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THE EFFECTS OF HIGH-AMPLITUDE IMPULSIVE NOISE ON HATCHING SUCCESS: A REANALYSIS OF THE SOOTY TERN INCIDENT

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In a widely cited article, Austin et al. (1970a, Proc. Int. Ornith. Cong. 15:627) attributed a mass hatching failure among 50,000 pairs of Sooty Terns (*Sterna fuscata*) nesting on the Dry Tortugas to damage caused by sonic booms from low-flying military aircraft. Theoretically, eggshells and embryonic tissues should withstand pressures much greater than those generated by even the most intense sonic booms, so we conducted a "worst case" experiment to test whether impulsive noise could cause mass hatching failures. We exposed 20 chicken (*Gallus gallus*) and 20 quail (*Coturnix coturnix*) eggs to explosions of four pest-control devices (mean peak flat sound pressure level 177.3 dB re 20 μPa; mean CSEL of 139 dB; mean frequency 620 Hz). None of these eggs showed the longitudinal cracks that had been reported on Dry Tortugas. We also exposed fertile chicken (13) and quail (8) eggs to five similar impulses and compared hatch rates with those of matched controls. The chicken eggs were exposed on Day 2 of incubation, the most sensitive phase of development; the quail eggs at half-way through incubation, the time of exposure on the Dry Tortugas. Hatch rates and weights between control and exposed embryos were not significantly different. Thus, we were unable to duplicate any of the effects attributed to sonic booms. Our data indicate that hatching failures due to physical effects of sonic booms are highly unlikely.

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ABSTRACT

In a widely cited article, Austin et al. (1970a, Proc. Int. Ornith. Cong. 15:627) attributed a mass hatching failure among 50,000 pairs of Sooty Terns (*Sterna fuscata*) nesting on the Dry Tortugas to damage caused by sonic booms from low-flying military aircraft. Theoretically, eggshells and embryonic tissues should withstand pressures much greater than those generated by even the most intense sonic booms, so we conducted a "worst case" experiment to test whether impulsive noise could cause mass hatching failures. We exposed 20 chicken (*Gallus gallus*) and 20 quail (*Coturnix coturnix*) eggs to explosions of four pest-control devices (mean peak flat sound pressure level 177.3 dB re 20 μPa; mean CSEL of 139 dB; mean frequency 620 Hz). None of these eggs showed the longitudinal cracks that had been reported on Dry Tortugas. We also exposed fertile chicken (13) and quail (8) eggs to five similar impulses and compared hatch rates with those of matched controls. The chicken eggs were exposed on Day 2 of incubation, the most sensitive phase of development; the quail eggs at half-way through incubation, the time of exposure on the Dry Tortugas. Hatch rates and weights between control and exposed embryos were not significantly different. Thus, we were unable to duplicate any of the effects attributed to sonic booms. Our data indicate that hatching failures due to physical effects of sonic booms are highly unlikely.

1.0 INTRODUCTION

In 1970, when exposure to sonic booms was a topic of much concern (Shurcliff 1970), Austin et al. presented a paper at the International Ornithological Congress (IOC) in which they concluded that sonic booms had caused mass hatching failure of Sooty Terns on the Dry Tortugas, Florida. The evidence admittedly was circumstantial (Austin et al. 1970a); yet, the abstract of this presentation has become the most commonly-quoted evidence that sonic booms harm wildlife. It is referenced in reviewed publications (Bell 1972, Feare 1976, Cottereau 1978, Haynes 1987), popular journal articles (Graham 1979, Anonymous 1969, Shotton 1982), government sponsored studies (Hinshaw et al. 1970, Subcommittee on Animal Response 1970, Fletcher and Harvey 1971, Bender 1977, Hurtubise et al. 1978, Manuwal 1978, Hecock and Rhoads 1979, Dufour 1980, Ellis 1981, Kull and Fisher 1988, Manci et al. 1988), and many Environmental Impact Statements (EIS).

