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678

The Natural History of Enewetak Atoll

Volume I The Ecosystem: Environments, Biotas, and Processes

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Foreword

As activity and funding at the Mid-Pacific Research Laboratory began to diminish in the early 1980s, it seemed fitting that a synthesis be prepared of the three decades of research that had been conducted at this Laboratory on Enewetak Atoll. For 30 years the Atoll served as a convenient, accessible location for studies of Mid-Pacific island ecosystems, and several hundred scientists utilized the facility. Primary funding was provided by the Office of Health and Environmental Research, Ecological Research Division, U. S. Department of Energy (formerly the Atomic Energy Commission and the Energy Research and Development Administration).

This is an attempt to synthesize in two volumes the results of the Mid-Pacific Research Laboratory studies that have been published in hundreds of widely dispersed publications. It is hoped that present and future scientists involved in studies of Mid-Pacific islands will find this synthesis a convenient resource for their research.

Considerable time and effort were expended by many contributors to make this synthesis possible. Thanks are extended to all these authors for their manuscripts. Special appreciation is expressed for Dr. Dennis Devaney's dedication in filling gaps in the taxonomic descriptions of several invertebrate groups. This publication would not have been possible, however, without the determination and persistence of Dr. Ernst Reese in organizing and collecting the material. Deepest gratitude is acknowledged for his conscientious efforts.

Helen M. McCammon, *Director*
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Preface

These volumes of *The Natural History of Enewetak* describe research done at the Mid-Pacific Research Laboratory from 1954 to 1984 under the auspices of the Department of Energy. The history of the laboratory and the reasons for its support by the United States Department of Energy are described in Chapter 1 of Volume 1.

Over a thousand persons—established scientists, their assistants, and graduate students—conducted research at the laboratory during the 30-year period. Their efforts resulted in 223 publications. These have been collected in three volumes of reprints entitled *Mid-Pacific Marine Laboratory Contributions, 1955–1979*, U. S. Department of Energy, Publication NVO 628-1. The laboratory has continued operation on a limited scale to the present. A collection of papers recently appeared in the *Bulletin of Marine Science*, Volume 38, 1986.

Much of the research conducted at the laboratory was on the marine environment. The reason was that the majority of scientists applying to work at Enewetak were marine biologists. For many, this was the first opportunity to study the biota of a coral atoll. Fewer studies were conducted in the terrestrial environment and its biota. Nevertheless, as these volumes attest, the coverage is amazingly complete and thorough, and there are few, if any, studies of an equivalent ecosystem that equal the total research effort reported in these volumes.

Volume I provides a synthesis of the research carried out under the subject headings of the respective chapters. Certain of the chapters, e.g., those on geology, subtidal and intertidal environments and ecology, and those on reef processes and trophic relationships, summarize a great diversity of research carried out by many scientists for many years. In contrast, the chapters on meteorology and oceanography summarize research carried out under one integrated program involving fewer scientists working over a shorter period.

Volume II of *The Natural History of Enewetak Atoll* provides information on the taxonomy of animals and plants known to occur at Enewetak Atoll. This taxonomy represents a fulfillment of one of the first assignments to the laboratory—to determine the scientific names of the biota of the atoll. The collections on which the checklists in each chapter are based are housed at the Bernice P. Bishop Museum in Honolulu and the U. S. National Museum of Natural History, Smithsonian Institution, Washington, D. C.

In addition to the species checklists, each chapter in Volume II provides a succinct summary of the biota with respect to endemism, range extensions, and other features that set the Enewetak biota apart from those one might expect to find on equivalent Indo-Pacific islands. This compendium of taxonomic information for an atoll should prove of immense value to scientists interested in biogeography and evolutionary biology of island ecosystems for years to come.

One of the problems of editing these volumes has been the correct use of place names. In some cases authors used the military code names for islands while others used the native names. Even the native names have changed from early phonetic spellings to the spellings currently in use and preferred by the Enewetak people. For example, the name of the atoll has changed from Eniwetok to Enewetak, and, although the correct current spelling is used throughout, the old spelling occurs in older references and maps which appear in these volumes. Maps giving the military code names and the native names preferred by the Enewetak people are located in Chapter 1 of Volume I. Surprisingly, it is difficult to determine the exact number of islands. Due to the effects of storms, small islands are ephemeral, and two islands and part of a third were obliterated by nuclear explosions. Currently there are 39 recognizable islands, and these are shown on the map used throughout the book.

These volumes do not report on the extensive radiological surveys and studies which have been conducted by the Lawrence Livermore Laboratory, University of California, and the Radiation Laboratory, University of Washington, also under the auspices of the U. S. Department of Energy.

Dennis M. Devaney, senior editor of this volume, disappeared while collecting specimens off the Island of Hawaii on August 13, 1983. Dennis was doing what he loved best, collecting marine invertebrates, at the time of his death. He collected extensively at Enewetak, and he undertook the task of organizing the systematic chapters of Volume II. Beatrice L. Burch, Devaney's assistant at the

Bishop Museum, completed the task, and she has written the introduction to Volume II.

It is fitting that the two volumes of this book are dedicated to the people of Enewetak Atoll. They, like so many other human beings, were caught up by forces beyond their control and understanding in an immense cataclysm of human history. In a small way, this book stands as something good that has resulted from those years.

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Introduction

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The first volume of *The Natural History of Enewetak Atoll* provides a summary of the research carried out over the 30-year period from 1954 to 1984. The frontispiece illustrates the dramatic contrasts between the immensity of the lagoon and the seemingly fragile necklace of small islands which surrounds it, and also between the sea condition on the windward, seaward side of the reef and the relatively sheltered waters of the lagoon.

The first chapter discusses the history of research at Enewetak Atoll. The reasons behind the establishment of the Enewetak Marine Biological Laboratory are described. The authors, Philip Helfrich and Roger Ray, have been associated with activities at Enewetak from the very early days. They conferred with Robert W. Hiatt, the first director of the laboratory. In Chapter 2, Robert C. Kiste, a foremost authority on the people of Micronesia, provides a history of the Enewetak people to whom these volumes are dedicated.

The next four chapters deal with the physical environments of Enewetak Atoll. In Chapter 3, Patrick L. Colin describes the physiography of Enewetak. Colin served as resident scientist in charge of the laboratory from 1979 to the end of 1983 when all resident scientific staff left the atoll. Following the description of the atoll, Byron L. Ristvet, a frequent scientific visitor to Enewetak, provides a summary of the geology and geohydrology in Chapter 4. Next, in Chapter 5, Marlin J. Atkinson describes the oceanography. Under the direction of Stephen V. Smith, Atkinson participated in an important study of the lagoon circulation. Chapter 6 on the meteorology and atmospheric chemistry is the final chapter in the group of chapters dealing with the physical environment of Enewetak Atoll. Written by John T. Merrill and Robert A. Duce, the chapter is based on the results of the SEAREX Project. Duce served as the director and principal investigator of the project.

The next four chapters are devoted to the marine ecosystem and its biota. They summarize the large amount of research carried out at the Mid-Pacific Research Laboratory in the marine environment. All of the authors were frequent visitors to the laboratory, and they have done a splendid job of reviewing the research carried out in their area of interest. In Chapter 7, Patrick L. Colin describes the subtidal environments of Enewetak and reports on the research done on the subtidal biota. This is followed in Chapter 8 by Alan J. Kohn's masterful summary of research in the intertidal environment. Kohn has been a student of tropical intertidal ecology for 30 years. He tackled a particularly difficult task because of the extensive study of the intertidal environment and its biota by many scientists over the years.

Chapters 9 and 10 deal with processes and relationships in the marine environment. In Chapter 9, James A. Marsh, another frequent visitor to the laboratory and a recognized authority on coral reef processes, reviews the extensive work which was carried out at Enewetak on the community metabolism of coral reefs and related topics such as calcification processes, nitrogen and phosphorus cycles, and the role of detritus in the ecosystem. Nelson Marshall and Ray P. Gerber extend the ecosystem approach in Chapter 10 to include the entire atoll. They discuss the trophic relationship between the shallow reefs and the lagoon. Both Gerber and Marshall conducted research at Enewetak.

The final three chapters are devoted to the terrestrial environment. Because fewer scientists applied to conduct research in the terrestrial environment, less work was accomplished, and an integrated overview is not possible. In Chapter 11, I report on the life history, behavior, and ecology of land crabs, review what is known about atoll soils, and conjecture on the carrying capacity of an atoll such as Enewetak. For a description of the vegetation, the reader is referred to Chapter 3 in Volume II by Janet O. Lamberson. William B. Jackson, a frequent visitor to Enewetak over the years, and his co-workers Stephen H. Vessey and Robert K. Bastian report on their long-term study of the rodents in Chapter 12, and Andrew J. Berger summarizes our knowledge of the bird life of the atoll in Chapter 13. Berger, a noted ornithologist and the foremost authority on Hawaiian birds, made a number of trips to Enewetak.

I suspect that few readers will read this volume from cover to cover, but those who do will gain an appreciation for the complexity of the atoll ecosystem and a better

understanding of the intimate relationships between the seemingly fragile components of the ecosystem: the lagoon, the reefs, the islands and their biotas, all perched on a volcanic and coral pinnacle in the vastness of the Pacific Ocean. In the final analysis, however, the book will serve its purpose best if the reader comes away with more questions than answers and a desire to find the answers to these questions in future research on the natural history of coral reefs and islands.

Chapter 1

Research at Enewetak Atoll: A Historical Perspective

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INTRODUCTION

The Pacific theater of operations in World War II brought millions of military personnel to the tropical Pacific and their activities on the Pacific Islands afforded close contact and awareness of the physiography and natural history of these small dots of land scattered in the vast expanse of ocean. This enhanced awareness, coupled with a recognized need by the military establishment for increased knowledge of Pacific Island areas, led to government-sponsored investigations, complemented by efforts of many individual scientists whose interest had been stimulated by wartime visits to these islands. In the postwar period, two activities of the U. S. government focused further interest on the coral atoll of the tropical Pacific and influenced the future of research at Enewetak Atoll (Figs. 1 and 2). The origin of the spelling "Eniwetok" is lost but would appear to be a phonetic rendering of what the people called their atoll. In 1973 it gave way to the current spelling, consistent with written Marshallese, and meaning "island which points to the east."

