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ABSTRACT

Cave diving is one of the most technical and potential dangerous forms of diving done today. It may involve use of multiple tanks, regulators and gas mixtures or rebreathers, in combination with powerful long-range diver propulsion vehicles, to penetrate thousands of meters into submerged cave systems where direct ascent to the surface in the case of emergencies is impossible. In order to carry out scientific studies under such difficult conditions, individuals must be highly competent and experienced cave divers. In spite of these problems, numerous scientific investigations in the fields of biology, ecology, microbiology, geology, hydrology and archaeology have carried out by cave diving scientists. Exploratory cave divers have provided the initial impetus for this research by exploring and mapping underwater caves.

CAVE DIVING SCIENTIFIC OBJECTIVES**Cave Mapping**

Since the most accurate way to describe a cave is to map it, most cave exploration teams routinely survey and draft maps of their discoveries. Surveying is routinely done by measuring distances between stations using a guideline knotted at 3 m increments. Compass bearings along line segments between stations and water depth at each station is recorded, along with distances to left and right wall, ceiling and floor. Water depths, measured with a depth gauge, provide information on the vertical distance beneath the surface of the water table. Electronic mapping devices have been used to map some large cave systems. An automated digital three-dimensional wall mapper was used during the Wakulla 2 project. It consisted of an array of 32 sonar transducers for measuring wall distances, plus sensors for measuring depth and water temperature, taking measurements at a rate of four per second. Repeated survey of a passage increased detail and resolution of the resulting map such that details as small as one mm could be resolved. Control of the electronic survey was done using waypoints within the cave determined by using low frequency magnetic induction beacons that could be precisely located from the surface.

Cave Biology

In addition to cave surveys, numerous scientific studies have been conducted in under-

water caves including biological, geological, hydrological and archaeological investigations. Faunal surveys of anchialine (coastal, marine) caves in particular have relied on cave diving. These caves typically have a surface layer of fresh or brackish water separated from underlying saltwater by a well-defined halocline (Iliffe, 2000). Thus, it is only through diving that access to the deeper saltwater layer in caves can be achieved. A unique cave-limited fauna, consisting primarily of crustaceans, has been collected using traps, plankton nets and visual collections. These discoveries include more than 200 new species with many higher taxa and even a new order of Crustacea—the Remipedia. A number of these taxa, such as Remipedia, are primitive living fossils with highly anomalous biogeographic distributions, occurring in caves from both the Atlantic and Pacific. Biologically significant anchialine limestone caves are present in Bermuda (Iliffe, 1994), the Bahamas (Juberthie and Iliffe, 1994), Cuba, Yucatan (Mexico) (Iliffe, 1993), Jamaica, the Balearic Islands and Western Australia (Humphreys, 2000), while anchialine lava tubes occur in the Canary Islands (Iliffe et al., 2000), Hawaii and the Galapagos (Iliffe, 1991).

The longest underwater caves on Earth are found in the Yucatan Peninsula. Since surface rivers are lacking in this area, all drainage is subterranean through the porous limestone bedrock. At present, the world's longest underwater cave is the anchialine Systema Ox Bel Ha on the Caribbean coast of Yucatan with more than 70,650 m of surveyed passage. Stable carbon and nitrogen isotope ratios have been used to discriminate food sources in anchialine caves from Yucatan and to trace their utilization by cave-limited crustaceans and fish (Pohlman et al., 2000). Populations of chemoautotrophic bacteria associated with haloclines, along with organic matter from open cenote pools and overlying jungle soil, were found to support the cave ecosystem. Most troglobites (cave-limited species) are observed in the water column thus implying that this is where they obtain their food.

Microbiological studies of underwater caves have been conducted using sterile sampling techniques (Brigmon et al., 1994). Visible colonies of *Thiothrix* spp., a sulfide oxidizing mixotrophic bacteria, were found in 6 of the 8 underwater caves in Florida sampled by divers during the study. Since *Thiothrix* generates sulfuric acid that can dissolve limestone, such bacteria may play a role in cave formation.

Cave Geology and Hydrology

Geological studies have included the isotopic dating of submerged stalagmites from anchialine caves. Since such speleothems are only formed in air by dripping water, they must have formed during the Pleistocene Ice Ages when sea level was substantially lower and the caves were dry. At that time, so much water was removed from the oceans to form glaciers on the continents that sea level was lowered by 100 m or more. By measuring the thorium—uranium ratios in sequentially deposited layers of now submerged stalagmites, it is possible to determine the time at which each layer formed (Harmon et al., 1978). By knowing the depth at which the stalagmite was found and the age that it was deposited, it is possible to construct paleo sea level curves from the Pleistocene.