Austin et al. (1970b) outlined their case in a lengthy and well-documented manuscript which was not submitted for publication. Briefly, normal numbers of ground-nesting Sooty Terns (*Sterna fuscata*; 50,000 pairs) and bush-nesting Brown Noddies (*Anous stolidus*; 2500 pairs) were found breeding on the Dry Tortugas in April and May of 1969. The expected numbers of eggs had been laid. On 23-27 May there were fewer chicks than expected, but adults appeared to be incubating normally. However, when the authors arrived in mid-June to count and band fledglings, they found half the adult Sooty Terns gone and the remaining ones "markedly wild and restless". Many eggs were lying on the rookery abandoned, containing partially developed embryos. They banded only 242 fledglings instead of the expected 20,000. This failure was particularly startling because the Brown Noddies, nesting in bushes in the same area, fledged normal numbers of young.

To explain the cause of the failure, Austin et al. considered and rejected many possible explanations, including predators, food shortages, pesticides, humans walking on the rookery, and abnormal weather conditions. An unusually heavy growth of underbrush might also have been a contributing factor. They also discovered that residents of the Fort Jefferson National Parks Service Station on neighboring Garden Key had been disturbed by sonic booms intense enough to shatter windows. Although sonic booms were a common occurrence on the Dry Tortugas at that time, unusually intense booms were heard on 4, 8, 9, and 11 May.

In the published abstract Austin et al. (1970a) were careful to state "we have no evidence that sonic booms caused physical damage to the eggs, but it is entirely possible that strong booms caused desertion". However, in their manuscript they deduced that physical damage to the eggs by sonic booms caused the losses because many of the failed eggs had longitudinal hairline cracks and because the timing of the overflights agreed well with the stage of development of the failed eggs. They speculated that very low-altitude military jets (100 m or below) flying at supersonic speeds had caused the damage. After discovering the hatching failure, the Parks Service prevailed upon the Navy to avoid the Dry Tortugas and also arranged to have the brush cleared off. The hatch the following year (1970) was normal, and no similar incident has occurred since (Woolfenden and Robertson pers. comm.).

The most compelling evidence used by Austin et al. was the correspondence between the sonic booms and the egg failures, although they did not provide any measurements or calculations to show that eggs are vulnerable to sonic booms. They explained the difference in success between the Brown Noddies and Sooty Terns by noting that there is a doubling of sound intensity close to the ground and by quoting an unpublished manuscript by the National Research Council of Canada (Kuhring 1970), which allegedly presented evidence that sonic booms from a supersonic aircraft could "completely demolish" exposed but not unexposed chicken eggs. In their view, these experiments could explain the difference in damages between the two species because Sooty Terns tend to stand over their eggs on warm days, but Brown Noddies sit.

Nevertheless, laboratory studies at the time and since have failed to find evidence that sonic booms can crack eggs (Stadelman 1958, Cottereau 1972, Heinemann and LeBrocq

1965, Teer and Truett 1973, Cogger and Zegarra 1980). In addition, unpublished calculations made by aeronautics engineers at the time indicated that the sonic boom from low-flying aircraft had insufficient magnitude to damage eggs (letter to Col. J. P. Taylor from Boeing Co., 5 November 1970). There are deficiencies in the previous experimental work, unfortunately. The theoretical calculations were never published or independently reviewed and none of the published experiments considered the shock wave or exposed eggs to the worst-case sonic boom from a military jet.

Because the incident is still treated as fact, we conducted a short series of experiments to determine whether it is possible for shock waves of a worst-case sonic booms to crack eggs or damage embryos. We also reviewed the literature on eggshell strength and resistance of tissues to accelerative damage.

