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[Article]

Effects of Explosives on Incubating Lake Trout Eggs in the Canadian Arctic

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Abstract.—Industrial development, including geophysical exploration and mining, has increased use of explosives in and near fish habitat. To protect fish and their incubating eggs, Canadian blasting guidelines contain maximum allowable limits for overpressure and peak particle velocity (PPV). Although many studies have focused on how overpressure causes mortality in fish, no studies have examined the effects of PPVs from explosives on fish eggs. We exposed the eggs of lake trout *Salvelinus namaycush* to blasts from an open-pit mine at Lac de Gras, Northwest Territories, and measured the effects on egg mortality. Twenty Plexiglas incubators, each containing 50 eggs, were placed in the lake substrate at four sites; blast-monitoring equipment was also positioned at these sites. Three sites were within 220 m of the pit's dike, in a zone where PPVs were predicted to exceed the guidelines. A reference site was located outside of this blast zone 2 km away from the pit. Substrate at one of the blast zone sites was composed of material used in dike construction, whereas other sites were natural spawning shoals. To assess egg mortality during the period of greatest egg sensitivity to physical disturbance, half of the incubators were retrieved after 20 d; the remaining incubators were retrieved at ice-out. After 20 d, mortality at two of the three blast zone sites was lower than reference mortality, whereas mortality at the third site did not differ from the reference level. At ice-out, the single blast zone site with nonnatural substrate had higher mortality (by 10%) than the reference site. Ice-out mortality at the other two blast zone sites was similar to that of the reference site. Given that the largest blast exposure (28.5 mm/s) throughout the incubation period was more than double the current maximum allowable limit but still produced mortality similar to the reference level, we suggest that existing guidelines provide ample protection under these blasting conditions. The margin of this protection, however, remains unknown.

Use of explosives in or near fish-bearing waters occurs with many activities, including geophysical exploration, construction, industrial development, and mining. Explosions produce seismic waves, which are manifest as small motions of the substrate or as pressure within the water column that radiate outward from the blast location. In engineering practice, the complex waveforms are usually quantified by characteristic measures, such as peak particle velocity (PPV) and overpressure. If the blasts are strong enough, the resulting pressure change and mechanical shock waves can negatively impact fish in the surrounding area. Past research has shown that the sudden pressure deficit, measured indirectly as overpressure, is responsible for most impacts on juvenile and adult fish by rupturing the swim bladder and other soft organs (Wright 1982). In contrast, the mechanical shaking of the substrate, measured as PPV, is believed to be most damaging to incubating eggs (Wright 1982). Appropriately, the Canadian Department of Fisheries and Oceans (DFO) developed guidelines for blasting that contain maximum allowable limits for both overpressure (100 kPa) and PPV (13 mm/s) in or near fish habitat (Wright and Hopky 1998).

If explosions generate PPVs that damage or kill incubating eggs, the habitat quality (sensu Marsden et al. 1995b) and productive capacity (sensu DFO 1986) of spawning reefs exposed to explosions may be compromised for species, such as lake trout *Salvelinus namaycush*, which broadcast their eggs onto those reefs. This, in turn, would require habitat compensation activities to offset reductions in productive capacity (DFO 1986). Physical shock, of which PPV is one type, has been demonstrated to increase mortality of lake trout eggs in laboratory experiments, and mortality is highest when the shock occurs during the final stages of epiboly (Fitzsimons 1994). This is comparable with what has been observed for other salmonid species (Smirnov 1954, 1955; Jensen and Alderice 1983, 1989). Similarly, Eshenroder et al. (1995) suggested that physical shock during a period that roughly corresponded with this development stage was largely responsible for differences in survival of eggs in buried

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versus exposed incubators on a Lake Superior spawning reef.

Although these largely qualitative studies of physical shock raise concerns about comparable effects of PPVs on incubating eggs, no research has examined the relationship between PPV and egg mortality, and there is uncertainty with respect to the 13-mm/s PPV guideline (e.g., Jensen 2003). There is also considerable uncertainty regarding the cumulative effects of repeated blasts on overwintering, developing eggs of fall-spawning fishes. Because use of explosives in or near waters will probably increase in the future, research is needed to assess the relationship between blast intensity (PPV) and its effect on developing fish embryos to assess the appropriateness of current blasting guidelines.

The objectives of our study were to (1) compare mortality of lake trout eggs exposed to PPVs exceeding the maximum allowable limit with mortality of eggs at a reference site and (2) assess whether egg mortality occurs primarily as the result of limited exposure during early development or repeated exposures throughout the incubation period.

