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COMMUNICATORS FOR HIGH-NOISE-LEVEL ENVIRONMENTS.(U)
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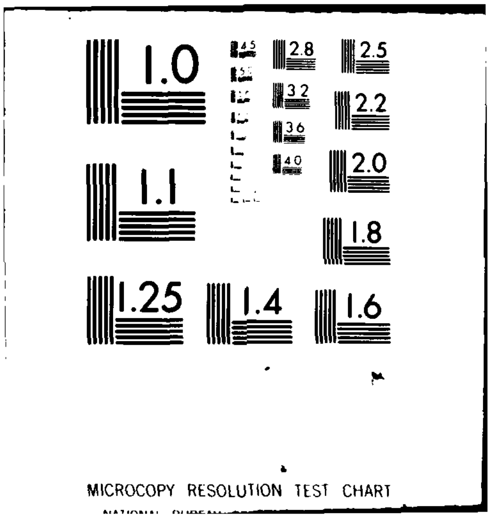
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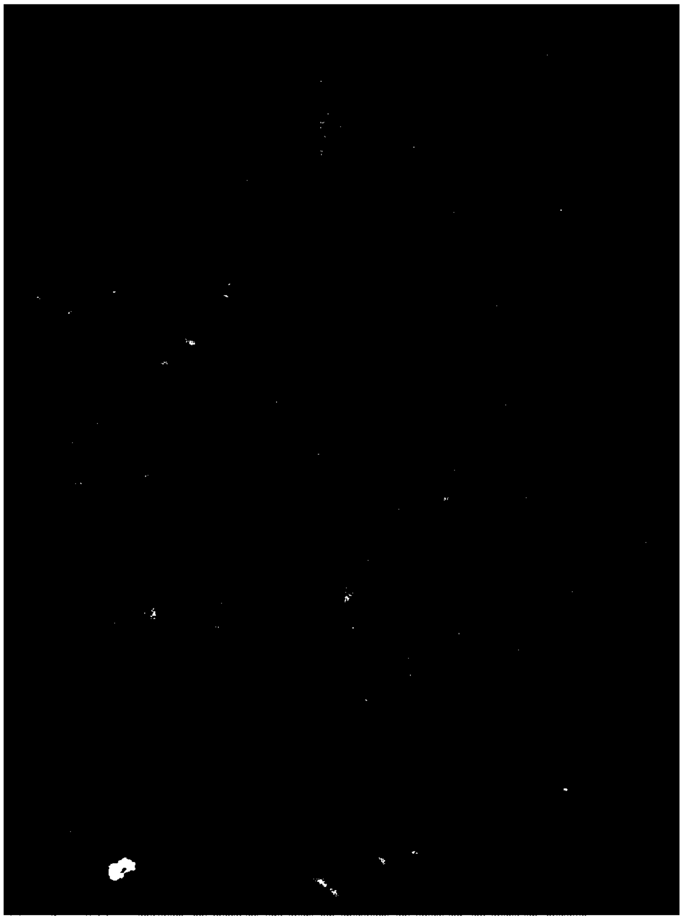

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At the request of the U.S. Geological Survey, the feasibility of equipping workers with a two-way communications system built into a construction hard hat for use in an extremely high ambient noise level has been investigated. As a result, several systems were tested on an offshore oil platform in the Gulf of Mexico.

The investigation indicates that a simple modification of a commercial low-power, frequency modulated system operating in the 49-MHz public service band could be used to considerable ad-

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SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*) vantage. Penetration through platform structures was excellent, and communication was possible from within an enclosed steel compressor room where noise levels were as high as 97 dBA to all points on the platform.

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1. INTRODUCTION

It has been stated in the literature that "Noise could very well be the United States industry's No. 1 migraine."[1] Our hearing takes place in hairlike nerve endings located in the cochlea, the spiral-shaped part of the internal ear located at the base of the skull. Under the pressure of sound waves, these hairs vibrate, transmitting the sound as electrical pulses to the brain. The cells are extremely delicate and, if damaged, cannot be repaired. Short exposures to 95-dB levels can cause temporary hearing loss; under prolonged exposure hearing loss can be permanent.

