Survival of Rats at Eniwetok Atoll[1]

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THE STORY of rats at Eniwetok Atoll (Marshall Islands) and their apparently uncanny ability to survive atomic detonations and inhabit areas with high levels of radiation has been referred to in various documents (Berrill, 1966; Hines, 1962 and 1966; French, 1965; Woodbury, 1962); all are to some degree incomplete or in error. The purpose of this paper is to pull together the fragments of data that are available and, at this late date, attempt to piece together the story of the survival of rat populations at Eniwetok.

HISTORICAL BACKGROUND

Eniwetok and Bikini atolls in the northern Marshall Islands were involved in the United States nuclear testing program between 1946 and 1958. During this period six major operations were carried out at Eniwetok Atoll and involved some 40 detonations. Many devices were small and made little impact on the environment; others, through shock, heat, and radiation waves, destroyed biotic communities within several miles of the test sites. The "Mike" explosion, rated at 10.4 megatons and by far the largest shot undertaken at Eniwetok, obliterated two islets, carved a crater in the coral reef a mile in diameter, and left scorched and singed plants and animals 14 miles away.

As with many operations, code names were given to each series and shot. The initial test program at Eniwetok in 1948 was labeled Sandstone; the Greenhouse series followed in 1951. In 1952 the Mike shot, involving a thermonuclear device, was part of the Ivy series. In 1954 the Nectar shot was the principal detonation of the Castle series. The Redwing series in 1956 and the Hardtack series in 1958, both involving a number of small shots, were the last in the test program (Hines, 1962).

While proof is lacking, I believe that the only rodent at Eniwetok Atoll prior to the initiation of the AEC program in 1946 was the Polynesian rat (*Rattus exulans*). This is the common rat of the Pacific islands, having moved with the Micronesians from island to island. Probably only the larger islets of the atoll (those with coconut plantings) were infested.

Although the Germans, and later the Japanese, were active in the Marshall Islands in the first half of the twentieth century, no specific records of rodents for Eniwetok Atoll seem to exist. St. John (1960) indicated that no botanical accounts existed from German (or the earlier Spanish) explorations. While botanical collections were made by the Japanese, I can find no descriptions of rats, and no rodent specimens from Eniwetok Atoll were present when I examined the collection in the Japanese National Science Museum in Tokyo. No specimens or recorded observations of rats from Eniwetok Atoll are known to exist prior to 1945.

Prior to the first test, a biological survey was made, and J. P. E. Morrison (U. S. National Museum, personal communication) has indicated that, in 1946 when he visited Eniwetok, he saw only Polynesian rats—on one islet (Igurin) on which he camped overnight. His observations at Bikini Atoll the same year were much more extensive. Though he observed rats on a number of islets there, he indicated that all were Polynesian rats. I have examined five specimens in the National Museum, each collected on a different islet, and I concur in the identification.

A similar, mono-specific rodent infestation can be cited for other relatively isolated areas in Micronesia prior to World War II or the postwar period. Thus it seems reasonable to conclude that only Polynesian rats were present at Eniwetok prior to 1946.

That an alternative hypothesis can be developed must be admitted. The Japanese had extensive fortifications at Eniwetok Atoll, largely on Engebi, Eniwetok, and Parry islets (Fig. 1). In

