New Mechanical Shock Sensitivity Units in Support of Criteria for Protection of Salmonid Eggs From Blasting or Seismic Disturbance

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2003

Canadian Technical Report of Fisheries and Aquatic Sciences 2452

Canadian Technical Report of

Fisheries and Aquatic Sciences 2452

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by

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Cat. No. 975/2452E ISSN 0706-6457

Correct citation for this publication:

Jensen, J.O.T. 2003. New mechanical shock sensitivity units in support of criteria for protection of salmonid eggs from blasting or seismic disturbance. Can. Tech. Rep. Fish. Aquat. Sci. 2452: 18 p.

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ABSTRACT

Jensen, J.O.T. 2003. New mechanical shock sensitivity units in support of criteria for protection of salmonid eggs from blasting or seismic disturbance. Can. Tech. Rep. Fish. Aquat. Sci. 2452: 18 p.

Mechanical shock refers to the force on eggs that occurs as a result of disturbance to eggs. Disturbances can occur during handling (i.e., egg removal from female, pouring eggs into incubators, egg transportation, egg picking) or from outside sources such as pile driving or blasting and seismic shock. Changes in mechanical shock sensitivity of 6 species of salmonids are reported as LD10 velocities (i.e. the velocity reached when eggs are dropped from a height that causes 10% mortality). The species tested were chinook (*Oncorhynchus tshawytscha*), chum (*O. keta*), coho (*O. kisutch*), pink (*O. gorbuscha*), sockeye (*O. nerka*), and steelhead trout (*O. mykiss*). These LD10s are reported along with accumulated temperature units (°C-days) and corresponding embryonic developmental stages. Minimum LD10 velocities (cm/sec) for the 6 species ranged from 14.6 to 83.8 cm/sec, which is at least 10 times greater than the peak particle velocity of 1.3 cm/sec recommended as a safe criterion for the use of explosives. Hence, these new mechanical shock units of LD10 velocities indicate that the current guidelines for the use of explosives near salmonid spawning redds provide at least a ten-fold margin of protection for Pacific salmon eggs at their most sensitive stages.

RÉSUMÉ

Jensen, J.O.T. 2003. New mechanical shock sensitivity units in support of criteria for protection of salmonid eggs from blasting or seismic disturbance. Can. Tech. Rep. Fish. Aquat. Sci. 2452: 18 p.

Dans ce rapport, les chocs mécaniques dont il est question sont les forces exercées sur les œufs qui résultent des perturbations auxquelles ceux-ci sont soumis. Ces perturbations peuvent survenir durant la manipulation (p. ex. l’extraction des œufs d’une femelle, le transvasement des œufs dans des incubateurs, le transport ou la cueillette des œufs) ou avoir d’autres causes comme le battage de pieux, le dynamitage et les chocs sismiques. Les changements de sensibilité aux chocs mécaniques des œufs de six espèces de salmonidés sont exprimés suivant la vitesse LD_{10} (c.-à-d. la vitesse atteinte au moment de l’impact quand les œufs tombent d’une hauteur entraînant un taux de mortalité de 10 %). Les espèces examinées étaient le saumon quinnat (*Oncorhynchus tshawytscha*), le saumon kéta (*O. keta*), le saumon coho (*O. kisutch*), le saumon rose (*O. gorbuscha*), le saumon rouge (*O. nerka*) et le saumon arc-en-ciel (*O. mykiss*). Les vitesses LD_{10} sont présentées en relation avec les températures cumulées (ºC-jours) et les stades de développement embryonnaire correspondants. Les vitesses LD_{10} minimales (cm/s) pour les six espèces variaient de 14,6 à 83,8 cm/s, ce qui est au moins dix fois plus que la vitesse de crête des particules de 1,3 cm/s qui est recommandée comme critère de sécurité pour l’utilisation d’explosifs. Par conséquent, ces nouvelles unités de choc mécanique que sont les vitesses LD_{10} indiquent que les lignes directrices actuelles pour l’utilisation d’explosifs au voisinage des nids des salmonidés procurent une marge de protection d’un facteur 10 au moins pour les œufs des salmonidés du Pacifique à leurs stades les plus sensibles.

