Enewetak: A Nuclear Atoll

by Andrea Chernov

Introduction

World War II has just ended. The United States wants to test out their nuclear weapons on Japanese war ships. Where do these nuclear weapons get tested? In the late 1940's, Enewetak Atoll seems to be the easiest answer.

Enewetak lies in the Pacific Ocean nestled within the Marshall Islands, lying at 11º30′N longitude, 162º15′E latitude (Robison *et al.*, 1999; Web *et al.*, 1975). The atoll is between 50 to 60 million years old, originating during the Eocene era (Reese, 1987), with a major transformation in its coastline during a change in sea level in the Holocene (Nunn, 1990). 39 islets with a land area of 2.5 mi^2 (Reese, 1987) compromise the majority of dry land of Enewetak. Enewetak Atoll brings an amazing view of the oceanic environment of an atoll lagoon with its unique oceanography, geology, biology, and history with nuclear weapons.

Oceanography

The von Arx's model of circulation, using primary circulation and secondary circulation to explain the oceanography, describes several atolls well, especially Bikini atoll (Atkinson *et al.*, 1981). However, the von Arx model does not hold up within the lagoon of Enewetak, though both are situated in the North Equatorial Current (Atkinson *et al.*, 1981).

Currents

Atkinson *et al.* (1981) first looked at Enewetak's cross-currents. Shallow currents flow across the atoll's windward reef margins and into the lagoon, having a large water exchange between the open ocean and Enewetak lagoon. The average speed of these currents is 10 to 150 cm/s; the average volume transport equals 0.05 m^3/s at low tide and 1.5 m^3/s at high tide. The leeward cross-reef currents have no particular pattern, generally flowing along the reef. These currents have a net drift towards the ocean and a net outflow of .4 x 10^8 m^3/tidal cycle (Atkinson *et al.*, 1981).

Channel currents affect the waters of Enewetak Atoll. Atkinson *et al.* (1981) first described the Deep Entrance current. This current has a speed of 80 cm/s and reverses during the tidal change. During the spring tide, the calculated volume transport is 3.0 x 10^8 m^3/half tidal cycle of water each direction. No net transport of water goes through the Deep Entrance. Water continuously flows from the South Channel at a speed from 8 to 30 cm/s with a steady outward flow of 6.9 x 10^8 m^3/tidal cycle. The tides reverse out of the South Channel like in the Deep Entrance, though it is minimal because of the outflow (Atkinson *et al.*, 1981). Atkinson *et al.* (1981) divided the lagoon currents of Enewetak into three categories: surface currents, middepth currents, and deep currents. Each current is distinguishable from the other by speed and direction. The surface currents respond to wind direction with current speed at 2% of the wind speed. Dye traces demonstrate that the middepth current flows northeast, opposite of surface currents, between 10 and 30 feet below the surface with speeds of 2 to 4 cm/s, transporting 8.6 x 10 m^3/tide cycle of water. The final current is the deep current, running south below 30 meters at 1 to 2 cm/s. The deep current flows around lagoon pinnacles every 6 to 12 hours with a volume transport of 2.2 x 10^8 m^3/tide cycle (Atkinson *et al.*, 1981).

Water Budget and Residence Time

The water budget and water residence time have unique distinctions. Water enters the lagoon primarily through the windward reef because it does not reverse directions and carries twice the amount of water of the other passages (Atkinson *et al.*, 1981). For the most part, water exits through the Deep Entrance, the leeward reef, the South Channel and Southwest Passage (Atkinson *et al.* 1981). Figure 3, taken from Atkinson *et al.* (1981), presents the water budget of the Enewetak Atoll lagoon.

To calculate residence time, divide the volume of the lagoon by the water input rate. Atkinson *et al.* (1981) found that the input rate total is the input from the windward reef added to the 30% from the Deep Entrance. Using this number, the average residence time of the lagoon water equals 28 days. However, the actual residence time varies in different parts of the lagoon due to the windward reef water input and South Channel water exit. A north to south recirculation does not exist within Enewetak: water entering from the northern end has a longer residence time than water entering from the southern end (Atkinson *et al.*, 1981).

Current	Volume transport mean and (range) 108m2 per 12.4 h	Comments
Windward cross-reef	+6.6 (+2.2 to + 19.8)	Continuous inflow
Leeward cross-reef	-0.4 (slightly plus to –0.8)	Variable Speed and direction
Deep Entrance	Net = 0 (-1.0 to +1.0) (.0 x 108 m3 transport each way	Reversing; typical tidal currents 0 – 80 cm•s-
South Channel	-6.9 (-4.5 to –8.5)	Continuous outflow; pulsing with the tide
Southwest Passage	Net = 0 (-2 to +2) (0.8 x 108 m3 transport each way)	Reversing; typical tidal currents
Surface	9.2 (3 to 30)	Variable; function of wind speed
Middepth	8.6 (unknown, but probably about the same as surface)	Variable; function of wind speed
Deep	.2 (unknown)	Variable; function of wind speed and windward cross-reef input

Figure 3 The water budget. The + represents water going into the lagoon and the – represents water going out of the lagoon. Taken from: Atkinson, M., S.V. Smith, and E.D. Stroup. 1981. Circulation in Enewetak Atoll Lagoon. Limnology and Oceanography 26(6):1074-1083.

Surf, Wind Stress, and Tides

Atkinson *et al.* (1981) also depicted surf, wind stress, and tides. The surf comes as breaking waves over the windward reef, putting water into the lagoon. Thus the cross-current reefs depend on the surf height and reef water depth. The net transport of the water is southward and increases as it moves south to hold the water coming over the windward side (Atkinson *et al.*, 1981).