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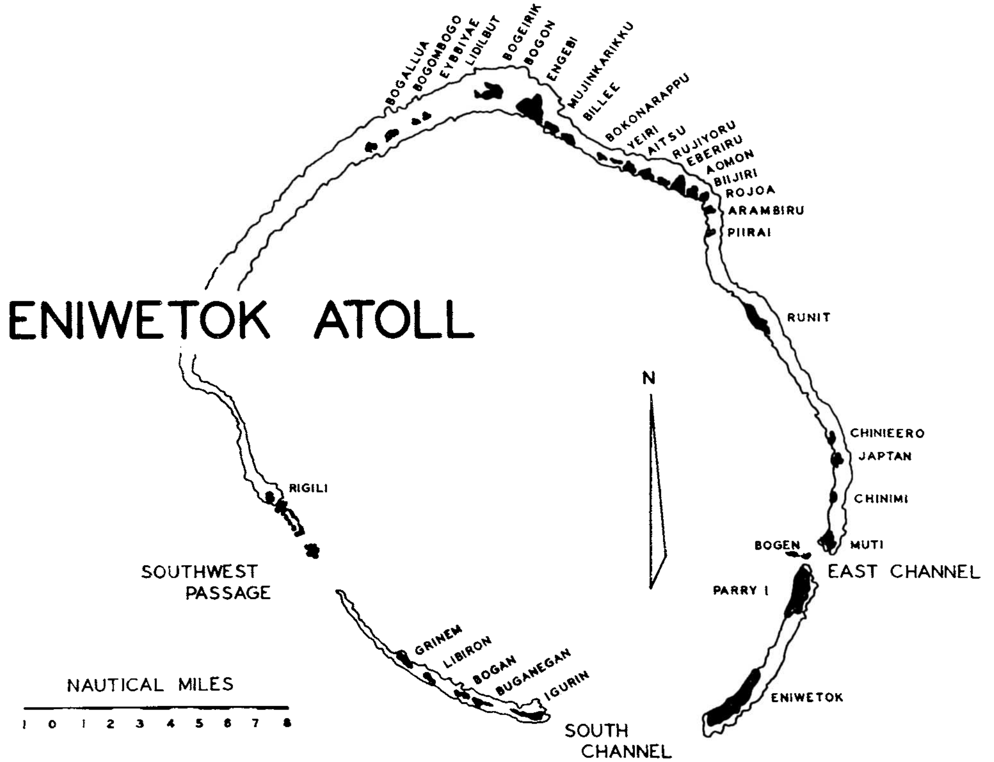

FIG. 1. Map of Eniwetok Atoll. Island names are taken from U. S. Naval Oceanographic Chart 6033 (revised January 1966).

1944 more than 3,500 troops and laborers were present on Engebi because of its air strip; Micronesians were restricted to the Biijiri, Aomen, Rojoa complex (Hines, 1962:84). Elsewhere in the Pacific, Japanese occupation on occasion brought with it the roof rat (*Rattus rattus*) (Johnson, 1962); this possibility cannot be excluded here. However, the roof rat populations now present at Eniwetok Atoll, and the Marshalls as a unit, are morphologically similar to the roof rat of the western world (*Rattus rattus rattus*) rather than to subspecies of the Asian mainland or western Pacific (*Rattus rattus mansorius* and other subspecies) (Johnson, 1962 and personal communication). While post-war invasions of western roof rats could have swamped and replaced earlier introductions, this seems unlikely, considering known interactions between the two subspecific groups in the Carolines (Johnson, 1962).

During the Japanese occupation, a major air field installation was constructed on Engebi. As a result, the islet was largely denuded, though a palm grove covering nearly one-sixth of the islet remained near its center, and some palms and/or second growth vegetation along the lagoon shore and the northwest tip of the islet appear in war-period photographs. Although some palms remained standing after the invasion, much of the vegetation was badly shattered (Bryan, 1944). Aerial photographs taken two months after the invasion show no trees and only isolated patches of ground cover. Thus rat habitat was relatively limited.

In the early test years, no specific observations of Eniwetok rats can be found, though reference is made to a collection of rats on Engebi in 1948 and 1949 (Hines, 1962:106). During the Sandstone series in 1948, one low-yield device was exploded on Engebi on April 15 from a 200-foot tower. At H + 1 day the gamma radiation in the islet center was estimated roughly at 12 R/hr; the accumulated dose, at H + 1 yr, 132 R (Laboratory of Radiation Biology, University of

Washington). Following the test, no exposed vegetation remained standing. Of the 43 plant species recorded from Engebi prior to the test, only 20 were not exterminated by the blast (St. John, 1950).

The Greenhouse tests in 1951 on Engebi (two detonations) produced an initial gamma radiation of 6,400–10,000 R in the islet center (Hines, 1962:210). At H + 1 yr the accumulated dose was 44 R. But the Polynesian rats apparently continued to exist on Engebi, since the affected area was small and probably only those rats close to the detonation sites were killed.

Probably about this time, the roof rat (*R. rattus*) was introduced. It may have arrived a few years earlier at the main supply areas of the atoll on ships from the United States or from other areas of the Marshalls where it was abundant. But we have no records of observations, and so this statement is conjectural.

In 1952, in preparation for Mike shot (Ivy series), rats on Engebi were collected; no radioactivity in their bones was found (Hines, 1962: 151), though slight activity occurred in other tissues (UWFL-33, 1955). Rats were also collected on Biijiri and Rojoa. All individuals were referred to as Polynesian rats. However, the single Engebi rat for which size data were recorded (UWFL-33) was obviously *not* a Polynesian rat; its weight (175 grams) was too great. In all probability it was a roof rat. Rats from the other two islets were most likely Polynesian rats, as judged from their weights (82 grams or less).