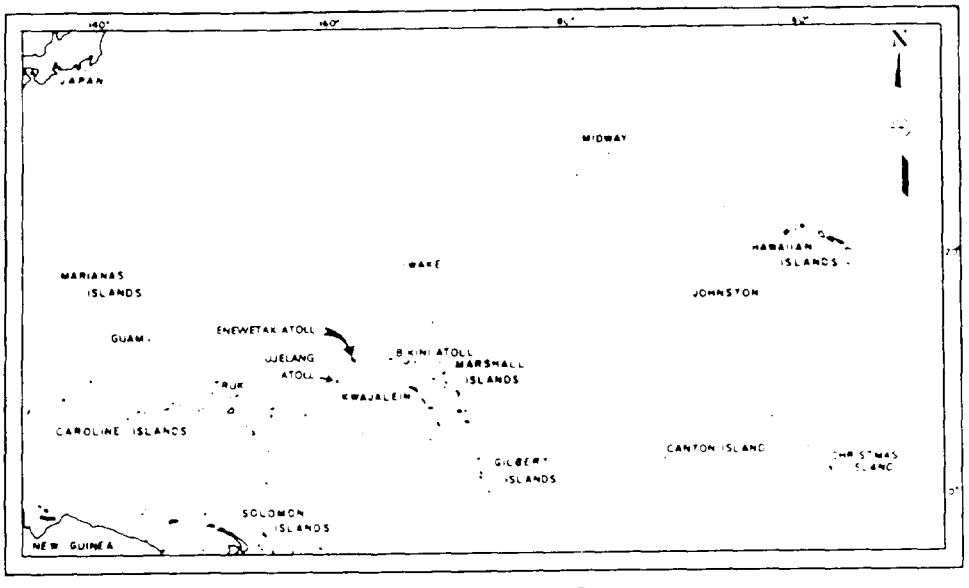
World War II demonstrated the importance of these scattered land masses to any military confrontation in the Pacific basin. After the war, the U. S. Navy moved to develop a series of permanent bases from among the many temporary wartime bases and outposts which had been established across the Pacific. With the prominent role of the Navy in developing and maintaining these bases, it is not surprising that the Navy's research arm, the Office of Naval Research (ONR), inaugurated a scientific program in the late 1940s aimed at a better understanding of atoll morphology and of all aspects of island life, from microorganisms to human inhabitants. The ONR sponsored a series of expeditions in conjunction with the Pacific Science Association, many of which were to atolls in the central and western tropical Pacific. Arno Atoll in the southern Marshall Islands and Onotoa Atoll in the Gilbert Islands (now Kiribati) were subjects of intensive investigation in 1950 and 1953, respectively. Scientists involved in these atoll studies contributed to the establishment of the Eniwetok Marine Biological Laboratory (EMBL) on Medren Island, Enewetak Atoll, in 1954.

The second postwar activity which served to focus attention on the mid-Pacific area was the atomic weapons testing program in the northern Marshall Islands. Two atomic weapons had inflicted mortal damage upon Japan and had brought a precipitous end to the war in the Pacific. Military planners and strategists knew very little about this new and awesome strategic resource. Thus, an area was sought which might accommodate full-scale testing of atomic weapons. Neil Hines (1962) in his book *Proving Ground* describes the process of choosing the northern Marshall Islands as the testing site. First Bikini Atoll and then Enewetak Atoll became test sites, to be known together as the Pacific Proving Ground. National security considerations soon led to research and development testing and, with the impetus of the cold war, to the testing of thermonuclear weapons in these islands. In all, between 1946 and 1958, 43 nuclear devices were tested at Enewetak and 23 on Bikini—events which were to have profound and lasting environmental, social, and cultural effects upon these two atolls as well as others nearby. The nuclear testing program provided a setting, a focus of interest, and an opportunity for research in the northern Marshall Islands which eventually led to the establishment of the EMBL.

THE WEAPONS TESTING PROGRAM

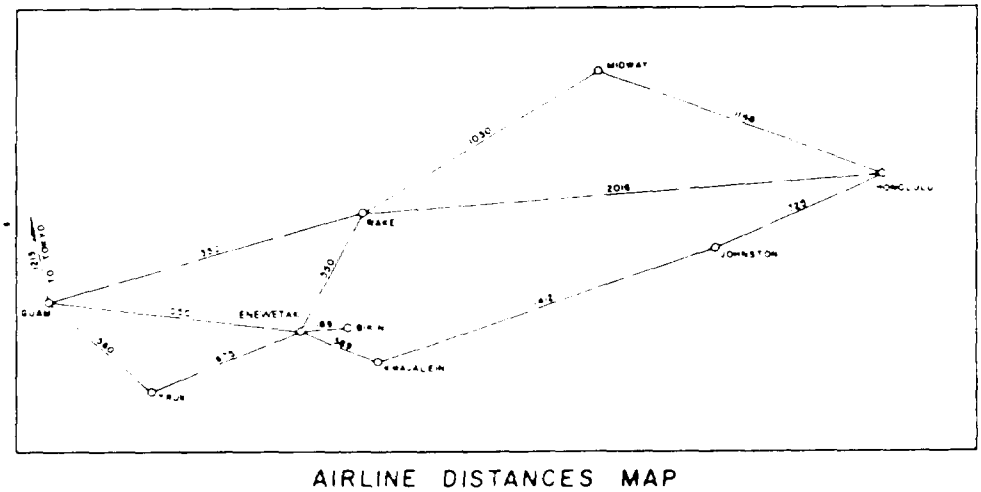
Soon after the 1946 tests at Bikini (Operation Crossroads), which had been designed to assess the military significance of atomic weapons, the United States Congress created the Atomic Energy Commission (AEC), a civilian agency charged with responsibility for the research, development, testing, and production of nuclear weapons. This new agency was to become host and manager of the Pacific Proving Ground and, later, sponsor of EMBL.

Operation Crossroads was largely a seaborne operation, with logistic support from the naval base at



REGIONAL MAP

GRAPHIC SCALE IN NAUTICAL MILES



AIRLINE DISTANCES MAP

NO SCALE

Fig. 1 Regional and airline distances maps of the Pacific and the Marshall Islands showing location of Enewetak Atoll.

Kwajalein. It consisted of two tests, one an airdrop and the other an underwater detonation. The radiation and other effects of both of these tests—code-named Able and Baker—were largely confined to Bikini Atoll, with such fallout as left the Bikini area being deposited in areas of open ocean. The same could be said of the early development tests, which began at Enewetak in 1947. The selection of these atolls had been strongly influenced by their remoteness and by the predictability of wind conditions.

The 1954 operation, code-named Castle, was planned contemplating use of both atolls. Detonation of Bravo, the first test of Castle, drastically altered that plan. The explosive power (yield) of Bravo was more than twice that which had been predicted, and local winds carried the debris, or local fallout, directly across Bikini Atoll, contaminating much of the land area and rendering the control area and many of the experimental sites unusable for the remainder of the Castle operation (Hines, 1962). Some testing continued at Bikini, but Enewetak, after Bravo, took on even greater importance in the atmospheric nuclear testing program. During the period which ended on October 31, 1958, Enewetak was the site of 43 nuclear