2.0 RATIONALE FOR THE CHOICE OF EXPERIMENTAL SIGNAL

Sonic booms break windows and damage structures. Eggs are fragile. Consequently, many people assume that sonic booms should break eggs. Eggs, being spheroidal, are extremely resistant to changes in a uniform pressure field. The skeptical reader can test this by attempting to crush an egg by squeezing it in his hand. Eggs are more vulnerable to directional or point pressures. A sonic boom is not a uniform pressure field, it has leading and trailing shocks, lending support to the assumption that it imperils eggs. We decided to test this assumption with a signal that had a much more severe leading shock and higher pressure than any sonic boom.

To determine the worst-case levels of sonic booms and their shock waves, we obtained data from the Air Force Medical Research Laboratory (M. Downing pers. comm., 30 August 1990). A small supersonic fighter of the sort used commonly in the late 1960's (an F-4) travelling at its highest speed (Mach 1-1.3) at the lowest possible altitude (30 m) would generate a peak overpressure of around 120 psf (143 dB CSEL) and would produce a shock wave of equal or lesser magnitude. These data agree well with measurements in a published report (Nixon et al. 1968). The "carpet" of the sonic boom would be about 610 m on either side of the aircraft at such low altitudes. The total duration of the sonic boom would be around 110 ms. Such severe booms have been recorded in field tests over runways (Nixon et al. 1968). Actual supersonic operations at such altitudes would be extremely hazardous to pilot and aircraft, however, particularly over the Dry Tortugas, where the prospects for a bird strike are high.

The impulses used in our experiments were chosen to meet or exceed these worst-case values. They differ from sonic booms in several ways. Although they lack the large negative shock of the typical sonic boom, they have much higher peak overpressure and faster rise-time. The thickness of the leading shock of a near-field sonic boom at least 1 m, whereas that of the impulses we used was only 50 to 135 mm thick. Brief, high frequency signals of this sort are more likely than a sonic boom to break a small hollow spheroid, such as an eggshell, so they provide a particularly rigorous test of the potential for breakage.

3.0 METHODS

Our test impulses were blasts from a small explosive charge, a Class-C pest-control device (64% potassium perchlorate, 10% sulfur) ignited by an electric detonator. These charges had peak sound levels of over 170 dB re 20μPa (138-144 dB CSEL), and rapid onset times (100-400 μsec). Table 1 lists the peak levels, onset times and durations of the test blasts. Calibrated sound levels from all test blasts were obtained with a B&K 8103 hydrophone connected to a B&K 2635 charge amplifier and recorded at 15 IPS on two FM channels of a Racal Store 4D tape recorder. The system was flat from 0-10 kHz. Absolute sound levels and spectra were calculated with a Spectral Dynamics SD380 two channel spectrum analyzer.

TABLE 1. ACOUSTIC CHARACTERISTICS OF THE HIGH-AMPLITUDE IMPULSES

Date	Shot No.	Peak Flat SPL (dB)	Frequency at Max. (Hz)	CSEL (dB)	Rise Time (μs)	Duration (ms)	Notes
21 Mar	1						Blast shield in place
	2						Blast shield in place
	3						Blast shield in place
	4	174.9	487.5	138.2	166	1.34	Blast shield in place
	5	175	775	138.7	166	1.20	Blast shield in place
	6	180	837.5	142.5	146	.95	Blast shield in place
	7	176.6	475	140.4	185	1.21	Blast shield in place
	8	175.8	625	140.0	185	1.51	Blast shield in place
	9	179.2	700	144.4	322	1.40	No blast shield
	10	177.6	625	142.7	293	1.38	No blast shield
	11	176.6	462.5	140.9	166	1.64	Blast shield in place
	12	179.8	725	144	351	1.42	No blast shield
	13	179.6	612.5	144.6	391	1.45	No blast shield
	14	177.5	500	143.1	342	1.54	No blast shield
29 Mar	15	172.9	437.5	139			No blast shield
	16	175.8	437.5	140.3			No blast shield

We exposed domestic chicken and quail eggs to these impulses using the setup in Figure 1a,b. Infertile eggs were exposed to at least two impulses and fertile eggs to at least four (Table 2). Impulses were separated by intervals of 5-10 minutes. A blast shield constructed of heavy felt was used to test the effects of the overpressure alone, and was later removed to add the shock wave. Charges were attached to a support 51 cm from the eggs, just outside the limit of the fireball from the blast.