Study Area

Lac de Gras is a large (surface area = 572 km^2), ultraoligotrophic (total phosphorus < 3 μg/L; DDMI 1998a), low-arctic lake located on the Barrenlands of the Northwest Territories, Canada, approximately 300 km northeast of Yellowknife. Our study area extended outward from the east side of East Island (approximately 64°31′N, 110°20′W; Figure 1), where Diavik Diamond Mines (DDMI) is conducting open-pit mining of kimberlite pipes in their A154 pit. Explosives are used as the primary method of excavating rock. While overpressure was not expected to cause concern (DDMI 1998a), it was predicted that a blast zone in which PPVs exceeded DFO's maximum allowable limit could extend up to 717 m beyond the pit's dike into Lac de Gras (DDMI 1998a).

Lac de Gras supports a stable, slow-growing community of at least eight coldwater fishes (DDMI 1997b), several of which are fall spawners (e.g., round whitefish *Prosopium cylindraceum*, cisco *Coregonus artedi*, and lake trout). Lake trout are dominant in Lac de Gras, both numerically and in terms of biomass (DDMI 1997b). Due to its position in the food chain, importance to traditional and sportfishing, and sensitivity to environmental change or disturbance, the lake trout was identified as a "sentinel species" for the lake (DDMI 1998b) and was the focus of our research. Eight potential lake trout spawning shoals were identified within the predicted blast zone of the A154 pit (DDMI 1997a). Eggs deposited on these shoals (late August to late September) incubate overwinter and hatch approximately 8–10 months later (May–July). During this long incubation period, they are exposed to both ambient environmental conditions and PPVs from blasts in the A154 pit.

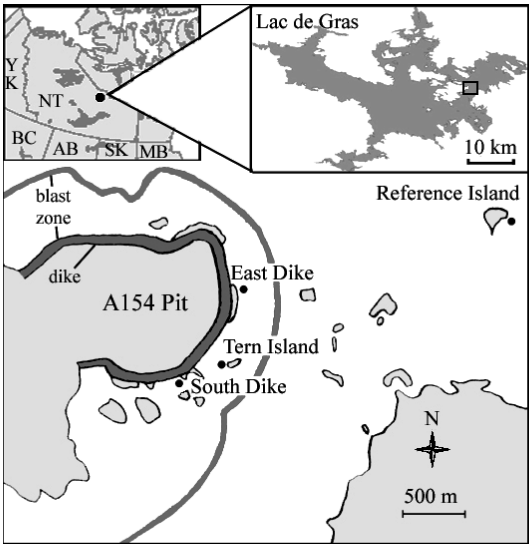

FIGURE 1.—Map of Lac de Gras, Northwest Territories (NT), Canada, and the four sites chosen for deployment of lake trout egg incubators and blast-monitoring equipment in 2003. The light gray line around the dike indicates the predicted blast zone, where maximum peak particle velocity was expected to exceed 13 mm/s for the A154 pit (Diavik Diamond Mines, Inc.) and a second proposed pit to be located to the south of A154.

Four sites with suitable spawning habitat were chosen for this study (Figure 1). Spawning habitat suitability was based on water depth (2.5–7.0 m, but next to deeper water), substrate size (4–30 cm, but up to 1 m) and shape (angular), interstitial space (0.2–1.0 m deep), and a location away from depositional effects (Scott and Crossman 1973; Gunn 1995; Marsden et al. 1995a; DDMI 1997a). Of the four sites, three were located within the predicted blast zone. Two blast zone sites, East Dike and South Dike, were located close to the dike wall; the South Dike site was composed entirely of crushed rock from the outer dike wall. In contrast, East Dike, although directly connected to the dike wall, was composed entirely of natural spawning substrate. The third blast zone site (Tern Island) was approximately 220 m east of the dike wall. A reference site (Reference Island) was located approximately 2,200 m east of the dike wall, well outside of the predicted blast zone (Figure 1). Both Tern and Reference islands were also composed of natural spawning substrate. All sites were at depths of 3–5 m and were close to land to enable deployment of geophysical blast-monitoring equipment.

Methods

Experimental procedures.—Lake trout were obtained with small-mesh gill nets (19–38-mm-bar mesh) between 2300 and 0130 hours on September 16–17, 2003. Eggs and seminal fluid were removed from three females and four males, respectively, and the eggs from individual females were mixed with the sperm from at least two males. Fertilized eggs were allowed to water-harden in lake water overnight (8 h), were disinfected with a weak iodine solution (1:600 by volume), and were rinsed in fresh lake water before being mixed into a bulk sample.

Lake trout eggs from this bulk sample were then loaded into Plexiglas "sandwich" incubators. These incubators were developed for investigations of survival and development of lake trout eggs (Kennedy 1980; Gunn and Keller 1984; Manny et al. 1989). Each incubator consisted of a 12.5- × 25.0- × 1.0-cm Plexiglas piece containing 50 separate cells that each held a single trout egg. These cells were enclosed on both sides with 2-mm Nitex mesh, which was held in place and protected by thinner pieces of Plexiglas (Manny et al. 1989: their Figure 1). The incubators allow exposure of eggs and fry to ambient conditions (including PPVs) in shallow interstitial waters but offer protection from other sources of mortality, such as predation, thereby allowing among-site differences in survival rate to be related to differences in local ambient conditions. Incubators were wedged into substrate interstices and held in place by side chains that were spaced approximately 1 m apart and that were attached to a main chain anchored to the bottom (Manny et al. 1989: their Figure 3).