Wind stress comes from the winds generating downwind drift of surface currents and upwind drift of middepth currents that, when mixed with a shallow current moving spirally, appears to be the Ekman spiral pattern (Atkinson *et al.*, 1981). The wind-driven currents overlay the net flow of water towards the South Channel, having speeds between 5 and 20 cm/s, or 2% of the wind speed (Atkinson *et al.*, 1981). If vertical mixing were absent, the lagoon surface water would turn-over in 5 to 10 days because of the wind driven currents. Finally are the tides and the tidal currents as described by Atkinson *et al.* (1981). Tidal currents completely influence waterflow within kilometers of the passes. These currents can be stronger than the wind-driven circulation, causing a left directed spiral one kilometer north of Enewetak island (Atkinson *et al.*, 1981).

Geothermal Convection and Dolotomization

The process of geothermal convection appears to be related to dolotomization at Enewetak Atoll (Wilson *et al.*, 2000; Jones *et al.*, 2000). Dolotomization, according to Jones *et al.* (2000), is the process of creating the mineral dolomite. Wilson *et al.* (2000) attempted to determine whether geothermal convection was part of the machinery behind dolotomization at Enewetak Atoll. Two holes were drilled through the carbonate cap over the volcanic island, finding two dolotomized intervals at 1300 meters, with sediments dating back to the Eocene age. The dolotomization is almost finished, but for some reason severely declines right above and below a 2 meter interval (Wilson *et al.*, 2000).

Wilson *et al.* (2000) first noticed that dolotomization may be transport-controlled. This transport-control comes in two reactions. One is the thermal gradient reactions, which move forward because of the equilibrium change from pore fluids streaming over temperature gradients. The thermal gradient reaction pattern is probably dispersed because of small thermal gradient sizes. Dolotomization moves forward on carbonate platforms because of a reaction front, meaning that seawater is supersaturated in reference to dolomite as it enters the platform. The water moves toward equilibrium along a flow path on the platform. Reaction fronts appear to produce a more solid reaction area than thermal gradients (Wilson *et al.*, 2000).

Wilson *et al.* (2000) produced reactive-transport simulations to attempt to determine other effects of reactions and transport on dolotomization. The dolomite precipitation rate has a large scale influence on dolotomization. Dolotomization occurs at the boundary of coarse and fine sediments because higher temperatures, which support dolotomization, happen at the lower areas of this zone. The simulations established dolotomization to occur at 45-60°C, which is above the typically estimated dolotomization temperature. Calcium-rich waters where water influx was weak occur along side of dolotomization (Wilson *et al.*, 2000).

Jones *et al.* (2000) describes dolotomization as it relates to geothermal and reflux circulation. Geothermal circulation occurs when the water temperature of the Pacific Ocean differs from the atoll ground water. Thermal convection dictates the transport of heat; however, a cooler strip of water exists between the atoll margin to the center of the atoll (Jones *et al.*, 2000). Reflux circulation is defined as circulation that happens when "lagoon waters, concentrated by evaporation, flow downward, displacing less dense groundwaters of near seawater salinity at depth" (Jones *et al.*, 2000). Lagoon brines reflux down up to 600 meters in a zone at the center of the lagoon, stretching for 10 km. At this point, geothermal circulation counteracts reflux circulation and groundwaters are pushed up and out through two places: the lagoon and upper slope (Jones *et al.*, 2000).

According to Jones *et al.* (2000), seawater causes dolotomization from high magnesium concentrations. To dolomitize 1 m^3 of limestone, 320 kg of seawater is needed. However, seawater contains only 1.34 kg/m^3 of magnesium. The 2 meter thick dolomitized interval (also described by Wilson *et al.*, 2000) could be produced if there was a flow velocity of 4x10^{-4} m/a. This would have to happen over the 5 Ma available in the area. So the amount of magnesium needed can be obtained from both geothermal and reflux circulation (Jones *et al.*, 2000).

The Lagoon Floor

Weins (1962) described various parts of the lagoon floor for several atolls, including Enewetak Atoll. Enewetak is one of the northern Marshall atolls with a lagoon terrace extending a maximum of two miles in width in some areas. Extensive soundings at Enewetak Atoll show 2,293 patch reefs. Within these patch reefs, there are coral knolls that are non-observable from the air (Weins, 1962).

According to Weins (1962), these coral knolls are an important part of the smoothness of the lagoon floor. The lagoon floor characteristics form because of sedimentation processes as well as coral knoll formation. The topography can be influenced by these two processes. The lagoon floor of Enewetak has a quite rough topography with an average smoothness coefficient of is 43% (Wiens, 1962).

The atoll's sediments contain four major constituents: foraminifera, fine debris, Halimeda debris, and coral (Wiens, 1962). Table 1 shows the percentage of these constituents at Enewetak and three other atolls. Yamano *et al.* (2002) found that other sediment constituents are coralline algae and molluscs.

Three types of lagoonal facies were identified within Enewetak, Majuro, and Kayangel: *Calcarina* facies, *Calcarina-Heterostegina* facies, and *Heterostegina* facies (Yamano *et al.*, 2002). The discussion here forth focuses on the facies within the lagoon. *Calcarina gaudichaudii*, a foraminifera species, characterizes the *Calcarina* facies along the reef flat, making it reef based. The sea-level change during the Holocene epoch may have contributed to the amount of *Calcarina* on the reef flat (Yamano *et al.*, 2002).