A thermonuclear device exploded on November 1, 1952, formed Mike crater on the former site of Elugelab and Teiteiripucchi islets, 3 miles northeast from Engebi. On November 8, no living animals were seen on Engebi; rats, ill and lethargic, were found on Biijiri. On November 10, six rats were found in traps on Rojoa that had been set on November 7 and had been empty on November 8. These two islets are approximately 9 miles from Mike crater. (No size data appear to have been recorded for these specimens; the presumption is that they were all Polynesian rats.)

The gamma dose rate on Engebi at H + 1 day was 1,000 R/hr; the accumulated dose at H + 1 yr, 11,000 R. (At Biijiri the annual accumulated dose was 1,440 R.) The shot caused a tidal wave over Engebi, and only stumps of vegetation remained. Rigili islet, 14 miles from Mike crater, had plants and birds scorched by thermonuclear heat.

Many observers supposed that rats on Engebi had been wiped out by the combined effects of the 1952 test. But in 1954 rats were found on Engebi. This has led to prolonged speculation (Hines, 1962:207–210). That the Polynesian rat was indeed exterminated by the thermonuclear test is a possibility. Roof rats perhaps survived, and their numbers may have been supplemented later by individuals from the supply boats traveling to Engebi.

The Laboratory of Radiation Biology (LRB) records give weights for 75 rats (identified as Polynesian rats) collected on Engebi in 1954. Of these, 71 were surely roof rats, as the animals were far too big (heavy) to be Polynesian rats; four were small enough, but no data on sexual maturity were given, so that no certain designation is possible. A poorly preserved remnant of one of the larger rats has been examined, and it was a roof rat.

During the pre-Nectar period in 1954, there was considerable experimental transportation of rats (all termed Polynesian rats) from Engebi to adjoining islets. Some 53 rats were involved, and the investigator (Major C. Barnes, LRB) records in his field notes that some of the rats on Engebi were of a "new gray species." This could be taken to indicate that two rat species were present at this time. I prefer to discount this hypothesis, since the measurements as well as two photographs of rats (identified as Polynesian) show them quite clearly to be roof rats. No weights or other data from the "gray species" have been found. Irradiation-induced depigmentation (Upton et al., 1960) due to inactivation of the follicle pigment cells might explain the appearance of gray animals.

Following the Nectar detonation of Castle series on May 13 in Mike crater, five rats from Engebi (H + 3 days) and twelve from Arambiru (H + 4 days) were transported to Bogombogo. On H + 7 days eight rats were caught on Engebi and transported to Bogombogo. No further notes were made about their survival, and no rats have subsequently been trapped on this islet. On the same day (H + 7), five rats that had severe radiation burns were captured on Engebi and returned to the laboratory for processing (Barnes, LRB). No rat collections were made after H + 7 days until September and October 1954, when six specimens (all of roof rat weight) were logged. Gamma radiation on Engebi on H + 1 day was 10.7 R/hr; H + 1 yr, 118 R (accumulated).

In 1955, rats (termed Polynesian) were reported present on Engebi in tremendous numbers (Hines, 1962:210). Pictures taken in 1957 of eight rats show that all individuals were roof rats. The first complete specimens of Engebi rats that we have been able to find were five animals (originally identified as Polynesian) collected in 1959 by LRB personnel. These are now in our possession and are quite clearly roof rats. Our field studies on Engebi (1964–1968) have shown through extensive trapping on the islet that only the roof rat is now present on this islet.

ANALYSIS OF RAT SPECIES

For a non-mammalogist, the distinction between these two rat species is not easy. Some differences in size and body and tail proportions exist, but the pelages may look amazingly alike; behavioral aspects may also provide a clue. It would be very easy for an individual who was not looking for species differences to be unaware of the problem. No mammalogists were involved in any of the field surveys, and, judging from field notes, correspondence, and conversations, no one (with the exception of Morrison) was aware of the rodent species which might be encountered at Eniwetok. Quite clearly, all of the workers expected to find the Polynesian rat.

