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Docket No. 50-313

JUN 12 1972

Mr. Lloyd Unverferth
Route 3
Russellville, Arkansas 72801

Dear Mr. Unverferth:

The Atomic Energy Commission has investigated the effects of radiation on insects, including the honeybee, over the past years. Enclosed are a few examples of the results of those studies. To summarize, it has been shown that insects (including honeybees) are very resistant to radiation exposures. The radiation exposure required before harmful effects begin to appear are measured in the order of thousands of roentgen. This exposure as used in the enclosed articles is given as kiloroentgen (kr).

The maximum exposures expected within the site boundary of the Arkansas Nuclear One are estimated to be in the range of miliroentgen (mr) or one-thousandth of a roentgen.

It is, therefore, our opinion that the operation of the Arkansas Nuclear One Power Station will have no harmful effect on your hive of bees.

Sincerely,

Original signed by
A. Giambusso

A. Giambusso, Deputy Director
for Reactor Projects
Directorate of Licensing

THIS DOCUMENT CONTAINS
POOR QUALITY PAGES

Enclosure:
"Honeybee Irradiation Studies" by
A. F. Shinn, E. Oertel and
A. M. Jenkins
"Radiation Sensitivity of Twelve Species
of Arthropods" by E. F. Menhinick and
D. A. Crossley, Jr.

Copy sent PDR

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HONEYBEE IRRADIATION STUDIES

A. F. Shinn E. Oertel A. M. Jenkins

There are no published studies of effects of ionizing radiation on field colonies of honeybees. Ecologically, we are most interested in effects on hive economy and the pollinating activities of the bees. Effects of gamma radiation on daily pollen collection and flight activity of field colonies and on longevity of both laboratory-caged bees and field colonies were previously investigated.

We have now investigated the effect of irradiation of nuclei (half-size) colonies of honeybees by exposing them to 1500 and 3000 R of ^{60}Co gamma radiation at the rate of 53 R/min. The 11 replicates of control and dose levels were placed singly at random in 33 cages on a pasture of red clover and fescue grass.

Number of capped brood cells (which contain bees undergoing metamorphosis) in each nucleus was determined from photo inventories (Table 1.6). Preirradiation counts showed that nuclei of controls and treatments were comparable for numbers of developing brood cells, but at ten days post irradiation the brood counts of irradiated colonies were substantially less ($P < 0.01$) than controls. A sharp decline in counts occurred by postirradiation day 20 for all colonies, and by postirradiation day 34 no brood was being raised by controls, and very little was present in the 1500-R nuclei. Remarkably, however, the 3000-R nuclei showed a tenfold increase in brood cells ($P < 0.01$). A possible explanation of cessation of brood rearing in controls was exhaustion of stored pollen in each colony and an inadequacy of pollen supply in the cages for rearing brood. Deaths of larvae and brood among irradiated nuclei conserved pollen supply, and brood numbers consequently declined more slowly.

Table 1.6. Number of Capped Brood Cells per Nucleus Prior to and Following Irradiation

Mean ± standard error

Sample Date and Post-irradiation Day	Controls	1500 R	3000 R
June 18 (preirrad.)	4260 ± 493	3005 ± 545	3998 ± 592
June 30 (PID 10)	2811 ± 354	1579 ± 825[a]	1552 ± 336[a]
July 10 (PID 20)	63 ± 45	466 ± 226	56.5 ± 23.0
July 24 (PID 34)	0	241 ± 95	598 ± 145

[a]Significant at $P < 0.01$.

Queens of controls and 1500-R colonies were laying eggs normally (10 of 11 in each case) on postirradiation day 12, but queens of 3000-R colonies were severely affected, with 2 dead and 5 nonlaying. By postirradiation day 20, egg laying was normal for all colonies (8 laying queens among controls, 8 among 1500-R, and 9 among 3000-R colonies). At the end of confinement to cages on postirradiation day 34, there was no difference in number of laying queens among controls and irradiated colonies (controls, 6; 1500-R, 10; 3000-R, 8).

Seed yields per cage were determined after 32 days of confinement and were not statistically different among controls and irradiated nuclei (N = 24, mean 37.6 ± S.E. 3.92 g, CV = 51%). Differences may have been masked by the unexpected large variability in density of clover blossoms per cage and in their absolute density per cage (N = 13, mean 314 ± S.E. 31, CV = 36%). At the end of the experiment, total weight of worker bees per nucleus was less for irradiated nuclei than for controls at $P < 0.01$ (N = 11 for each: controls, 0.751 ± 0.0636 kg; 1500 R, 0.481 ± 0.0334 kg; 3000 R, 0.355 ± 0.05787 kg).

Radiosensitivity of a mixed sample of eggs and larvae less than three days old was found to be an order of magnitude lower than that of adult workers (1700 R was the $LD_{50\text{-}4}$ for eggs and larvae, compared with 16,300 R for the $LD_{50\text{-}5}$ for workers).

Mean mortality of random samples of honeycombs of larvae and pupae in sealed cells was greater than controls (6%) for exposures to ^{60}Co gamma radiation of 3000, 4000, and 5000 R (19, 38, and 31%), but not for those of 500, 1000, 1500, and 2000 R. These laboratory results parallel our observations that field colonies exposed to ^{60}Co gamma radiation of 3000 R or more die at least by the overwintering period.

1969 Annual Report: Division of Ecological Science, Oak Ridge National Laboratory

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A. F. Shinn E. Oertel A. M. Jenkins

There are no published studies of effects of ionizing radiation on field colonies of honeybees. Ecologically, we are most interested in effects on hive economy and the pollinating activities of bees. Effects of gamma radiation on the daily pollen collection of field colonies and on the longevity of both laboratory-caged bees and field colonies were previously investigated.