The high ambient noise level aboard offshore oil rigs is a severe environment, and acoustic noise levels approach or exceed the hazardous level for continuous exposure of 85 dBA. Not only are these noise levels hazardous to hearing, but safety problems develop when communication becomes impaired. Communication in such noise levels is difficult, if not impossible, for the unaided ear, particularly when workers are wearing ear cups for hearing protection. For this reason, the Harry Diamond Laboratories (HDL) was asked by the U.S. Geological Survey (USGS) to investigate the feasibility of a short range, person-to-person, hands-free communications system for voice transmission between workers wearing hearing protection on offshore oil platforms. The initial requirement was that the range be between 25 and 50 ft (7.5 and 15 m). However, during field tests the desirable range was extended to include the entire platform. It was recognized that this investigation was to be exploratory and would not produce a final design, providing instead a foundation on which to build a final concept.

2. SYSTEMS CONSIDERED

Induction field links were frequently used in localized areas such as museums to provide one-way communication. They have been used also in large areas such as steel mills where the fixed installation consists simply of a single loop antenna oriented around the sensitive areas. Two-way induction field systems have been used, for example, where riveters work on opposite sides of aluminum panels. However, the use of a two-way induction field system on a drilling rig would require relatively high-powered transmitters, and mounting such transmitters on the hard hat seemed impracticable.

The Naval Ocean Systems Center had demonstrated Redcap, a helmet-mounted optical transceiver,* which receives from all directions and transmits into a wide field of view in the forward hemisphere. One attraction of this scheme is the security that results from the short range of the system. It also resists electromagnetic interference. The system would fail if there were blockage of the optical path; therefore, approach is limited to line-of-sight operation or to the use of multiple relay stations.

The most common and lowest cost communications link is a hard-wired link using discrete microphones, amplifiers, and earphones. Such a link is unacceptable in the proposed application because it limits mobility. The most satisfactory product found is a relatively expensive, high-quality multichannel radio link using a belt mounted electronics package. Voice-operated transmission (VOX) is offered as an option for hands-off automatic switching of the transmitter and the receiver; however, the use of VOX in noisy areas has been discouraged by some manufacturers for fear that the high noise level would trip the VOX. The use of noise cancelling microphones can be used to advantage in all of these systems, but are particularly needed for VOX units.

3. FIELD SURVEYS

The communications business is highly developed and is supported by some of the

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[1] *J. Obrzut and Pat S. Aiman, Why Everyone's Shouting About Noise Control, Iron Age (24 July 1978), 31.*

**Naval Ocean Systems Center, San Diego, CA.*

largest electronics companies in the country. Prior to any HDL construction, the field was surveyed for availability of a commercial product. Unfortunately, at the time of the survey, no commercial systems were built into or were readily adaptable to a construction hard hat.

A high-quality unit built into a fireman's helmet was commercially available; however, the microphone was mounted in the helmet and a push-to-talk (PTT) switch rather than VOX was used for transmitter-receiver switching. Its physical construction was such that the system could not be modified for a construction hard hat without major engineering changes. Hence, it was not considered for adaptation.

A radically different product was discovered in the survey.* This proprietary design was adapted to a hard hat and later tested with other designs. It used a pulse-time modulation scheme that provides full duplex operation without PTT switching or VOX and operates much like a closed telephone circuit in that all persons can speak and be heard simultaneously. The electronic design is such that there is no heterodyne during transmissions, and it had the unique advantage that an unattended unit can, without modification, become a repeater and retransmit what it receives. The main disadvantage is the inherent high background noise and the fact that it requires two antennas, one for transmit and another for receive.

With no ready-made solution to the problem, it was decided that a prototype communicator would be assembled at HDL by using a commercially available citizens-band transceiver and repackaging it with necessary modifications to the electronics. At the same time, a contract was awarded to a small electronics firm† to build a pair of communicators of their own design that would meet our test requirements. In addition, the pulse-time modulation system was modified and adapted to a hard hat.

Just prior to field tesing of the prototype communicators, a new product‡ appeared on the market. It was a commercial version of a hard hat communicator that was purchased and evaluated. Many of the features desirable for offshore use were incorporated in its design. It was purchased, not in commercial form, but with noise reducing ear cups for hearing protection.