TABLE 2. NUMBERS AND TYPES OF EGGS EXPOSED UNDER EACH TEST CONDITION.

Egg type	Number of Eggs	Test Condition	Number of Impulses Each	Shot Number
Infertile chicken eggs (both grades)	10	with blast shield	2	4 - 8
Infertile chicken eggs (both grades)	10	without blast shield	2	9 - 10
Infertile quail eggs	20	without blast shield	2	9 - 10
Fertile chicken eggs (Grade A large)	13	without blast shield	5	12 - 14
Fertile chicken eggs (Grade A large)	11	controls	0	none
Fertile quail eggs	8	without blast shield	4	13 - 16
Fertile quail eggs	4	controls	0	none

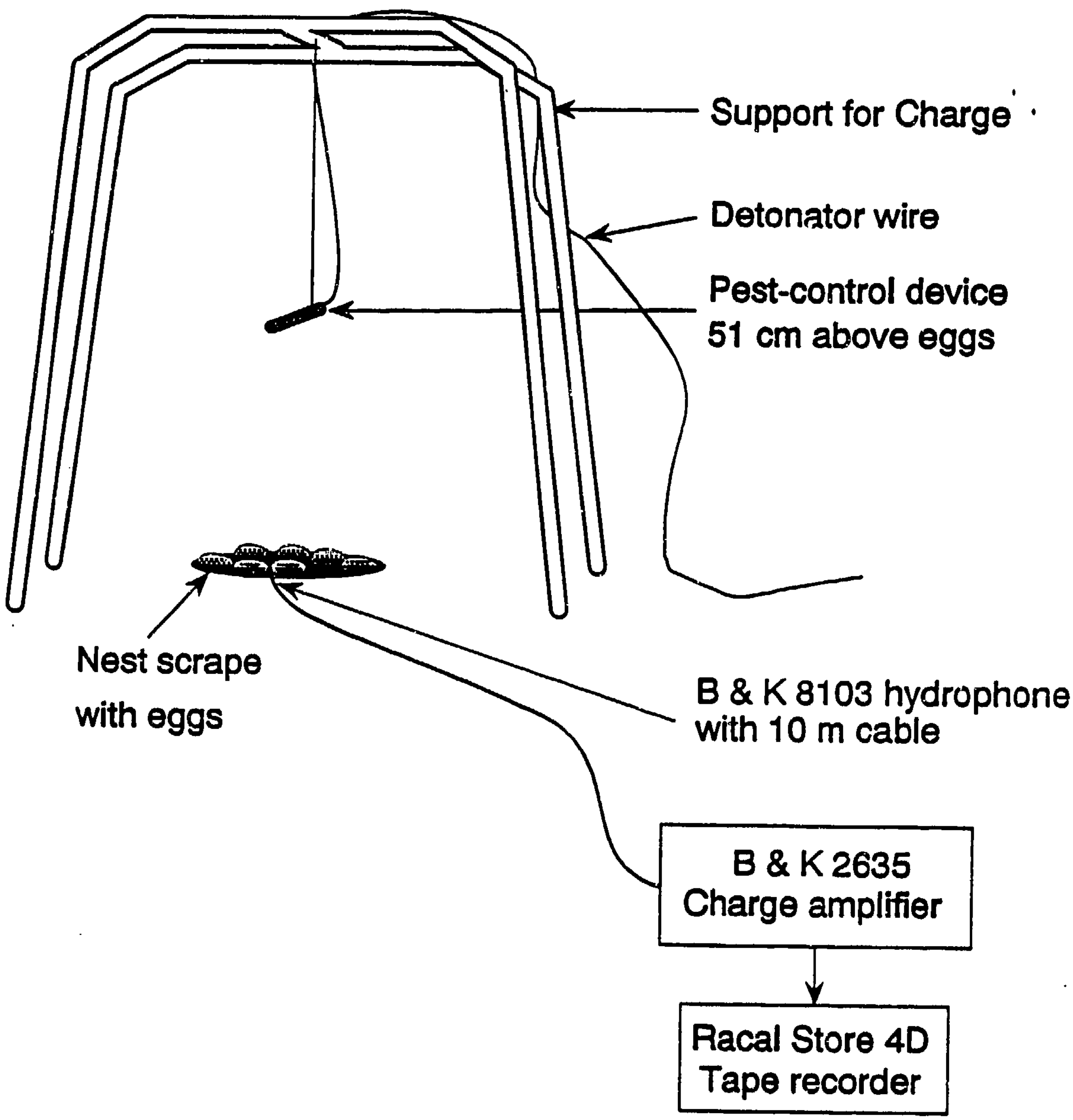

Figure 1a. Diagram of setup for exposing unshielded eggs to blast from pest-control device.

