 63



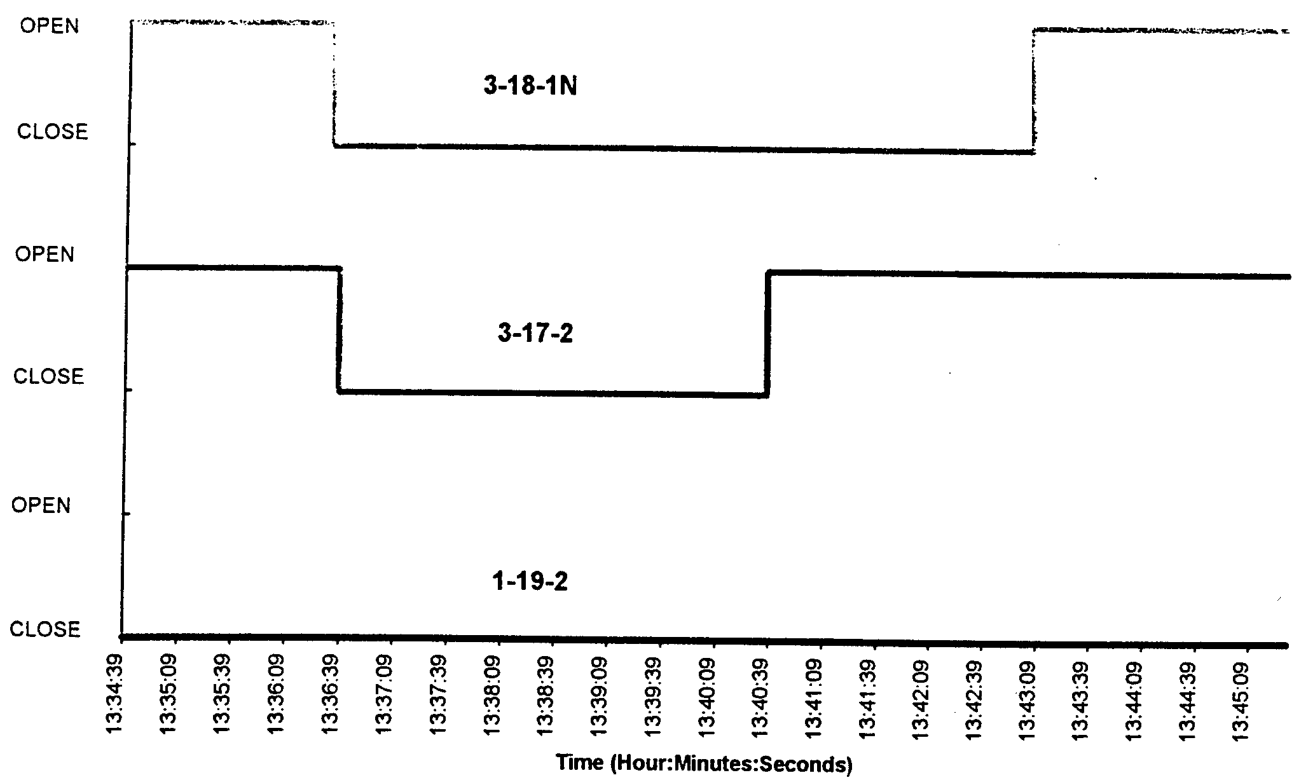
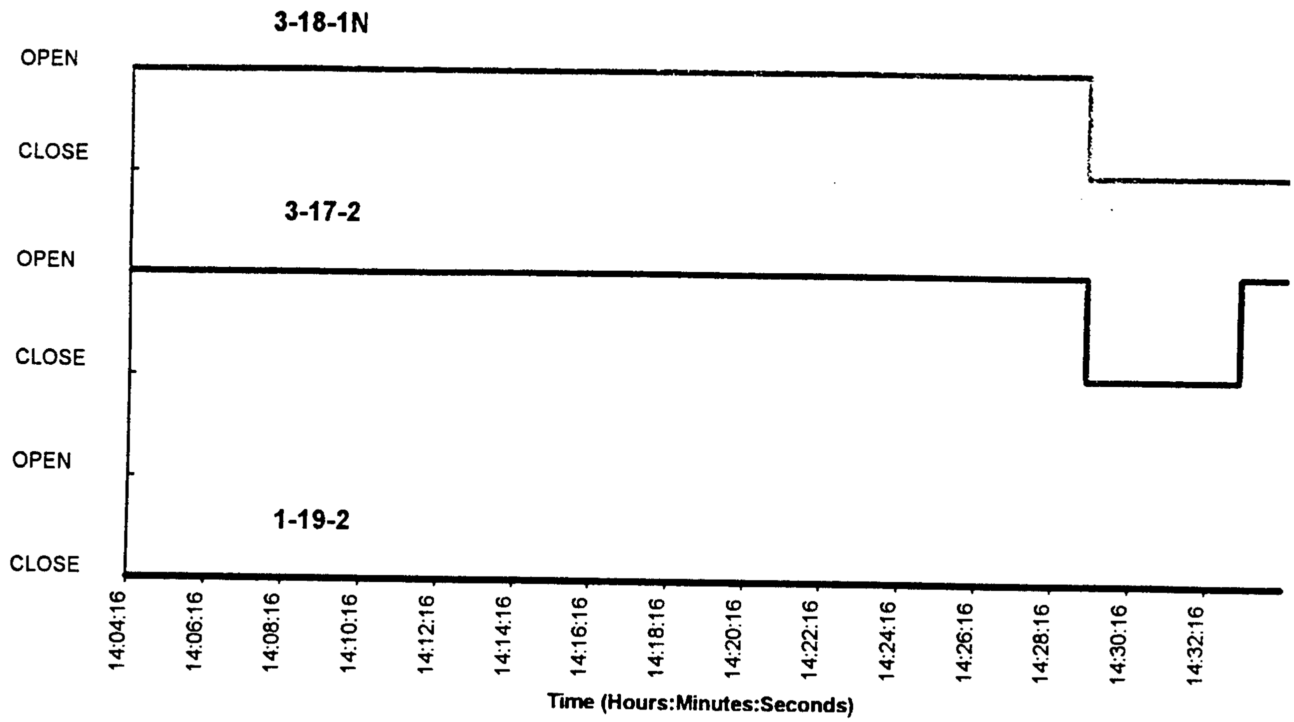