After the incubators were loaded with lake trout eggs, 20 incubators were randomly assigned to each of the four sites. Incubators were inserted by divers into the substrate at the appropriate sites following the procedure of Manny et al. (1989). Deployment at all sites was completed on the same day starting with Reference Island and followed by Tern Island, South Dike, and East Dike. Each site received two chains of 10 incubators each that were located in close proximity and in similar suitable habitat conditions (described above).

Given that the period in which lake trout embryos are most sensitive to physical shock is early in development (Fitzsimons 1994), half of the incubators on each chain ($n = 5$) were retrieved after 20 d of exposure (September 17–October 7) to assess mortality during this early period (early retrieval). The remaining incubators were left in the lake until ice-out the following summer (July 16–18; final retrieval). During retrievals, sedimentation at the sites was noted qualitatively, as was whether each incubator had remained in the substrate or had been dislodged. When incubators were brought to the surface, they were immediately placed in containers of lake water.

Survival data analysis.—During early retrieval, the contents of two of the five incubators per chain were preserved in Davidson's solution for histological analysis at CDFO's Freshwater Institute, Winnipeg. Preserved eggs were examined at 40× magnification, and the presence and stage of development (Balon 1980) were determined for each egg. Any deformities of the embryos were also noted. Survival was calculated for each incubator as the number of eggs alive when preserved divided by the initial number of eggs ($n = 50$). The other early-retrieval incubators ($n = 3$ per chain) were transported by air to the University of Alberta's BioSciences Aquatics Facility. Eggs were kept in the incubators there and were held in a recirculation chiller unit at 4°C until after hatch. To assess survival of early-retrieval lake trout eggs incubated at the university, the incubators were monitored through the remainder of the incubation period (October 8 until the following spring), at which time the fates of all eggs were classified as dead, deformed, or hatched. Hatched fry were monitored in the incubator cells for an additional 45 d after hatch for better comparison with incubators remaining in the lake until final retrieval was possible. Survival of laboratory-incubated eggs was calculated for each incubator as the number of hatched (but not deformed) embryos divided by the initial number of eggs ($n = 50$).

At final retrieval, lake trout embryos still in the lake had already hatched, so contents of incubator cells were classified as dead, alive, or empty. Empty cells were subsequently classified as either dead (eaten or decomposed) or alive (escaped) to allow comparison with early-retrieval results. Two approaches, involving an escape correction of either 100% or 50%, were used for this classification. In incubators maintained in the laboratory, fry were frequently observed escaping from the incubator cells as the contents of yolk sacs were used up. Because we knew that fry were capable of escaping, we assumed in the 100% escape correction that all empty cells at final retrieval resulted from escapement of successfully hatched embryos; therefore, all empty cells were classified as alive. The 50% escape correction was based on data from Casselman (1995 and unpublished), who noted that half (50.3%) of the empty cells in his study had contained embryos that hatched prematurely, died, and decomposed or were consumed by invertebrate scavengers. In both cases, only mucoid remains of highly decomposed fry

TABLE 1.—Percentage survival (mean ± SE) per incubator ($n = 50$ eggs/incubator) for laboratory-reared ($n = 3$ incubators/chain) and preserved ($n = 2$ incubators/chain) lake trout eggs retrieved from substrate after 20 d (early retrieval) of exposure to blasts from an open-pit mine in Lac de Gras, Northwest Territories, Canada, in 2003. Survival did not differ between preserved and laboratory-reared eggs for any chain (t-tests: $P > 0.05$).

Site	Chain	Survival (lab-raised)	Survival (preserved)
South Dike	1	55.3 ± 2.7	53.0 ± 5.0
	2	56.0 ± 5.3	48.8 ± 8.0
East Dike	1	52.7 ± 6.7	52.0 ± 2.0
	2	54.7 ± 7.4	50.0 ± 2.0
Tern Island	1	43.3 ± 4.7	46.0 ± 6.0
	2	46.0 ± 4.2	47.0 ± 3.0
Reference Island	1	45.3 ± 2.7	50.0 ± 2.0
	2	42.0 ± 10.3	56.0 ± 2.0

were left in some of the empty cells. There was no explanation for the other half (49.7%) of the empty cells. Therefore, we also used a correction factor assuming that only half of the empty cells were the result of escapement. Survival at final retrieval was then calculated for each incubator as the number of live embryos (assuming either that 50% or 100% of the empty cells had contained a live embryo that escaped) divided by the initial number of eggs ($n = 50$).