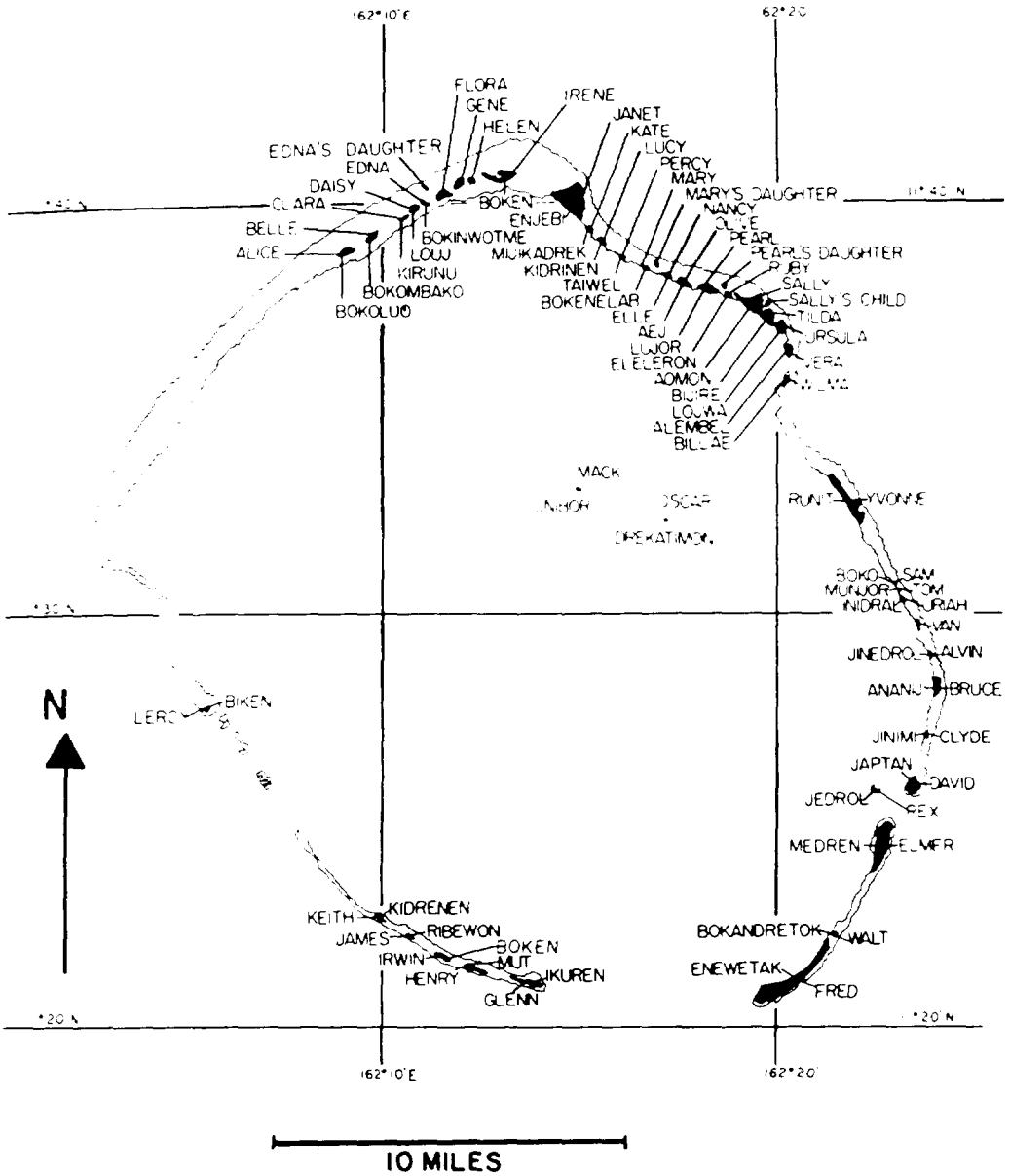


Fig. 2 Islands of Enewetak Atoll with Marshallese names shown on the lagoon side and English code names on the ocean side.

tests. Enewetak, Medren, and Japtan Islands ...ed the command, administrative, logistic, and technical support facilities, and the islets in the northern and eastern portions of the atoll served as test areas. Table 1 lists the detonations at Enewetak, and Fig. 3 illustrates the test locations on the atoll.

The nuclear testing program required the mobilization of a vast assemblage of scientists, technicians, and support ...onnel and the establishment of laboratories, shops, and ...quarters, in addition to port facilities and an air ter... to connect with a supply system extending through ...aii to mainland bases as far as 8000 miles away. Test operations over more than a decade were conducted by a series of Joint Task Forces (JTFs), consisting of Army, Navy, Air Force, and AEC elements, in a coordinated operational command. The commander was a senior military officer of flag rank and had as his deputy a senior AEC scientist.

The test detonations were grouped in series which, typically, lasted several months. During the times between series—usually a year or more—the support apparatus continued to function. This availability of logistic and administrative support made it feasible to consider the establishment of a laboratory facility. The AEC interest in

TABLE 1

Nuclear Tests at Enewetak Atoll

Operation event name	Date	Type and height, ft	Yield	Location
Sandstone				
X-ray	4/14/48	Tower 200	37 KT	Janet, west tip
Yoke	4/30/48	Tower 200	49 KT	Sally
Zebra	5/14/48	Tower 200	18 KT	Yvonne, north end
Greenhouse				
Dog	4/7/51	Tower 300		Yvonne, north end
Easy	4/20/51	Tower 300	47 KT	Janet, west tip
George	5/8/51	Tower 200		Ruby
Item	5/24/51	Tower 200		Janet, north tip
Ivy				
Mike	10/31/52	Surface	10.4 MT	Flora
King	11/15/52	Airdrop 1500	500 KT	Yvonne, 2000′ N
Castle				
Nectar	5/13/54	Barge	1.69 MT	Mike Crater
Redwing				
Lacrosse	5/4/56	Surface	40 KT	Yvonne, north end
Yuma	5/27/56	Tower 200		Sally, west tip
Erie	5/30/56	Tower 300		Yvonne, by airstrip
Seminole	6/6/56	Surface	13.7 KT	Irene
Blackfoot	6/11/56	Tower 200		Yvonne, middle
Kickapoo	6/13/56	Tower 300		Sally, north tip
Osage	6/16/56	Airdrop 670		Yvonne, middle
Inca	6/21/56	Tower 200		Pearl
Mohawk	7/2/56	Tower 300		Ruby
Apache	7/8/56	Barge		Mike Crater
Huron	7/21/56	Barge		Mike Crater
Hardtack, Phase I				
Cactus	5/5/58	Surface	18 KT	Yvonne, north end
Butternut	5/11/58	Barge		Yvonne, 4000′ SW
Koa	5/12/58	Surface	1.37 MT	Gene
Wahoo	5/16/58	Underwater 500		James, 7400′ S
Holly	5/20/58	Barge		Yvonne, 2075′ SW
Yellowwood	5/26/58	Barge		Janet, 6000′ SW
Magnolia	5/26/58	Barge		Yvonne, 3000′ SW
Tobacco	5/30/58	Barge		Janet, 4000′ SW
Rose	6/2/58	Barge		Yvonne, 4000′ SW
Umbrella	6/8/58	Underwater 150		Glenn, 7400′ N
Walnut	6/14/58	Barge		Janet, 6000′ SW
Linden	6/18/58	Barge		Yvonne, 2000′ SW
Elder	6/27/58	Barge		Janet, 4000′ SW
Oak	6/28/58	Barge	8.9 MT	Alice reef, 3 mi SW
Sequoia	7/1/58	Barge		Yvonne, 2000′ SW
Dogwood	7/5/58	Barge		Janet, 4000′ SW
Scaevola	7/14/58	Barge		Yvonne, 561′ SW
Pisonia	7/17/58	Barge		Yvonne, 12000′ W
Olive	7/22/58	Barge		Janet, 4000′ SW
Pine	7/26/58	Barge		Janet, 8500′ SW
Quince	8/6/58	Surface		Yvonne, middle
Fig	8/18/58	Surface		Yvonne, middle

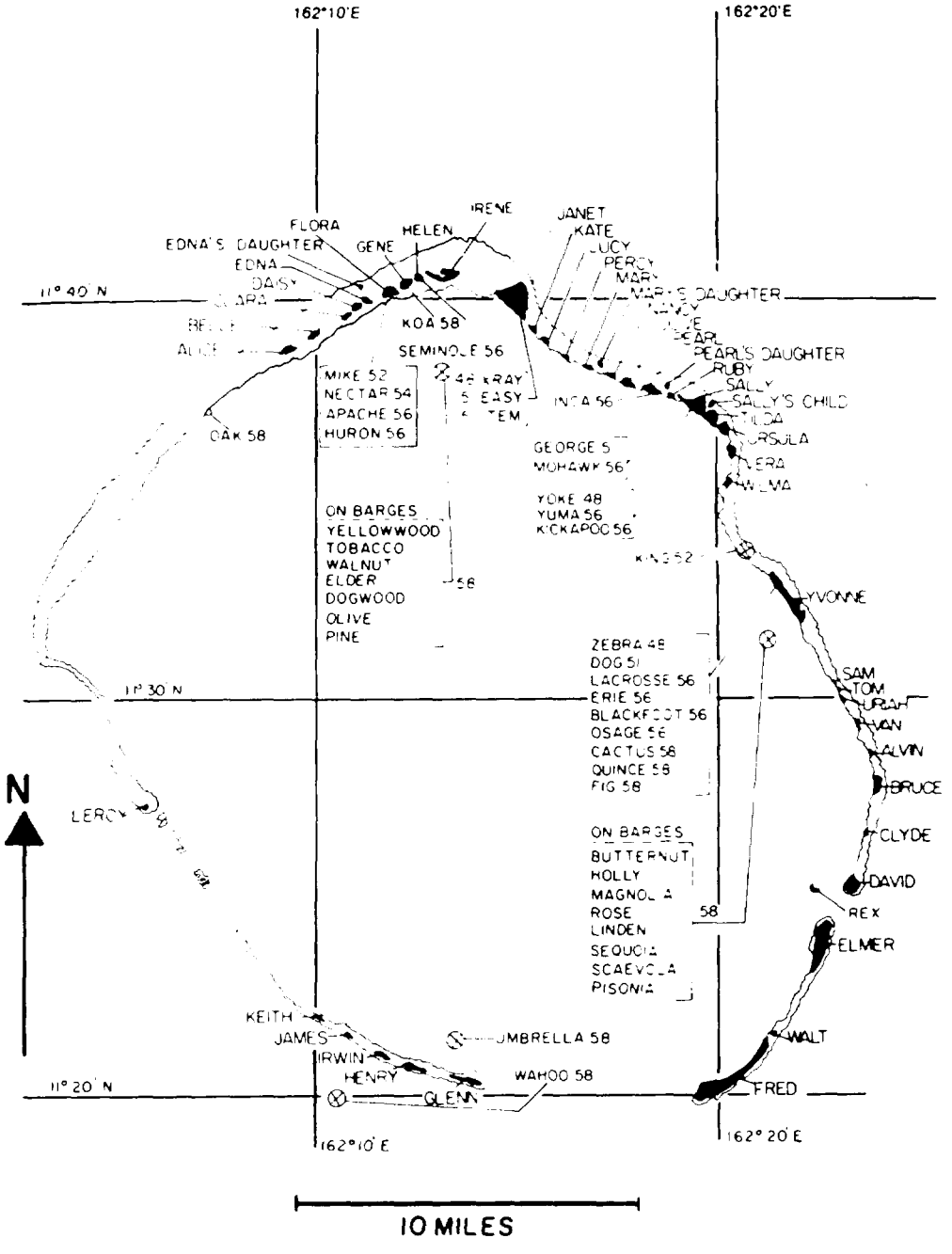


Fig. 3 Enewetak Atoll nuclear tests with name, year of detonation, and approximate locations.

expanding knowledge of the environmental setting in which the tests were being conducted provided the basis for discussions which led to the establishment of the EMBL.