Table 1 Sedimentary Constituents in four atolls, including Enewetak. Taken from Wiens, H.J. 1962. Lagoon terraces to lagoon sediments. In: Atoll Ecology. Yale University Press

Sedimentary Constituents in an Atoll				
		Percent occupied by		
Atoll	*Foraminifera*	*Fine debris*	*Halimeda debris*	*Coral*
Bikini	5	30	56	9
Rongelap	3	53	36	8
Enewetak	9	52	26	13
Rongerik	3	36	27	34

The *Calcarina-Heterostegina* facies, a mix of *Calcarina* and *Heterostegina* tests, tend to be located on the windward side of the reef (Yamano *et al.*, 2002). The *Calcarina-Heterostegina* facies form from reef-based materials (*C. gaudichaudii*) and organisms from deep-lagoon areas (*Heterostegina*) (Yamano *et al.*, 2002). Since Enewetak is subject to NE tradewinds, currents and wind-driven waves may be responsible for taking *C. gaudichaudii* to the deep-lagoon (Yamano *et al.*, 2002).

The final facies, the *Heterostegnia* facies, is completely composed of *Heterostegina* sp. and distinctly lacking in *Calcarina* (Yamano *et al.*, 2002). The *Heterostegina* facies make up the sediments in the deep lagoon, the main components of which are *Halimeda* and several foraminifera species, including *Amphistegina* and *Heterostegina* (Yamano *et al.*, 2002). Since these facies are below 40 meters, bioturbation, or the modification of the sediments by burrowing organisms, may affect them more than typhoons, hurricanes or deep water currents (Yamano *et al.*, 2002; Duxbury *et al.*, 2000).

Marine Biological Factors

Nitrogen Cycling

It is thought that nitrogen is a limiting factor within the tropical Pacific (Webb *et al.*, 1975). The atomic ratio between nitrogen and phosphorous was 2:1- the Redfield Ratio states the required ratio of nitrogen to phosphorous be 16:1 (Webb *et al.*, 1975). Webb *et al.* (1975) suggest that this low amount of nitrogen may be an indicator of nitrogen deficiency, especially upstream of the windward reefs. This deficiency is not due to a decrease in biomass, otherwise the entire community would disappear in 2 to 6 months (Webb *et al.*, 1975). The next question, therefore, is how the coral reef community gets nitrogen. The most plausible explanation is nitrogen fixation: blue-green algae may have significant nitrogen-fixation abilities, and the blue-green algae *C. crustacea* has a broad distribution at Enewetak Atoll (Webb *et al.*, 1975).

Webb *et al.* (1975) calculated the nitrogen fixation rate, using the acetylene technique, as 100 nM N/m^2/sec. Using nitrogen export data, daytime nitrogen fixation was calculated as 190 nM N/m^2/sec. Also dissolved organic matter, ammonium and the total nitrogen exported were higher between 12:00 pm and 12:00 am (Webb *et al.*, 1975).

The *Calothrix* community needs to be in either light or dark for a certain amount of time before it started nitrogen fixation, so nitrogen fixation and photosynthesis are slackly tied to each other (Webb *et al.*, 1975). Dissolved Organic Nitrogen (DON) was seen during the day and used at night, indicating that nitrogen fixation is dependent on light and DON as the major source of nitrogen (Webb *et al.*, 1975). Non-nitrogen fixing organisms are nitrogen limited and the nitrogen fixers are phosphorous limited because of the low N:P ratio (Webb *et al.*, 1975).

Lagoon Biology and Ecology

Enewetak Atoll has the most marine benthic algae species out of all the atolls in the Indo-Pacific (Tsuda, 1987). There are 238 species in 106 genera of marine benthic algae with the following breakdown: 16 species of Cyanophyta, 89 species of Chlrophyta, 24 species of Phaeophyta, and 109 species of Rhodophyta (Tsuda, 1987). No seagrasses exist at Enewetak (Tsuda, 1987). The dispersal mechanisms have not allowed seagrasses to reach the atoll, though it could survive in the lagoon environment (Colin, 1987). This is also the reason why mangroves are also absent from Enewetak (Colin, 1987).

Branched stony coral grows as deep as 60 meters; between 60 and 112 meters, the stony corals become flat (Colin *et al.*, 1986). However, the substratum consisted of less than 1% of stony corals at a depth of 90 meters (Colin *et al.*, 1986). Halimeda was the most easily seen macroalgae at or below 100 meters with algal films and smaller macroalgae below 140 meters (Colin *et al.*, 1986). Below 100 m, the substratum was covered by gorgonians and alcyonaceans (Colin *et al.*, 1986). Colin *et al.* (1986) observed dents and caverns at depths of 120-160 meters and discovered sponges, antipatharians, what may have been sclerosponges, and more invertebrates that were sessile. At 220 meters, seapens are abundant along a sand slope (Colin *et al.*, 1986).

Miller (1986) studied the hermit crabs and gastropods at Enewetak. The hermit crab and gastropod populations live within the middle/upper intertidal zones on the reef flat that looks toward the ocean. Apparently, population sizes of hermit crabs and gastropods oscillated more in areas with greater topographic relief and a larger amount of algae. However, algae that covers the bottom adds to the topography and is prone to the effects of strong waves, e.g. shortening and displacement (Miller, 1986).