4. EXPERIMENTAL COMMUNICATORS

Four communicators were evaluated in the laboratory prior to field tests. The first communicator was constructed at HDL by modifying a commercially available hand-held citizens-band transceiver designed to operate in the 27-MHz band. It was amplitude modulated and rated at 100-mW direct current (dc) input. To meet the requirements for hands-free operation, its mechanical PTT switch was removed and replaced with a small multipole dc relay and the electronics to drive it. The relay performed all the switching functions within the transceiver except for the application of voltage from the power supply. The power supply consisted of two 9-V batteries connected in series to ground. One battery supplied power to the receiver, the transmitter, and the VOX circuitry, while the series connection energized the relay through the VOX output transistor. A relatively new microphone, advertised as a skin microphone, was used for its potential noise rejecting qualities. It used an electret as a transducer and, unlike an ordinary microphone, is intended to respond to vibrations on the surface of the skin. It was designed for communication in areas where external noise is unusually high and has been used for such projects as the HGU-35/P Navy fighter and the HGU-27/P helicopter. A hinged metal strap used in place of a boom holds the microphone against the skin just below the cheek bone. Once initial adjustments are made, the assembly becomes self-adjusting each time it is placed into use.

The VOX circuit was designed and built in the laboratory to provide automatic transmitter-receiver switching. Since the skin microphone

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*Bendix Corp. Communications Division, East Joppa Road, Baltimore, MD.

†JMR Systems Corp., 168 Lawrence Road, Salem, NH.

‡Remic Corp., P.O. Box 1446, Elkhart, IN.

was mounted to the ear cups via a heavy brass strap, audio from the ear cup had a tendency to periodically trigger the VOX via mechanical coupling to the microphone. To prevent triggering, an anti-VOX circuit was added to the control circuitry. Basically, it sampled the audio output from the receiver and supplied a signal whose amplitude was equal to but opposite from that which was received through the microphone. This opposition had the net effect of cancelling the unwanted signal in the VOX circuit and preventing VOX energizing from the receiver. The circuit had no net effect during periods of transmission since the audio was automatically disconnected in the transmit mode. The turn-on time of the VOX circuit was adjusted to be approximately 0.5 s with a turn-off delay of 1 s.

The antenna was mounted inside the hat and consisted of a 36-in. (0.9-m) piece of No. 24 wire. A small loading coil was used at the base for resonating purposes, but no attempt was made to peak its response because initial tests indicated that the radiated signal adequately covered the original 25- to 50-ft range requirement.

Figure 1 shows the HDL receiver with its protective cover removed. The board on the left contained the VOX circuitry and the input audio stages used basically for impedance matching. The board on the right contained the receiver-transmitter portion of the circuit and the control relay. The transceiver was mounted in an aluminum box 2-3/16 × 5-1/4 × 3 in. (5.6 × 13.3 × 7.6 cm) and was attached to a construction hard hat that meets Occupational Safety and Health Administration (OSHA) requirements for head protection. Plastic ear cups designed for hearing protection were installed on the hat by using a Mine Safety Appliance Co. (MSA) series 600 retaining ring assembly. One of the ear cups was supplied by JMR Systems Corp. as part of the skin microphone assembly; the other was an MSA Comfo 600 ear cup. Each cup has soft vinyl, foam-filled ear seals that enclose the ears and seal the cups against the head. This hearing protection helped minimize auditory interference from ambient noise. The entire communicator including hat and batteries weighed approximately 2.5 lb (1.1 kg).

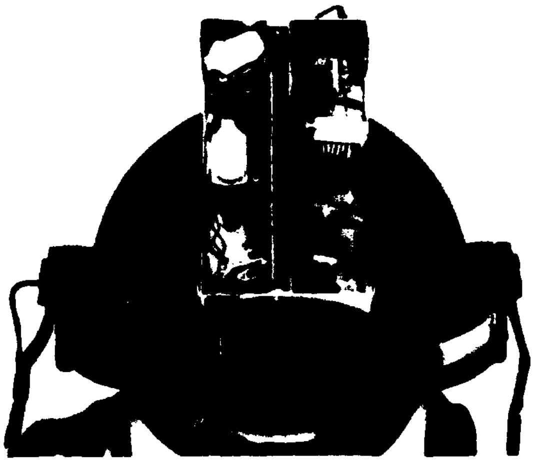

Figure 1. Harry Diamond Laboratories communicator (cover removed).