ESTABLISHMENT OF EMBL

Of necessity, the nuclear testing program of the 1940s 1950s was conducted in a climate of national urgency and classification security. Important scientific and strategic information had been lost to foreign powers in the immediate postwar period, and the pace of atomic weapons research and development had become a vital indicator of political power. In this environment, the establishment of a university-associated research laboratory, with its traditions of academic freedom and open publication of research results, was nothing less than remarkable. It reflected the enlightened scientific climate of the AEC and the AEC's concern regarding the long-term consequences of applica-

tions of nuclear technology. There was a need for more complete knowledge of the dynamic biogeochemical processes which might lead to the transport of radioactive contaminants in the atoll system to man. More fundamental was the acknowledged inadequacy of our understanding of the systematics and ecology of the highly diverse atoll biota. Early records of environmental monitoring during the test series included entries such as "red fish" and "green filamentous algae," reflecting the lack of any pertinent taxonomic descriptions of the local biota. The College of Fisheries of the University of Washington, under contract to the AEC, had conducted studies at Bikini and Enewetak of the interaction of environmental radioactivity with various species and had made substantial contributions to the literature regarding these nuclear-affected atolls (Hines, 1962). There remained, however, a need for a broader base of information about the systematics, ecology, and life history of the atoll flora and fauna.

Details of the discussions leading to the establishment of EMBL are unavailable. In the early 1950s, however, the eminent biologist, H. Burr Steinbach, then of the University of Chicago and later of Woods Hole Oceanographic Institution, was asked by Sidney Galler of the Office of Naval Research to travel to Enewetak Atoll to explore the feasibility of establishing a marine biological laboratory. Steinbach's trip and his subsequent report recommending the establishment of a laboratory on Enewetak Atoll were instrumental in AEC's action to contract with the University of Hawaii to establish and operate the EMBL.

The contract, signed on June 3, 1954, required the university to manage the laboratory and to direct and coordinate its scientific programs. Policy direction and sponsorship were provided by the Division of Biology and Medicine of the AEC Headquarters in Washington, D. C. Robert W. Hiatt, Director of the Hawaii Marine Laboratory, became the first director of EMBL. The first orders of business were to provide supplies, equipment, and work areas for visiting investigators and to establish a reference collection of animals and plants with an ecological index for their use.

To facilitate scientific investigations of terrestrial and intertidal biota, two islets on Enewetak Atoll—Ikuren and Mut—were set aside as reserves for the exclusive use of EMBL scientists. This was done to ensure that a continuously available source of typical fauna and flora would be protected, to the extent possible, from proving ground activities. During these early years, EMBL scientists were permitted to use the laboratory only in the intervals between test series. However, marine scientists from the University of Washington Applied Fisheries Laboratory, under separate contract to the AEC, were in residence during the actual test events. Their work at Enewetak and elsewhere in the Pacific is recounted by Hines (1962) and is reported in numerous published papers.

The laboratory was first quartered in a rectangular metal building, with an aquarium lanai, located on the southwest shore of Medren Island. The building was equipped with a simple seawater system, a single air-conditioned instrument room containing microscope small library, and an assortment of nets, diving gear other field equipment. Being a sponsored tenant in proving ground—which in peak periods accommod hundreds of scientists, technicians, and support sonnel—the laboratory enjoyed superb facilities for di housing, recreation, and medical care.

During the 1950s, 1960s, and early 1970s, the la tory was operated on a part-time basis, with the a periods generally dictated by university class sched Thus, most investigators visited during the summer mo and the periods of winter or spring academic holi Also during this period, visit authorizations were restri to male U. S. citizens who had passed a security scr ing. Travel to Enewetak from Honolulu was by militar military charter aircraft. The flight time from Honolul Enewetak was about 10 hours, usually with stops at Jo ston Island and at Kwajalein and/or Wake Island. noteworthy that, despite considerable resistance to invasion by women of what had been traditionally exclusively male territory, arrangements were made accommodate the eminent zoologist E. Alison Kay at Enewetak Laboratory in December 1970. Her arrival naled a new era in which the merits of the scient research proposed were the only criteria for acceptance a researcher at EMBL.

Initially, the research emphasis at EMBL was tow the establishment of a reference collection of the lo marine flora and fauna. This was accomplished by spec ists, who made extensive collections of particular groups animals and plants, identified the individual specime (including those new to science), labeled, cataloged a preserved them, and placed them in the laboratory coll tion room. To complement the reference collection, a sm library was established on site, providing convenient acce not only to published references and texts but also to th works, both published and unpublished, of visiting inves gators. Notices placed annually in the journal *Scienc* served to call this facility and its superb atoll environme to the attention of the community of marine scientist This early research and subsequent publicity regarding th EMBL facility, combined with the availability of mode research grants, brought an enthusiastic response. Fro 1954 until this writing, 1028 scientists have worked a Enewetak, many returning for several periods of field co lection and investigation. Notable was the response of tem perate zone biologists who had not previously worked i the tropics. Entering the strikingly clear lagoon waters fo the first time, with no more complex equipment than face mask, was an exciting experience. Examination of coral pinnacle, with its enormous diversity of organisms brought a whole series of new dimensions to the work o these scientists. The limitations of the physical facilities and the remoteness of the EMBL field station were offse by an abundance of exciting research opportunities and vir tual freedom from the pressures and distractions of cam pus life. These features resulted in a level of scientific pro ductivity unequaled in the experience of most researchers.

The original EMBL building eventually proved inadequate to the needs of the scientists and in 1956 was expanded to include an extension for storage and a 4 · 20' concrete tank to hold experimental animals. A further expansion of the laboratory occurred in 1959 when Tester of the University of Hawaii initiated a research program in shark physiology and behavior. For this program, two interconnected parallel tanks were constructed, which allowed sharks to swim in an oval pattern. This facility permitted Tester and his colleagues to hold and condition sharks, to test their reactions to various chemical stimulae, and to elucidate some of the anatomical and neurological bases for their aggressive behavior.

Nuclear testing activities at Enewetak ended in late [illegible] the declaration by President Eisenhower of a [illegible] accompanied by a similar Soviet moratorium) [illegible] clear testing. The 1958 moratorium, originally a 1 year commitment, was actually continued until September 1961. At that time, the Soviets suddenly resumed testing at a high rate. Even then, however, the United States, in its response, did not return to testing in the Marshall Islands. Although the AEC continued to administer the Pacific Proving Ground until it was transferred to the Navy in 1960, AEC gradually withdrew activities and [illegible] Medren until EMBL was the only active facility [illegible]. This made support such as power, water, [illegible] eeping and messing, and logistics difficult. In 1961 EMBL moved from Medren to Enewetak Island where an active support infrastructure still existed. The laboratory's new home became a building on the lagoon side of Enewetak Island, previously used as a recreation center (Figs. 4 and 5). This building was modified to provide two small air-conditioned rooms for the protection of instruments and chemicals. A rectangular aquarium was constructed in the center of the large main room which was [illegible] on three sides and open to the lagoon. A seawater system was installed, and living quarters were provided for EMBL personnel and visiting scientists in a building across the lagoon road from the laboratory complex. Although adequate, this facility had one important drawback. Boat operations required the use of the utility pier at the northeast end of the island, making loading and unloading difficult, and necessitating the carrying of equipment and specimens between the pier and the laboratory. By 1969, another move was in order.

In this same year, the directorship of EMBL passed [illegible] from Robert W. Hiatt to Vernon E. Brock, and then, a few months later, to Philip Helfrich. Helfrich continued as director until January 1, 1975.

In 1969, military activities at Enewetak dictated another move for EMBL, this time to the vicinity of a large, three-story dormitory building which had been constructed on the ocean side, toward the middle of Enewetak Island. The new location was a complex of aluminum buildings previously used as library, recreation center, and [illegible] room. This location was more desirable because of its proximity to sleeping quarters, food service facilities, and the boat launching ramp. In addition, it included a large, covered lanai—which was supplied with running seawater for aquaria—and two portable swimming pools used as holding tanks. With about twice the space that had previously been allocated, the new facility included a large general laboratory, a shop, photo darkroom, library, equipment room, communications room, a dive locker, and a separate building for the storage of hazardous chemicals (Fig. 6). In the early 1970s, EMBL acquired its own communication system, providing a voice and teletype link to the University of Hawaii.

MOVES TOWARD RESETTLEMENT

The year 1972 brought significant political developments which were to have a lasting effect upon the future of the people of Enewetak and upon the fortunes of EMBL. Political status talks had been going on for several years between the government of the United States and representatives of the people of the Trust Territory of the Pacific Islands (TTPI). These talks were aimed at ultimate termination of the United Nations trusteeship over the Micronesian Islands (with the United States as trustee) and the establishment of one or more new and independent self-administering political entities. During the 1972 talks, responding to the pleas of the people of Enewetak for the return of their home islands, the United States took the first steps toward that return. In April, Ambassador Hayden Williams, the President's personal representative to the talks, was joined by High Commissioner Edward Johnston of the TTPI in a public statement of U. S. intentions. It provided that military use of Enewetak would shortly be completed, thus permitting the atoll to be returned to the administration of the Trust Territory, and that steps necessary to rehabilitate the islands for resettlement could then begin.

Later in 1972, the AEC's Nevada Operations Office, using the resources of its national laboratories and contractors, mounted a massive radiological survey of Enewetak Atoll as a preliminary step toward cleanup and rehabilitation. These activities are described in official reports (U. S. AEC, 1973; U. S. DOE, 1982; Holmes and Narver, 1973; and U. S. DNA, 1975). Although EMBL did not participate directly in either the 1972 survey or the cleanup, the director and other scientists consulted and assisted in many ways. While applied science and engineering were at work to restore the atoll, the basic studies of EMBL continued apace. Although this tiny, remote research station might have been overwhelmed by the enormity of the cleanup effort (thousands of men, over 3 years, at a cost of more than $100 million), those responsible in the AEC (now the U. S. Department of Energy) and the U. S. Defense Nuclear Agency (DNA), recognized the lasting worth of the science program and saw to it that the laboratory's interests were protected.