50 species of invertebrates classified into 7 phyla live within the lagoon sediments, along with 15 families of fish, participate in the bioturbation, (Suchanek *et al.*, 1986). The amount of sediments disturbed have been calculated for Callianassids and Enteropneusts, as can be seen in Table 2. Bioturbation in Enewetak Atoll lagoon can have a major consequence: radionuclides buried deep in the lagoon sediments can be put back into the water (Suchanek *et al.*, 1986). The re-entry of radionuclides via deep bioturbation into the water can be a re-entry for those radionuclides into higher levels of the food chain (Suchanek *et al.*, 1986).

Table 2 Organisms and sediment production due to bioturbation for two organisms. Adapted from: Suchanek, T.H., and P.L. Colin. 1986. Rates and effects of bioturbation by invertebrates and fishes at Enewetak and Bikini atolls. Abstract. Bulletin of Marine Science 38(1):25-34.

Organism	Sediment production, cc/day	Mean estimates per m^2 cc/m^2/day
Callianassids	1,300	800
Enteropneusts	700	600

There are 800 known species of fish at Enewetak Atoll (Colin, 1987). Several of the fish are herbivores, living on the reef flat or on patch reefs (Colin, 1987). Predatory fish are also important, the Carangidae family (species *Cranx melampygus*, *Carnax ignobilis*, and *Elagatis bipinnulatus*) having a major role

(Colin, 1987). Some fishes are detritivores, or those organisms that eat decaying organic material- the mullet species *Crenimugil crenilabis* has been seen to expel sand through the gills after feeding (Colin, 1987).

Several species are coralivores (coral eaters), with some being obligate coralivores (Colin, 1987). The coralivores include the Chaetodontidae family and the species *Oxymonocanthus longirostris*, *Labrichthys unilineata*, and the *Labropsis* spp.; the only known species to feed on sponges is the puffer *Arothron mappa* (Colin, 1987). Ciguatera is the most common fish toxin, with the fish following the typical form of toxicity: large, roaming predators that are mostly piscivorous (fish eating) (Colin, 1987).

Gladfelter *et al.* (1980) compared coral reef fish communities of Enewetak Atoll and St. Croix. Diurnal planktivores, which point toward the larger amount of daytime plankton within the water column, nocturnal plankton feeders, and piscivores were found to be slightly higher at Enewetak (Gladfelter *et al.,* 1980). Most significant about the Enewetak patch reefs is the low numbers of nocturnal feeders, mostly because the low amount of nocturnal foraging grounds (Gladfelter *et al.*, 1980).

Labroides dimidatus, a cleaning fish, may have a significant effect on the ectoparasite infecting the damselfish *Pomacentrus vaiuli* (Gorlick *et al.,* 1987). *L. dimidiatus* tend to eat larger ectoparasite copepod *Dissonus* sp., reducing numbers on *P. vaiuli* hosts (Gorlick *et al.,* 1987). The ectoparasite reduction seen by Gorlick *et al.* (1987) may be an immune system response post-infection. However, Gorlick *et al.* (1987) reminds that any symbiosis, like the one between *L. dimidatus* and *P. vaiuli*, are not that simple. *L. dimidatus* removes larger members of the ectoparasite, allowing for smaller members to grow on the host. This ensures the cleaner a constant supply of food and reduces the ectoparasite biomass on *P. vaiuli* (Gorlick *et al.*, 1987).

Sharks are a major part of the lagoon community. The blacktip reef shark (*Carcharhinus melanopterus*) can be found on the reef flats while the whitetip reef shark (*Triaenodon obesus*) can be found on the main reefs and sandy areas on the marginal areas (Colin, 1987). *Negaprion brevirostris*, the lemon shark, is a large shark that is able to travel into shallower lagoon waters (Colin, 1987).

Carcharhinus amblyrhynchos, the gray shark, can be typically found in the lagoon but is more abundant on the seaward reef and is considered the most dangerous (Colin, 1987). Gray reef shark movement was studied at Enewetak using ultrasonic telemetry and direct observation by McKibben *et al.* (1986). Shark movement was divided into two categories. One, *C. amblyrhynchos* tagged along reefs near the ocean appear nomadic, moving an extended length along the reefs (McKibben *et al.,* 1986).

Two, sharks tagged at either lagoon reefs or lagoon pinnacles had a home range, going off to a different area at night and returning to the tagging sight during the day (McKibben *et al.*, 1986). During the day, *C. amblyrhynchos* groupings can be divided into three groups:

1. Polarized schools: schools that stay near the bottom of flat areas
2. Loose aggregations: groups that congregate around the drop-off between the ocean and reef
3. Single sharks: individuals that stay over shallow reefs and pinnacles (McKibben *et al.,* 1986).

The silvertip shark, or *Carcharhinus albimarginatus*, is found at a depth between 20 and 30 meters along the seaward slope (Colin, 1987). The silvertip shark can be seen in Picture 1. *C. galapagensis* (the Galapagos Shark) is large and dangerous but is not typically seen in Enewetak lagoon (Colin, 1987). The biggest shark that is dangerous at Enewetak is *Galecerdo cuvier*, the tiger shark (Colin, 1987).