Cave exploration and mapping have contributed significantly to our understanding of subterranean hydrology. In the Wakulla Karst Plain of north Florida, mapping of a network of more than 42 km of cave passage has helped hydrologists to understand the complexity of groundwater flow in the area (Werner, 1998). Similar cave exploration and mapping projects along the Caribbean coast of the Yucatan Peninsula have better defined regional flow patterns.

The complex structure of the water column in anchialine caves has been investigated with the aid of electronic water quality loggers made by Hydrolab and Yellow Springs Instruments. These instruments can record measurements of depth, salinity, temperature, pH, dissolved oxygen, redox potential and turbidity as frequently as once per second, thus providing highly detailed profiles of the cave water column (Figure 1). The lead diver typically carries the instrument with sensors held forward into undisturbed water. At the end of the dive, data from the instrument is downloaded to a computer for analysis and interpretation. In most anchialine caves, all measured parameters show their greatest variation in the halocline region (Ilfie, 2000). In some caves, multiple haloclines are encountered. Comparison of water quality profiles made using rebreathers, in contrast with conventional scuba, indicate that scuba diving disrupts the physico-chemical environment and may adversely affect the endemic anchialine fauna (Humphreys et al., 1999).

Cave Archaeology

Cave divers have made a number of important archaeological discoveries. In 1991, cave diver Henri Cosquer entered a submerged cave near Marseilles, France and discovered a wealth of prehistoric art in air-filled interior rooms of the cave (Clottes and Courtin, 1996). The opening to the cave, once several miles

inland from the Mediterranean, became submerged when the sea began to rise at the end of the last Ice Age, about 12,000 years ago. With the aid of radiocarbon dating, it was determined that the images in the Cosquer cave were made during two different eras. The earliest drawings of stenciled hands were created about 27,000 years ago, while drawings of land and marine animals, including cold-loving plains horses, ibex, huge ice-age deer, seals and great auks, are some 18,500 years old.

Numerous cenotes or water filled sinkholes in Yucatan were used as sites for ceremonial offerings and sacrifices by the Mayans. Cave diving archaeologists have discovered a wealth of artifacts from such sites. Cenote Xlacah is located in the center of the ruined Mayan city of Dzibilchaltun. Divers on a National Geographic Society expedition to this site in 1958, recovered more than 6000 artifacts including pottery and human remains (Marden, 1959). The cenote was explored to a depth of 44 m where a large tunnel was found extending away from the entrance pool. Thousands of additional cenotes are known from Yucatan, many of which are likely to contain Mayan artifacts.