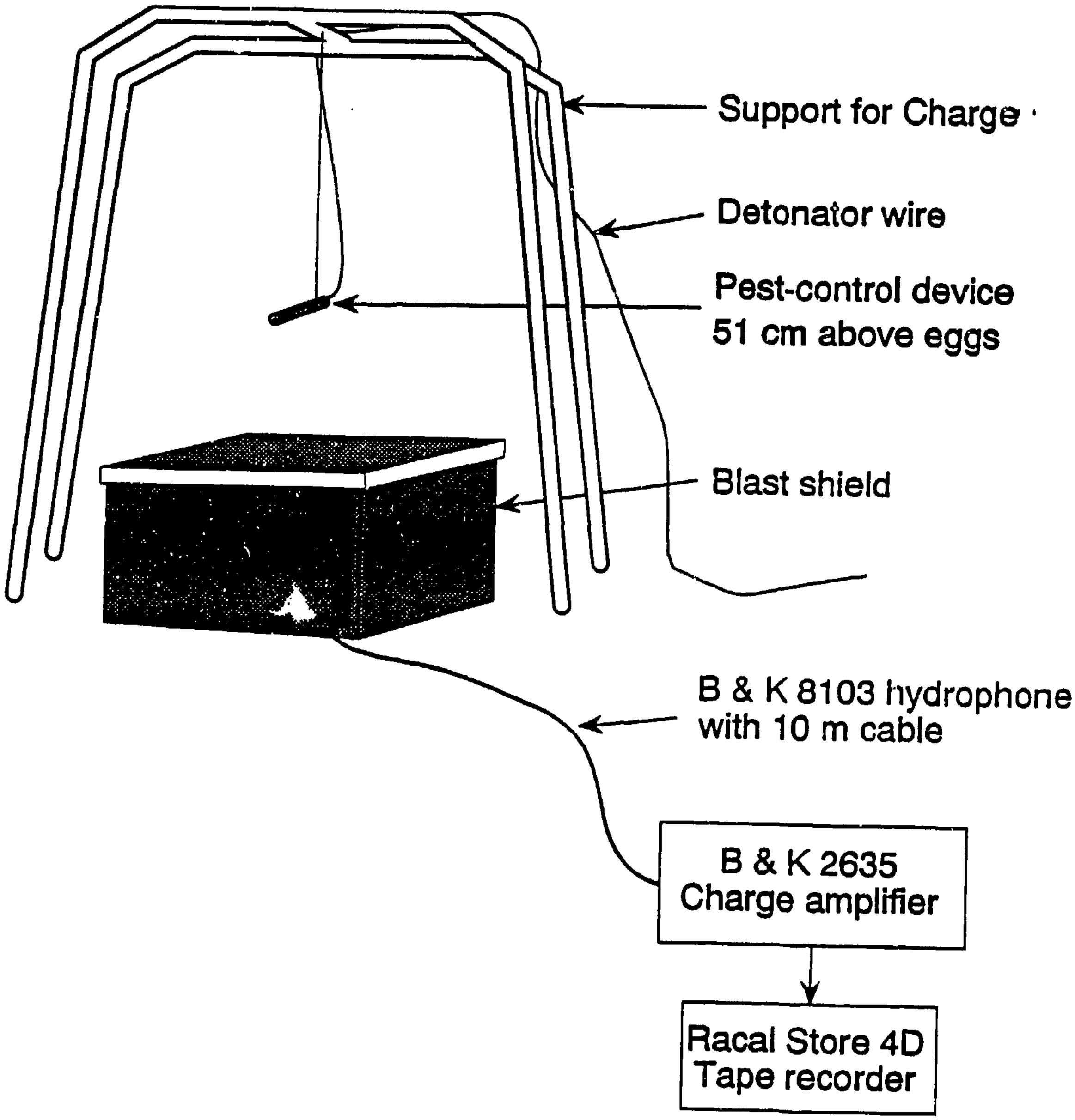

Figure 1b. Diagram of setup for shielding eggs from direct blast of pest-control device.

Fertile eggs were exposed to ambient temperatures of 16-20°C for no more than an hour during testing and were transported in a down-filled bucket for warmth and protection. They were kept in an automatic Petersyme incubator at 37°C (dry-bulb temperature) and 28°C (wet-bulb). At pipping, eggs were moved from the turning cage of the incubator to a padded hatchette. They were sprayed with a fine mist of water twice daily to moisten them during hatching. All chicks were reared for a week to determine whether they had suffered any damage. Control eggs were transported in the same manner as the experimental eggs, but were not exposed to blasts.

The chicken eggs were four days old at the time of testing. The quail eggs were about two-thirds of the way through incubation, the same age as the Sooty Tern eggs in the 1969 incident.

Before testing, all eggs were measured (Table 3) and examined for cracks with a 10x magnifier. The eggs were then placed in a sandy scrape similar to a Sooty Tern nest. Some were left in contact with each other (six chicken eggs) but most were separated by at least 1 cm (Sooty Terns only lay one egg).

4.0 RESULTS

None of the infertile eggs developed cracks of any kind, with or without the blast shield (Table 1). We cracked several eggs, marking the fracture lines with a dark pen, to determine whether impulses would worsen an existing crack. They did not.