I propose that this misidentification has seriously clouded the picture. In the absence of adequate records and specimens, we can only guess about the history of rat populations on the atoll. In all probability, the Polynesian rat was exterminated by the Mike test in 1952. On the strength of a single record, we can hypothesize that the roof rat had been introduced to Engebi prior to the 1952 Mike test. Had it been exterminated, the only source of this species on the atoll would have been Eniwetok and Parry islets, and perhaps Biijiri and Runit islets; so natural invasion by swimming was not a possibility. Currents surrounding Engebi are such that rats could not have crossed from adjoining islets, even if these islets had had rats. Exposed reefs at low tide do not provide the necessary pathway between islets. Movement on storm driven flotsam is possible but not considered likely.

As a result of earlier construction activity and tests and finally the thermonuclear blast in 1952, Engebi was stripped of vegetation. The only remaining source of protection would have been various construction artifacts, test buildings, photographic and instrument bunkers, and cable tunnels. Many have assumed that rats which had burrowed under such structures would have been sufficiently shielded to permit survival.

The Polynesian rat is not a burrowing animal but makes a nest under surface vegetation or debris. The roof rat, while often nesting in much the same way, may burrow. Usually the tunnels we found were adjacent to a concrete wall or slab, or under or adjacent to a coral block or tree root. This kind of physical support may be necessary if the burrow walls are not to collapse in the friable coral sand. Thus, if any rats were to survive a nearby detonation, the roof rat was the likely species.

Rats are highly adaptable and successful animals. While they orient poorly when visual contact with land has been broken (while swimming in the lagoon, for example), they often do live in marsh areas and successfully survive seasonal flooding (Steiniger, 1949). Perhaps the ability of hibernating ground squirrels to survive early spring floods (Quanstrom, 1966) has some parallel in the possible tidal wave survival of rats on Engebi. Air trapped in burrows might have prevented complete flooding and provided the necessary oxygen supply.

How many could have lived to form the nucleus of a new population can only be surmised, though sufficient protection probably existed for some hundreds of rats. The major limiting factor, after the period of heavy radiation, would have been food. Although some resprouting of plants occurred within two weeks and regrowth had begun within two months (Frank G. Lowman, Puerto Rico Nuclear Center and LRB, personal communication), until sufficient vegetation reappeared, the rats would have had to exist on beach debris (of which there was probably a considerable amount) and beach invertebrates, and by cannibalism. Their omnivorous food habits make this a reasonable possibility.

Not until a year after the Mike test did intensive preparations start for the Castle series of tests, and no observations of flora and fauna on Engebi for the intervening period are available. Rats could have been transported to Enbegi in the movement of supplies in early 1954. Field notes of LRB personnel (especially Barnes) indicated that rats were relatively common immediately prior to the Nectar shot in 1954; by 1955 the population asymptote probably was being approached, for Lowman (LRB) recorded his "rat colony" observations during this period (Hines, 1962:206–213). Thereafter, the population probably declined to the present-day level.

Lowman's estimate of the Engebi rat population was meant only as an approximation. In an area 100 feet square, he saw up to 60 rats at once during the day. Extrapolating to the 15 acres of available grassland yielded an estimate of 1,000–4,000 rats (Hines, 1962:209). Since total land area on Engebi is 260 acres, and some scrub areas were present, further extrapolation to an island population of 10,000 animals was not difficult (French, 1965). A current estimate, based on trapping data, suggests that the population now does not exceed 4,500 rats.

Additional construction and vegetational succession may have caused a lowered carrying capacity. Lowman's old "rat colony" area is now overgrown with *Scaevola taccada* and *Tournefortia argentea* trees 15–20 feet in height (Figs. 2 and 3). While the airfield remains a grassland complex, the rest of the islet is covered to various degrees by second growth. That the sand burr (*Cenchrus echinatus*) might have been virtually exterminated by the rats is possible, since Lowman observed rats frequently feeding on the seeds. In 1964 none could be found (though in 1966 a few small patches were discovered). The loss of this single plant species by intensive feeding might of itself have reduced the islet's carrying capacity significantly. In any event, rats are no longer as abundant as