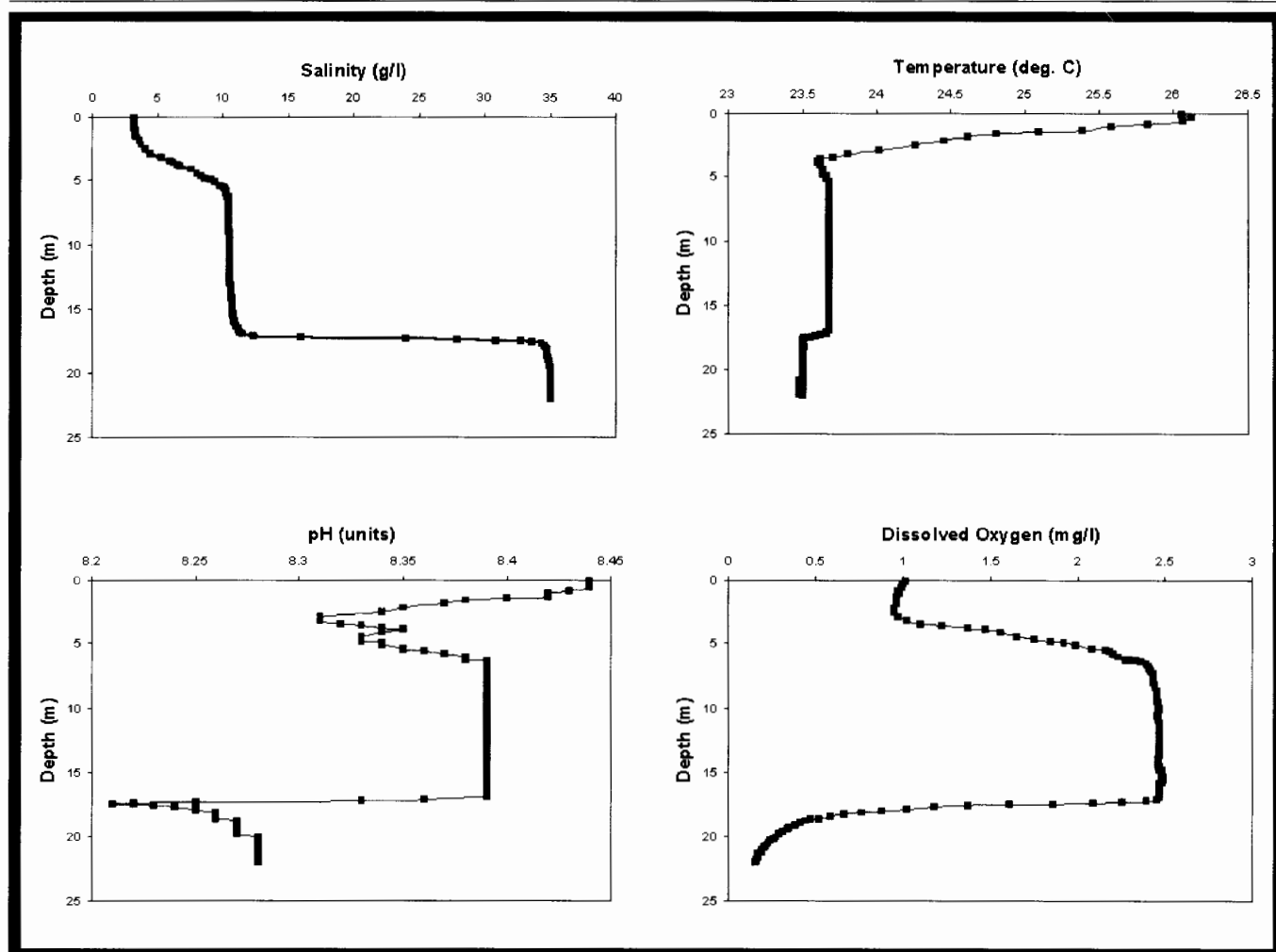
Prehistoric human remains along with Ice Age mammals including mastodons, saber-tooth tigers and giant sloths have been found in springs and sinkholes in Florida. In 1972, archaeologists found an 11,000 year old, full human skeleton at a depth of 13 m in Warm Mineral Springs, near Sarasota, Florida. Similar remains of early man in North America have been recovered from Little Salt Springs.

CAVE DIVING METHODOLOGY

Exploration and study of submerged caves is a highly specialized and potentially dangerous form of diving. As of 1999, 478 cave diving fatalities have been recorded, but only 47 of the victims were trained in cave diving (Bozanic and Halpern, 1999). In contrast to open water diving, cave diving presents a number of specific and potentially life threatening hazards. First and foremost, in cave diving, a rock ceiling is overhead so that in case of emergency, a direct ascent to the surface is not possible. In most cases, it is necessary to exit the cave in the same way it was entered. Thus, a cave diver at 30 m depth, 300 m inside a cave needs considerably more air reserves and emergency planning than does an open water diver at the same depth. Other hazards include depth, decompression requirements, limited visibility, and psychological pressures.

Many of the safety procedures routinely used by cave divers today are based on analysis of the numerous accidents, usually fatalities, which occurred early in the history

Figure 1. Salinity, temperature, dissolved oxygen and pH water column profiles from Mermaid's Lair, an anchialine cave on Grand Bahama Island, Bahamas; sampled on 5 August 1997 using a Hydrolab Data Sonde 3 Water Quality Logger.



of this sport (Prosser and Grey, 1992). Five general rules of cave diving derived from accident analysis are:

- 1) Do not dive beyond your level of training
- 2) Use a single, continuous guideline extending from open water outside the cave to the point of farthest penetration.
- 3) Reserve at least two thirds of the starting air supply for exiting the cave.
- 4) Avoid deep diving in caves.
- 5) Carry at least three independent sources of light.