Figure 1 A silvertip shark. <www.elasmodiver.com/silvertip%20shark.htm> 29 Nov. 2004

Figure 2 A Striped Dolphin <www.cetacea.org/striped.htm> 29 Nov 2004

Table 3 Marine Mammals anticipated at Enewetak Atoll. All have dorsal fins. Taken from: Reese, E.S. (b). 1987. Mammals of Enewetak Atoll. In: Devaney et al. The natural history of Enewetak Atoll. 2:348

Large whales	Medium whales	Small Cetaceans
Blue Whale	Minke Whale	Spotted Dolphins
Fin Whale	Bottlenose Whale	Spinner Dolphin
Sei Whale	Cuvier's Beaked Whale	Striped Dolphin
Bryde's Whale	Beaked whales, genus	Common Dolphin
	Mesoplodan	
Humpback Whale	Killer Whale	Fraser's Dolphin
Sperm Whale	False Killer Whale	Bottlenose Dolphin
	Short-finned Pilot Whale	Rough-toothed Dolphin
	Risso's Dolphin	Pygmy Killer Whale
		Melon-headed Whale
		Pygmy Sperm Whale
		Dwarf Sperm Whale

Marine mammals are only seen occasionally at Enewetak (Reese (b), 1987). Two dolphins have been positively identified: the spinner dolphin from photographs and the striped dolphin, seen in Picture 2, from skeletal remains (Reese (b), 1987). It is not known if any Pinnipeds (walruses, seals, sea lions, otters, etc.) occur at Enewetak (Reese (b), 1987). Table 3 is of those marine mammals that can be anticipated at Enewetak and is taken from Reese (b) (1987).

Lagoon Trophic Relationships

There are three major trophically linked sections in Enewetak atoll lagoon - the coral reefs and knolls, the open lagoon, and the lagoon floor environment that excludes the coral knolls (Marshall *et al.*, 1987). The reef and the lagoon are linked, as seen by the fact that there are plenty of fish within the lagoon, possibly because of matter like detritus, mucus flakes and algal fragments that are coming off the reef (Marshall *et al.*, 1987). For example, two zooplankton species in the lagoon had detrital material in their gut (Marshall *et al.*, 1987).

Marshall *et al.* (1987) point out that the copepods and larvaceans eat phytoplankton as well as detritus and had particulate organic carbon (POC) in their guts. In the lagoonal water column, fishes had stomachs filled with copepods and larvaceans, thus taking up the detritus and POC (Marshall *et al.*, 1987). Based on data from Atkinson *et al.* (1981), Marshall *et al.* (1987) calculated the productivity of Enewetak lagoon: 1.07 mgC/m^3/day in summer and 3.21 mgC/m^3/day in the winter. Marshall *et al.* (1987) believe that phytoplankton may be making up for the difference in nutrients (especially carbon and nitrogen) due to their increased numbers in the summer.

Land-based factors

The People of Enewetak: Before World War II

Enewetak Atoll is isolated, even among the Marshall Islands, and has been so for thousands of years (Kiste, 1987). The people of Enewetak mastered the sailing art and built outrigger canoes 55 feet long with 30 foot tall masts into the 1960's (Kiste, 1987). Their natural resources included coconuts, pandanus, papaya, bananas, and arrowroot; domestic animals included pigs and chickens, though these were only eaten on holidays (Kiste, 1987).

The Enewetak people were divided into two groups: those who lived on Enewetak Island and those who lived on Enjebi Island (Kiste, 1987). These groups, nevertheless, did intermarry and cooperate during many activities (Kiste, 1987). The Enjebi islanders and the Enewetak islanders, called riEnjebi and riEnewetak respectively, are headed by a patrilineal chief but are divided into matrilineal clans (Kiste, 1987). The clans practiced exogamy, or marrying outside the clan; clan members consider each other family, so sex within the clan equates to incest (Kiste, 1987). The couple lived with the male's family after marriage, so having a patrilocal extended family was quite common (Kiste, 1987). Children inherit lands bilaterally (from both parents), and most people can trace their land back almost six generations (Kiste, 1987).

Soils

The soils are calcareous, with constituents of limestone, rubble, sand, organic litter, and humus, and tend to have poor water retention abilities (Reese (a), 1987). Reese ((a), 1987), describes five different types of soil. First is a buildup of coral rubble about the size of stones. Second is soil made of coral sand/gravel that is unaffected. Third are weak A horizon soils that are slightly darker than the sand above and have no obvious structure. Fourth are strong A horizon soils, which are below and darker than the weak A horizon soils. Fifth are raw humus soils that have a deep A horizon (Reese (a), 1987).

Weather and Climate

Enewetak Atoll lies within the NE tradewind zone, though it is not considered part of the typhoon belt (Yamano *et al.*, 2002). The tradwinds blow around 95% of the year (Reese (a), 1987). Enewetak has two seasons: the dry season (December-March) and the wet season (April-November) (Reese (a), 1987; Merrill *et al.*, 1987). The atoll has a 1470 mm average annual rainfall with 85% falling during the wet season (Reese (a), 1987; Merrill *et al.*, 1987); in spite of that Enewetak is considered one of the driest atolls within the Marshall Islands (Reese (a), 1987). The average minimum and maximum temperatures can be seen in Table 4.

Table 4 The minimum and maximum average temperatures, °C. Taken from Merrill, J.T., and R.A. Duce. 1987. Meteorology and Atmospheric Chemistry of Enewetak Atoll. In: Devaney et al. The natural history of Enewetak Atoll. 1:228 pp

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec
Min.	23.5	23.4	23.6	23.8	23.5	24.0	23.6	23.6	23.8	23.4	23.7	23.8
Max.	30.4	30.5	30.6	31.1	31.4	31.6	31.8	32.3	32.3	32.1	31.7	30.9

Tropical storms, the severest called typhoons, happen without warning (Reese (a), 1987). Tropical storms typically form during the wet season, more specifically between the months of July and October (Merrill *et al.*, 1987). Eight tropical storms have hit Enewetak between 1959 and 1979, and only Alice in 1979 gained enough strength to be labeled Typhoon (Reese (a), 1987).