1.0 INTRODUCTION

Mechanical shock refers to the force on eggs that occurs as a result of disturbance to eggs. Disturbances can occur during handling (i.e., egg removal from female, pouring eggs into incubators, egg transportation, egg picking) or from outside sources such as pile driving or blasting and seismic shock. Researchers have attempted to determine the effect of such disturbances on egg survival. Tests have been conducted by pouring eggs and water from arbitrary heights, by vibrating eggs, by dropping eggs in simulated gravel redds, and by simulating pressure waves on eggs (Hata, 1927; Battle, 1943; Smirnov, 1954, 1955, 1975; Ievlava, 1967; Post et al., 1974; Sutherland and Ogle, 1975;). To overcome many of the difficulties and uncertainties of interpreting the egg survival responses to these various types of mechanical shock, a device was developed at the Pacific Biological Station in the early 1980s to expose 6 species of salmonid eggs to standardized, quantifiable shock intensities (Jensen and Alderdice, 1983, 1989). The species tested were chinook (*Oncorhynchus tshawytscha*), chum (*O. keta*), coho (*O. kisutch*), pink (*O. gorbuscha*), sockeye (*O. nerka*), and steelhead trout (*O. mykiss*).

Jensen and Alderdice (1983, 1989) reported changes in shock sensitivity in units of energy (ergs; gram · cm^2/sec^2) transferred to eggs on impact, based on the egg weight and drop height that caused 50 % and 10 % mortality (i.e. LD50s and LD10s, respectively). This standard unit was useful in demonstrating the changes of egg sensitivity during incubation. However, over the years, numerous requests have been received by Jensen to make recommendations about the potential hazards of disturbances such as pile driving or blasting for such activities as road construction and most recently explosive blasting for densification of the earth fill component of a dam.

Hence, this paper describes a new approach to convert the original data, reported by Jensen and Alderdice (1989), from LD10s (i.e. drop height, cm, causing 10% mortality) to the final velocity (cm/sec) that the eggs reach when dropped from a height resulting in 10% mortality (i.e. LD10 velocity). This new unit of egg sensitivity can then be compared to the peak particle velocity (PPV) criteria of 1.3 cm/sec recommended by Wright and Hopky (1998).

2.0 DESCRIPTION OF MECHANICAL SHOCK TESTS

As reported by Jensen and Alderdice (1983, 1989), changes in mechanical shock sensitivity of 6 species (Oncorhynchus tshawytscha, O. keta, O. kisutch, O. gorbuscha, O. nerka, and O. Mykiss) of salmonid eggs were determined by using a device developed to expose small groups of eggs to a series of standardized, quantifiable shock intensities. The apparatus (Fig. 1) consists of a metal carrier with a slot to hold a petri dish (60-mm diam. x 15 mm) containing a single layer of eggs. The carrier is attached to a release platform by a release trigger. The platform can be moved to any drop height ranging from 0 to 100 cm. The carrier falls freely, guided by two guide wires when the trigger is released. Oversized Teflon sleeves mounted in the carrier guides minimize friction. The egg carrier was designed to come to an abrupt stop upon impact when dropped. This was accomplished by partially filling a hollowed-out portion of the carrier with lead shot. In addition, a 2-mm thick plate of synthetic elastomer (i.e. Teflon®), with high impact strength and ability to absorb shock, was fastened to the base to prevent the carrier from bouncing.

The shock tests consisted of a minimum of three drop heights (5 – 100 cm) and one control (0 cm); these tests were replicated three times at each time interval. Samples of 20 – 30 eggs were placed in a petri dish, free of surrounding fluid, and then placed in the carrier. The tests were carried out on eggs beginning with unactivated eggs, continued at very short time intervals (i.e. minutes and hours) post fertilization, followed by daily tests until egg sensitivity was no longer measurable. To assess changes in sensitivity in relation to embryonic development, eggs were categorized by representative stages of embryonic development (Table 1) as they developed at 10°C. Jensen and Alderdice (1983, 1989) originally reported the results in relation to time from fertilization. The accumulated temperature units (°C-days) have been calculated and are reported herein, along with LD50 and LD10 (i.e. the drop heights, in cm, that caused 50% and 10% mortality (Tables 2 to 7).