Although the sample size of fertile eggs was too small to detect subtle effects from blast exposures, there was no evidence of significant hatching failure (Table 4). The results of the tests on fertile chicken eggs were most illuminating because these eggs were exposed at 48 hours of age, a time when the embryo is very sensitive to acceleration (Besch et al. 1965). One control and one exposed egg died before testing. All the remaining eggs hatched, so there was no significant difference between control and exposed eggs in hatchability. Control and exposed eggs did not differ in hatch date or weight (Student's t-test, $P > 0.05$).

TABLE 3. SHELL LENGTH, WIDTH AND THICKNESS OF FERTILE AND INFERTILE EGGS EXPOSED TO HIGH-AMPLITUDE IMPULSES DURING EXPERIMENTS

Egg Type	Number	$\bar{x}$ Length in mm (st. dev.)	$\bar{x}$ Width in mm (st. dev.)	$\bar{x}$ Shell Thickness in mm (st. dev.)	$\bar{x}$ Shell Thickness in mm without membrane (st. dev.)
Infertile eggs					
Grade AA large	20	59.87 (.94)	42.12 (.64)	.2064 (.0159)	.1812 (.0207)
Grade A jumbo	20	61.14 (1.84)	45.43 (.73)	.2221 (.0140)	.1869 (.0116)
Quail	20	31.55 (2.12)	25.16 (1.5)	.1319 (.0155)	.0981 (.0092)
Fertile eggs*					
Chicken (exposed)	13	54.7 (0.94)	42.0 (.64)	-	-
Chicken (unexposed)	11	55.4 (1.29)	42.3 (.64)	-	-

* Fertile quail eggs from same stock as infertile eggs.