Survival data were arcsine transformed before analysis to meet test assumptions (Zar 1999). Survival between incubator chains within and among sites was analyzed by means of a nested analysis of variance (ANOVA) design. When a significant difference in survival among sites was found, least-significant-difference multiple comparison was used to identify sites with survival different from the reference site. Results from the two retrieval periods were analyzed separately. Differences in survival between the early- and final-retrieval groups at each site were evaluated by a Student's t-test (Bonferroni-corrected significance level $\alpha = 0.0125$). All statistical tests were performed with SYSTAT (SPSS 2000). For all statistical tests, an α of 0.05 was used unless otherwise noted.

Blast data.—Blasts were monitored and recorded at all four sites using an OYO Sea Array 4 (OYO Geospace Corp., Stafford, Texas) four-component underwater geophone sensor attached to an Instantel Mini Blast Mate monitor (Instantel, Inc., Ottawa, Ontario). The sensor, attached to one of the chains at each site, was wedged between large boulders (in a manner similar to the incubators) to ensure coupling to the lake substrate. The sensor was then attached to a monitor placed on shore. Due to short battery life and extended length of time between blasts, we had to retrieve monitors between blasting events so that data could be downloaded and batteries could be recharged. As many blasts as possible were measured throughout the incubation period; however, due to poor weather conditions and equipment malfunction, some blasts were missed. These missed events were greatest at sites located away from the dike wall (Tern and Reference islands) because of difficulty in travel under arctic field conditions, especially at times of extreme cold and at lake freeze-up and thaw. To estimate the exposures of blast events not recorded, a plot of PPV versus scaled distance was created for each site with the use of blasting records for the entire incubation period and following the methods of Dowding (1985).

Scaled distance plots are commonly used for prediction of blast strength. They are based on an empirical relationship between blast size and location and measured PPV at a site. The measured PPV is plotted against the scaled distance, which is a normalized value that takes into account both the blast weight per delay and the distance from the blast. With the scaled distance relation in place, a PPV prediction can be made based on blast weight and distance from the blast. Upper and lower limits that contain 95% of the data were also calculated according to Dowding (1985). The upper limit is generally used to predict safe distances from a blast.

Additional details of how the PPV and overpressures are determined will be provided in a later contribution. Briefly, the geophone sensor includes three orthogonal geophones and one hydrophone. Different seismic detectors are sensitive to different aspects of the ground motion, such as particle displacement, particle velocity, or particle acceleration. The geophones are sensitive to the particle velocity component, which is the actual speed at which the ground is moving in response to the passing of a seismic wave. The particle velocity must not be confused with the speed at which the seismic wave itself propagates. The PPV is derived from the appropriately corrected motions of the three geophones and is the largest peak-to-peak value for a given event. Similarly, the overpressure is the positive or negative pressure change relative to ambient caused by motion of the seismic wave in the water. Neither

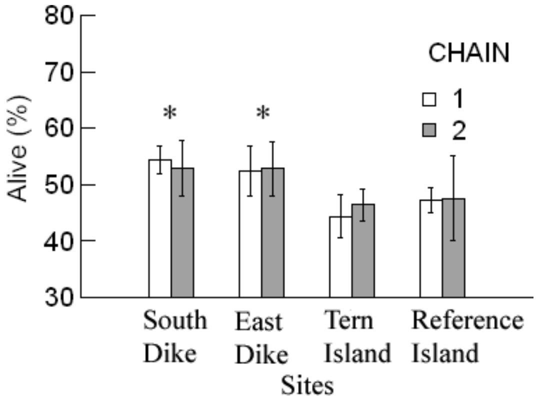

FIGURE 2.—Percentage of live lake trout eggs (mean ± SE) recovered from five incubators per chain at early retrieval (laboratory raised and preserved combined) after 20 d of exposure to blasts from an open-pit mine in Lac de Gras, Northwest Territories, Canada, in 2003. Sites at which survival differed from that at Reference Island (control site; least-significant-difference test: $P < 0.05$) are marked with asterisks.

value gives any indication as to the length and magnitude of the total exposure, but these values are frequently used (in this case, for blasting guidelines) for logistical reasons.

From the measured and estimated PPV exposures, we calculated two different measures of blast exposure: "mean PPV" for each site was the average of all measured and estimated blast events over the appropriate exposure period (early- and final-retrieval exposures), and "max PPV" was the highest measured or estimated exposure at a site during an exposure period. The number of exposures measured or estimated (within the 95% confidence interval [CI]) to exceed the 13-mm/s guideline was also reported for each site. Overpressure data were not recorded for the early-exposure period; because overpressure values were so low, only maximum measured values are presented for the final-retrieval exposure period.

Results

General Observations

Lake trout appeared to show no avoidance of the blasting area. Both juvenile and adult lake trout were observed within the blast zone, even shortly after blasting events. Lake trout in spawning condition were caught within 100 m of the dike, suggesting that they spawned within the blast zone. During both retrievals, no significant sedimentation was observed at any site and no incubators became dislodged.