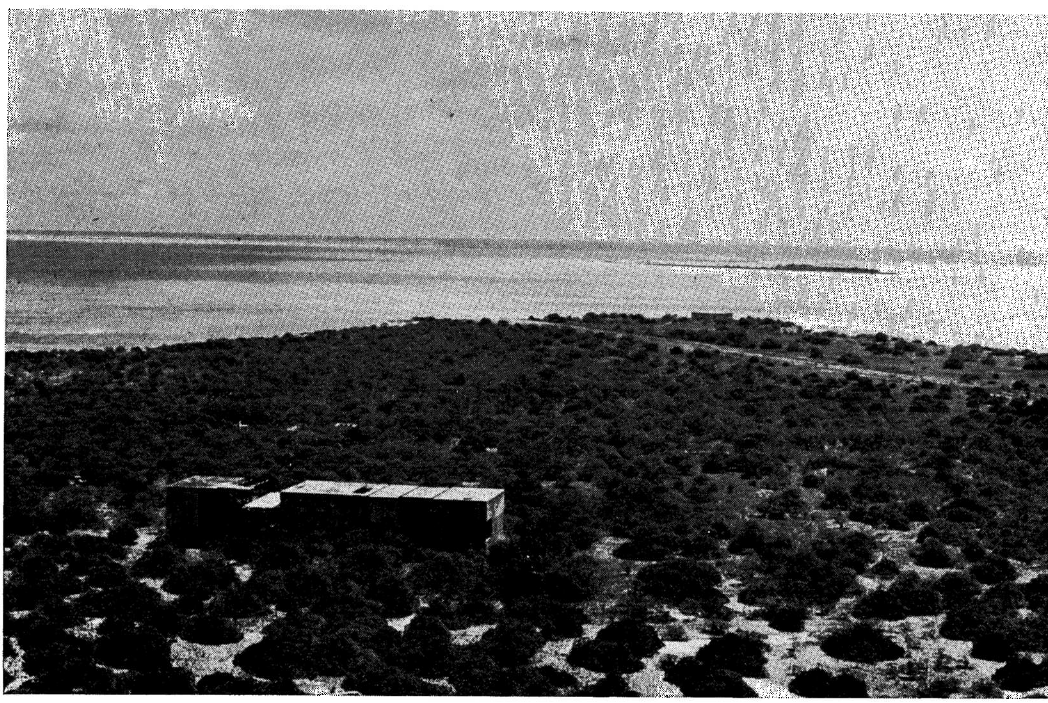

FIG. 2. Engebi islet viewed looking west toward "Mike" crater (1967). Lowman's rat colony area is just beyond and to the right of the large test building. Remnants of the air strip can be seen on far side of islet.

FIG. 3. Vegetation in rat colony area (1965). Shrubs are *Tournefortia argentea* and *Scaevola taccada* and are up to 15 feet in height.

they were in 1955; rodent activity during the day (prior to late afternoon) and large numbers of rat burrows are not now observed.

RADIATION EFFECTS

For very practical reasons few studies have been able to evaluate radiation-induced population changes of rodents under field conditions (Dunaway, 1965). Several studies (briefly reviewed by Provost et al., 1965) have subjected individuals to acute radiation and returned them to their natural environment. Doses below 500–750 R generally were ineffective in reducing reproductive rates or population size.

Only one field study under conditions of chronic low-level radiation has been reported in detail. Dunaway and Kaye (1964) evaluated a cotton rat population living in an area with a radiation level of 15 mR/hr; no unequivocal effect of radiation on body weight or breeding could be demonstrated. Analysis of roof rat data from H. T. Odum's El Verde study in Puerto Rico revealed no change that could be related to radiation exposure (Jackson, unpublished manuscript). Several recent reports are concerned with the assimilation of radioisotopes by small mammals at the Nevada Test Site (French et al., 1965; French, 1966; Turner et al., 1966). Because of low concentration levels, only temporary physiological changes were noted, though concentrations in specific tissues (e.g., I-131 in the thyroid) did occur.

Laboratory studies (cited by Dunaway and Kaye, 1964) of the impact of radiation on mammalian reproduction suggest that cumulative doses above 300 R result in sterility. Except for the Mike shot, estimated annual and accumulated gamma doses (exclusive of prompt radiation) for rats living on Engebi did not exceed 132 R (Sandstone). For Nectar the dose was 118 R. At daily doses of less than 1 R, some reproductive cycle disturbances do occur, and partial loss of fertility would by expected at sublethal levels (see Dunaway and Kaye, 1964).