The second communicator was designed under contract and manufactured for HDL by JMR. Like the HDL communicator, it operated in the 27-MHz citizens band. It, too, used a skin microphone of JMR design; however, there were major differences in the two communicators.

The transceiver and its control circuitry were divided into five boards. The boards contained the receiver, the transmitter, the preamplifier, the audio driver, and the VOX circuitry, and each was protected and shielded by a lightweight metal box. The preamplifier and the audio driver were mounted in the ear cup next to the speaker, and the remaining electronics, including a 9-V battery, was mounted around the lower perimeter of the hat. Some physical protection and containment of the electronics were provided by a removable elastic band that fit over the boxes and extended around the base of the hat, being held in place by three snap fasteners. With the total weight placed low and distributed around the hat, this design provided a somewhat more comfortable fit than the HDL design. A function switch was mounted in the center of the visor. With its toggle in the appropriate position, the transmitter could be operated in the fully automatic mode or, if desired, in the PTT mode. It was requested that PTT be included in the JMR design because it was not known how a VOX system would respond in an unusually high-noise-level environment. With the PTT option, VOX operation is disabled when the function switch is placed in the PTT mode, and operation becomes manual by pressing a spring-loaded switch located at the front brim of the hat.

Another feature of the JMR design was the use of solid-state switching rather than electromechanical switching. Two complementary transistors were used to switch power from the receiver to the transmitter; however, no provision for antenna switching was made. The receiver was designed to have a relatively high input impedance using a field-effect transistor (FET) in the front end, and the high input impedance (along with relatively low output power from the transmitter) allowed the transmitter output and the receiver input to be coupled to the antenna through a common feed point with essentially no interaction. Since there were no relay contacts to arc, the switching in the JMR transceiver becomes attractive when one must consider intrinsic safety[2] as an aspect of design.

The antenna was No. 24 copper wire 52 in. (1.32 m) long spiraled in the top of the hat and tuned to represent 50 ohms. An additional length of wire was cemented around the base of the hat and connected to the shield of the transmission line to form a ground plane.

The complete communicator was mounted in a hard hat similar to that used in the HDL design (fig. 2). The entire system, including battery, weighed approximately 2.4 lb (1.08 kg)

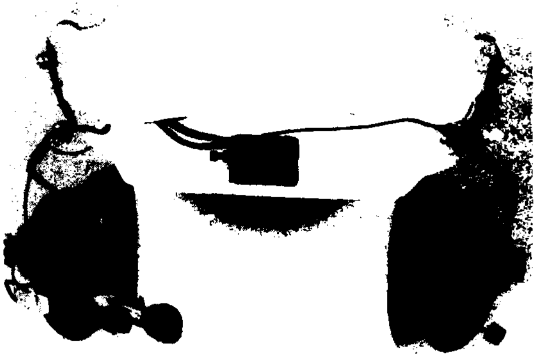

Figure 2. JMR Systems Corp. communicator.

Figure 3 shows the third communicator evaluated, a Bendix Radio MC-457C transceiver, a proprietary design that also operates in the 27-MHz citizens band. Unlike the HDL and JMR designs, which used amplitude modulation for the transmission of intelligence, the Bendix design used a unique modulation scheme combining frequency modulation (FM) and pulse-time modulation employed in phase-locked oscillator circuitry.

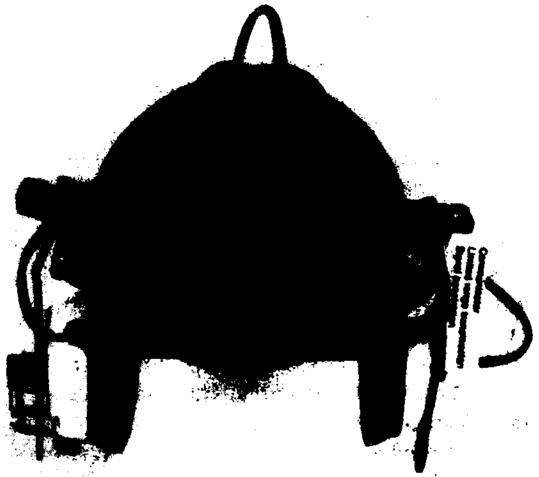

Figure 3. Bendix Corp. Multicom Radio.