In 1978, the U. S. Coast Guard LORAN Station, which had occupied a complex of buildings at the eastern end of Enewetak Island, was closed. By agreement with DNA and with the people of Enewetak, DOE obtained the

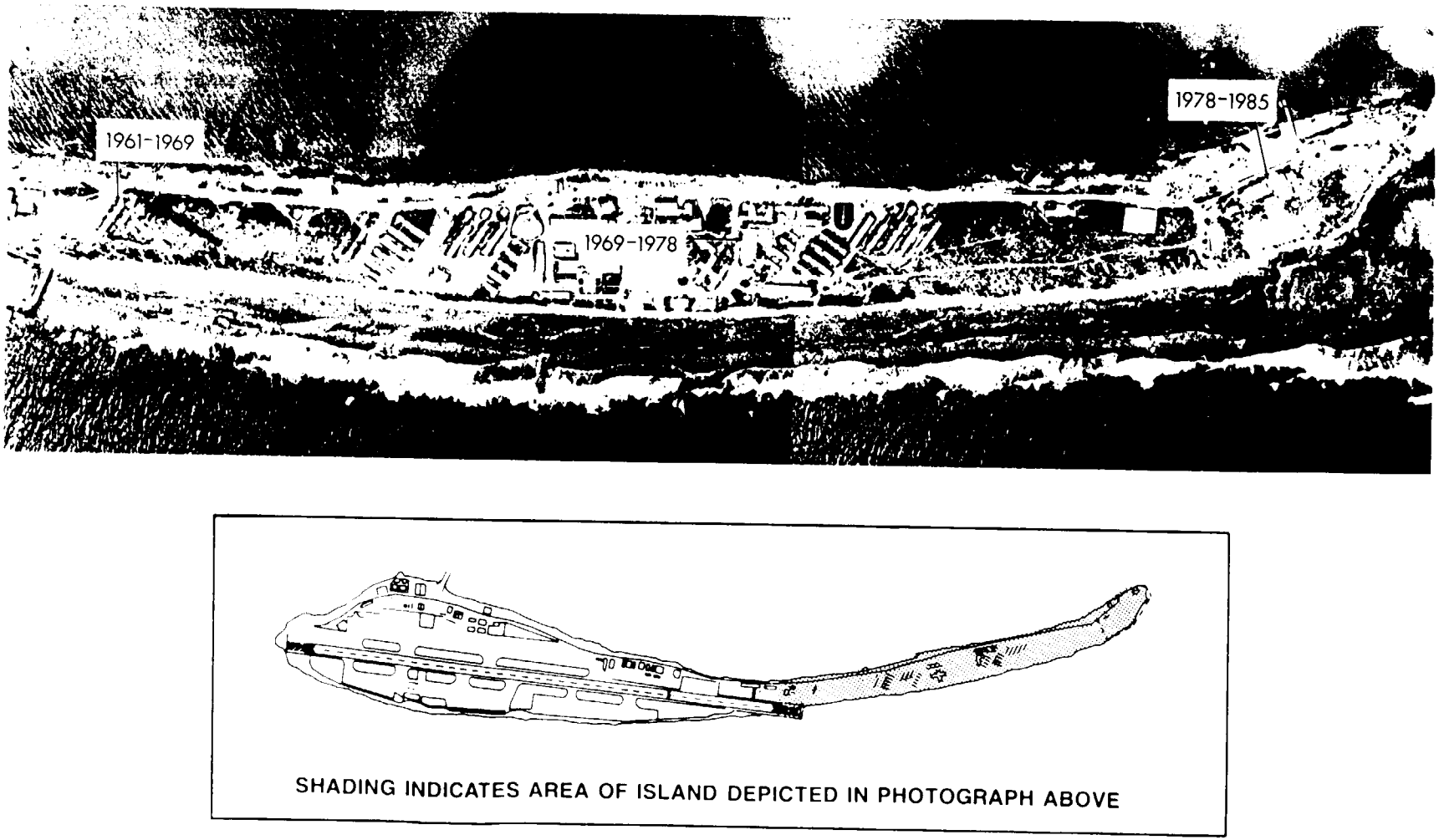


Fig. 4 Map and aerial photograph showing locations of laboratory sites on Enewetak Island.

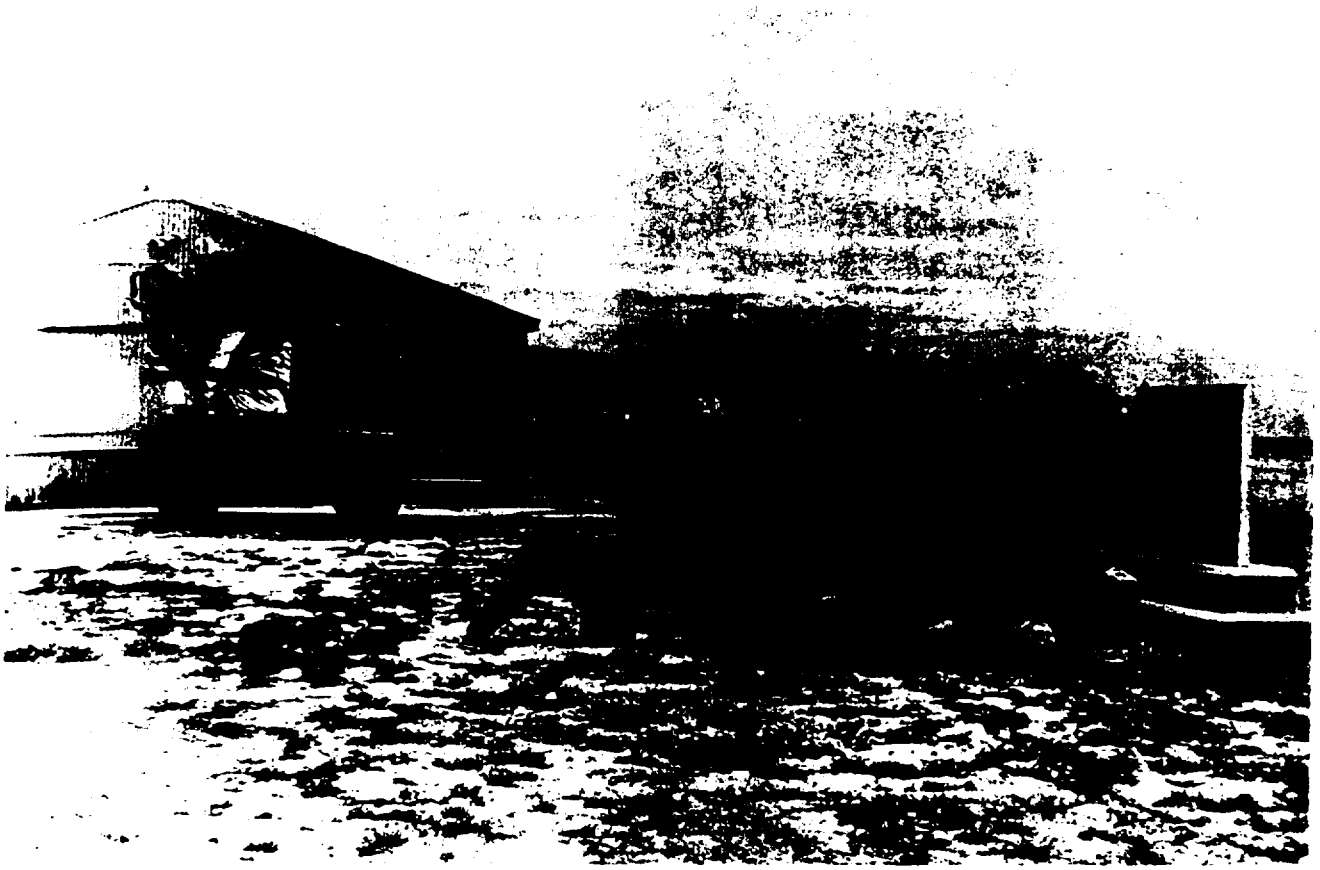


Fig. 5 The second laboratory facility was located on Enewetak Island from 1961 to 1969. [Photo by E. S. Reese.]

long-term use of these facilities and allocated them to the laboratory (Fig. 7). Over the next 2 years, in anticipation of the demobilization of the cleanup force and the sharp reduction in available logistics and life support facilities, steps were taken to make the laboratory ready to "stand alone." The complex was augmented with several portable housing and laboratory units, and plans were made for local power, fresh and salt water systems, and other support. The new location was a considerable improvement, consolidating all operational and support activities in one location. The new facilities included a main air-conditioned laboratory building with work benches and equipment space, a library, communications room, dark room, reference collection room, and several storage rooms. Attached to the main building were a generator room and a storage shed. Four additional buildings provided sleeping quarters accommodating as many as 18 persons. Other buildings provided a kitchen, food storage, a wet laboratory, a scientific shop, a dive locker, a vehicle maintenance shop, and a covered seawater lanai. A 50-foot tower on which two 600-gal tanks were located provided gravity feed for a seawater system. Good quality unfiltered seawater for this system was pumped from a former quarry in the reef.

Access to the lagoon for boats and personnel was provided by a conveniently located concrete ramp and a wooden pier. Laboratory boats were moored offshore or launched and retrieved from trailers at the ramp.

Fresh water was provided by catchment of rain from the roofs of several buildings and stored in four 10,000-gal cisterns. Diesel and gasoline fuels were stored in tanks on the lagoon side of the laboratory complex. These fuels, along with other supplies, were delivered to the laboratory approximately every 2 months by the DOE research vessel *Liktanur*, which was based at Kwajalein and supported DOE's environmental research, radiation protection, and medical programs in the northern Marshall Islands. Personnel, mail, and light cargo were usually transported via the Airline of the Marshall Islands (AMI) on approximately a biweekly schedule and occasionally on a chartered flight.