Land Plant Post-Dispersal Survival

Louda *et al.* (1985) looked at the predation that occurred on seeds and fruits post-dispersal. During the experiment, the main predator observed was hermit crabs and the plant species used were *M. argentea*, *G. speciosa*, *T. catappa*, and *S. taccada*. The initial hypothesis: seeds have higher survival rates within the forest over the beach area. Seeds for each species were placed in a small-mesh bag, a large mesh bag, or the control basket at three areas: the beach, the fringe scrub, and the central forest. In the control baskets, which were open, all four species disappeared at significant levels. Survival in the open was found to be a factor of two things: perseverance of the fruit and the amount of fruit and seeds that remained undamaged. (Louda *et al.*, 1985).

Part of the experiment excluded predators: fruit species perseverance went up and predator-induced damage went down with predator exclusion (Louda *et al.*, 1985). Though finding that survivorship related to predation pressures were species specific, Louda *et al.* (1985) discovered three points in their study. One, *M. argentea* and *T. catappa* recruitment capability was diminished by insect predation. Two, *S. taccada* was missing in the forest because of land crabs and possibly birds. Third, land crabs were the biggest predator of fruit and seed post-dispersal, especially for *T. catappa* (Louda *et al.*, 1985). Overall, post-dispersal survival depends on “predation intensity…, by generalized omnivorous predators,…” (Louda *et al.*, 1985).

Land Biology: Animals

Land crabs are one of the major animals depicted by Reese (a, 1987). One of the species found was the land hermit crab *Coenobita perlatus* that are bright to brownish red (Reese (a), 1987). *Birgus latro*, as described by Reese ((a), 1987), is the coconut crab, a scavenger that is the largest invertebrate known. It is nocturnal and typically lives in dense vegetation on the southwest islands ranging between and including the islands of Ikuren and Biken (Reese (a), 1987). Coconut crab mating happens on land and the male transfers the spermatophore to the female. Though it is not known when fertilization happens, the female carries the eggs on the plepods for a period of three weeks, typically between the months of April and August. After three weeks, the female can be seen walking out into the water, flexing her abdomen several times, and releasing the eggs as free-swimming zoeae larvae (Reese (a), 1987). This larval stage turns into the postlarval stage of the glaucothoe, which lives in a mollusc shell for two to three years (Reese (a), 1987).

There are a total of seven species of land lizards and one species of blind snake on Enewetak (Lamberson, 1987). None of the reptile species are endemic to Enewetak or even Micronesia. The House Gecko, *Hemidactylus frenatus*, may have come from tropical areas in Asia, Africa, and India and can be frequently found in places where humans live (Lamberson, 1987). The House Gecko can be seen in Picture 3.

A second lizard found on Enewetak is the mourning gecko, *Lepidodactylus lugubris*, that also tend be found in areas of human habitation (Lamberson, 1987). It is a parthogenic species and the eggs are highly adhesive, so can be carried easily to other places by boat (Lamberson, 1987). A third species of lizard is *Hemiphyllodactylus typus*, the tree gecko; the tree gecko is quick to escape and is an agile species so may be more common than previously thought (Lamberson, 1987).

Figure 3 The House Gecko <www.wildherps.com/species/H.frenatus.html> 29 Nov 2004

There is also *Gehyra oceanica* (the Polynesian gecko), which can be found on the trunks and leaves under several trees; *Emoia cyanura* (blue-tailed skink) tends to be found under plant debris and scrub vegetation (Lamberson, 1987). The last two lizards found on Enewetak are the moth skink (*Lipinia noctua*) and the monitor lizard (*Varanus indicus*), the latter of which is the largest found on Enewetak (Lamberson, 1987).

The blind snake is the Brahminy blind snake, *Ramphotyphlops bramina*, and was introduced from the Philippines and Southeast Asia (Lamberson, 1987). The blind snake tends to be a secretive, nocturnal reptile that is parthogenic (Lamberson, 1987). Blind snakes eat termites, soft-bodied bugs, and bug larvae, so benefit those who live on the atoll (Lamberson, 1987). The Brahminy blind snake is presented in Picture 4.

Figure 4 The Brahminy blind snake <www.ecologyasia.com/Vertebrates/braminy_blind_snake.htm> 29 Nov 2004

Sea birds whose main breeding range is to the North use Enewetak as a nesting ground (Berger, 1987). Enewetak has one enduring species, the reef heron (*Egretta sacra*), but it has a wide range that includes places such as Korea, Japan, Australia, and Polynesia (Berger, 1987). *Eudynamis taitensis*, the long-tailed cuckoo seen in Picture 5, nests in New Zealand but spends the non-breeding season on Enewetak (Berger, 1987).

Figure 5 The Long Tailed Cuckoo <orongorongo.wellington.net/nz/long_tailed_cuckoo.htm> 29 Nov 2004

The main land mammal of Enewetak is man, bringing with him the Polynesian rat (*Rattus exulans*) and the domestic pigs (*Sus scrofa*) (Reese (b), 1987). The Polynesian rats tend to eat primarily plant detritus but will eat some animal detritus, mainly insects (Reese (a), 1987). They aerate the soil through burrow digging and eat the carrion, thereby reducing fly reproduction (Reese (a), 1987). 19th century Europeans are believed to have brought the domestic dog, *Canis familiaris*, and the domestic cat, *Felix catus* (Reese (b), 1987).