Figure 14 - Hatch and Door Closure Sensor Test Results SBD 63 14Sep95

SHADWELL TEST SBD 64



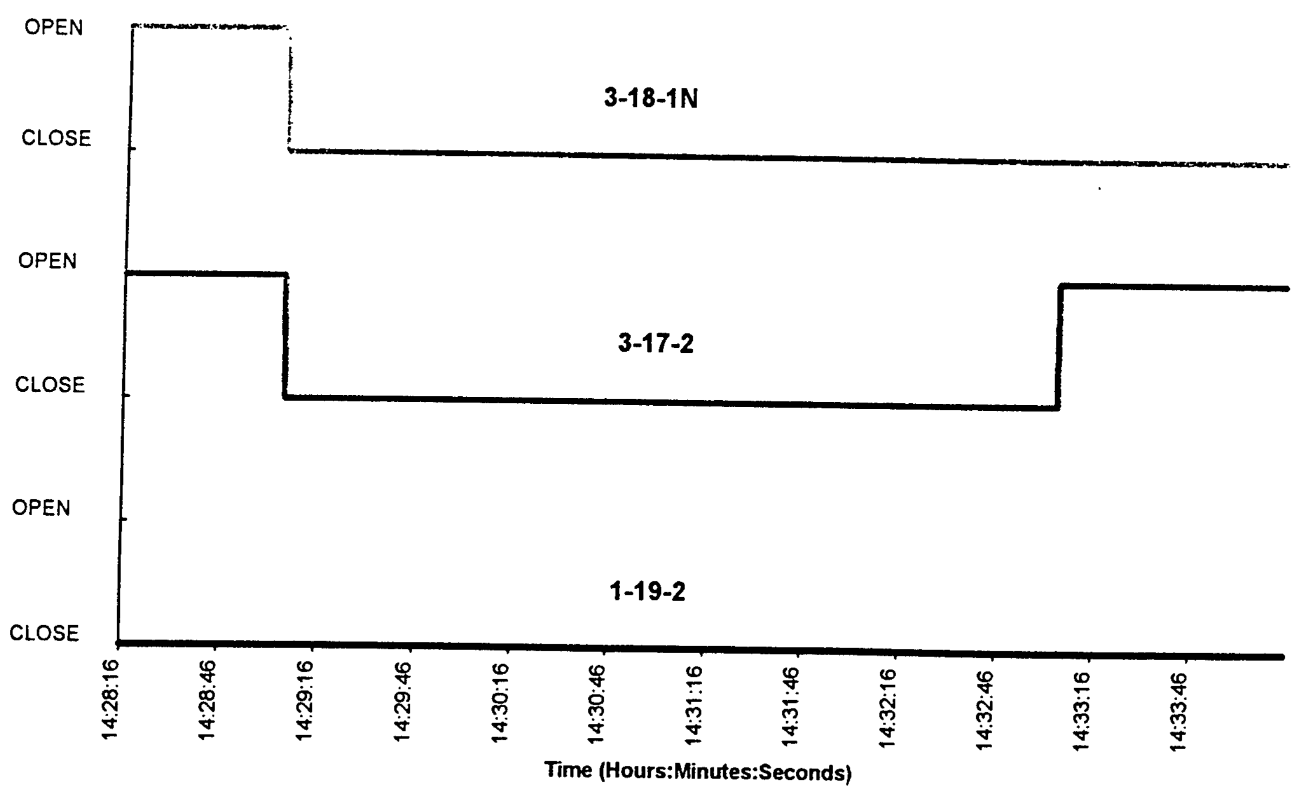
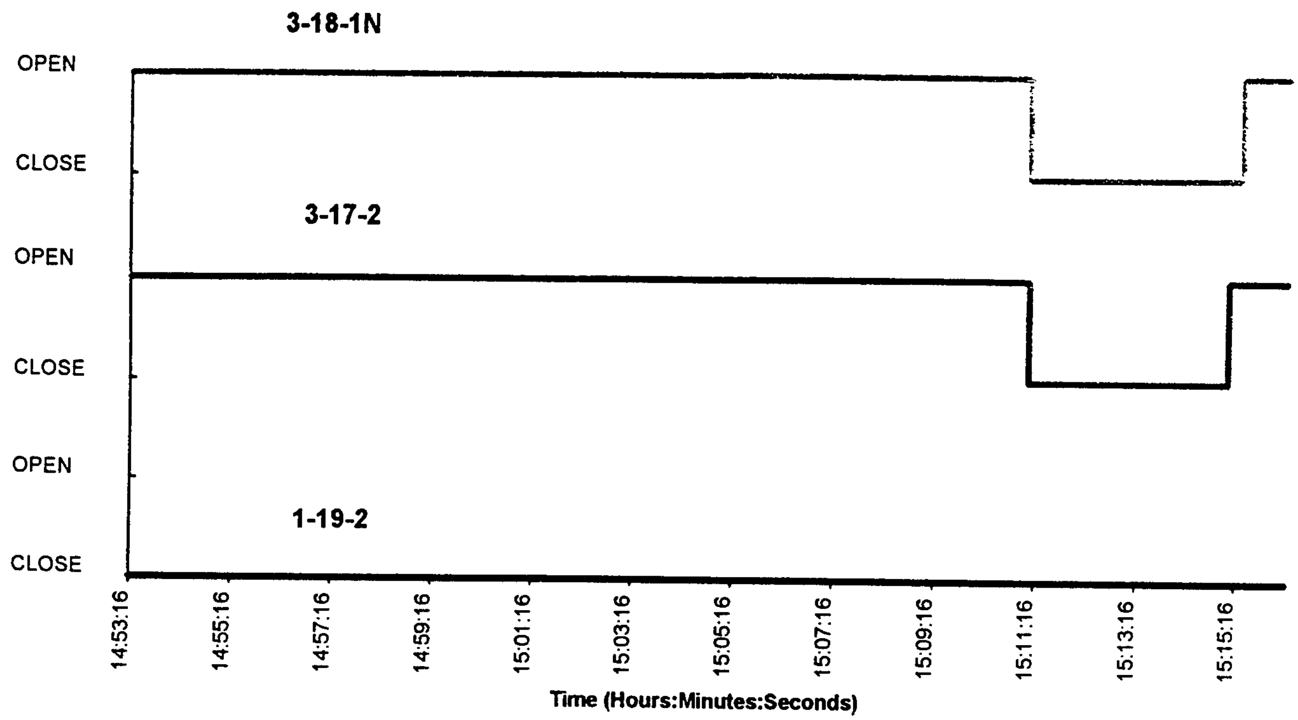