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[2] *R. J. Redding, Intrinsic Safety, McGraw-Hill Book Co., New York (1971).*

In operation, each station has its audio coupled to a low-frequency oscillator in a manner such that the period of the oscillator varies at the audio rate. The oscillator, in turn, controls the generation of narrow synchronized pulses that gate the transmitter. All stations in the system transmit the synchonization (sync) pulses and, with no modulation, the electronics locks all oscillators together in frequency and phase. When a transmitter is modulated, the repetition rate of the sync pulses varies at an audio rate, and all receivers in the system lock on the variation. The variation is detected at the output of each transmitter in the system and is fed back to the receiver as audio. Detection at the transmitter output allows the originator to hear his own voice in the earphones, and the net result is that the system can operate in full duplex with two or more persons conversing at the same time. No PTT switch or VOX is necessary and, as a result of design, there is no heterodyne generated.

An additional advantage is that an unattended transmitter can act as a repeater since it retransmits whatever it receives. Thus, when strategically placed, it can extend system range. The chief disadvantages are that the background noise is high, and the design requires separate antennas for transmitting and receiving.

The transceivers were housed in a metal box approximately 1 × 3 × 5 in. (2.54 × 7.62 × 12.7 cm) and were mounted on the back of a construction hard hat by means of a metal bracket. The transmitting antenna consisted of a piece of copper braid 19-1/2 in. (0.5 m) long that passed from the rear to the front of the hat. It was mounted inside a piece of semirigid plastic tubing, which gave it support while maintaining its orientation on the outside of the hat. Since the antenna was short, an impedance matching network was designed to couple the transceiver to the base of the antenna. Cabling from the transceiver to the ear cups on either side of the hat served as the receiving antenna.

Two MSA Comfo 600 ear cups were mounted to the hat by using the MSA series 600 retaining ring, with Electro Voice Model H-143/AIC earphones mounted inside each cup. A noise cancelling dynamic microphone, an Electro Voice Model M-87/AIC, was mounted to an adjustable metal boom and held in place by a thumbscrew attached on one side of the ear cups.

Power for the system was supplied by two 4.05-V mercury batteries, and the entire system weighed approximately 2.4 lb (1.08 kg).

The fourth communicator evaluated was a Remic Corp. Hatcom Model 7700 (fig. 4). It is a commercial hard hat communicator that appeared on the market just before the three HDL prototypes were field tested. Hatcom has most of the attributes for the USGS intended use. It is built into a high impact industrial hard hat that meets ANSIZ89.2-1971 Class B requirements and has recently been certified by the Federal Communications Commission (FCC) for license free operation. The system has been certified also as intrinsically safe by Factory Mutual Research for Class I, Division 1, groups C and D, hazardous locations and by the Mine Safety and Health Administration for use in gassy coal

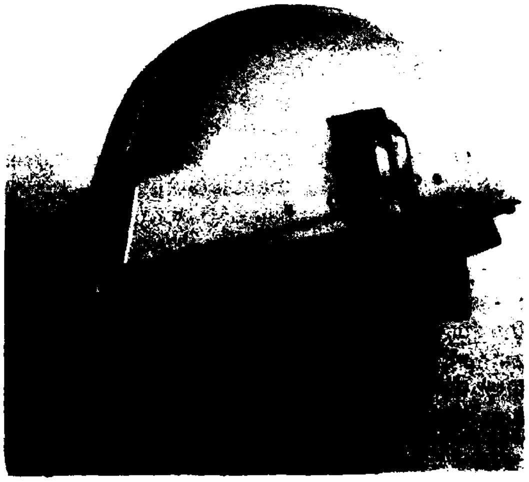

Figure 4. Remic Corp. Hatcom communicator.

mines. It is lightweight, weighing approximately 2.5 lb. (1.12 kg), and its transceiver is completely solid state with hands-free VOX operation.

The basic system was similar to the three HDL designs in that all the electronics was self-contained within the hard hat. The transceiver was assembled on an etched-circuit board on the inside front of the hat. It was modulated with narrow-band FM and crystal controlled on 49.86 MHz. Due to FCC restrictions for radiated field strength in the 49-MHz band, the transmitter was designed to give very low power, approximately 0.01-W output from the final stage.