For the continuation of honeybee studies, Italian cordovan hybrid bees were used, which were supplied from the Genetic Bee Stock Center of the University of California at Davis. Thirty-two of forty colonies of bees were converted to this type by replacing the queens with the genetically homogeneous cordovan queens. The brightly colored, orange cordovans were easily distinguished from the dark native bees. The cordovans foraged up to 2 miles from the apiary, or over an area of some 8000 acres. No native bees invaded the cordovan colonies.

Laboratory cages of approximately 150 Italian cordovans in each of three replicates were irradiated with 1000, 2000, and 4000 rads of ^{60}Co gamma radiation at ~600 rads/min and maintained at internal hive temperature (34°C) with sugar syrup as food. Only the 4000-rad samples had a mean life-span (8.9 days) statistically different from controls (23 days). These results are similar to those previously obtained for East

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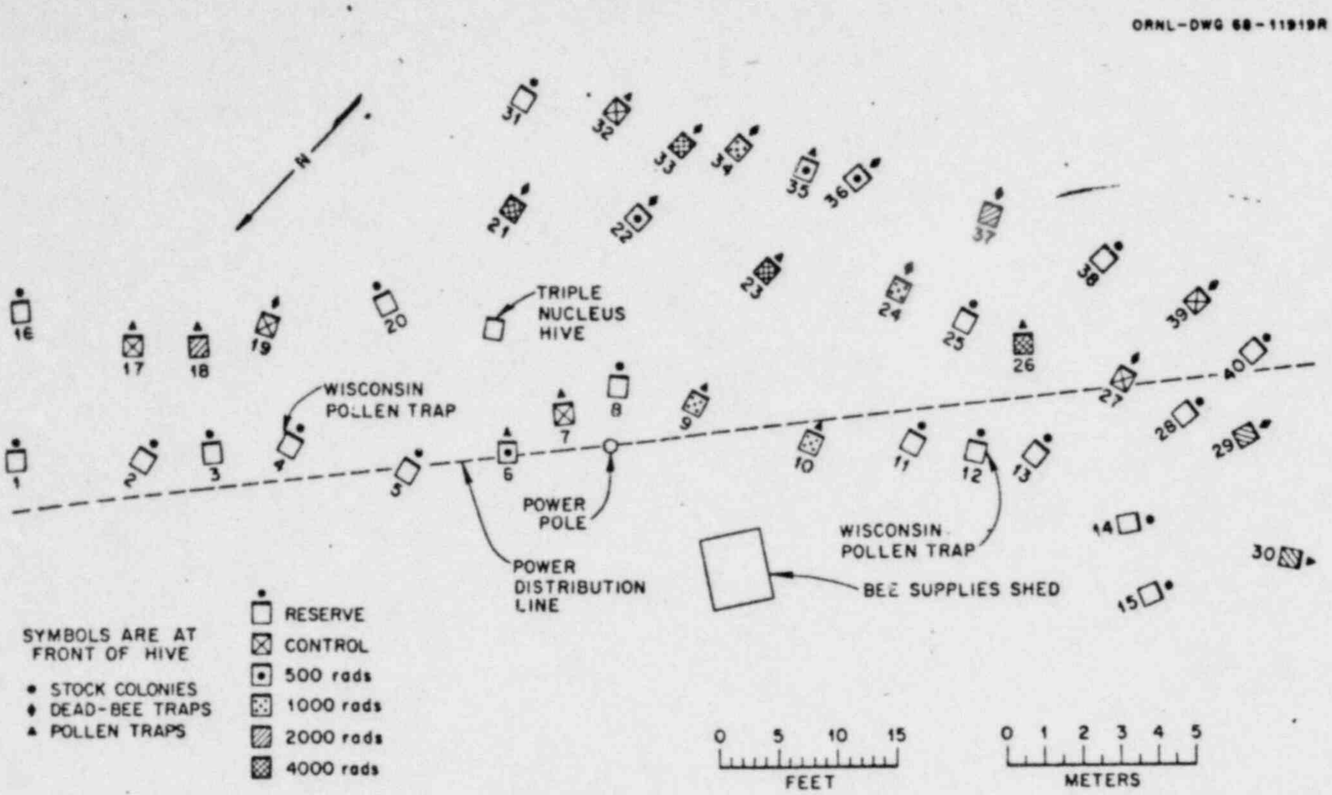

Fig. 8.8. Apiary of the OCD Honeybee Project, 1968.

Tennessee mixed bees (8.5 days) and Illinois Italian bees (7.7 days), which were irradiated with 5000 rads and maintained in the same wa a year earlier.

The life-span of laboratory-caged worker bees was determined at three temperatures (24, 34, and 40°C) for starved bees and for bees supplied with 66% sugar syrup, water only, and queen-cage candy. The temperatures had no demonstrable effect on the mean life-spans of unfed bees (1.8 days) or of bees fed 66% sugar syrup (28 days). Bees supplied only with water lived significantly longer at the hive temperature of 34°C than at 24 or 40°C (2.8, 2.0, 2.0 days respectively). Bees fed queen-cage candy had significantly different mean life-spans of 13, 8, and 2 days at 23, 34, and 40°C respectively.

Our field colonies were placed on burial ground 4 and sited so as to discourage the drifting of bees from one hive to another (Fig. 8.8). The colonies of bees were equalized for size and vigor as closely as possible, and those for the several levels of irradiation were chosen at random. Sets of four colonies each received 500, 1000, 2000, and 4000 rads, respectively, of ^{60}Co gamma radiation at ~65 rads/min in the Variable Dose Rate Irradiation Facility of the UT-AEC Agricultural Research Laboratory. They were returned at once to their original position in the apiary along with eight control colonies which had accompanied them (Fig. 8.8).