Certainly any rat caught unprotected above ground by a detonation would have been killed immediately or in a short time by radiation effects. The gamma dose above ground during the first hour ranged from 6,400–10,000 R

(Greenhouse) to 2,800–6,700 R (Mike) to somewhat lower levels in subsequent tests. Animals protected in burrows were estimated to have received an integrated dose (beta and gamma) in the nine days following the Mike shot of 250–2,500 R; in the week following the Nectar shot, 55–80 R (Hines, 1962:210–211). Rats in deeper burrows would have had more protection, but those moving above ground to feed would have proportionately increased their load. Certainly, these estimates provide a basis for assuming survival of some individuals, for the $LD_{50\ (5\ days)}$ for laboratory rats is 800 R (Bond et al., 1965).

POPULATION DYNAMICS OF RATS

At the Hanford symposium, "Radiation and Terrestrial Ecosystems," French (1965) considered the growth potential and recovery of the Engebi rat population. Since he assumed the wrong species, based on published sources, his calculations of reproductive and survival rates were not strictly applicable. In the time period available, could the roof rat have populated Engebi to the density observed?

Let us assume maximal reproductive rates, even though the roof rat population on Engebi probably has now stabilized and shows a very low level of reproduction. Under conditions of habitat exploitation, high reproductive and low death rates would be expected (Davis, 1951).

Data on the reproduction of Pacific roof rats are inadequate. Average litter size, for example, varies considerably. For a different subspecies on Ponape, the value was 3.8; in Malaya, 5–6. For the same subspecies in temperate regions the litter size was 6–7; in the southern Marshalls (Majuro) in a limited sample, 5 (Jackson, 1962, 1965). In our current Eniwetok studies, litter size has averaged 4.8 (32 pregnancies). As an estimate for the increasing Engebi population, we used a litter size of six.

Mortality data are even more limited. Harrison (1956) cites some data for a similar species (*R. diardii*) in Malaya (Fig. 4), but this is a mainland population, and the mortality rates calculated probably are considerably higher than those experienced in an island situation.

Let us assume the same natural mortality estimate used by French (1965)—an annual probability of disappearance of 0.4. This figure was a composite of estimates for Polynesian rats on Ponape in the eastern Caroline Islands (Jackson and Barbehenn, 1962) and Harrison's (1956) estimates for the same species in Malaya. On this basis, using a litter size of six, the annual rate of population multiplication (R_a) is 7.5 (more than twice that calculated by French).

Following through with calculations and assumptions made by French, estimates of surviving populations necessary to produce the 1955 estimated population have been made (Fig. 5). The interval between shots was 18 months; between the 1954 shot and the 1955 obervation, 12 months. French had taken a three-year period; consequently his estimated initial populations were actually too small. For example, where $R_a = 4$, initial population would have had to be 300, not 150; where $R_a = 3$ (1 y post-Nectar), $R_a = 2.1$ (1.5 y post-Mike), or 1,050 rather than 700 rats. Assume also, as did French, a 50 percent reduced fertility (multiplication rate) following the Mike shot; following the Nectar shot, a 25 percent reduction.

With these restrictions and assuming that no mortality resulted from the Nectar shot, 250 survivors of the Mike thermonuclear shot could have produced a population of 10,000 rats in 1955. If no loss of fertility were assumed, only 63 surviving rats would have been necessary.

If a lesser initial population mortality rate were assumed (a straight line relationship with 40 percent of the initial cohort remaining after 12 months—Fig. 4), an annual multiplication rate (R_a) of 11.0 results, and an initial population of only 25 rats is required. With adjustments for reduced fertility—$R_a = 8.2$ (1 y), $R_a = 5.5$ (1.5 y)—an initial population of 961 animals is indicated (Fig. 5). This initial survival rate is only slightly higher than that found by P. Q. Tomich (unpublished manuscript) for roof rats in Hawaiian cane fields (mean survival: females 8.00 months; males, 6.63 months).

Rats certainly were killed by the Nectar shot (1954). Most of these estimates require between 1,000 and 2,000 survivors after this shot, a figure perhaps not too unreasonable, considering the cable tunnels, bunkers, and other protected sites available, the relatively low level of