Past and Present Issues

World War II

Laurence Marshall Carucci (1997) describes the events of World War II that caused devastation at Enewetak Atoll. Between the years 1885 and 1915, Germany used the Enewetak islet of Wjlan as a place for copra (dried coconut meat) production. After Germany exited, the Japanese established a colony with missionaries trained in Kosrae coming to Enewetak afterwards. In the 1930's, the first trading post was opened with two more opening later that decade. In the early 1940's Japan decided to build a military installation on the islet of Enewetak as part of the plan to expand in the West Pacific. (Carucci, 1997).

On February 17 1944, Enewetak Atoll was taken from Japan by the United States during Project CATCHPOLE; over 3,200 Japanese people were killed in the attack (Carucci, 1997). After Project CATCHPOLE, the U.S. decided to use the atoll for bomb testing, so the people of Enewetak were relocated (Carucci, 1997).

According to Carucci (1997), the Enewetak people believed their relocation would be short lived; they lived away from their native home for 33 years. When they came back to their home islet, they found their home in ruins. By 1958, over 45 nuclear tests had been conducted and the atoll became a target for ballistic missiles that were launched all the way from California (Carucci, 1997). The nuclear tests were performed on the surface of or beneath the lagoon waters and above or on the land surface (Robison *et al.*, 1999). In the 1970's, the US tried to recreate the outcomes of the nuclear weapons by detonating from 5 to 500 tons of explosive, but this practice was stopped in 1974 via court injunction (Carucci, 1974).

Radionuclides

The nuclear tests during World War II left several radionuclides at Enewetak Atoll; over the years several have decayed out of the environment (Robison *et al.*, 1999). Currently, the sediments of Enewetak atoll act as holdings for $^{239+240}$Pu, ^{241}Am, and ^{238}Pu, as well as various fission and activation products like ^{90}Sr, ^{137}Cs, and ^{207}Bi (Robison *et al.*, 1999). Robison *et al.* (1999) point out that radionuclides do not remain in the fine sediments they originally deposit in; radionuclides have been found in biogenic materials such as Forams, coral, *Halimeda* bits, and mollusc shells.

Robison *et al.* (1999) compares the amounts of the previously mentioned radionuclides between Enewetak and Bikini Atoll. The following discussion of these radionuclides comes from Robison *et al.* (1999). ^{241}Am was found to be more widespread at Enewetak, especially in surface sediments on the lagoons west side. There is also ten times more ^{207}Bi at Enewetak.

The radionuclide concentration in different reef fish was looked at by Robison *et al.* (1999) as well. At Enewetak, the highest levels of ^{137}Cs were found in fish that reside in the northern part of the atoll. Most of this radionuclide can be found in the flesh over the bones, viscera, or liver. In goat fish, there was a significant value of ^{207}Bu concentration within the muscle tissue: goat fish use 70% of their muscle tissue for whole body movement (Robison *et al.*, 1999). But why look at these concentrations? It is to see the dosage of these radionuclides based on the consumption of these fish. Yet the dose of radionuclides from the nuclear tests only measure 0.1 to 0.3% of the total dose, perhaps because the concentrations some radionuclides are found within parts not eaten e.g., the bone, viscera, and organs (Robison *et al.*, 1999).

Halimeda sp. is the major macroalgae within the Enewetak lagoon (Spies *et al.*, 1981). One of the species Spies *et al.* (l981) looked at in conjunction with radionuclides was *Halimeda incrassate* by transplanting several plants from Runit Island to Enewetak Island. Within twenty days, those plants had lost six radionuclides.

Halimeda tends to uptake ^{241}Am, ^{155}Eu, and $^{239+240}$Pu all at the same rate, which suggest that all the radionuclides had similar preliminary accumulation within the macroalgae (Spies *et al.*, 1981). $^{239+240}$Pu tends to accumulate within the coencytic filaments of Halimeda, which may be due to the large surface area: volume ratio (Spies *et al.*, 1981).

Anti-Cancer Drugs

Allen *et al.* (1986) sampled 137 species of marine invertebrates from different environments on Enewetak atoll. Some of the invertebrates were screened for an ability to inhibit the growth of L1210 mouse leukemia cells in culture. Of all the samples, 35 species had extensive action against L1210 cancer cells. These 35 species were collected again with another 10 species (previously uncollected). Researchers took aqueous and ethanolic extracts of 33 of the recollected organisms and were screened for the capability to increase the survival rate of mice that have P388 leukemia. Extracts of 14 species were able to increase the survival time by 20% or more (Allen *et al.*, 1986).

Potential Lobster Fisheries

Ebert *et al.* (1986) studied the fishery potential of *Panulirus penicillatus*, the spiny lobster, between 1978 and 1979. 791 lobsters were caught in order to study this, with more being caught on the north reefs over the south reefs and more females being caught then males (Ebert *et al.*, 1986). The lobsters had a 25% mortality rate, with a natural mortality rate coefficient of 0.284/yr for male lobsters and 0.244/yr for female lobsters (Ebert *et al.*, 1986). The maximum yield weight/lobster is 450 grams, which was used to assess the yield characteristics to the possible intensity of fishing (Ebert *et al.*, 1986).

Conclusion

Enewetak has an amazing history, especially in relation to man. The Atoll has amazing biology both on land and in the lagoon. The lagoon itself brings unique features to the environment of Enewetak. The future holds boundless opportunities, if only the present can be healed.

REFERENCES

Allen, T.M., A. Sharma, and R.E. Dubin. 1986. Potential new anti-cancer drugs from marine organisms collected at Enewetak Atoll. Abstract. Bulletin of Marine Science 38(1):4-8.