The criteria for effects of ionizing radiation on the colonies were: (1) the mortality within the hive, (2) the quantity of pollen collected daily by a colony, (3) the flight activity of a colony, and (4) the final status of a colony at the end of the observation period of the experiment. The data were obtained during a 37-day postirradiation period.

Table 8.4 summarizes the data for the first three criteria. The mean daily mortality of the 4000-rad colonies (200 bees) was statistically different from controls (22 bees). The mean daily collections of pollen were not statistically different, but the data suggest that more replicates would yield significance. The mean daily number of flights of the 2000-rad colonies (36 flights per 2-min period) was less ($P > 0.01$) than the 500- and 1000-rad colonies (67 and 61 flights respectively), but we know of no biological basis for the difference.

The final status of the colonies was determined by an inventory of the colonies expressed as square centimeters of honeycomb containing honey, pollen, pupae, larvae, and eggs. The inventories of the 500-, 1000-, and 2000-rad colonies were statistically different from

Table 8.4. Mean Daily Values of Effects of Acute Gamma Radiation on Entire Cordovan Italian Honeybee Colonies

Dose, rads	Controls	500	1000	2000	4000
Mortality, number of dead bees	22.1	18.5	31.1	37.7	200.4[a]
Pollen, g	7.7	17.9	20.9	2.7	0.37
Activity, number of flights per 2-min period	48.2	66.6[b]	61.4	35.6	42.9

[a] $P < 0.01$, compared with each other treatment.

[b] $P < 0.05$, compared with controls, 2000, and 4000.

controls only for pollen ($P > 0.05$); the 1000- and 2000-rad colonies had significantly less pollen per colony (297 and 368 cm^2 respectively) than the controls (768 cm^2). The 4000-rad colonies were obviously moribund, with two dead at inventory time and two more almost dead. More replicates would likely have detected differences between controls and the 2000-rad colonies. Despite as uniform a genetic composition as current knowledge permits, there was still a large amount of variation among colonies within a given dose level.

Radiation Sensitivity of Twelve Species of Arthropods[1]

EDWARD F. MENHINICK[2] AND D. A. CROSSLEY, JR.[3]

Radiation Ecology Section, Health Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee

ABSTRACT

Eleven species of insects and 1 species of isopod were exposed to gamma radiation from cobalt-60 with total doses ranging from 1 to 512 kiloroentgens (kr) in 100% increments. Insects were irradiated and maintained under comparable conditions at 28°C. Mean and median life expectancy were estimated for each dose level. Life expectancy was significantly lowered for all species by exposure to 8 kr or more. Most species were affected by 4 kr. Exposure to 1 or 2 kr generally had no effects. Of the species tested the American cockroach, *Periplaneta americana* (L.), was the most sensitive to radiation; the black carpet beetle, *Attagenus piceus* (Olivier) was the least sensitive. Correlations between radiation sensitivity and taxonomic grouping were poor. However, within insect orders size appeared to be a good basis for estimating mortality response to irradiation. Large species were found to be more sensitive to irradiation than smaller species.

Information on radiation-induced mortality in different species of insects is necessary to estimate ranges in radiosensitivity of species not examined. Such information would enable evaluation of possible insect problems in postnuclear attack environments, and would be useful in control of insects by irradiation. Correlation of sensitivity with other physiological characteristics of insects might suggest mechanisms of radiation injury. No general principle for predicting radiosensitivity of insects has been tested for a wide variety of species over a wide range of doses.

Hassett and Jenkins (1952), Huque (1963), and Cornwell (1966) have reported extensive studies on the effects of ionizing radiation on stored-grain insects. Cole et al. (1959) tested 7 species of insects affecting man and determined the radiation doses required to kill each in 1 day. Most radiation studies have involved single species. Conditions of dose, dose rate, temperature, and stage of insect irradiated varied with different experiments, and often were not even given. Different doses, times of observation, and end points have also made difficult or impossible comparison of data from different experiments. To standardize conditions, we irradiated 12 species of arthropods under the same conditions of dose, dose rate, and temperature, using mean and median life expectancy as criteria of radiation effect. Radiosensitivity was compared with various characteristics of the different species.

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MATERIALS AND METHODS

Table 1 lists species and stages irradiated. Cultures of *Blatta*, *Blattella*, and *Thermobia* were established from individuals collected locally. Stocks of *Periplaneta* were obtained from cultures of Dr. James N. Liles, University of Tennessee. *Acheta* were purchased from Joe's Cricket Ranch, Aiken, S. C. These species were all reared in plywood boxes or cardboard drums. Aluminum tape was placed around the inside of the containers and coated with vaseline to prevent the insects from escaping. Wet sponges placed in the troughs of chicken waterers provided water. Food consisted of Byrdseye® cricket and earthworm meal supplemented with Moorman chick mintrate.

Harpalus, collected locally at lights at night, were maintained in soft plastic tubs 1½ ft diam, and were fed *Tenebrio* larvae and pupae. *Armadillidium*, collected locally under boards, were maintained in soft plastic tubs and fed cricket meal, lettuce, potatoes, and *Tenebrio* pupae. *Oncopeltus*, collected locally on milkweed, were reared in screened plastic tubs and were fed milkweed seeds. Water was supplied to the 4 just-named species in chicken waterers. *Crematogaster*, collected locally under boards, were reared in gallon plastic containers covered with screen. Cotton provided shelter; water was supplied by a wet sponge in a 30-ml vial; food consisted of honey and *Tenebrio* pupae. *Sceliphron*, collected locally on flowers, were maintained in screen cages 2×2×2 ft; they were fed honey and water. *Tenebrio* were raised in soft plastic tubs containing about 2 in. of ground Purina® Laboratory Chow; potatoes were added to supply moisture. *Attagenus*, collected locally in meal, were fed a mixture of ⅓ cricket food, ⅓ dried milk, and ⅓ dried

Table 1. — Species of arthropods irradiated.