3.0 VELOCITY CONVERSIONS

The advantage of the shock device described herein is that it employs basic principles of physics which allow for the determination and reporting of the results using standard units of measure such as the acceleration (cm/sec^2) and velocity (cm/sec) of eggs dropped from various heights, assuming minimal influence of friction. Hence, the drop heights that were determined to cause 10% mortality (Jensen and Alderdice, 1989) were used to determine the corresponding final velocity reached by the eggs. The relationship of the parameters of drop height (s; cm), initial velocity (vo; cm/sec), final velocity at time of impact (vt; cm/sec), and acceleration due to gravity (g; cm/sec^2) is illustrated in the following equation The equation relating initial velocity (vo), acceleration due to gravity (g), and drop height (s) to final velocity (vt) at the time of impact.

$$vt = (vo^2 + 2 \bullet g \bullet s)^{1/2} \qquad \text{Eq. 1}$$

where vo=0, g=980 cm/sec^2. The relationship between drop height, s, and final velocity (vt) is illustrated in Fig. 2. The calculated LD10 velocities, calculated by substituting LD10 drop heights for s in Eq. 1, are tabulated in Tables 2 to 7.

Jensen and Alderdice (1989) modelled changes in sensitivity (from fertilization to embryonic stage 8, i.e. flattening of blastodisc) using a linear model and a parabolic model from stage 8 to at least stage 17 (i.e. blastodisc flattening to heart beat and spontaneous trunk movements). The LD10 velocities also showed linear and parabolic patterns. However, in this paper the LD10 velocities were modelled in relation to accumulated temperature units (i.e. ATUs; °C-days) instead of days from fertilization (Table 8). Hence, the resultant equations can be applied to temperatures other than the 10 °C test temperatures, making the models much more versatile at various temperatures. To illustrate these changes in egg sensitivity as embryonic development progresses, the LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (based on log-linear models and parabolic models as described above), are plotted against days (at 10°C) and ATUs, along with corresponding embryonic stages, from fertilization for each of the 6 salmonid species tested (Figs. 3 to 8).

4.0 DISCUSSION

Jensen and Alderdice (1983, 1989) showed that salmonid egg sensitivity increased soon after fertilization and that eggs became extremely sensitive to shock during epiboly or yolk overgrowth. In addition, they reported the magnitude of sensitivity in units of drop height (cm) and energy (ergs) that caused 50% and 10% mortality. These units were useful in illustrating the changes in egg sensitivity during egg incubation. However, these units were not directly applicable to such forms of shock as blasting, pile driving, or seismic shock. The new mechanical shock sensitivity unit of LD10 velocity has been tabulated and illustrated (Tables 2 – 7, and Figs. 3 – 8) along with embryonic development in relation to ATUs to aid in determination of changes in egg sensitivity at various temperatures. This assumes that changes in egg sensitivity are associated only with changes in embryonic development. It is possible that egg sensitivity could be affected by temperature alone. Therefore, these results may differ for temperatures other than 10 °C. However, until egg sensitivity tests are conducted at temperatures other than 10 °C, these models represent the best information at present.

Wright and Hopky (1998) describe guidelines for protection of fish in response to explosives. In their report they recommend that no explosives should produce a peak particle velocity (PPV) greater than 1.3 cm/sec. Hence, it follows that the LD10 velocities reported herein should be much greater than 1.3 cm/sec. to ensure that no egg mortality occurs. The worst case scenario occurs at the minimum LD10 velocity (i.e. the lowest velocity causing 10 % mortality). To calculate the LD10 velocity minima, based on the coefficients for each species from the parabolic models in Table 8, Xmin (ATUs) was first calculated using the following equation

$$X\,\min(ATUs) = \frac{-b}{2 \bullet c}$$ Eq. 2

This was followed by calculating Ymin (i.e. minimum LD10 velocity) using the parabolic equation with the Xmin values for each species as described in the following equation

$$Y\,\min(cm/\mathrm{sec}) = a + b \bullet X\,\min + c \bullet (X\,\min)^2$$ Eq. 3

These LD10 velocity minima and corresponding ATUs for the 6 salmonid species tested are listed in Table 9. Notice that the LD10 velocity minimum values are at least ten times greater than the PPV of 1.3 cm/sec recommended as a safe criterion for the use of explosives by Wright and Hopky (1998). For example, in order to cause 10 % egg mortality in chinook (the most sensitive salmonid species tested), the recommended safe criterion of 1.3 cm/sec PPV would have to be exceeded by more than ten times, which it is (i.e. minimum LD10 velocity for chinook is 14.6 cm/sec.). Hence, these new mechanical shock units of LD10 velocities indicate that the current guidelines for the use of explosives near salmonid spawning redds provide at least a ten-fold margin of protection for Pacific salmon eggs at their most sensitive stages.