Receiver sensitivity was good, specified at better than 1 μV for 12 dB of quieting. Image response and selectivity were improved over the HDL designs by using a dual conversion superheterodyne receiver with intermediate frequencies of 4.5 and 455 MHz. The antenna consisted of a piece of No. 14 wire approximately 17 in. (0.43 m) long sandwiched between a foamed-plastic liner at the top of the hat and matched to the transmitter and the receiver.

The original Hatcom model did not have ear cups. Instead, audio from the receiver was fed to a small speaker located on the inner right side of the hat. A small plastic tube was acoustically coupled to the speaker and routed to a point just above the ear. Although this method was considered sufficient for general communications, it was not considered adequate for use in a high-noise-level environment. For this reason, the hat was modified by the manufacturer at HDL's request by mounting a pair of Bilsom International Inc. ear cups* to either side of the hat. A small hole was drilled in one of the cups to accept the plastic tubing so that sound could be coupled to the ear directly from the speaker, minimizing the amount of interference from ambient noise. A later version with speakers mounted in each ear cup was acquired and used as a second station.

A noise cancelling microphone with a 67-bB threshold level was mounted to one of the ear cups by means of a thumbscrew and a metal boom. The high threshold level was intended to help screen undesirable background noise. This level requires that the user speak louder than normal in order to trigger the VOX, but this effort is not considered a great disadvantage in actual use. An additional scheme to further reduce ambient noise pickup is in the design of the speech amplifier. It is designed to have a bandpass of 300 Hz to 3 kHz, a bandpass used frequently in the communications field and considered acceptable for the transmission of voice frequencies. The intent of the filter is to prevent frequencies above and below the normal voice range from triggering the VOX circuitry. Field adjustments for the VOX circuits were not provided, but were preset at the factory to have a rapid turn-on time and an extremely short turn-off delay.

The transceiver controls were located under the front brim of the hat and consisted of two thumb-wheel potentiometers and an on-off switch. One potentiometer controlled the receiver volume, the other controlled the squelch level, and the on-off switch controlled power from the 9-V battery.

5. EXPERIMENTAL METHODS

Arrangements were made to test the communicators in their intended environment. After discussions with John H. Hodges, Radio Liaison Officer, and William Terrabon, Chief Technician, of the Conservation Division, USGS, Department of Interior, Gulf of Mexico Region, Metaire District, it was decided that the test would be conducted on West Delta 31, an Exxon production platform and its block of satellite platforms, about 30 miles (48 km) offshore in the Gulf of Mexico (fig. 5).

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*Bilsom International Inc., 11800 Sunrise Valley Drive, Reston, VA.

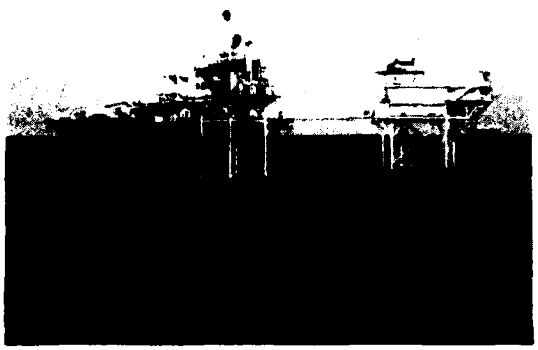

Figure 5. Aerial view of West Delta 31.

West Delta 31 is a headquarters platform that is actually three closely spaced platforms interconnected by walkways (fig. 6, 7). Each platform has several levels or decks, plus catwalks and small loading platforms at the lowest levels. Decks can be reinforced concrete, steel plate, steel grating, or, in the case of old rigs like West Delta 31, part wood planking and part steel grating. The framework is steel in all cases. The production field supervisor who runs the block briefed us on the platform's operation, gave us a walking tour of the installation to familiarize us with the platform in general, and then let us perform our tests wherever necessary.