Species	Common name	Stage irradiated
Armadillidium vulgare (Latreille)	Sowbug	medium-sized nymph
Thermobia domestica (Packard)	Firebrat	"
Periplaneta americana (L.)	American cockroach	"
Blatta orientalis L.	Oriental cockroach	"
Blattella germanica (L.)	German cockroach	"
Acheta domesticus (L.)	House cricket	"
Oncopeltus fasciatus (Dallas)	Large milkweed bug	young adult
Attagenus piceus (Olivier)	Black carpet beetle	medium-sized larva
Tenebrio molitor L.	Yellow mealworm	"
Harpalus pennsylvanicus De Geer	Ground beetle	mixed-age adult
Sceliphron caementarium (Drury)	Mud dauber	"
Crematogaster lineolata (Say)	Ant	"

blood. Before and after irradiation, all species were maintained at 28±1°C in a small insectary building.

Irradiations were performed in 1 of 2 cobalt-60 sources in the laboratory of C. J. Hochenadel, Chemistry Division, Oak Ridge National Laboratory (Ghormley and Hochenadel 1951). A source giving 2650 R/min±2% (~2330 rad/min) was used for doses of 4 kr (4000 R) or less; a 26,500 R/min±2% source was used for doses greater than 4 kr. Doses ranged from 1 kr to 512 kr in 100% increments (i.e., 1 kr, 2 kr, 4 kr, 8 kr, etc.). The animals were irradiated at room temperatures. Transport to and from the source took less than 3 min. Arthropods were transported in insulated containers to protect against temperature changes.

The unit of radiation used here is the roentgen (R), which expresses exposure to radiation or exposure dose. The radiation sources were calibrated to this unit, and our irradiations were calculated from those calibrations. Multiplying our value by 0.93 yields (approximately) the absorbed dose of radiation (in rad).

After irradiation, *Sceliphron* were marked by clipping their tarsi and returned to the cages for observation. All other species were placed in jars 3½×3½ in. They were fed the same food used in rearing. Water was given to all species except *Tenebrio* and *Attagenus*. It was supplied through a sponge in a 30-ml vial. A strip of foam plastic was placed in the jar as a climbing surface. *Tenebrio* were placed in jars containing about 2 in. of food; *Attagenus* had about ½ in. of food.

After treatment, arthropods were examined daily for the 1st week, every other day for the 2nd and 3rd week, and twice a week every week thereafter until all were dead. Dead animals were removed and counted at each examination. *Mean life expectancy* was determined as the sum of individual life expectancies (in days) divided by the number of the individuals. Standard deviation and standard error were also determined for each stage and for each dose, and Student's t test (Ostle 1954: 98) was used to compare mean life expectancies of the same stage given different doses of radiation. Use of time intervals of variable sizes introduces more variability in the standard deviation than there would have been if small intervals had been used throughout. *Median life expectancy* was the time when 50% of the individuals were dead and was interpolated for periods longer than 1 day. *Median life expectancy corrected for control mortality* was the time at which percent survival of irradiated arthropods divided by percent survival of controls was equal to 0.50. Except in cases of high control mortality, median life expectancy and median life expectancy corrected for control mortality were similar.

RESULTS

Mortality responses of the various species are given in Table 2, which presents the mean and median survival (in days) following exposure to various doses of ionizing radiation. For most of the arthropod species the lowest radiation exposure (1 kr) had little or no effect on longevity. With increasingly higher exposure doses a radiation dose was reached which severely or markedly shortened life expectancy. Further increases in exposure dose resulted in further reduction in average lifespan. Finally, a range was attained in which further increases in exposure dose produced only slight additional decreases in life expectancy. These results are illustrated graphically in Fig. 1 and 2 for 8 of the species for which life expectancy has been normalized to percentage of control life expectancy. A significant feature of these curves is the radiation dose which produces an abrupt decrease in survival. This dose we term the "threshold dose." The inflection points of the curves would indicate a threshold dose precisely, but because of limitations in the experimental design the inflection point could not be determined. The radiation dose area (i.e., between 2 exposure doses) in which the inflection point occurred could be identified.

Attagenus was the most resistant species examined, living longer after irradiation than any other species (Table 2, Fig. 1). The threshold dose was between 2 and 4 kr. Control mortality was only 8% at 257 days, when adults began to emerge; adults lived about 3 weeks. Only 20% of larvae given 4 kr pupated and emerged as adults compared with 92% emergence of control larvae and larvae given 1 kr. Doses of 8 kr paralyzed most larvae by 19 days; all were paralyzed by 62 days; none pupated and all were dead by 103 days. Hassett and Jenkins (1952) found *A. piceus* larvae to be the most resistant of 6 species examined: individuals exposed to 16 kr had a median life expectancy (corrected for controls) equal to 48 days; 32 kr = 27 days; 128 kr = 13 days; 193 kr = 3 days; 256 kr = 0 days. Those life expectancies are only about half as long as our results would indicate. Temperatures were not given in their paper and may have accounted for these differences.

Armadillidium also was resistant to radiation damage. Controls died at a regular rate, 1 about every 10 days. All were dead after 265 days. Individuals exposed to 1 or 4 kr had survivals similar to controls. Those exposed to 8 kr survived several days without mortality and then suddenly died off. *Armadillidium* lived only about half as long as *Attagenus* after a similar radiation exposure (Table 2), but had a threshold dose between 4 and 8 kr, higher than that for *Attagenus*, and survived well compared with con-

Table 2.—Life expectancies (days) for 12 species of arthropods following exposure to gamma radiation from cobalt-60. n = number of individuals per dose; $\bar{x}$ = mean survival time; SD = standard deviation; M = median survival time; M_{corr} = median corrected for control mortality. Means not having the same prescript (a, b, c, or d) are significantly different from each other at the 1% confidence level.