Figure 15 - Hatch and Door Closure Sensor Test Results SBD 64 14Sep95

SHADWELL TEST SBD 65



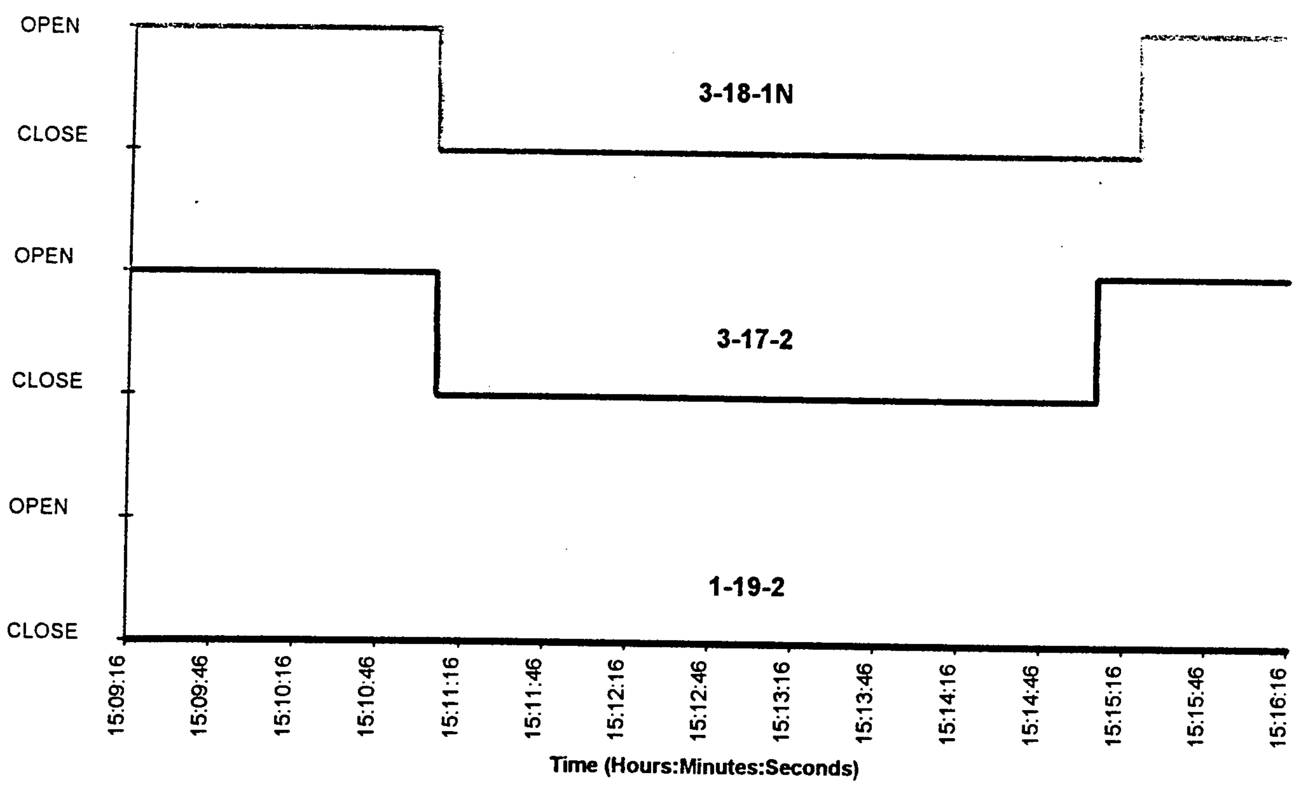


Figure 16 - Hatch and Door Closure Sensor Test Results SBD 65 14Sep95

MULTIPLEXING AND SENSOR COST REDUCTION

Minimizing the cost of the final design of hatch and door closure sensors is very important for getting the products accepted for implementation on new ship construction. The hatch and door closure sensor designs are very simple in nature and could be mass produced at low cost, perhaps in the range of $100 per sensor or less.[c]

Cost could be reduced even more by multiplexing. There are opto-mechanical switches presently available that could poll several hatch and door closure sensors from one opto-electronics package. There are also all optical and electro-optical switches presently under development that might be used in the near future for multiplexing.

CONCLUSIONS

These test results demonstrate that fiber optic hatch and door closure sensors can be operated successfully in the shipboard environment. They have two primary advantages over electrical sensors. Operation to 300 degrees Centigrade was demonstrated and designs were made to extend temperature operation to 800 degrees Centigrade. There was no electromagnetic interference induced on the optical fiber part of the sensors. One set of sensors was commercial off the shelf (COTS) and fits in very well with the Navy desire to use private industry products. Sensor cost was a few hundred dollars per channel and can be reduced by using opto-mechanical switches and benefiting from the economies of scale.

We have completed experiments with multiplexing fiber optic sensor networks that offer improved survivability properties by utilizing optical couplers on the inputs of the sensors. When the hatch and door closure sensors are combined with other fiber optic sensors for temperature, smoke, flooding, holes in the hull, and fire main status, we can create sensor networks that are sufficiently survivable that holes can literally be shot in the network and the surviving portions of the network around the boundaries of the blast zone will operate giving vital information on the status of fires and flooding. The fiber optic sensors can be designed to be more robust, have high operating temperature and small footprint reducing the probability of blast damage, and be more likely to survive in the boundaries of the blast areas. **Implementation of multiplexing of fiber optic sensors in a survivable architecture should improve the availability of the damage control information such that automatic response or computer/machine aided response would be acceptable alternatives to the present doctrine of fighting fires and flooding manually. This would significantly reduce manning.**

There are several areas that must be improved and demonstrated to facilitate wide spread application of fiber optic sensors in damage control systems in the Navy. Manufacturing costs must be controlled and reduced below electrical equivalents for all kinds of sensors. Reliable operation over several years must be proven. Sensors must be designed with sufficient processing to be considered "smart," and thus be able to be inserted in open architecture systems, allowing the Navy to take advantage of the latest sensing techniques.

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c. It is important to note that the authors of this report are developers of new instruments, not production engineers. Cost estimates from the commercial industry would be more accurate.

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