5.0 ACKNOWLEDGEMENTS

I gratefully acknowledge the suggestions and comments from W. E. McLean and T. Sweeten.

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7.0 TABLES

Table 1. Salmonid embryonic developmental stages (from Velsen, 1987).

Stage	Description
	CLEAVAGE
1	Bipolar Differentiation: gathering of cytoplasm into a high mound at the animal pole; (bipolar differentiation also occurs in activate eggs that are not fertilized)
2	2 Cells (first cleavage); the first 5 divisions are in the horizontal plane only; shape and arrangement of individual cells (blastomeres) is regular
3	4 Cells
4	8 Cells
5	16 Cells
6	32 Cells; successive divisions occur in the horizontal as well as the vertical plane
7	Morula (mulberry blastodisc) with numerous small cells visible and the establishment of the periblast surrounding the morula; the morula changes into a high, nearly hemispherical mound with a cobbled surface, later to become a lower mound with more gradual slopes and a nearly smooth surface
8	Blastodisc flattening and starting to spread to nearly cover the periblast and the small oil droplets underneath it; posterior region of the blastodisc may start bulging
	EPIBOLY AND CONVERGENCE
9	Appearance of embryonic shield, germ ring and terminal node
10	1/3 epiboly; germ ring 1/3 of the way toward total overgrowth of the yolk; neural groove on the embryonic shield
11	1/2 epiboly; overgrowth of the yolk half completed and germ ring at the equator; formation of axial strand and neural keel; first somites; Kupffer's vesicle
12	3/4 epiboly; germ ring 1/3 overgrown; optic anlagen and three brain vesicles
13	Yolk plug less than head width; germ ring narrowing toward vegetal pole; blastoderm nearly covering entire yolk; otic and optic placodes
14	Yolk plug closed; yolk enclosed in cellular envelope (blastoderm)
	ORGANOGENESIS
15	Hindbrain (rhombencephalon) enlarging; trunk-tail mound raised but not undercut
16	Tail bud just free from yolk; one or two branchial pouches detectable; hindgut visible in side view
17	Heart beat; first branchial cleft formed; cloaca visible and free from yolk sac; metencephalon and myelencephalon clearly distinct; head not undercut; spontaneous C-coil (movement) of trunk
18	1/4 of yolk surface vascularized; pectoral fin buds present; posterior half of body free from yolk sac; faint eye pigmentation
19	2/3 yolk surface vascularized; pectoral fins disc-shaped; head undercut to jaw level; mouth not open
20	Eyes fully pigmented; yolk sac 3/4 vascularized; head free and mouth open; cerebral hemispheres forming
21	Caudal flexing of the vertebral column; mesenchyme concentrations in caudal and anal fins; pectoral fins twitching

Table 2. Chinook egg sensitivity.

Time (min)	Time (hr)	Time (day)	Stage Table 1	LD50 (cm)	LD10 (cm)	ATUs (10°C* days)	LD10 velocity (cm/sec)
5	0.0833	0.003	1	144.1	48.1	0.035	307.04
10	0.1667	0.007	1	183.4	35	0.069	261.92
15	0.25	0.010	1	175	24.4	0.104	218.69
30	0.5	0.021	1	103	45.1	0.208	297.31
60	1	0.042	1	111.9	19.9	0.417	197.49
120	2	0.083	1	78.1	7.7	0.833	122.85
240	4	0.167	1	70.9	16.9	1.667	182.00
480	8	0.333	1	34.2	14.5	3.333	168.58
720	12	0.500	2	38.1	15.7	5.0	175.42
1440	24	1.000	5	38.1	10	10.0	140.00
2880	48	2.000	7	18.2	6.5	20.0	112.87
4320	72	3.000	8	25	5.9	30.0	107.54
5760	96	4.000	8	30.3	2.8	40.0	74.08
7200	120	5.0	8	13.4	3.2	50.0	79.20
8640	144	6.0	9	11.5	5.3	60.0	101.92
12960	216	9.0	10	10.8	3.8	90.0	86.30
15840	264	11.0	11	3.1	0.4	110.0	28.00
18720	312	13.0	13	2.6	0.8	130.0	39.60
20160	336	14.0	15	2.9	0.5	140.0	31.30
21600	360	15.0	16	4.4	1.7	150.0	57.72
23040	384	16.0	16	6	2.8	160.0	74.08
24480	408	17.0	17	1.8	0.1	170.0	14.00
25920	432	18.0	18	20.8	12.6	180.0	157.15
27360	456	19.0	18	47.8	22	190.0	207.65
28800	480	20.0	18	69.8	39.2	200.0	277.19
30240	504	21.0	18	81.5	61.3	210.0	346.62
33120	552	23.0	19	293.8	86.5	230.0	411.75

Table 3. Chum egg sensitivity.