Dose (kr)		Life expectancy (in days) $\bar{x}$	SD	M	M_{corr}
		***Attagenus:* medium larvae (n = 25)**			
0	a	284.6	37.11	292.7	...
1		...	...	...	...
2	a	268.9	57.86	289.9	...
4		145.4	84.95	119.1	119.1
8	b	71.0	19.77	70.6	70.6
16	b	72.8	18.39	73.2	73.2
32		55.8	16.34	52.5	52.5
64		36.9	17.48	36.1	36.1
128		9.0	2.32	9.1	9.2
256		2.7	0.95	2.5	2.5
512		0.2	.29	0.0	0.0
		***Sceliphron:* mixed adults (n = 10)**			
0	a	44.2	25.71	42.0	...
1	a	43.2	29.21	58.5	...
2	ab	24.8	15.05	20.5	21.6
4	bc	16.1	3.98	16.0	16.4
8	c	11.5	7.71	14.5	15.2
16					
32					
64					
128					
256					
512					
		***Tenebrio:* medium larvae (n = 50)**			
	a	73.4	43.15	57.7	...
	a	72.8	37.77	62.9	...
	a	84.3	49.97	72.1	...
	b	35.6	20.44	33.5	34.2
	b	29.6	22.99	19.0	21.0
		13.6	3.35	13.4	13.4
		8.9	3.36	8.8	8.8
		5.2	1.91	5.5	5.5
		2.7	0.93	2.6	2.6
		1.5	.36	1.5	1.5
		0.3	.23	0.0	0.0
		***Blattella:* medium nymphs (n = 20)**			
	a	136.2	41.07	147.5	...
	a	127.2	25.82	123.0	...
	a	116.4	12.62	114.9	...
	b	28.2	17.52	23.6	24.1
	b	21.2	5.28	22.0	22.3
		16.0	3.37	16.3	16.3
		6.4	1.66	6.6	6.6
		3.2	0.67	3.1	3.1
		0.9	.50	0.8	0.8
		.5	.00	.5	.5
		.0	.00	.0	.0

(kr)	Life expectancy (in days) $\bar{x}$	SD	M	M_{corr}
	***Armadillidium:* medium nymphs (n = 25)**			
ab	116.9	78.71	118.0	...
a	164.6	83.17	142.5	...
	...	...	...	...
a	110.4	59.58	81.2	...
b	67.7	23.84	71.3	83.0
	38.2	14.12	42.6	44.5
	18.4	9.00	22.0	23.3
	8.5	3.34	8.6	8.6
	0.4	0.21	0.4	0.4
c	.0	.00	.0	.0
c	.0	.00	.0	.0
	***Acheta:* medium nymphs (n = 25)**			
a	69.7	15.13	72.3	...
ab	63.4	26.64	67.4	...
b	42.5	39.19	25.6	26.0
c	9.9	1.44	10.1	10.1
c	9.2	1.71	9.3	9.3
	5.5	1.70	5.9	5.9
	3.5	0.62	3.4	3.4
	1.9	.48	1.8	1.8
	1.0	.46	1.0	1.0
d	0.0	.00	0.0	0.0
d	.0	.00	.0	.0
	***Blatta:* medium nymphs (n = 20)**			
a	167.3	20.80	172.5	...
ab	143.5	56.16	172.2	...
b	108.4	75.25	139.0	157.2
	...	...	...	...
c	17.3	10.77	22.3	22.2
c	14.9	9.02	13.0	13.0
	4.0	1.96	3.4	3.4
	1.4	1.04	0.8	0.8
	0.4	0.22	.3	.3
d	.0	.00	.0	.0
d	.0	.00	.0	.0
	***Oncopeltus:* young adults (n = 15)**			
a	26.3	29.93	17.0	...
a	25.5	24.90	10.5	...
a	33.4	20.20	36.5	...
a	24.3	16.53	27.6	...
a	22.8	9.38	24.0	...
b	8.1	3.16	8.5	9.5
b	8.7	2.89	8.5	10.5
	5.3	2.19	5.6	6.0
	2.7	0.86	2.5	2.6
	1.3	.31	1.4	1.4
	0.0	.00	0.0	0.0

Table 2.—(Continued)

Dose	(kr)	Life expectancy (in days) $\bar{x}$	SD	M	M_{corr}	(kr)	Life expectancy (in days) $\bar{x}$	SD	M	M_{corr}
		Thermobia: medium nymphs ($n = 10$)					*Crematogaster:* mixed adults ($n = 30$)			
		500[c]		...	...	ab	82.7	49.78	83.5	...
		500[c]		...	...	a	102.0	50.07	87.7	...
		...[a]		...	...	bc	57.5	28.05	42.7	45.5
	a	59.2	13.37	62.0	63.9	c	39.4	40.77	18.8	20.5
	a	64.2	19.14	65.5	72.5	d	20.3	10.20	19.5	20.1
		26.0	7.56	27.0	28.0	d	18.4	7.71	18.3	19.0
		11.4	4.51	11.0	11.0		12.0	3.76	12.2	12.4
		4.9	3.60	5.0	5.0		5.9	1.89	5.7	5.7
	b	0.1	0.21	0.0	0.0		3.3	0.61	3.3	3.3
	b	.0	.00	.0	.0		0.5	.00	0.5	0.5
	b	.0	.00	.0	.0		.0	.00	.0	.0
		Harpalus: mixed adults ($n = 15$)					*Periplaneta:* medium nymphs ($n = 20$)			
		224.4		243.0	...		400[c]	...	...	...
		166.5	95.88	205.3	...		400[c]	...	...	...
		31.9[d]	...	8.0	8.1		400[c]	...	...	...
	a	5.8	1.82	5.8	5.9	a	11.5	11.00	5.5	5.5
		4.4	1.23	4.3	4.3	ab	6.4	4.98	4.7	4.7
	a	6.4	1.84	6.0	6.0	b	4.0	2.59	3.0	3.0
	b	3.0	1.11	3.0	3.0		2.0	0.76	1.9	1.9
	b	2.3	0.59	2.2	2.2		1.3	.41	1.4	1.4
		1.1	.57	1.2	1.2		0.5	.00	0.5	0.5
		0.0	.00	0.0	0.0	c	.0	.00	.0	.0
		.0	.00	.0	.0	c	.0	.00	.0	.0