TABLE 4. HATCHABILITY OF EXPOSED AND CONTROL CHICKEN AND QUAIL EGGS

	Exposed	Control	Exposures
CHICKEN EGGS			
Total	13	11	5
Number Fertile	13	11	
Number Hatched	12	10	
Number Normal	11*	10	
QUAIL EGGS			
Total	18	18	4
Number Fertile	8	4	
Number Hatched	6	3	
Number Normal	4**	3	
ALL EGGS COMBINED			
Total	32	29	-
Number Fertile	21	16	
Number Hatched	18	14	
Number Normal	14	14	

* One chick hatched with difficulty and had abnormal development of one foot. Conditions in the incubator apparently were insufficiently humid.

** One chick could not orient on food items and one hatched with abnormal development of one foot.

The results on quail eggs were similar. Unfortunately, the control and experimental samples of fertile eggs were unbalanced. Fertilities of 50-75% are not unusual in commercial quail eggs, and by chance the fertility rate in the control group was half that in the exposed group (four vs. eight fertile eggs, respectively). Although the sample was too small to test statistically, hatch rates did not appear to differ between experimental and control groups. Two exposed quail embryos died, one at about the time of exposure and one just before hatching. One control embryo died just before hatching. The losses certainly were not indicative of mass hatching failure.

TABLE 5. DURATION OF INCUBATION AND CHANGES IN WEIGHT OF EXPOSED AND CONTROL CHICKEN EGGS

Treatment	Weight at Hatch	Weight loss during incubation	Duration of Incubation
Exposed	49.0g	5.75g	22.5 days
Controls	49.5g	5.90g	22.6 days

We found possible abnormalities in two of the exposed quail and one chicken embryo after hatch. One of the quail chicks had difficulty balancing during pecking, suggestive of damage to the vestibular system, which could have been caused by exposure to extreme sound levels during the latter half of development. One chicken and one quail chick had difficulty hatching and had to be aided. They had abnormal development of one foot, probably caused by insufficiently humid conditions in the incubator, but blast/sound exposure could not be ruled out. Note, however, that even if these abnormalities were caused by the tests, they appeared after hatching and did not affect the bulk of the eggs.

5.0 DISCUSSION

The experiments we conducted with worst-case high-amplitude impulses did not crack eggs or kill embryos. These results are in accord with studies on chicken eggs, which are similar in size and shell thickness to those of Sooty Terns (chickens: 60x43 mm, 0.2 mm thick; Sooty Terns: 50x35 mm, 0.25 mm thick; W.B. Roberston, pers. comm). Worst-case peak overpressures of 145 psf would not be expected to crack chicken eggs or kill the embryos. Sluka et al. (1965) found that chicken eggs cracked only when uniform pressures, measured hydrostatically, equalled or exceeded 28 psi (4032 psf, 200 dB re 20 μPa). Besch et al. (1965) studied embryonic damage in chicken eggs that were accelerated suddenly to simulate impacts during transport. For accelerations lasting 100 ms no damages would be observed for induced accelerations below 1000 G, although the shock wave from an aircraft could not be expected to impart an acceleration of even 10 G. Thus, from a theoretical point of view, the hypothesized effect of the overflights on the Dry Tortugas would be impossible.

Previous empirical experiments have supported these analyses. Cottereau (1972) and his coworkers used a large sonic boom simulator at the Institute Saint Louis in France to expose chicken eggs to 300 ms sonic booms with peak overpressures of around 100 psf (163 dB), approximating the worst case expected from overflights of the Concorde supersonic transport. The eggs were exposed six times per day throughout incubation. Hatch rates actually exceeded those of matched controls by a few percent, and no evidence of cracking or embryonic damage was found. Cottereau's results agreed with other experiments exposing chicken and quail eggs to simulated peak overpressures in the range typical for loud sonic booms (120-140 dB, Heinemann and LeBrocq 1965, Teer and Truett 1973, Cogger and Zegarra 1980).