Such analysis of diving accidents shows that many incidents could have been avoided if the diver had used sufficient and proper redundant equipment, setup in a reliable configuration (Bowen, 1995). However, one problem associated with redundant systems is the belief that the more gear a diver carries, the safer he will be. This problem is most commonly associated with beginning cave divers, where the diver carries far too much equipment

for the type of dive being conducted. When a diver carries too many cylinders, second stages, pressure gauges, reels and lights, the possibility of equipment failure, equipment confusion and equipment entanglement greatly increases. Divers must evaluate the type of dive being conducted and only carry the redundant equipment needed to provide an acceptable level of risk for each dive.

Double Tank Configuration

Standard cave diving doubles configuration includes matched cylinders, typically low-pressure 72 to 121 cubic foot steel (Figure 2). Cylinders are banded together using steel bands, while a standard or isolator valve manifold connects the gas supply between the tanks. Both valves on the manifold are turned on throughout the dive. In the event of a failure in any part of one of the regulators, such as a blown hose, the manifold valve connected to that regulator can be turned off preventing loss of gas.

In this case, all gas contained in both cylinders is still available through the remaining functional regulator. This event demands an immediate return to the surface or first scheduled decompression stop.

Two independent regulators are required for full redundancy. Two first stages are required for connection to each of the two valves on the manifold. A primary second stage with a longer hose (2 m) is typically connected to the valve closest to the diver's right shoulder. The primary second stage can then be used in an emergency air sharing situation with two divers exiting single file in confined spaces. Another second stage and a high-pressure hose with gauges are connected to the valve closest to the diver's left shoulder. A low-pressure inflator hose is connected to each first stage for BCD/Wings and drysuit inflation. All regulator second stages should be within easy reach, and all hoses should be streamlined to prevent entanglement.

In addition to the back mounted tanks, an additional 13 to 121 cubic foot stage cylinder can be carried for extended bottom times or decompression gases. The stage is usually clipped on the left side of the diver (Figure 3). In cave diving, the stage cylinder is usually dropped and clipped to the guideline when one-third of the gas volume is used. It is picked up on the return and a second third is used on the exit (rule of thirds). Any dropped stage cylinders should be turned off to prevent loss of gas. The stage regulator is a single independent regulator with one first stage, one second stage, and a high pressure hose with pressure gauge only. No inflator hoses are attached to the stage. Stage cylinder regulators should have their MOD (Maximum Operating Depth) clearly marked with a high contrast label (i.e., black type on a white label) to minimize the possibility of confusion at depth. Heavy rubber bands can be stretched around stage cylinders for stowing stage regulators and hoses to streamline the configuration.

Sidemount Configuration

As an alternate to back mounted doubles, many cave divers now utilize twin sidemounted tanks (Hires, 1999). This low profile configuration allows divers to penetrate bedding plane passages, not high enough for divers with back mounted tanks to access. Furthermore, sidemount configuration is quite suitable for expedition cave divers, since single tanks are more readily found in most areas of the world. Tanks are 72 to 121 cubic foot cylinders carried under each arm (Figure 4). A cam band around the middle of the tank is connected by a carabiner or clips to D rings on the waistband or backplate. Brass clips or elastic bungee cords

Figure 2. Schematic representation of standard doubles cave diving rig.