[a] Accidental death.
[b] 5% confidence limits.
[c] Extrapolated from 218 days' data, or from literature references.
[d] Corrected for accidental death; no statistical comparisons made

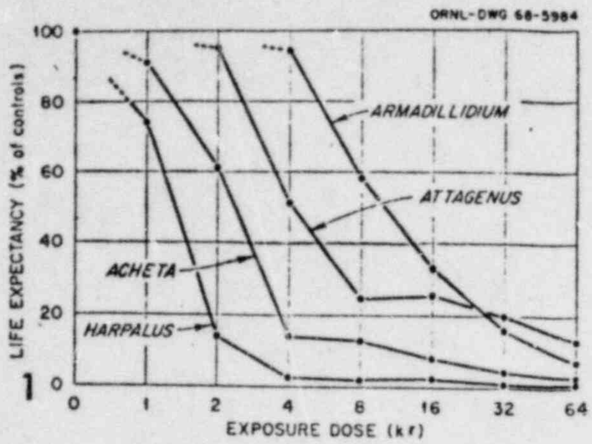
trols (Fig. 1). Styron (1969) found aquatic isopods to be less susceptible to radiation under optimum conditions of temperature and humidity, than isopods subjected to drought heat stress. On the other hand Edwards (1969) found *Porcellio scaber* Latreille to be the most susceptible of a series of soil arthropod species subjected to gamma radiation.

Thermobia had a dose-response curve similar to that for *Armadillidium*, but was less sensitive (Table 2). After 150 days only 1 of 10 controls was dead, and only 3 of 10 given 1 kr were dead. The threshold dose was between 2 and 4 kr. Observations were discontinued after 150 days, and life expectancy of medium-sized nymphs was estimated at 500 days based on Sweetman's (1938) data.

Adult *Crematogaster* of mixed (unknown) ages were irradiated. Mortality of controls and experimentals exposed to 1 kr was regular, there being no period of exceptionally high mortality. *Crematogaster* survived relatively high doses of radiation (Table 2) but was still affected by lower doses: the threshold dose was between 1 and 2 kr. A few individuals seemed to be much more resistant to radiation than others. Of individuals receiving 8 kr, 92% were dead after 25 days, but 100% mortality was not reached for 67 days. Two periods of mortality were observed for 2 kr: 43 and 109 days. For 4-kr exposures, 1 period of high mortality occurred at 21 and another at 116 days.

Blattella controls and individuals exposed to 1 or 2 kr survived well (Fig. 2). Only 1 animal died before 95 days. Those exposed to 4, 8, or 16 kr survived 11 days with little mortality. Controls reproduced regularly after 39 days; individuals exposed to 1 kr or more were apparently sterile. Threshold doses occurred between 2 and 4 kr. An exposure of 4 kr reduced survival to about 20% normal life expectancy (Fig. 2). Ross and Cochran (1963) obtained similar results with medium and large nymphs of *Blattella:* a dose of 6.4 kr reduced median survival time to 26 days; 9.6 kr further reduced it to 17 days. Growth was retarded by 9.6 kr, and molting was prevented. A dose of 0.8 kr reduced fertility to 48% of controls; 1.6 kr reduced fertility to 3%.

Oncopeltus was difficult to rear in quantity because of high mortality evidently caused by an unknown disease with symptoms similar to those described by Beard (1959). A series of experiments was run in which temperature, humidity, and incandescent lighting were varied systematically; mortality was unpredictable in all cases. This high mortality resulted in large standard deviations and reduced mean lifespan in controls (many individuals in the control group lived 47 days although the control mean was 26 days). Consequently, mean life expectancies of irradiated replicates did not differ statistically from the control lifespan until doses of 16 kr were attained (Table 2). That lower doses did produced a mortality effect is demonstrated by the decrease in time required to reach 100% mortality. For controls, this equaled 110 days; for 1 kr, 82 days; 2 kr = 68 days, 4 kr = 54 days, 8 kr = 40 days, 16 kr = 15 days. In other ex-



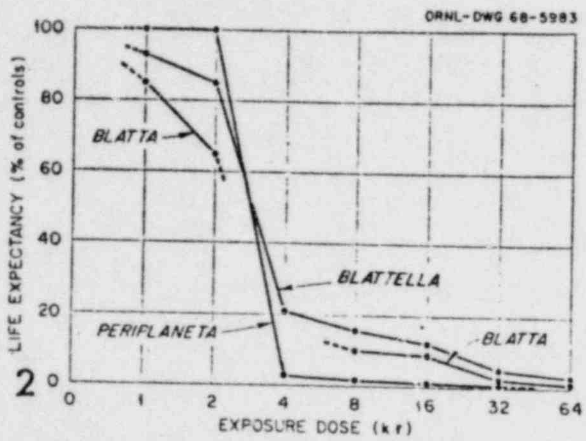


FIG. 1.—Mortality responses of 4 arthropods to gamma irradiation from cobalt-60.