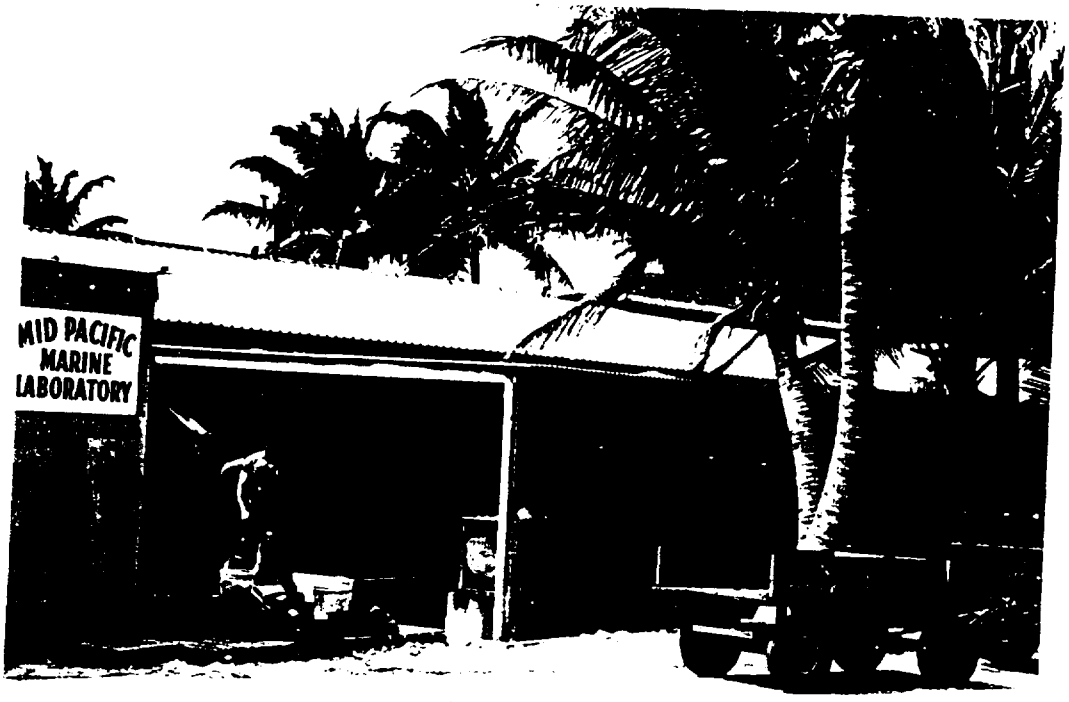


Fig. 6 The third laboratory facility was larger and in a more convenient location on Enewetak Island from 1969 to 1978. The name was changed to the Mid-Pacific Marine Laboratory (MPML) to emphasize the broader research purview of the laboratory. [Photos by E. S. Reese.]

Fig. 7 The fourth and final location of the laboratory was in the former U. S. Coast Guard LORAN Station on Enewetak Island from 1978 to the present; a, The dormitory is to the left and the mess hall to the right; b, View of the laboratory complex from the 50-ft-high water tower with one of the cisterns in the foreground. The name was again changed to the Mid-Pacific Research Laboratory (MPRL) to note the inclusion of terrestrial as well as marine research. [Photos by P. Helfrich.]

RESEARCH EMPHASIS

There were two major periods of research at Enewetak conducted by the University of Hawaii under contract with DOE and its predecessors. During the first 20 years (1954 to 1974), the AEC supported independent research that was broadly aimed at increasing our knowledge of this rich and diverse coral atoll ecosystem. The rationale for supporting this broadly based research was that it was impossible to predict what aspects of the system might be most perturbed by the test activities or what the lasting effects of these perturbations might be. Thus, a broad spectrum of investigations was considered appropriate. In retrospect this was a wise choice because later events and decisions depended upon information resulting from this early research. Scientists from EMBL, with their acquired data base, were frequently called upon for advice and assistance, especially during the period of preparation of the atoll for the return of the Enewetak people. The modest cost of maintaining and operating the laboratory over these years provided the AEC with a bargain in science because the support systems were in place for AEC and defense department programs. The incremental cost of supporting the laboratory was, therefore, relatively small. The scientific research was accomplished at low cost because most of the participating scientists were salaried by their home institutions.

Much outstanding research was accomplished at EMBL (Fig. 8). The record of accomplishment is set forth in the volumes of collected reprints of scientific publications which were issued in 1976 and 1979 (U. S. ERDA, 1976; U. S. DOE, 1979). As knowledge of coral reef ecosystems advanced, it was deemed advisable to mount a major effort to understand the metabolism of an entire atoll (Fig. 8). Discussions and planning conferences culminated in the initiation of a major program in the summer of 1971 under the name SYMBIOS. This program lasted for 12 weeks and involved the research vessel *Alpha Helix*, 25 participating scientists, and numerous support personnel under the leadership of Robert Johannes. SYMBIOS was jointly sponsored by the National Science Foundation, the AEC, and the Janss Foundation. Its initial objective—to study the metabolism of an entire atoll—proved to be too ambitious, but a thorough study of the windward reef was accomplished and some major advancements were realized in our knowledge of reef metabolism. As with other research, this effort posed many new questions and challenges, and resulted in repeat visits to Enewetak by SYMBIOS scientists to further pursue work initiated in this landmark study. The results of SYMBIOS are summarized in Chapters 9 and 10 of this volume.

In 1972, the DNA began a series of studies to better understand cratering effects of nuclear explosions. Craters formed by the nuclear explosions of earlier years were analyzed by direct observation, seismic response measurements, and dynamic experiments utilizing chemical explosives. Scientists from EMBL were called upon to advise the defense department, especially upon the expected impact of their experiments on the marine environment. Later, following a strong protest and legal action by lawyers for the people of Enewetak, the dynamic experiments were canceled and only shallow coring of the atoll rim and seismic studies of the reef structure were pursued to complete the project.

The second period of research began with the reorganization of the laboratory in 1974. Following discussions with the Chairman of the Atomic Energy Commission, Dixie Lee Ray, a visit was made to the laboratory by an ad hoc advisory group, including officials and scientists from the University of Hawaii, the AEC, and several independent consultants. Chairman Ray had expressed an interest in reorganizing and upgrading the laboratory to a full-time operation, with research objectives more directly relevant to AEC interests. The advisory group met at Enewetak in February 1974 and later made brief visits to Bikini and to Majuro, the capital of the Marshall Islands. Participants were William O. Forster, Nathaniel Barr, and Charles Osterberg of AEC Headquarters; Roger Ray of the Nevada Operations Office of the AEC; Philip Helfrich of the University of Hawaii (Director of EMBL); William R. Coops of the Research Corporation of the University of Hawaii; Robert Hiatt of the University of Alaska (first Director of EMBL); and Glen Fredholm, an independent consultant. The advisory group: (1) articulated in some detail its recommended objectives for a laboratory agenda which would be responsive to AEC direction, (2) suggested that the field station at Enewetak be upgraded to full-time activity with a resident staff, and (3) recommended that the name of the laboratory be changed to the Mid-Pacific Marine Laboratory (MPML) to reflect its interest in a wider geographical area, including such areas as Bikini, where the AEC continued to have an active interest.

In March 1974, following the advisory group meetings, Roger Ray and Philip Helfrich returned to Majuro to meet with officials of the government of the Marshall Islands and with members of the Enewetak Municipal Council. The latter meetings were hosted by Micronesian Legal Services Corporation, counselors for the people of Enewetak. The Enewetak Council expressed its desire that the laboratory continue to function in the Enewetak community after the return and resettlement of the atoll residents. It approved the site of the Coast Guard LORAN Station as the ultimate home of MPML.

With the approval of reorganization and redirection of goals, the laboratory entered a new and productive phase. Support and encouragement of basic studies continued under AEC sponsorship, while mission-oriented research was being planned and implemented. The major AEC-oriented projects of the 1975 to 1980 period were (1) a study of the circulation of the Enewetak Lagoon, (2) research on the dynamics of groundwater resources of Enewetak Atoll, and (3) studies of ciguatera fish poisoning at Enewetak.

On Jan. 1, 1975, Philip Helfrich left the University of Hawaii and was replaced as director of MPML by Stephen V. Smith, who served in that capacity until 1977. During