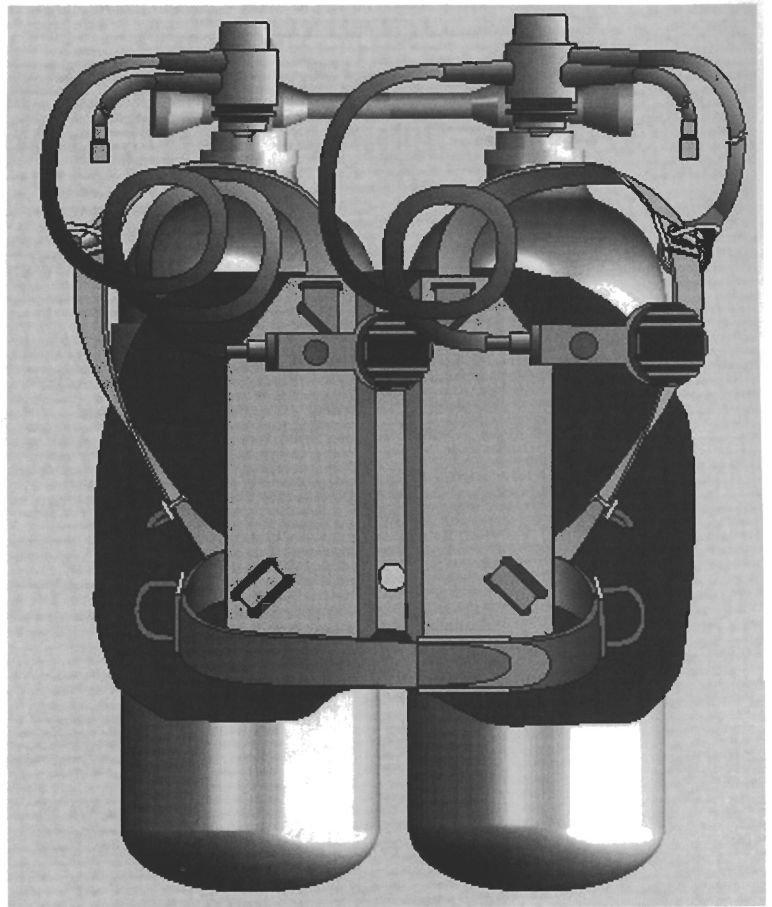


Figure 3. Schematic representation of standard doubles cave diving rig with attached stage bottle.

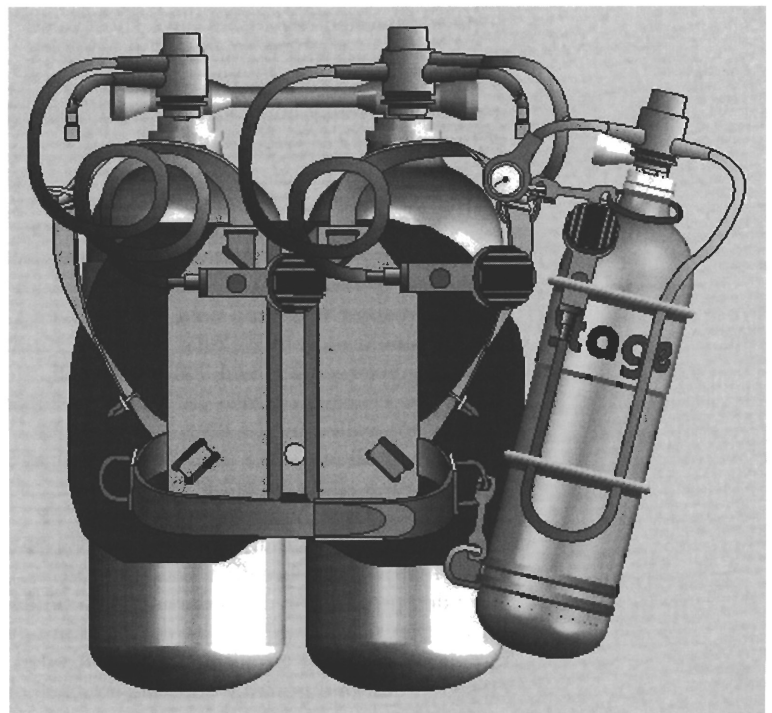
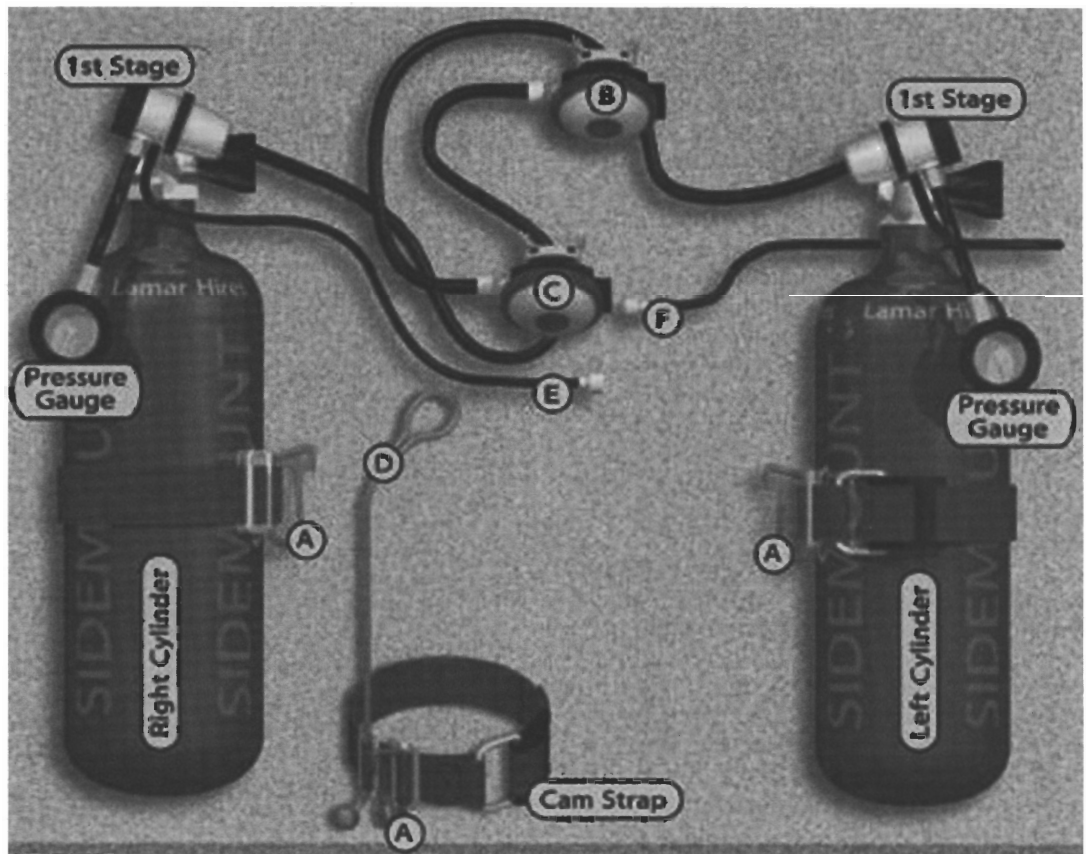