Fewer experiments have been conducted using sonic booms, mostly because the sonic boom generated by an aircraft is usually small, let alone damaging. The unpublished manuscript by Kuhring is not relevant to aircraft overflights. It was conducted in a high-speed wind-tunnel and the "shock effect" was one of blowing the eggs (literally) from their simulated nests (T. Weibust, National Research Council of Canada, pers. comm). Richmond and his coworkers used a 24-inch air-driven shock tube to test the effects of air blasts on a variety of animals (Richmond et al. 1968, Richmond 1966, unpub. memorandum). They exposed 19 fresh quail eggs to 5-6 msec side-on overpressures of 360 psf (178.7 dB) and 15 eggs to 691 psf (184.4 dB). Eggs were tested in pairs and received two exposures. The shock waves were great enough to blow four of the 19 (22%) and five of the 15 (33%) eggs out of the nest. One of the remaining eggs in each test was cracked (7-10% of eggs). These exposures were 3-5 times the magnitude of any sonic boom that could be produced by an aircraft; yet, fewer than 10% of the eggs were cracked. Thus, it is difficult to understand how the shock wave of a low-flying aircraft could have been responsible for a mass hatching failure.

Mass reproductive failures due to aircraft overflights have not been documented elsewhere, despite repeated laboratory and field experiments (e.g. Black et al. 1984, Schreiber and Schreiber 1980). If aircraft overflights actually played any role in the mass hatching failure on the Dry Tortugas, the circumstances must have been highly unusual. Acute and severe startles, such as the panic flights induced by human intrusions or low-flying aircraft, usually cause low percentages of reproductive failure from egg breakage (Hunt 1985), opportunistic predation (e.g. Burger 1981), and unknown causes (Ellison 1978, Fetterolf 1983).

While we have not ruled out the possibility of lowered reproductive success due to exposure when adults leave the nest, most "panic flights" after a noise disturbance are of such short duration that such damages are unlikely (e.g. Bowles and Stewart 1980, Schreiber and Schreiber 1980, Awbrey and Bowles 1990). Austin et al. considered this possibility, but ruled it out, because the weather was unusually mild in the spring of 1969 and because they never saw Sooty Terns leave their eggs exposed for more than ten minutes after a panic flight, even response to a very low-level overflight (100 m or less). Desertions caused by sonic booms would have occurred within a few days of exposure, but observers on the Dry Tortugas found Sooty Terns incubating normally on 23-27 May, over a week after the sonic booms that damaged Fort Jefferson.

Mass hatching failures have been reported in marine birds due to predators (e.g., Emlen et al. 1966), weather, inadequate food supplies (e.g. Schreiber and Schreiber 1984) and infestations of Idotid ticks (Feare 1976). Austin et al. (1970b) eliminated predators, weather and inadequate food supply as possible causes of the reproductive failure on the Dry Tortugas, but did not consider parasites. The evidence presented in their manuscript is consistent with Feare's description of a tick-induced mass hatching failure of a Sooty Tern colony on the Seychelles. However, Woolfenden and Robertson (1990 pers. comm.), who banded the few chicks present in June, camped on the island and found no evidence of ticks during their stay.

Our reanalysis of the "Sooty Tern incident" does not explain the mass hatching failure; instead, it eliminates one hypothetical explanation. This incident illustrates an all-too-common problem in population studies - even with prolonged and thorough study it is sometimes impossible to determine the causes of annual variation in breeding success. However, in our opinion, the adverse effect of sonic booms and aircraft overflights on birds has been greatly exaggerated. The focus of research and environmental concern about aircraft overflights should be on plausible effects, specifically impact on the auditory and vestibular system after exposure to high-amplitude impulses (over 140 dB) and on the long-term impact of small reproductive losses after startle reactions. Scientists and management agencies must develop supportable, quantitative and predictive models for such effects to justify their estimates of potential impact. Without these experiments or other direct documentation, the Sooty Tern incident is uninterpretable and should not be treated as evidence of an effect.

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