Early Retrieval

All developing lake trout embryos preserved at early retrieval had completed epiboly and were into Balon's (1980) $E^2 5$ developmental stage, which corresponds to the beginning of organogenesis, when the tail bud is free from the yolk. Survival was similar between incubators preserved immediately at early retrieval and the incubators subsequently held at the University of Alberta until after hatch for all incubator chains within sites (*t*-tests: $P > 0.05$; Table 1). After combining both sets of incubators, survival did not differ between chains within sites (nested ANOVA: $F = 0.055$; df = 4, 32; $P = 0.994$) but did differ among sites ($F = 38.715$; df = 3, 4; $P = 0.002$). Survival at Tern Island was slightly but not significantly lower than survival at the reference site (least-significant-difference test: $P = 0.156$). In contrast, survival at South and East dikes was higher than survival at the reference site (least-significant-difference test: $P < 0.02$; Figure 2).

Final Retrieval

The percentage of dead cells was very similar within and among sites (50.0–55.6%), except for South Dike, which had lower survival (60.0–69.2% dead; Table 2). In contrast, variation was large among cells classified as alive (0.8–33.3%) and empty (15.6–47.2%; Table 2), and the two categories were highly negatively correlated ($r = -0.75$; $n = 40$; $P < 0.001$); on the other hand, the percentages of alive and dead cells ($r =$

TABLE 2.—Percentage (mean ± SE) of lake trout incubator cells (seeded with 1 egg/cell; 50 cells/incubator) classified as (1) containing a dead embryo, (2) empty, or (3) containing a live embryo after exposure (Sep–Jul) to blasts from an open-pit mine and retrieval after ice-out (final retrieval 5 incubators/chain) in Lac de Gras, Northwest Territories, Canada, 2003–2004.

Site	Chain	Dead	Empty	Alive
South Dike	1	60.0 ± 3.8	22.0 ± 4.6	18.0 ± 7.0
	2	69.2 ± 1.0	24.0 ± 5.6	6.8 ± 5.8
East Dike	1	50.0 ± 2.7	22.4 ±3.6	27.6 ± 5.0
	2	51.2 ± 4.1	15.6 ± 5.2	33.3 ± 3.8
Tern Island	1	53.6 ± 7.0	30.0 ± 3.8	16.4 ± 3.8
	2	52.0 ± 4.1	47.2 ± 3.4	0.8 ± 0.8
Reference Island	1	53.6 ± 3.2	36.0 ± 7.6	10.4 ± 5.4
	2	55.6 ± 4.5	42.4 ± 4.4	2.0 ± 1.6

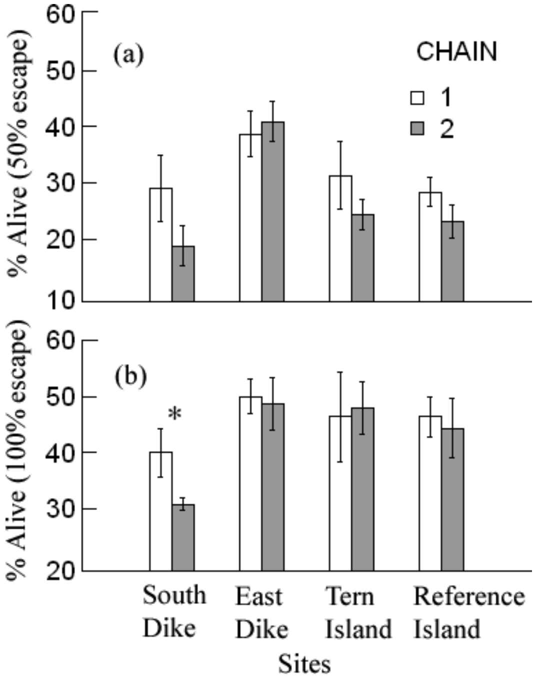

FIGURE 3.—Percentage of live lake trout embryos (mean ± SE) at final retrieval of incubators (50 cells/incubator; 5 incubators/chain) after exposure (Sep–Jul) to blasts from an open-pit mine in Lac de Gras, Northwest Territories, Canada, in 2003. Estimates were based on an escape correction of **(a)** 50% or **(b)** 100%. Sites at which survival differed from that at Reference Island (control site; least-significant-difference test: $P < 0.05$) are marked with asterisks. Survival between chains within sites did not differ.

-0.36; $n = 40$; $P = 0.074$) and of empty and dead cells ($r = -0.35$; $n = 40$; $P = 0.077$) were each only weakly correlated. Furthermore, a sample of empty cells ($n = 100$) examined at 40× magnification showed no remnants of embryos.