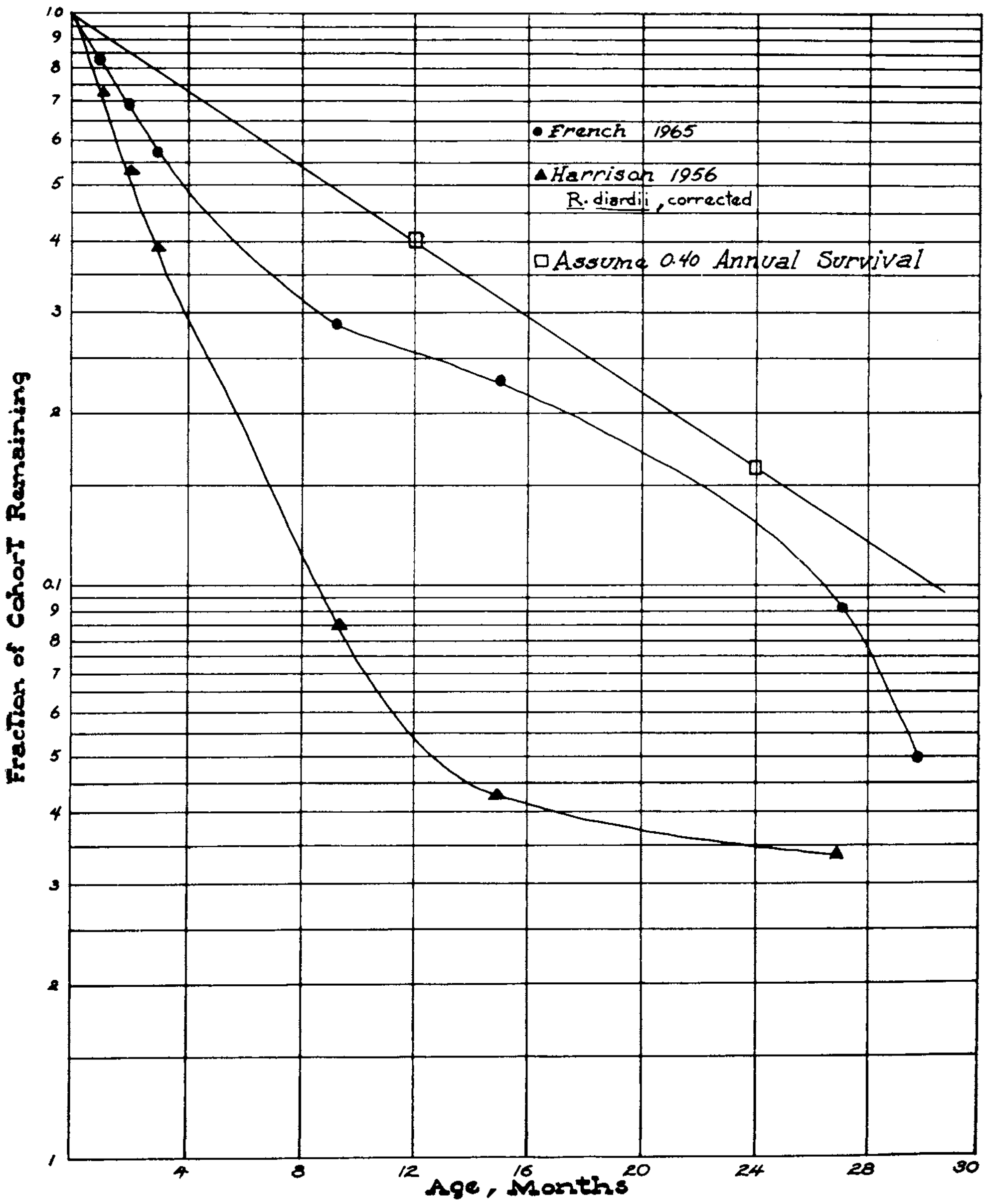

FIG. 4. Survival curves for roof rats (after French, 1965).

radiation, and the relatively limited physical damage to the islet—the central area was not covered by the tidal wave.

Regardless of the rat species designated, repopulation of Engebi by the survivors of the Mike test (1952) was theoretically possible. Indeed, by involving the roof rat with its larger litter size, even fewer survivors were needed. Though such survival cannot be actually documented, the circumstantial evidence strongly suggests that it did occur.