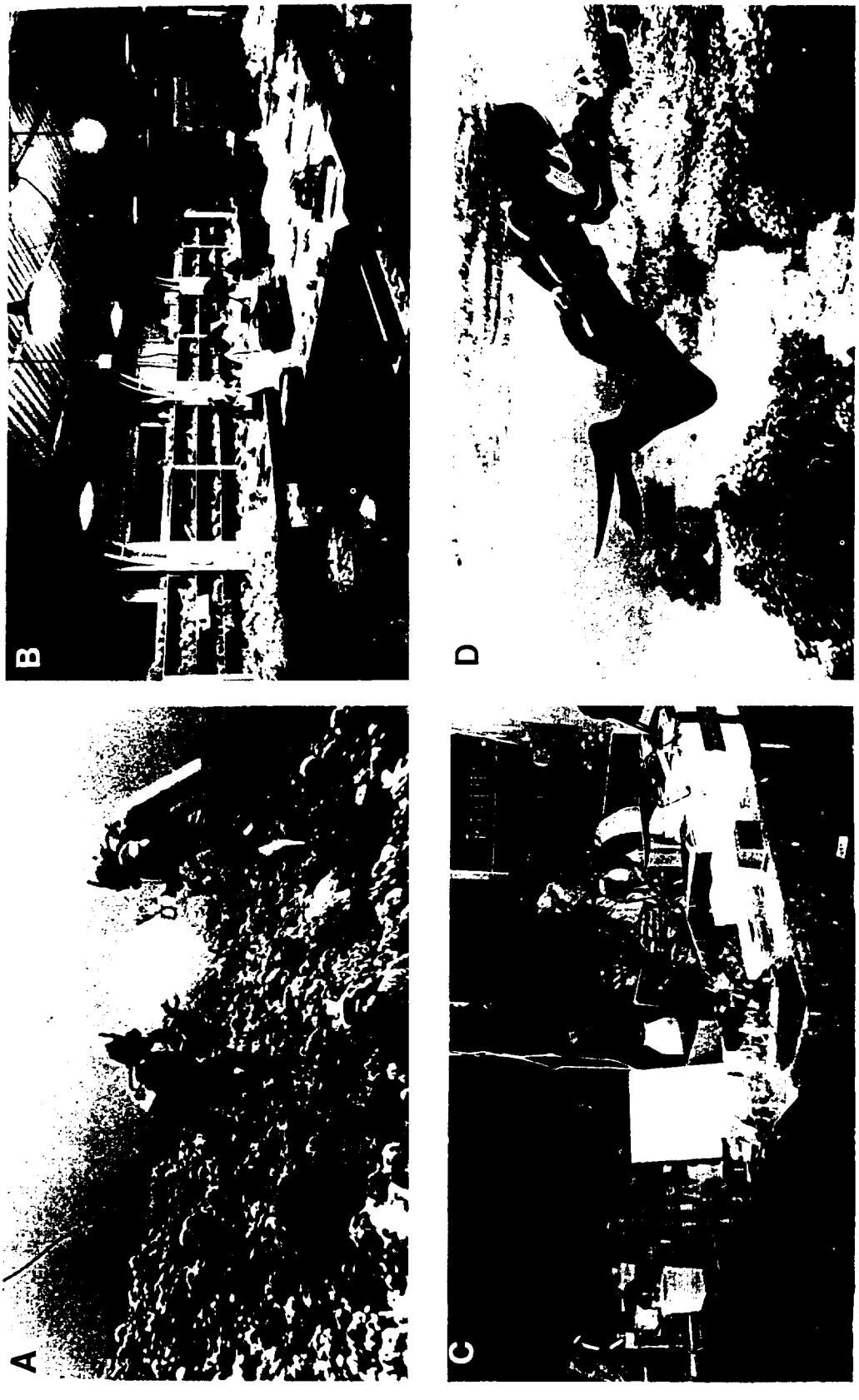


Fig. 8 Research activities as MPRL; a, Researchers making observations with the aid of scuba equipment; b, Coral studies in the laboratory; c, Microscopic analysis of organisms collected from the reef; d, Researcher making observations on a shallow reef. [Photo credits unknown.]

Smith's tenure the three research projects mentioned above dominated the activities of the laboratory. A study of the oceanography of Enewetak Lagoon was prompted because—despite intensive studies of various facets of Enewetak's geology, physiography, biota, ecosystem dynamics, radiation contamination, etc.—only cursory information existed on the circulation patterns of the lagoon (Chapter 5 of this volume). This comprehensive study directed by Smith resulted in information on the physical and chemical dynamics of the entire lagoon. The topic of the second investigation was the dynamics of groundwater resources of Enewetak, a study that developed information vital to the returning Enewetak people who required uncontaminated water for drinking and agriculture. This investigation was directed by Robert W. Buddemeier (Chapter 4 of this volume). Ciguatera fish poisoning, the topic of the third study, had plagued the people of the Marshall Islands for many years, waxing and waning in an inexplicable manner. The return of the people and their dependency on fish for sustenance placed a special urgency on the results of this study that was directed by John E. Randall (Chapter 7 of this volume).

During 1975, the AEC was reorganized, and the functions pertinent to MPML were assigned to the newly formed Energy Research and Development Administration (ERDA). In turn, ERDA gave way to the U. S. DOE in 1977.

Resident managers were established at MPML on a year-round basis in 1975, and these individuals became integrated into the Enewetak community. This was an important aspect of MPML's operations because these scientists represented a benign, if not benevolent, element among the numerous government-sponsored activities related to the radiological survey, cleanup operations, and various medical and agricultural programs. The individuals who served as the resident laboratory managers were all exemplary in their dedication, and there were numerous examples of extraordinary service. From 1975 to 1977 the resident laboratory managers were Philip and Janet Lamberson.

In June 1977, Ernst S. Reese assumed directorship of MPML, replacing Smith. During Reese's tenure (1977 to 1979), the research on lagoon oceanography, groundwater dynamics, ciguatera, and other aspects of atoll research continued. Planning and implementation of the move to the former Coast Guard LORAN Station took place. In addition to continuing to fully support the research mission of MPML, the laboratory personnel cooperated in many ways with the DNA. A highlight of this cooperation was the production of an audio-slide presentation to acquaint the military personnel of the DNA with the natural history of a coral atoll and to describe the recreational opportunities offered by the atoll environment. There was also a cautionary note about the dangers of the atoll environment ranging from severe sunburn to the presence of sharks. The audio-slide presentation contained an important message about conservation of the atoll environment as well: observe and enjoy but do not destroy.

Following the cleanup, support services were w drawn, and the laboratory was placed on a "stand alo status, having to provide for all of its own life support a laboratory operations needs, with resupply from infrequ supply ships and light aircraft. During this challeng period, Reese was ably assisted by Victor R. Johnson a Maridell Foster and by several capable resident laborato managers: Paul M. Allen, Michael V. DeGruy, and G Long (1977 to 1979). In 1979, Patrick L. Colin and Jo T. Harrison (1979 to 1983) took over the operation of t laboratory. Throughout this period the laboratory cont ued to accommodate a few visiting scientists as transpor tion and logistics could be arranged.

In 1979, with the cleanup of Enewetak nearing comp tion and the return of the atoll's residents imminent, workshop was held at the Asilomar Conference Cente Monterey, Calif., to consider the future role of the labo tory and its relationship to the other DOE scientific pr grams in the Marshall Islands. The DOE headquarte sponsor at that time was the Division of Biomedical a Environmental Research under the direction of Helen L McCammon. The DOE policy enunciated at this time si naled the ultimate phase down of the laboratory over th following 2 to 3 years and the determination that signi cant effort should be devoted to synthesizing the researc product of the laboratory's entire history into a publishab work. The present volumes are the result. It was decide also that, to the extent that the laboratory continued activ research programs during the phase down years, thes should not be confined to the marine environment. Thi latter decision was reflected in yet another name change MPML became MPRL, the Mid-Pacific Research Labora tory. In 1980, soon after the Asilomar meeting, Helfrich again assumed the directorship of MPRL.

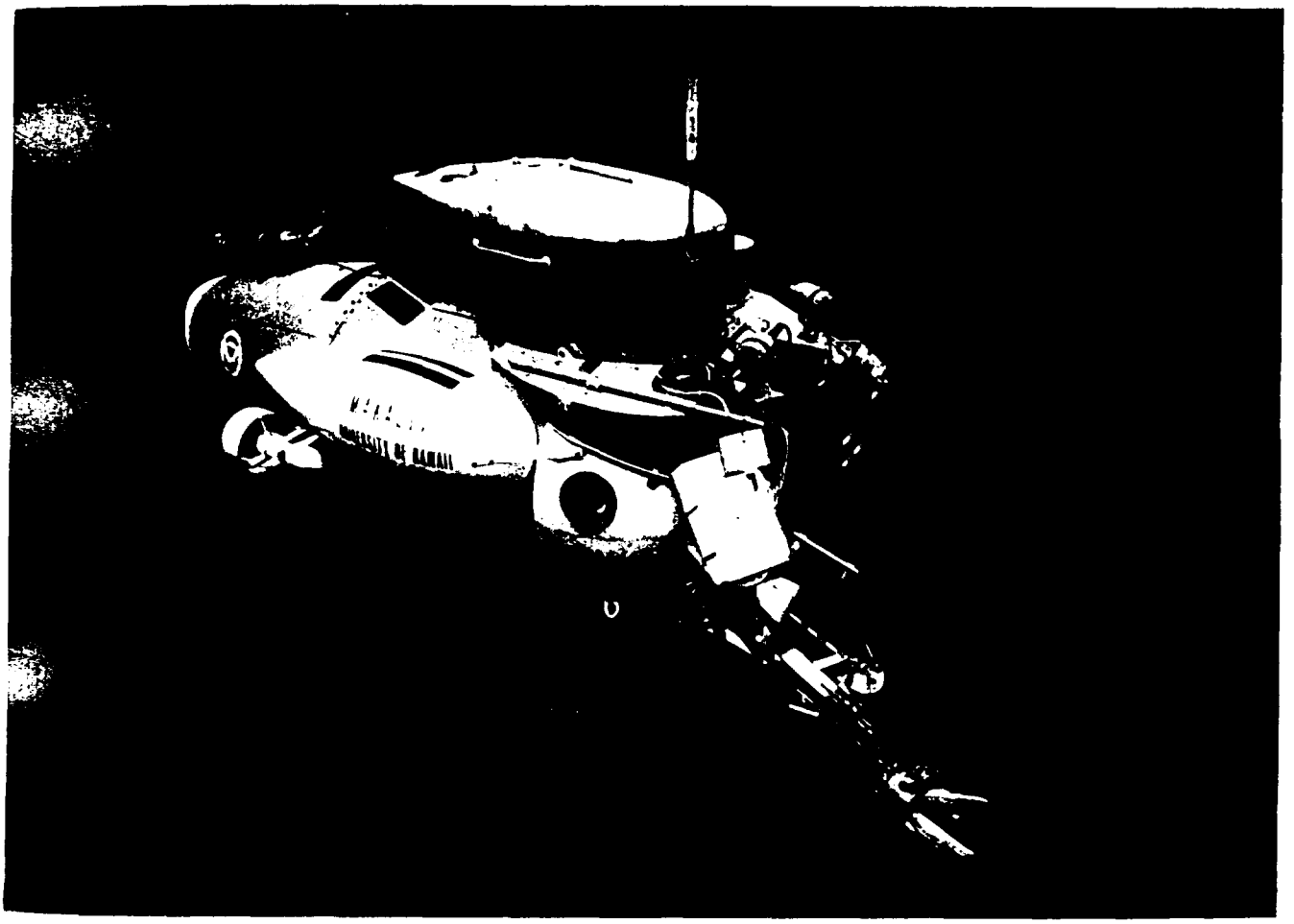
For most of the time between 1977 and 1980, a large joint military force was at Enewetak—with a peak popula tion of about 1000 drawn from the Army, the Navy, th Air Force, civilian government agencies, predominately DOE and civilian contractors. Research at MPRL continued through this period and in some ways the laboratory thrived upon the ready availability of logistic support, espe cially frequent and dependable airlifts, and a generally har monious relationship with the joint cleanup command. In fact, through the cleanup years, the resident manager of the MPRL facility met daily with the Joint Task Group Commander and his staff to discuss mutual interferences and mutual support. Many interesting aspects of the cleanup effort required an intimate knowledge of the atoll system, and the laboratory was often called upon for con sultation and advice. Selection of a suitable site for lagoon disposal of debris, protection and exploitation of food resources, and the preservation of scientifically valuable artifacts were but a few examples. On one occasion a major earth-moving effort was planned for an island which had unexpectedly become a nesting ground for a very large flock of migratory birds. The laboratory's data base facilitated an immediate assessment of the length of time these birds would require protection, and it was possible to