Time (min)	Time (hr)	Time (day)	Stage Table 1	LD50 (cm)	LD10 (cm)	ATUs (10°C*days)	LD10 velocity (cm/sec)
5	0.0833	0.003	1	92.1	52.9	0.035	322.00
10	0.1667	0.007	1	59.3	18.2	0.069	188.87
15	0.25	0.010	1	60.8	10.4	0.104	142.77
30	0.50	0.021	1	125.2	34.8	0.208	261.17
60	1	0.042	1	95.9	37.7	0.417	271.83
120	2	0.083	1	35.7	3.4	0.833	81.63
240	4	0.167	1	41.6	12.0	1.667	153.36
480	8	0.333	1	23.6	6.5	3.333	112.87
720	12	0.500	2	71.1	1.3	5.0	50.48
1440	24	1.0	6	19.2	5.7	10.0	105.70
2880	48	2.0	7	26.1	7.6	20.0	122.05
4320	72	3.0	8	19.7	4.0	30.0	88.54
5760	96	4.0	8	17.5	3.0	40.0	76.68
7200	120	5.0	9	14.2	2.7	50.0	72.75
8640	144	6.0	9	8.7	2.6	60.0	71.39
10080	168	7.0	9	7.6	2.6	70.0	71.39
11520	192	8.0	10	3.6	0.7	80.0	37.04
12960	216	9.0	10	7.7	2.4	90.0	68.59
14400	240	10.0	10	6.9	1.8	100.0	59.40
15840	264	11.0	11	7.3	2.4	110.0	68.59
17280	288	12.0	12	8.1	2.5	120.0	70.00
18720	312	13.0	13	3.4	0.8	130.0	39.60
20160	336	14.0	16	3.8	0.7	140.0	37.04
21600	360	15.0	16	5.9	1.5	150.0	54.22
23040	384	16.0	17	13.4	5.0	160.0	98.99
24480	408	17.0	18	15.2	5.9	170.0	107.54
25920	432	18.0	18	32.3	15.8	180.0	175.98
27360	456	19.0	18	36.4	16.4	190.0	179.29
28800	480	20.0	18	52.3	27.0	200.0	230.04
30240	504	21.0	18	74.1	15.0	210.0	171.46
31680	528	22.0	19	73.8	39.4	220.0	277.89
34560	576	24.0	21	107.0	78.0	240.0	391.00

Table 4. Coho egg sensitivity.

Time (min)	Time (hr)	Time (day)	Stage Table 1	LD50 (cm)	LD10 (cm)	ATUs (10°C*days)	LD10 velocity (cm/sec)
1	0.0167	0.001	1	142.0	34.6	0.007	260.42
5	0.0833	0.003	1	383.4	20.9	0.035	202.40
10	0.1667	0.007	1	45.2	14.9	0.069	170.89
15	0.25	0.010	1	38.8	6.4	0.104	112.00
30	0.50	0.021	1	47.6	8.8	0.208	131.33
45	0.75	0.031	1	54.3	9.9	0.313	139.30
60	1	0.042	1	31.1	2.7	0.417	72.75
120	2	0.083	1	21.1	9.9	0.833	139.30
240	4	0.167	1	18.8	7.3	1.667	119.62
480	8	0.333	2	16.4	5.8	3.333	106.62
720	12	0.50	3	16.0	5.6	5.0	104.77
1440	24	1.0	6	15.2	4.3	10.0	91.80
2880	48	2.0	8	19.4	4.8	20.0	96.99
4320	72	3.0	8	15.4	7.4	30.0	120.43
5760	96	4.0	8	7.4	3.4	40.0	81.63
7200	120	5.0	8	2.4	0.4	50.0	28.00
8640	144	6.0	9	8.1	3.3	60.0	80.42
11520	192	8.0	10	7.0	1.3	80.0	50.48
20160	336	14.0	16	3.5	1.4	140.0	52.38
23040	384	16.0	17	15.7	4.3	160.0	91.80
25920	432	18.0	18	59.3	21.0	180.0	202.88

Table 5. Pink egg sensitivity.