The 50% Escape Correction

Using the 50% escape correction at final retrieval, survival did not differ between incubator chains within sites (nested ANOVA: $F = 1.75$; df = 4, 32; $P = 0.164$) or among sites ($F = 4.57$; df = 3, 4; $P = 0.088$; Figure 3). Survival was lower at final retrieval than at early retrieval for all sites. Decreases in survival relative to early retrieval ranged from 13% at East Dike ($t = 3.60$; df = 18; $P = 0.002$) to 30% at South Dike ($t = 7.41$; df = 18; $P < 0.001$; Figure 4).

The 100% Escape Correction

With the 100% escape assumption for empty cells, survival was similar between chains within sites ($F = 0.59$; df = 4, 32; $P = 0.672$) but differed among sites ($F = 7.12$; df = 3, 4; $P = 0.044$; Figure 3b). Survival was lower (by 10%) than the reference site only at South Dike (least-significant-difference test: $P = 0.042$). Likewise, survival decreased between early and final retrieval only at South Dike (18%; $t = 5.413$, df = 18, $P < 0.001$; Figure 4).

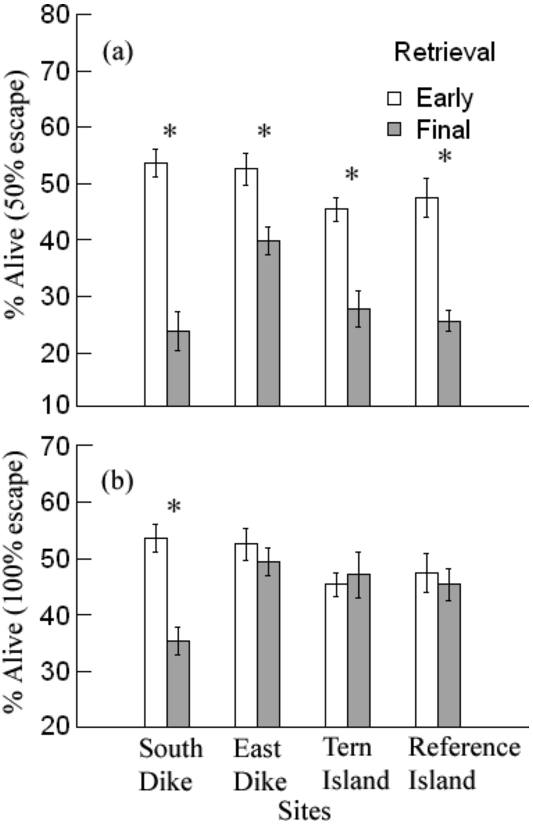

FIGURE 4.—Survival of incubated lake trout embryos (mean ± SE) at early (after 20 d; $n = 10$ incubators/site) and final (Sep–Jul; $n = 10$ incubators/site) retrieval after exposure to blasts from an open-pit mine in Lac de Gras, Northwest Territories, Canada, in 2003–2004; for final retrieval, an escape correction of **(a)** 50% or **(b)** 100% was used. Sites with significant differences in survival between retrieval periods (t-tests: $P < 0.0125$) are marked with asterisks.

Blast Exposures

During the early-exposure period, six blasting events occurred. No measured or estimated blasts exceeded the Canadian guideline of 13 mm/s, although only one or two blasts per site were measured directly. The 95% CIs of the estimated max PPVs were large and marginally included 13 mm/s at all blast zone sites (Table 3). Estimated mean PPV for the three blast zone sites did not differ ($F = 0.031$; df = 2, 15; $P = 0.970$).

TABLE 3.—Measured and estimated peak particle velocities (PPVs; mm/s) at one reference and three blast zone sites in Lac de Gras, Northwest Territories, Canada, during an early-retrieval (20-d) exposure period for lake trout eggs, 2003. The total number of blasting events, the number recorded, and the number that were below the trigger levels of the recorders at each site are shown (0.51 mm/s at Reference Island, 1.5 mm/s at the other sites). The remaining events were missed because of poor weather or equipment malfunction. Exposures during missed events were estimated by the methods of Dowding (1985). Final column indicates the number of measured or estimated blasts that exceeded Canada's 13-mm/s maximum allowable limit.

	Blasting events						
Site	Total	Recorded	Below detection	PPV mean (SE)	Measured maximum PPV	Estimated maximum PPV (95% CI)	Blasts >13 mm/s
South Dike	6	2	1	3.80 (0.5)	3.70	5.7 (2.30–14.30)	1
East Dike	6	1	2	4.00 (0.5)	3.10	5.6 (2.20–16.20)	3
Tern Island	6	2	1	4.00 (0.7)	4.40	6.1 (1.50–13.50)	1
Reference Island	6	1	2	0.57 (0.0)	0.58	0.6 (0.08–4.59)	

The highest recorded PPV at the reference site was only 0.58 mm/s.