The first platform, a residential platform, held (from top to bottom) the helicopter landing pad, offices, crew quarters, the mess, and electrical power generators. A second platform held separators, driers, and a gas pipeline compressor. Gas is recovered from West Delta 31 wells at about 700 psi (≈48 atm) and boosted to 4000 psi (≈270 atm) by a three-stage 1550-hp compressor before being pumped directly into the cross-country line. Fluids under these pressures generate considerable noise when flowing through various valves and fittings. The third plarform held the injection compressor and separators for recovery and, on a lower level, the "Christmas trees": the various wells are capped with a multitude of valves, reducers, and other fittings and look like metal Christmas trees (fig. 8). This shape provides a variety of apertures and resonant structures that would be impractical to analyze mathematically.

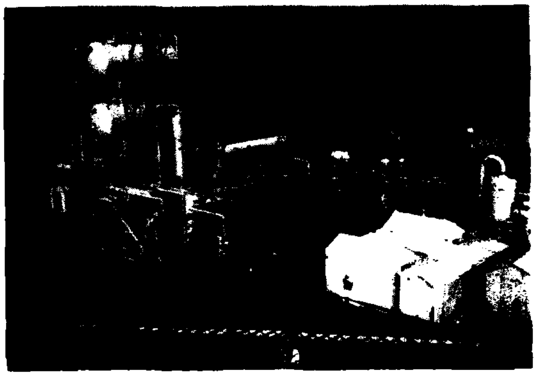

Figure 6. Typical superstructure of offshore oil platform.

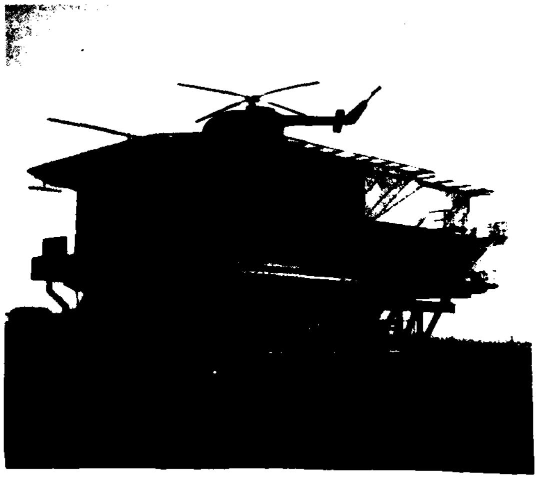

Figure 7. West Delta 31 residential platform.

Figure 8. "Christmas trees."

All operating power on the platform is normally derived from an internal combustion engine fueled by natural gas produced from the wells. Standby power is diesel, and most engines are of the reciprocating type. Some pumps in the field are driven by gas turbines. Unfortunately, the two turbine-driven pumps used on West Delta 31 were not operating during our visit and, hence, could not be used as part of our test environment.

For long distance communications, Exxon uses commercially available equipment operating on several assigned channels in the 158- and 450-MHz bands with repeaters strategically placed around the Gulf of Mexico to extend the range to more than line of sight. Overall performance of this system is rated as excellent.

Due to space limitations aboard the helicopter used for transit, only two of the three types of experimental hard hat communicators were transported to West Delta 31. It was decided that, since the HDL amplitude modulated system and the JMR system were so similar in design, only one would be used for testing. The JMR communicator was chosen because of its PTT option. Also, only two hats equipped with the Bendix communicator were taken so that testing this system in the repeater mode was not possible.

The first communicator tested was the JMR communicator. Basic performance was considered fair to good for line-of-sight distances up to approximately 150 ft (45 m), and no noticeable nulls were detected as long as the transmission path was relatively free from obstructions. However, dead spots were noticeable near dense clusters of piping and heavy steel structures, and the units could not transmit effectively to other areas through doorways and windows of metal structures. There was a tendency on the part of the authors to speak more rapidly than normal when submerged in noise, and the first word to be spoken after the VOX had reset was occasionally lost. This loss was a function of the VOX threshold, but it could not be reset in the field. In addition, the gain of the communicator was too sensitive for the noise level in the compressor room, and the VOX circuitry latched when the hard hat wearer entered the doorway. However, the PTT option was effective in overriding the VOX, and, when the hard hat wearer moved amid heavy machinery in tight quarters, the advantages of an effective VOX were readily apparent.

Performance of the Bendix communicator was judged fair for distances up to 100 ft (30 m) and, as with the JMR communicator, as long as there were no obstructions in the transmission path, there were no noticeable nulls in the radiation pattern. The Bendix communicator had similar problems near clusters of pipes and metal structures, and transmisssion into and out of metal enclosures was not possible. Transmission between decks was not consistent. The metal grating and steel superstructures provide enough shielding to prevent propagation into those areas. The frequency of the communicator has to be increased significantly for effective penetration.