Time (min)	Time (hr)	Time (day)	Stage Table 1	LD50 (cm)	LD10 (cm)	ATUs (10°C*days)	LD10 velocity (cm/sec)
1	0.0167	0.001	1	191.8	62.7	0.007	350.56
5	0.0833	0.003	1	115.4	34.0	0.035	258.15
10	0.1667	0.007	1	64.4	26.9	0.069	229.62
15	0.25	0.010	1	87.8	25.0	0.104	221.36
30	0.50	0.021	1	63.1	18.7	0.208	191.45
45	0.75	0.031	1	67.5	16.0	0.313	177.09
60	1	0.042	1	54.4	21.2	0.417	203.84
120	2	0.083	1	55.0	12.3	0.833	155.27
240	4	0.167	1	23.7	3.6	1.667	84.00
720	12	0.500	2	26.1	8.8	5.0	131.33
1440	24	1.0	6	28.2	4.9	10.0	98.00
2880	48	2.0	8	28.1	7.1	20.0	117.97
4320	72	3.0	8	28.1	8.8	30.0	131.33
5760	96	4.0	9	23.7	4.1	40.0	89.64
7200	120	5.0	9	20.2	7.1	50.0	117.97
8640	144	6.0	9	46.3	4.3	60.0	91.80
10080	168	7.0	9	13.0	2.9	70.0	75.39
11520	192	8.0	10	12.2	2.7	80.0	72.75
12960	216	9.0	10	30.0	2.2	90.0	65.67
14400	240	10.0	10	13.4	2.3	100.0	67.14
15840	264	11.0	11	17.1	4.3	110.0	91.80
17280	288	12.0	11	15.6	7.2	120.0	118.79
18720	312	13.0	11	18.8	6.1	130.0	109.34
20160	336	14.0	11	18.0	3.2	140.0	79.20
21600	360	15.0	13	26.2	11.0	150.0	146.83
23040	384	16.0	15	40.0	9.8	160.0	138.59
24480	408	17.0	17	60.8	21.6	170.0	205.76
25920	432	18.0	17	103.3	47.6	180.0	305.44
27360	456	19.0	17	95.7	57.9	190.0	336.87

Table 6. Sockeye egg sensitivity.

Time (min)	Time (hr)	Time (day)	Stage Table 1	LD50 (cm)	LD10 (cm)	ATUs (10°C*days)	LD10 velocity (cm/sec)
1	0.0167	0.001	1	233.4	53.3	0.007	323.22
5	0.0833	0.003	1	132.4	67.0	0.035	362.38
10	0.1667	0.007	1	115.8	40.1	0.069	280.35
15	0.25	0.010	1	93.5	41.9	0.104	286.57
30	0.50	0.021	1	109.3	82.3	0.208	401.63
45	0.75	0.031	1	172.2	64.9	0.313	356.66
60	1	0.042	1	116.3	24.5	0.417	219.13
120	2	0.083	1	109.8	39.6	0.833	278.60
240	4	0.167	1	78.9	18.4	1.667	189.91
480	8	0.333	2	18.3	3.9	3.333	87.43
720	12	0.500	2	21.6	8.0	5.0	125.22
1440	24	1.0	6	35.6	10.6	10.0	144.14
2880	48	2.0	7	26.4	10.0	20.0	140.00
4320	72	3.0	8	49.3	7.4	30.0	120.43
5760	96	4.0	8	39.3	4.5	40.0	93.91
7200	120	5.0	8	39.6	5.9	50.0	107.54
8640	144	6.0	9	28.1	4.8	60.0	96.99
10080	168	7.0	9	21.1	4.4	70.0	92.87
11520	192	8.0	10	14.6	6.9	80.0	116.29
12960	216	9.0	10	15.5	6.0	90.0	108.44
14400	240	10.0	11	23.1	2.9	100.0	75.39
15840	264	11.0	11	14.3	4.8	110.0	96.99
17280	288	12.0	12	26.0	4.8	120.0	96.99
18720	312	13.0	15	19.1	5.1	130.0	99.98
20160	336	14.0	16	48.7	7.0	140.0	117.13
21600	360	15.0	16	35.4	15.8	150.0	175.98
23040	384	16.0	17	44.1	25.2	160.0	222.24
24480	408	17.0	18	61.7	28.9	170.0	238.00
25920	432	18.0	18	76.0	28.3	180.0	235.52
27360	456	19.0	18	148.3	45.7	190.0	299.29
28800	480	20.0	18	152.7	75.6	200.0	384.94

Table 7. Steelhead egg sensitivity.