During the entire incubation period, there were 96 blasting events; measured PPVs exceeded guidelines at all three exposed sites. The max PPV was highest at East Dike, where it was more than double the maximum allowable PPV limit (Table 4). Consistent with the early-retrieval period, however, the three exposed sites did not differ in mean PPV throughout the entire exposure period ($F = 0.785$; df = 2, 270; $P = 0.457$; Table 4). Exposures at the reference site were similar to those during the early-retrieval period (max PPV = 0.7 mm/s). In total, blasts may have exceeded guidelines more than 20 times at exposed sites (Table 4). The maximum observed overpressure (0.011 kPa) measured at South Dike was well below the Canadian guidelines of 100 kPa.

Discussion

During the early-retrieval exposure period, recorded and estimated PPVs at all three blast zone sites were very similar, although measurements were obtained for only 25% of the blasts. The highest recorded PPV (4.4 mm/s at Tern Island) was still well below the guidelines. All lake trout eggs preserved at early retrieval either showed no signs of development (indicating they had not been viable) or contained embryos at Balon's (1980) $E^2$5 development stage (corresponding to early organogenesis). This suggests that there was no additional mortality after incubators were placed in the lake and that the embryos were past the developmental stage most sensitive to physical shock (Fitzsimons 1994) at the time of retrieval. Early-retrieval survival at South and East dikes was actually higher than survival at the reference site, and survival at Tern Island was similar to that at the reference site, indicating that low-level blast exposure exerted no negative effects during the early stages of egg development. We suggest that factors other than blasting (e.g., natural variation among sites or handling effects) caused the observed differences in survival. Indeed, during incubator installation, one cooler held incubators destined for South and East dikes (having higher early survival) and another cooler was used for Tern and Reference islands (with the lower survival). Even though attempts were made to ensure that each cooler and all incubators were treated equally, we cannot rule this out as a possible source of variation.

TABLE 4.—Measured and estimated peak particle velocities (PPVs; mm/s) for the entire lake trout egg incubation period (Sep–Jul) at one reference site and three blast zone sites in Lac de Gras, Northwest Territories, Canada, 2003–2004. The total number of blasting events, the number recorded, and the number that were below the trigger levels of the recorders at each site (0.51 mm/s at Reference Island; 1.5 mm/s at other sites) are shown. The remaining events were missed because of poor weather or equipment malfunction. Exposures during missed events were estimated by the methods of Dowding (1985). Estimated maximum PPVs and 95% CIs are reported only if they exceeded the largest measured event at the site. Final column indicates the number of measured or estimated blasts that exceed Canada's 13-mm/s maximum allowable limit.

	Blasting events						
Site	Total	Recorded	Below detection	PPV mean (SE)	Measured maximum PPV	Estimated maximum PPV (95% CI)	Blasts >13 mm/s
South Dike	91	64	4	6.40 (0.4)	24.90	≤24.90	24
East Dike	91	61	8	5.90 (0.4)	28.50	≤28.50	23
Tern Island	91	25	3	5.80 (0.3)	17.40	9.90 (2.40–21.80)	33
Reference Island	91	5	23	0.59 (0.0)	0.70	0.66 (0.09–5.00)	

Regardless, there were no measurable effects of blasting during the early-exposure period, when the eggs were most sensitive to physical shock.

Exposures at all three blast zone sites throughout the entire incubation period were similar. All sites received exposures greater than the maximum allowable limit; the highest recorded PPV was 28.5 mm/s at East Dike. Final-retrieval results were not as straightforward, however, owing to the presence of empty cells. Previous studies that used similar incubators with the same mesh size have also noted empty cells, which were explained (albeit only in part) by predation or disintegration of lake trout eggs or embryos (Casselman 1995; Eshenroder et al. 1995; Manny et al. 1995). In our laboratory-reared eggs, we observed that the screen mesh used to cover the incubator cells was large enough to allow young fish to escape when their yolk sacs were almost completely absorbed. Because final retrieval was not possible under our arctic field conditions until mid-July (versus March–June in other studies), when yolk sac absorption was nearly complete, we suggest that empty cells in our study were largely or entirely the result of escapement since (a) the incubation period was sufficiently long to allow the lake trout larvae to absorb their yolk sacs and increase their chance of escape, (b) we observed postabsorption escapes in the laboratory, (c) there was no physical evidence (i.e., residual organic matter) of predation or disintegration (Casselman 1995), (d) the number of live fish and empty cells at final retrieval were strongly negatively correlated, and (e) survival between the early and final retrievals did not generally differ, assuming the 100% escape correction. Eshenroder et al. (1995) also reported that the number of empty cells (up to 88.8%) increased with duration of incubation, suggesting that the presence of empty cells may increase with reduction in the size of the yolk sac. In addition, Claramunt et al. (2005) showed that there was minimal loss of eggs after 2 weeks of exposure in a natural setting, even while the eggs were exposed to outside predation. Nevertheless, because we could not rule out the possibility that some embryos were eaten or had completely disintegrated, we analyzed the final-retrieval data using both 50% escape and 100% escape possibilities.