reschedule the cleanup activities so as to have only a minimal effect upon them.

The atoll rehabilitation program consisted of the removal and disposal or isolation of debris and contaminated materials, the construction of homes and community buildings and facilities, and the planting of more than 30,000 pandanus, and breadfruit trees. The cost was $ million. In April 1980, a ceremony was held at Enewetak, commemorating completion of the cleanup and the return of 543 Enewetak people to their ancestral home. A short time later, the last elements of the Joint Task Group departed Enewetak, leaving the laboratory as the only American presence in the community.

Over the next 3 years, major emphasis was placed upon studies of a portion of the atoll ecosystem which had been largely unexplored—the soft lagoon sub- This research was directed by Patrick L. Colin. the fallout material which remained from the nuclear tests had settled in the lagoon floor, and the dynamics of this biotope were little understood. As a result of this research, a fresh perspective was acquired. What had formerly been considered to be a largely passive system into which materials were sedimented from the water column was revealed to be an area in which burrowing organisms were continually reintroducing material into the water column—a process which led to some revision of the understanding of important biogeochemical processes. Interest in these processes helped to stimulate interest, in 1981, in one more interdisciplinary initiative at Enewetak.

A significant improvement in understanding of the deeper sediments of the lagoon required direct observation and sampling, and these techniques required the use of a research submersible. With the cooperation of the Hawaii Undersea Research Laboratory, the research submersible *Makali'i* was made available for a period in the summer of 1981 (Fig. 9). Other sponsors of the expedition were the National Oceanographic and Atmospheric Agency (NOAA) and the DOE. The DOE support included use of the research vessel *Liktanur*. Fifteen scientists and seven support personnel participated in a program which included



9 The research submersible *Makali'i* operated by the University of Hawaii shown on one of its 53 research dives in the Enewetak Lagoon in the summer of 1981. [Photo courtesy of HURL Program, University of Hawaii.]

52 successful research dives between July 7 and Sept. 29, 1981. The results were presented in a special symposium of the Western Society of Naturalists in Los Angeles in December 1982 and were published in *Bulletin of Marine Science* (Harrison, 1985).

AN ERA ENDS

Although the plans for an autonomous laboratory after the 1980 departure of the cleanup forces were thoughtfully and thoroughly prepared and enthusiastically carried out, and despite the welcome that MPRL had received from the returning Enewetak community, its anticipated position as a permanent fixture in that community was not to be. At a time of constrained research dollars in the DOE, and with support grants from all sources limited, the cost of maintaining a resident staff and operating the MPRL facility as a self-sustaining field station became prohibitive. Support from the Division of Biomedical and Environmental Research was terminated in 1982, whereupon DOE's Nevada Operations Office sought and obtained funding for one more year through the DOE Office of Defense Programs. This additional year of funding permitted an orderly phase down of the laboratory activities and the preservation of some of MPRL's unique assets.

The reference collection which had been started during Hiatt's early tenure had grown and had been well preserved and cataloged. For several years this was accomplished through a contract with the Bernice P. Bishop Museum, under the able supervision of the late Dennis M. Devaney. The collections were carefully packaged and shipped to Hawaii to be placed in the temporary custody of the Bishop Museum. Early in 1985, negotiations were completed by the DOE with the Smithsonian's National Museum of Natural History and with the Bishop Museum for the permanent transfer of the reference collection to the latter institution. The MPRL's library and much of the laboratory equipment were transferred to Hawaii Institute of Marine Biology.

The remaining U. S. government activity at Enewetak is now conducted on a campaign basis, usually supported by the research vessel *Liktanur*. At this writing, however, two DOE contractor employees remain at the atoll, and the field station remains intact and capable of limited support. Philip Helfrich retains the title of Director of MPRL and, with modest funding from DOE, entertains inquiries from scientists who desire to explore the feasibility of continuing studies at the atoll. There is every indication that the people of Enewetak would welcome such visits.

ACKNOWLEDGMENTS

The wisdom and foresight of H. Burr Steinbach and Robert W. Hiatt and of those in the Office of Naval Research and the AEC who spawned and nurtured the idea of a research facility at Enewetak deserve special note. Time has proven that the decisions to establish, maintain, and support EMBL and its successors were wise and fruitful commitments which resulted in important contributions tc our knowledge of atoll ecosystems and more broadly to marine science. Assuredly, there are still many unanswered questions, but just as surely new knowledge will continue to be built upon the foundation of about 250 published scientific papers which have resulted from research conducted at Enewetak Atoll over the past 30 years. The writers of this chapter, who have been partners in the administration and support of the laboratory for almost half of that period, record their hope that new ways will be found by interested scientists and their sponsors to continue, even on a limited scale, the exciting and rewarding experience of research at this remote and isolated atoll.

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Introduction

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The organization and coordination of the taxonomic section of this volume was initiated by Dr. Dennis M. Devaney of the Bernice P. Bishop Museum and was completed by Beatrice L. Burch after Dr. Devaney died in a tragic scuba-diving accident on August 13, 1983, as he was investigating shrimp offshore from the Big Island of Hawaii. His great interest in all invertebrates in the tropics was increased when the opportunity arose for him to work at the Mid-Pacific Research Laboratory at Enewetak Atoll. Devaney made his first collecting trip to the atoll in the early 1960s while he was still in graduate school. As the collection grew and taxonomy of the organisms became better known, it was soon apparent that the reference collection at Enewetak was becoming increasingly valuable. Devaney was pleased to participate in the Coral Reef Workshop held at the atoll in 1976, because he believed that the scleractinian coral collection was the key for the study of other organisms. The workshop brought together international coral specialists to establish species limits on this important and variable group. After the workshop was held, reference material from Enewetak was deposited in European and American museums for ready reference by a wider audience of scientists. Each year after the Coral Reef Workshop, Devaney went to Enewetak to curate the reference collection and to conduct his own research on echinoderms. At the same time, he encouraged the work of specialists to compile taxonomic and other research from Enewetak for this publication.

The diversity of the organisms at Enewetak made it difficult to find specialists to study all groups, so Devaney prepared several chapters himself. Unfortunately, most groups were collected in the course of other work such as physiology, toxicity, etc., and were not extensively collected by specialists for a particular taxonomic group.

The number of families, genera, and species reported in this volume either from the literature or from new records determined by the authors of this volume are presented in Table 1.

References in this volume show that some or much work was done on a particular taxon. Many groups remain

TABLE 1

Taxonomic Groups at Enewetak Atoll

Taxon	No. of species	No. of genera	No. of families
Algae	238	106	40
Fungi	112	58	18
Vascular plants	123	97	48
Forams and nonplanktonic protozoa	279	144	58
Porifera	40	33	26
Actiniaria	27	21	14
Octocorallia	31	17	12
Scleractinia	169	53	12
Brachiopoda	4	4	4
Bryozoa	84	61	39
Sipuncula	11	77	3
Echiura	2	2	2
Platyhelminthes	31	11	10
Nemertea	1	1	1
Nematoda	1	1	1
Polychaeta	132	110	34
Mollusca (fossil, recent)	1240	453	151
Insects and related arthropods	190	157	93
Pycnogonida	5	4	4
Stomatopoda	12	4	4
Cirripedia	10	7	6
Lagoon plankton	285	177	82
Ostracoda	10	10	5
Natantia	145	56	14
Reptantia	4	3	3
Anomura	76	29	10
Brachyura	293	114	16
Holothuroidea	20	11	5
Echinodermata other than Holothuroidea	97	65	32
Fishes of the Marshall Islands	815	338	92
Reptilia	9	9	5
Aves	41	27	12
Mammalia	9	7	6
Miscellaneous	124	87	40
Totals	4671	2284	902

to be worked on more thoroughly by specialists in particular fields, such as Porifera or Tunicata, which, at the present time, seem to be represented so lightly at Enewetak Atoll. By having a named reference collection, the researchers there were able to identify organisms used in their studies on biochemistry, ecology, productivity, animal or plant associations, physiology, immunology, radiobiology, growth rates, and reproduction. They were also able to make broad interpretations of reef chronology, geochemistry, stratigraphy, and biogeographic distribution.

The checklist contained in each chapter has a coded entry symbol placed before the generic designation to indicate (1) if the organism represents a newly recorded species for Enewetak or for the Marshall Islands, (2) if it is a fossil record, or (3) if it has some other reason to be so marked. The explanations for these codes follow each species checklist.