Atkinson, M., S.V. Smith, and E.D. Stroup. 1981. Circulation in Enewetak Atoll Lagoon. Limnology and Oceanography 26(6):1074-1083.

Berger, A.J. 1987. Birds of Enewetak Atoll. In Devaney *et al*. The natural history of Enewetak Atoll. 2:348 pp.

Carucci, L.M. 1997. Nuclear Nativity: Rituals of Renewal and Empowerment in the Marshall Islands. Northern Illinois University Press, DeKalb. 217 pp.

Colin, P.L., D.M. Devaney, L. Hillis-Colinvaux, T.H. Suchanek, and J.T. Harrison III. 1986. Geology and biological zonation of the reef slop, 50-360 m depth at Enewetak Atoll, Marshall Islands. Abstract. Bulletin of Marine Science 38(1):111-128.

Colin, P.L. 1987. Subtidal Environments and Ecology of Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetak Atoll. 1:228 pp.

Duxbury, A.C., A. B. Duxbury, and K.A. Sverdrup. 2000. An Introduction to the World's Oceans. 6th ed. McGraw-Hill Companies, Inc. Boston. 528 pp.

Ebert, T.A., and R.F. Ford. 1986. Population ecology and fishery potential of the spiny lobster Panulirus penicillatus at Enewetak Atoll, Marshall Islands. Abstract. Bulletin of Marine Science 38(1):56-67.

Fosberg, F.R. 1953. Vegetation of Central Pacific atolls, a brief summary. Atoll Res. Bull. 23:1-26.

Gladfelter, W.B., J.C. Ogden, and E.H. Gladfelter. 1980. Similarity and Diversity Among Coral Reef Fish Communities: A Comparison between Tropical Western Atlantic (Virgin Islands) and Tropical Central Pacific (Marshall Islands) Patch Reefs. Ecology 61(5):1156-1168.

Gorlick, D. L., P.D. Atkins, and G.S. Losey. 1987. Effect of Cleaning *Labroides dimidiatus* (Labridae) on an Ectoparasite Population Infecting *Pomacentrus vaiuli* (Pomacentridae) at Enewetak Atoll. Copea 1:41-45.

Jones, G., F. Whitaker, P. Smart, and W. Sanford. 2000. Numerical modelling of geothermal and reflux circulation in Enewetak Atoll: implications for dolotomization. Journal of Geochemical Exploration 69-70:71-75.

Kiste, R.C. 1987. History of the People of Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetak Atoll. 1:228 pp.

Lamberson, J.O. 1987. Reptiles of Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetak Atoll. 2:348 pp.

Louda, S. M., and P.H. Zedler. 1985. Predation in Insular plant Dynamics: an Experimental Assessment of Postdispersal Fruit and Seed Survival, Enewetak Atoll, Marshall Islands. American Journal of Botany 72(3):438-445

Marshall, N., and R.P. Gerber. 1987. Trophic Relationships in Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetak Atoll. 1:228.

Merrill, J.T., and R.A. Duce. 1987. Meteorology and Atmospheric Chemistry of Enewetak Atoll. In: Devaney *et al*. The natural history of Enewetak Atoll. 1:228 pp.

McKibben, J.N., and D.R. Nelson. 1986. Patterns of movement and grouping of gray reef sharks, Carcharhinus amblyrhynchos, at Enewetak, Marshall Islands. Abstract. Bulletin of Marine Science 38(1):89-110.

Miller, A.C. 1986. Long-term fluctuations in algal cover and populations of hermit crabs and gastropods at Enewetak Atoll. Abstract. Bulletin of Marine Science 38(1):12-18.

Nunn, P.D. 1990. Recent Environmental Changes on Pacific Islands. The Geographical Journal 156(2):125-140.

Reese, E.S. (a). 1987. Terrestrial Environments and Ecology of Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetk Atoll. 1:228 pp.

Reese, E.S. (b). 1987. Mammals of Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetak Atoll. 2:348.

Robison, W. L. and V.E. Noshkin. 1999. Radionuclide characterization and associated does from long-lived radionuclides in close-in fallout delivered to the marine environment at Bikini and Enewetak Atolls. The Science of the Total Environment 237-238:311-327.

Spies, R. B., K.V. Marsh, and J.R. Kercher. 1981. Dynamics of Radionuclide Exchange in the Calcareous Algae Halimeda at Enewetak Atoll. Limnology and Oceanography 26(1):74-85.

Suchanek, T.H., and P.L. Colin. 1986. Rates and effects of bioturbation by invertebrates and fishes at Enewetak and Bikini atolls. Abstract. Bulletin of Marine Science 38(1):25-34.

Tsuda, R.T. 1987. Marine Benthic Algae of Enewetak Atoll. In: Devaney *et al.* The natural history of Enewetak Atoll. 2:348.

Webb, K.L., W.D. DuPaul, W. Wiebe, W. Sottile, and R.E. Johannes. 1975. Enewetak (Eniwetok) Atoll: Aspects of the Nitrogen Cycle on a Coral Reef. Limnology and Oceanography 20(2):198-210.

Wiens, H.J. 1962. Lagoon terraces to lagoon sediments. In: Atoll Ecology. Yale University Press.

Wilson, A.M., W. Sanford, F. Whitaker, and P. Smart. 2000. Geothermal convection: a mechanism for dolotomization at Enewetak Atoll? Journal of Geochemical Exploration 69-70:41-45.

Yamano, H., H. Kayanne, F. Matsuda, and Y. Tsuji. 2002. Lagoonal facies, ages and sedimentation in three atolls in the Pacific. Marine Geology 185:233-247.