FIG. 2.—Mortality responses of 3 cockroach species to gamma irradiation from cobalt-60.

periments with *Oncopeltus* nymphs, the ability to molt successfully to the next instar was used as a measure of radiation sensitivity. Unlike mortality, this biological end point is not time dependent, but it may be less responsive than mortality. Results indicated threshold doses between 8 and 16 kr (Table 3) for instars I, II, and IV. A similar threshold dose was estimated for adult mortality. Results for nymphal stage III were erratic. Eggs were much more sensitive; 0.5–1.0 kr greatly reduced hatchability (Table 3). Adults exposed to 2 kr or more were apparently sterile, although individuals exposed to 1 kr reproduced. *Oncopeltus* adults seemed comparatively resistant to radiation-induced paralysis. It did not generally occur until 1 day before death. A few individuals were still walking 7 days after exposure to 64 kr.

Tenebrio larvae exposed to 1 kr survived as long as controls. Those given 2 kr had a longer life expectancy than controls (although the difference was not statistically significant). Threshold doses occurred between 2 and 4 kr. All individuals were dead 1 day after exposure to 512 kr. Results with immatures and adults of *Tenebrio* have been reported in detail elsewhere (Menhinick and Crossley 1968).

Table 3.—Radiation sensitivity of immature *O. fasciatus*. Percentage hatch of eggs or molt of nymphs following exposure to cobalt-60 gamma irradiation. (I–IV are nymphal instars. Each value based on 20–40 nymphs.)

Dose (kr)	Eggs		Nymphs			
	1 day old	3 days old	I	II	III	IV
0.0	86	95	81	70	90	90
.5	50	90	...[a]			
1.0	0	40	100	...	...	...
2.0	3	0	95	...	...	...
4.0	0	0	77	74	19	75
8.0	0	0	80	54	20	50
16.0	0	...	28	45	55	10
32.0	...	...	0	10	0	5
64.0	...	...	0	0	0	0

[a] Not investigated.

Blatta nymphs had a generation time of about 7 months. Most mortality of controls and individuals exposed to 1 kr occurred within a terminal 30-day period. The threshold dose was between 1 and 2 kr. This species was especially sensitive to higher doses; 64 kr killed most individuals within 2 days.

Sceliphron was the only species not confined to jars for observation. Individuals were marked by tarsal clipping according to dose received and placed in flight cages. They were removed after they died. Limitations of material and cage space reduced the number of doses which could be investigated (Table 2). The threshold dose occurred between 2 and 4 kr. Individuals exposed to 8 kr died at 2 different times: 30% died during the 1st day after irradiation, and then the remainder survived about 15 days. Paralysis preceded death by less than 1 day. Bodine and Evans (1934) irradiated *S. caementarium* (Drury) larvae. Pupae failed to emerge from prepupae after exposures of 0.8–1.0 kr; diapaused pupae failed to emerge from prepupae after exposures of 1.2–1.3 kr. Shinn et al.[4] reported that utilization of radioactive mud by *S. caementarium* resulted in a 40% reduction in emergence from cells evidently caused by a radiation exposure of about 10,000 rad from the radioactive mud.

Acheta was 1 of the more sensitive species we tested. The threshold dose occurred between 1 and 2 kr. Life expectancy was decreased sharply following exposure to 4 kr, but further increments of dose had only slight additional effects on reduction of life expectancy. Doubling the dose reduced life expectancy by only about 20–30% (Table 2, Fig. 1). A dose of 256 kr killed all individuals instantly. Sumarukov (1962) irradiated 7- to 14-day-old adults of *A. domesticus* at 270 R/min and found the $LD_{50-25\ days}$ was 4200 R. *Acheta* used in our experiments were found to be more sensitive, perhaps because of the higher dose rates we used. Results for *A. domesticus* have been reported in more detail elsewhere (Menhinick and Crossley 1968).

Harpalus adults were unusually sensitive to radi-

[4] A. F. Shinn, G. J. Dodson, and C. L. Corley. 1964. Transport of radioactive materials by mud-dauber wasps. Oak Ridge National Laboratory Report no. ORNL-3697, p. 71–72

ation mortality, having a threshold dose between 1 and 2 kr (Table 2, Fig. 1). Doses of 4 kr reduced life expectancy from 224.4 days (control) to 5.8 days. Control mortality was low until after 54 days, when it became regular; 1 individual died about every 2 weeks.

Periplaneta was more sensitive to radiation than any other species examined. It is long lived with slow development; generation time is about 10 months. After 218 days controls and individuals exposed to 1 or 2 kr had exhibited little mortality response. Observations were discontinued at that time (218 days) and average life expectancy was estimated at 400 days from extrapolation of the data. However, at 4 kr exposure life expectancy was only 11.5 days (Table 2). Mean survival time decreased rapidly at higher doses and was lower than that for any other species following exposures to 16, 32, or 64 kr. All individuals were killed immediately by exposure to 128 kr. Wharton and Wharton (1959) irradiated *Periplaneta* nymphs with 2-Mev electrons and found it an unusually sensitive species. They reported a T_{50} of 4.0 days for 30 krep (rep = roentgen equivalent physical), 5.2 days for 20 krep, 7.5 days for 10 krep, and 14 days for 6 krep.