SUMMARY

The story of the survival of rats at Eniwetok during the nuclear testing program (1948–

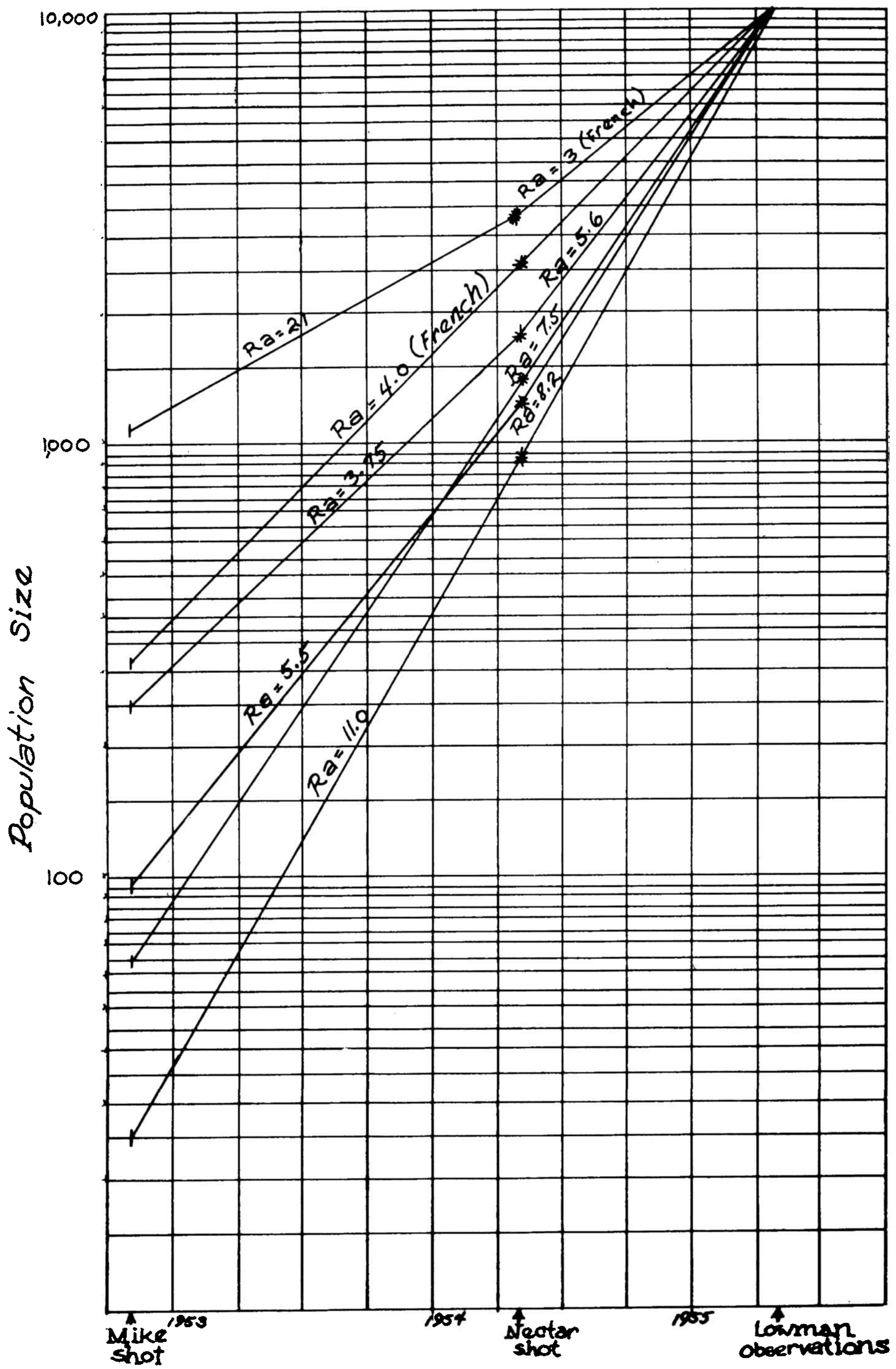

FIG. 5. Initial populations surviving the 1952 "Mike" shot, using several estimates of the annual rate of multiplication (R_a), required to produce a population of 10,000 roof rats in 1955.

1958) is made difficult by taxonomic confusion and lack of specimens. At best, a hypothetical reconstruction can be attempted. Early in the test program at Engebi islet, the Polynesian rat (*Rattus exulans*) was exterminated, probably by heavy surface radiation. Prior to the detonation of a thermonuclear device in 1952, the roof rat (*R. rattus*) had become established on Engebi, and a nucleus survived the heavy initial radiation by being in deep burrows. Calculations show that repopulation by the time of the 1954 and 1955 observations was theoretically possible. The decline of the Engebi rat population from its high density in the mid-fifties probably was a result of a change in the carrying capacity of the environment.

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