Part of the problem with the Bendix communicator was due to low gain in the speech amplifier and audio output circuit; the low gain may have been due in part to a poor match between the microphone and the speech input stage. The microphone used in place of the original Bendix microphone was selected on the basis of its noise cancelling qualities; it was known that there would be some loss in gain by its use. The low gain precluded proper squelch adjustment and has to be increased considerably for use in a high-noise-level environment. Since these communicators were on loan from Bendix, their modification was limited. Hence, there was no attempt to correct the deficiency before the units were field tested.

Operating in a duplex mode rather than in a simplex mode was relaxing. Users could interject thoughts immediately during a conversation, rather than having to wait for the end of a transmission and the associated VOX or PTT delay. Unfortunately, the audio gain and the operating frequency were too low to test the Bendix communicator more effectively.

The Hatcom communicator performed exceptionally well, and overall performance was considered excellent. There were no noticeable nulls in the radiation pattern, and there were no problems in communicating to all points on the platform. Receiver sensitivity was very good, and the receiver operated at full quieting during all tests. For example, communication was possible from the gas compressor room, where two people standing side by side could not normally converse without difficulty to another person standing amid steel piping and machinery two decks below. Penetration was excellent, even though compex transmission paths existed such as the path shown in figure 9.

The Hatcom VOX worked well. Its high threshold level coupled with the frequency response of the speech amplifier and a wind sock on the microphone proved to be a solution to automatic voice control in a high-noise-level environment. It was possible to walk about freely in the compressor and power generating rooms, where noise levels were as high as 98 dBA, without false triggering. The Hatcom high threshold required that the user speak in a louder than normal voice, but this effort was not considered objectionable by anyone that tested the units aboard the platform. That the microphone has to be positioned very close to the mouth can distract some people at first. However, when not in use, the microphone can be repositioned.

Figure 9. Steel superstructure below main deck of West Delta 31 platform.

Since Hatcom performance was beyond expectations on West Delta 31, it was decided that tests should be performed on platforms more difficult for radio reception. For this reason, the Hatcom communicator was tested briefly on platform WD31-Y, which had an upper deck constructed completely with metal plate, and on platform WD32-S, which was constructed with a reinforced concrete deck and some steel grating. Again, the Hatcom communicator performed favorably, and penetration was excellent. At one point during the test, an enclosed steel cylinder on the top deck of WD32-S was entered through a small entry hatch. Communications were maintained from within the cylinder to a point three levels down near the waterline.

6. CONCLUSIONS

The information presented here is intended to give some idea of the practicability of equipping workers on an offshore oil rig with a self-contained communications system mounted in a construction hard hat. From the experience gained during the test, it seems desirable that at least some form of communication be available for use amid much noise or in improving a job function. Unaided oral communication in a 98-dB environment is impossible when the participants are more than a few feet apart, not to mention the debilitating effects from trying to converse under such conditions.

A communicator could be used for emergency communication in a situation such as a blowout or a fire, where contact throughout the platform and hands-free operation are required. Also, daily tasks aboard a platform could benefit by use of a communicator. For example, it was observed that, during an unloading operation, the crane operator had his view of the unloading boat obscured by decking and protruding metal members of the platform so that it was necessary that another person signal by hand to help him unload materials. Equipping the crane operator and at least the boatswain with a communicator would enable them to converse during the unloading. There would be no need to interpret hand signals, and the crane operator could respond immediately in an emergency. Operation would be more efficient and safer.

Although the experimental communicators worked within their original range requirement (25 to 50 ft), adequate penetration of complex structures requires operation at higher frequencies. The 49-MHz public service band seems acceptable for two reasons. First, the power output on this band is restricted by FCC regulations such that the radiated field strength cannot exceed 10,000 μV/m when measured at 3 m. With this restriction, it is not likely that there would be any interference from stations operating on nearby platforms or from land based stations. Second, penetration at these frequencies is excellent.

Frequency modulation is the preferred method of modulation because if can reject random noise and other interference much better than can conventional amplitude modulated systems.

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