DISCUSSION

Comparison of Mortality Responses.—That comparisons between species would be valid, all experiments were maintained at near-indentical conditions of temperature and humidity. Irradiations were performed with the same machines and in an indentical manner. Insofar as possible, experiments were run concurrently. An alternative to this procedure would have been to maintain each species under its own optimal culture conditions (for survival). However, for some of the species included, culture optima are not well known. Also, differential responses to the different culture conditions might have increased the accuracy of comparisons with controls, but mitigated against comparisons between species. For the species included, only *Oncopeltus* gave indications that culture conditions were suboptimal.

A greater problem is the necessity for comparing different life-history stages of different species. Some species are easily studied only as adults, while the adult stage in other species is short or not suited to maintenance in cultures. Studies with immatures of *Acheta* and *Tenebrio* (Menhinick and Crossley 1968) and *Blattella* and *Periplaneta* (Menhinick, unpublished) indicated that medium-aged or older immatures (nymphs or larvae) had about the same patterns of survival following irradiation as do adults. Also, responses to a given dose level were similar. Accordingly, we have atempted to compare medium-aged immatures of some species with adults of others, in terms of their mortality responses to irradiation. Unfortunately, immature stages cannot always be separated by sex, so we are unable to report any differences in survival rates of males and females.

Dose-effect curves had different slopes for the different species. Slopes were relatively gentle for *Attagenus, Armadillidium*, and *Harpalus*. They were more abrupt for *Acheta, Blatta, Blattella*, and *Periplaneta*. The differences in slope (and in threshold dose where effects become manifest) suggest that the relative order of sensitivity for species could be different at different exposure doses, which is indeed the case. Comparisons of sensitivity are valid only at the dose for which they are made. Table 4 compares responses of the species to doses of 8, 16, and 32 kr. These doses were selected because they are higher than threshold, so corrections for control mortality are possible, and lower than doses producing quick kills or paralysis. The order of species in Table 4 is from least sensitive (*Attagenus*) to most sensitive (*Periplaneta*). All 3 doses were considered in arranging species in the order given. Some adjacent species might be reversed, but this course would have little effect on conclusions.

Relation of Radiosensitivity to Species Characteristics.—Previous work has suggested the hypothesis that sensitivity to radiation mortality may be related to lifespan; that is, that species normally living longer may be more sensitive than others to radiation. In our experiments species with longer (control) life expectancies (*Attagenus, Thermobia, Harpalus*, and *Periplaneta*) varied from most resistant to most sen-

Table 4.—Comparative radiosensitivity and biological data for 12 arthropods.

Organism	Mean life expectancy (days) after exposure to				Arthropod order	$\bar{x}$ adult wt (mg)	
	0	8 kr	16 kr	32 kr		Wet wt	Dry wt
Attagenus	284.6	70.6	73.2	52.5	Coleoptera	4.3	1.7
Armadillidium	116.9	83.0	44.5	23.3	Isopoda	76.1	23.7
Thermobia	~500	72.5	28.0	11.0	Thysanura	23.0	7.3
Crematogaster	82.7	20.1	19.0	12.4	Hymenoptera	0.5	0.1
Blattella	136.2	22.3	16.3	6.6	Orthoptera	101.6	35.0
Oncopeltus	26.3	...	9.5	10.5	Hemiptera	56.3	14.2
Tenebrio	73.4	21.0	13.4	8.8	Coleoptera	52.3	23.7
Blatta	167.3	22.2	13.0	3.4	Orthoptera	683.5	213.3
Sceliphron	44.2	15.2	...	...	Hymenoptera	107.0	42.3
Acheta	69.7	9.3	5.9	3.4	Orthoptera	398.3	[illegible]
Harpalus	224.4	4.3	6.0	3.0	Coleoptera	152.0	47.0
Periplaneta	~400	4.7	3.0	1.9	Orthoptera	937.3	322.6

sitive. Likewise, species with short life expectancy varied greatly in radiosensitivity (Table 4). Radiation sensitivity appears to be independent of lifespan.

There does appear to be a relationship between radiation sensitivity and activity of the species. The most resistant species tested, *Attagenus*, is a sedentary feeder on grains. *Armadillidium*, also a resistant species, exhibited little movement in our cultures. Likewise, the more sensitive species tend to be active. *Periplaneta, Harpalus*, and *Acheta*, all sensitive to radiation, were active in cultures. However activity is difficult to quantify, and our observations are qualitative.

Phylogenetic relationships are among the more obvious which might be related to radiation sensitivity. Inspection of Table 4 shows that related species may have widely differing radiation sensitivities. The 3 species of cockroaches vary in their mortality responses from "intermediate" to "sensitive." *Attagenus* and *Harpalus* varied widely in their sensitivity to radiation, but both are beetles. At lower levels in the taxonomic heirarchy, phylogenic relationships may be better indicators of radiation sensitivity.

Predictability within insect orders and families may improve when size relationships are considered. Cole et al. (1959) determined the $LD_{50-24\ hr}$ for 7 species of insects affecting man and found that "of the species of insects tested, the larger the insect the lower was the dose required to kill." Comparison of radiosensitivity with weights of adults (Table 4) suggests that such a gross relationship is present. Larger species tended to be more radiosensitive. The relationship is improved if comparisons are made within insect orders. For the Orthoptera, particularly the Blattidae, smaller species tended to be more resistant to radiation-induced mortality (Table 4, Fig. 3). For Coleoptera and Hymenoptera, radiosensitivity varied directly with weight of adults: *Attagenus, Tenebrio*, and *Harpalus* follow this rule, as do the 2 hymenopterans.

The reasons larger species appear to be more radiosensitive are not at all obvious. There may be a relationship with the total dose of radiation received rather than the radiation per unit weight. Larger species, having more mass, would absorb more total radiation if not more per unit weight. Since the mechanisms by which radiation produces mortality in insects are still largely undescribed, further speculation would be premature.

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