Figure 4. Schematic representation of sidemount tank and regulator configuration. A = large carabiner; B = right cylinder second stage; C = left cylinder second stage; D = cam strap positioning strap; E = dry suit inflator hose; F = low pressure inflator hose.



attach the neck of the cylinder to shoulder strap D rings. Matched regulators have short hose pressure gauges and BC or dry suit inflators. Either a jacket or wings BC with harness are used for buoyancy control. The battery canister of the dive light is butt mounted.

Rebreathers

Specially designed rebreathers have been used for deep, extended penetration caves dives. The Halcyon Semi Closed Passive Addition Rebreather was used on a record dive to 5547 m penetration in Wakulla Springs, Florida at depths between 280 and 300 ft. (Bowen, 1999). The Halcyon delivers gas from a premixed source, controlled by the diver's respiratory demands. It allows more than 100 minutes at 90 m depth on a single 80 cubic foot bottle.

Cis-Lunar manufactures the MK-5P Electronic Closed Circuit Rebreather (Nordstrom, 1999). This rebreather was used on extended penetration dives during the Wakulla 2 Expedition. The MK-5P can be operated in open circuit, semi-closed circuit, manual controlled closed circuit or automatic controlled closed circuit modes.

Diver Propulsion Vehicles

Diver propulsion vehicles (DPVs or "scooters") allow divers to penetrate considerably farther into underwater caves than would be possible with swimming alone. Increased speed and decreased breathing gas consumption resulting from lower exertion levels greatly extend cave penetrations. WKPP (Woodville Karst Plain Project) divers used the Gavin scooter for thousands of long range mixed gas cave dives. This DPV can produce average speeds of 53 m per minute at depths to 90 m.

Cave Diver Training

A significant concern of cave divers involves dealing with the problem of task loading. The cave diver needs to continuously monitor air supply, position of the guideline, depth, location of the dive buddy, passage configuration, presence of silt, etc. In addition, the scientific cave diver must do all this, plus carry out scientific task such as sample, specimen or data collection. Thus, it is imperative that the scientist diving in caves must first and foremost be a competent and highly experienced cave diver.

Several organizations, including the National Speleological Society Cave Diving Section (NSS-CDS), the National Association of Cave Divers (NACD) and Global Underwater Explorers (GUE) offer training programs in cave diving. Such programs begin with training in cavern diving—diving with single tanks in the entrance zone of caves where daylight is always visible. This training progresses from single to double tanks with increasing difficulty and distance of penetration into the cave.

CONCLUSION

Scientific cave diving is important because it provides direct human access and the resulting opportunities for scientific study to environments that previously were not known to exist. Such studies cover a broad gamut of investigations including biology, ecology, microbiology, geology, hydrology and archaeology. However, substantial training, equipment and expertise, considerably beyond that required for open water diving, is essential to carrying out scientific cave diving safely.

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