Time (min)	Time (hr)	Time (day)	Stage Table 1	LD50 (cm)	LD10 (cm)	ATUs (10°C*days)	LD10 velocity (cm/sec)
1	0.0167	0.001	1	62.5	20.4	0.007	199.96
5	0.0833	0.003	1	124.9	48.5	0.035	308.32
10	0.1667	0.007	1	65.9	25	0.069	221.36
15	0.25	0.010	1	67.1	12.5	0.104	156.52
30	0.5	0.021	1	67.6	21.8	0.208	206.71
45	0.75	0.031	1	68.5	27.4	0.313	231.74
60	1	0.042	1	25.2	3.5	0.417	82.83
120	2	0.083	1	27.6	5	0.833	98.99
240	4	0.167	1	22.4	3.8	1.667	86.30
480	8	0.333	1	14.5	3.6	3.333	84.00
720	12	0.500	3	19.9	4.8	5.0	96.99
1440	24	1.0	6	16.2	5.5	10.0	103.83
2880	48	2.0	8	14.4	2.1	20.0	64.16
4320	72	3.0	8	13.9	3.6	30.0	84.00
5760	96	4.0	8	11.3	3.6	40.0	84.00
7200	120	5.0	9	7.9	1.7	50.0	57.72
8640	144	6.0	9	6.1	0.7	60.0	37.04
10080	168	7.0	10	6.2	1.9	70.0	61.02
11520	192	8.0	11	3.5	1.3	80.0	50.48
12960	216	9.0	15	4.7	1.9	90.0	61.02
14400	240	10.0	16	4.8	1.6	100.0	56.00
15840	264	11.0	16	6.3	1.7	110.0	57.72
17280	288	12.0	17	10.4	3.1	120.0	77.95
18720	312	13.0	18	36	8.2	130.0	126.78
20160	336	14.0	18	41.3	14.5	140.0	168.58
21600	360	15.0	18	97.7	40.9	150.0	283.13

Table 8. Log-linear and parabolic model coefficients for LD10 velocities (cm/sec) for 6 salmonid species during 2 developmental time periods (ATUs).

Species	Model type	Model coefficients a	b	c	Time period ATUs	n	r^2
Chinook	y=a+blnx	191.813486	-27.604286		0 - 50	14	0.826208
	$y=a+bx+cx^2$	372.914357	-6.468933	0.029199	50 -230	14	0.904477
Chum	y=a+blnx	161.876465	-26.359391		0 - 40	13	0.554601
	$y=a+bx+cx^2$	203.083120	-3.237649	0.016230	60 -240	20	0.925421
Coho	y=a+blnx	126.211035	-15.956642		0 - 50	16	0.649024
	$y=a+bx+cx^2$	216.596882	-4.087539	0.021588	50 - 180	20	0.925421
Pink	y=a+blnx	168.386172	-25.844475		0 - 30	13	0.804388
	$y=a+bx+cx^2$	248.262505	-4.233782	0.024102	30 - 190	17	0.900141
Sockeye	y=a+blnx	225.228193	-33.570647		0 - 50	16	0.729549
	$y=a+bx+cx^2$	273.584965	-4.189878	0.023123	50 - 200	16	0.953769
Steelhead	y=a+blnx	138.671408	-22.213301		0 - 40	15	0.611474
	$y=a+bx+cx^2$	284.510542	-6.420712	0.041003	40 - 150	12	0.909880

Table 9. Predicted LD10 velocity minima, based on parabolic model coefficients in Table 8.