The 50% escape correction suggested that mortality increased significantly between early and final retrieval at all sites, even though the most sensitive stage of development had passed. On the other hand, this correction provided no evidence of blast effects on overwinter survival of lake trout eggs, as survival did not differ among all four sites at final retrieval. Thus, the apparent increase in mortality between early and final retrievals would have only resulted from natural mortality, something that was not observed in the early-retrieval incubators that were subsequently held in the laboratory. The lack of organic residue or of predators in the cells also does not support this possibility.

As discussed above, we believe the 100% escape correction provides the best estimate of survival at final retrieval. Under this scenario, South Dike was the only site where survival was lower (by 10%) than that at the reference site and where survival decreased between early and final retrievals (by 18%). Because neither mean nor maximum exposure to PPVs was higher at South Dike than at the other blast zone sites, we suggest that survival during this period was related more to the difference in spawning substrate characteristics than to blasting. Indeed, South Dike was the only site that did not contain natural spawning substrate; instead, the substrate was composed of large, jagged pieces of rock that had recently been crushed. Furthermore, the largest PPV was recorded at East Dike, which also had the highest survival.

The highest PPV exposure recorded at the reference site throughout the entire incubation period was 0.70 mm/s, which is only 0.19 mm/s above the detection limit and far below the Canadian guideline limit of 13 mm/s. An exposure of this level should not have any negative effects on incubation, as it is probably comparable with background vibrations (e.g., from wave action). To reduce such false triggers, the trigger levels of the Blast Mate recorders at the exposed sites were set at more than double the 0.51-mm/s detection limit. As such, the reference site provided a good estimate of lake trout egg survival at a site free from blasting effects. Survival at the reference site (early retrieval = 48.3%; final retrieval with 50% escape = 25.8%; final retrieval with 100% escape = 45.4%) was also comparable with that reported in studies done with similar incubators (1–49%; Casselman 1995; Eshenroder et al. 1995; Manny et al. 1995).

Difference in mean PPV exposure among all exposed sites was small (0.6 mm/s) and nonsignificant throughout the entire incubation period. For this estimate of exposure, we used every blasting event regardless of PPV size, as all sites were exposed to all blasting events. There are numerous alternative ways to calculate an index of overall PPV exposure, but without understanding how or at what level a single blast exposure causes mortality in fish eggs, it is difficult to develop a meaningful measurement of cumulative exposure.

The largest blast exposure (28.5 mm/s at East Dike) was more than twice the maximum allowable level in the Canadian blasting guidelines (Wright and Hopky 1998). However, this blast occurred when the lake trout eggs were past the developmental stage considered most sensitive to mechanical disturbance (Fitzsimons 1994). Because East Dike also showed the highest survival throughout the incubation period, it appears that an exposure of 28.5 mm/s does not increase mortality of eggs at that stage of development. We cannot rule out that this exposure can increase mortality when eggs are at an earlier, more sensitive stage.

Exposure levels at each site depend not only on the amount of explosives used in any given blast but also on the location of the blast within the pit, the size of each blast, and possibly environmental conditions (e.g., presence of ice), all of which vary among blasting events. Because of these differences, there can be no simple relation between exposure and distance from the pit. When combined with changes in sensitivity of the lake trout eggs over time and natural variation in egg survival among sites, this variation in exposure means that determining a specific distance or blast level that increases mortality is very difficult under operational field conditions, even if some exposures are large enough to cause significant mortality in some locations at some times.

Although the level of blasting conducted at DDMI's A154 pit appeared not to result in reduced survival of lake trout eggs during our study, the level at which PPVs from blasting will increase mortality of eggs remains unknown. A recent study suggested that the maximum allowable PPV level contained in the Canadian blasting guidelines is an order of magnitude lower than that required to cause 10% mortality in eggs of Pacific salmon *Oncorhynchus* spp. (Jensen 2003). Additionally, Post et al. (1974) found that peak vertical accelerations up to 10 times the force of gravity (*g*) and repeated five times did not increase mortality in eggs of rainbow trout *O. mykiss*, regardless of the developmental stage tested (37.5, 75.0, 125.0, and 250.0 degree-days postfertilization). Given that the peak vertical acceleration from our largest exposure (28.5 mm/s) was equivalent to a gravitational force of only 0.212 *g*, this suggests that Post et al.'s (1974) PPVs were much greater than 13 mm/s. Unknown, however, is how the sensitivity to PPV varies among different species (but see Jensen 2003).

A laboratory study that could control the size, number, and timing of exposure relative to fish egg development is needed to more accurately determine the PPV levels that increase mortality of incubating eggs. Such information may help predict the effects of blasts on fish egg mortality in the field within the constraints described above. Development of a reliable and standardized blast simulation procedure in the laboratory would also facilitate the testing of additional species of interest that should result in improved guidelines for protecting developing fish embryos from blasting.

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