Species	**Minimum LD10 Velocity (Y_{min}; cm/sec)**	**ATUs (X_{min}; °C-days)**
Chinook	14.6	110.8
Chum	41.6	99.8
Coho	23.1	94.7
Pink	62.3	87.8
Sockeye	83.8	90.6
Steelhead	33.2	78.3

8.0 FIGURES

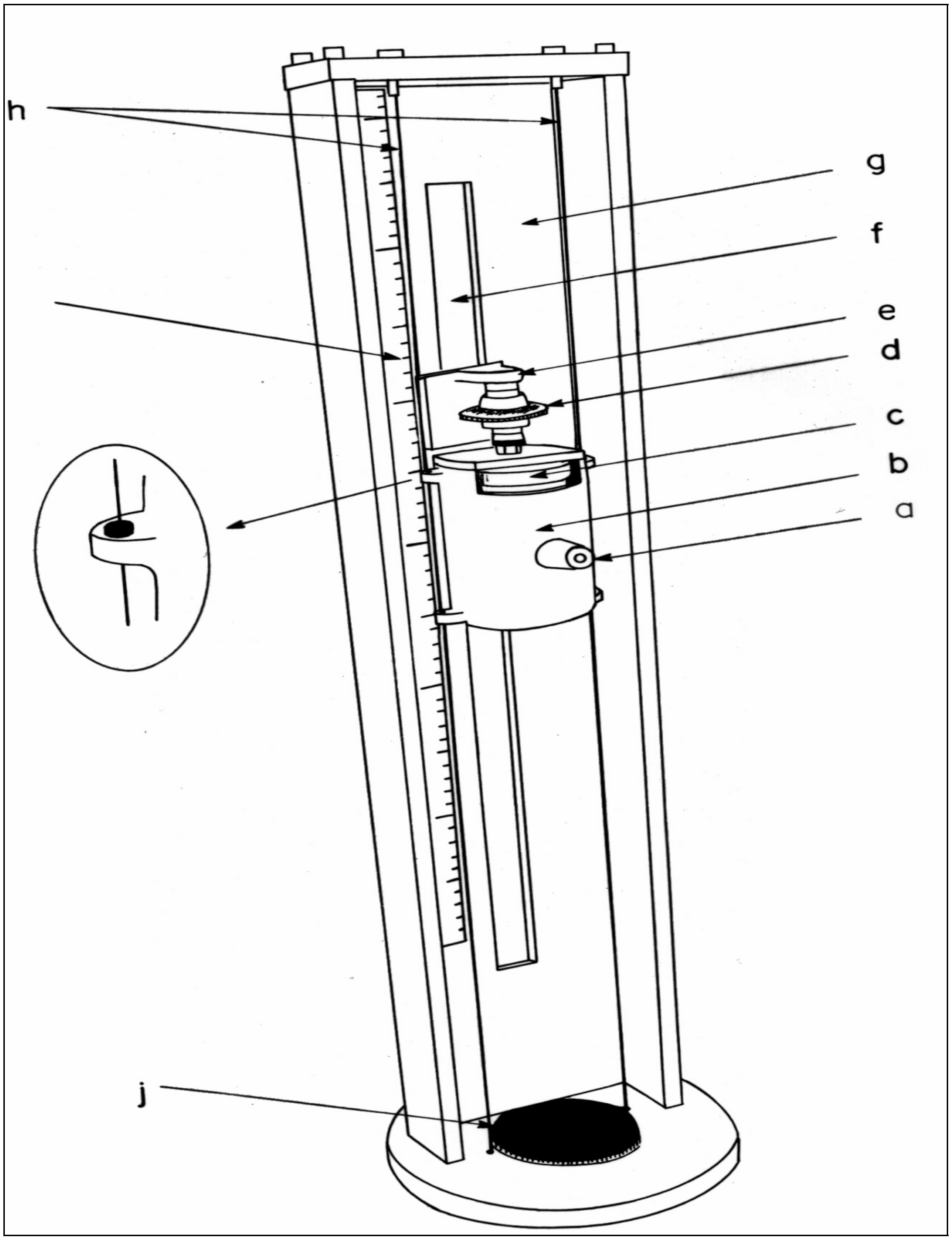

Figure 1. Mechanical shock device for salmonid eggs (from Jensen and Alderdice, 1983).

a: handle for raising carrier; **b:** metal carrier; **c:** slot for petri dish in position; **d:** release trigger; **e:** release platform; **f:** slot for adjustment of release platform height; **g:** stage frame; **h:** metal guide wires; **i:** 100-cm scale; **j:** base plate. Inset: showing guide wire passing through Teflon® sleeve.

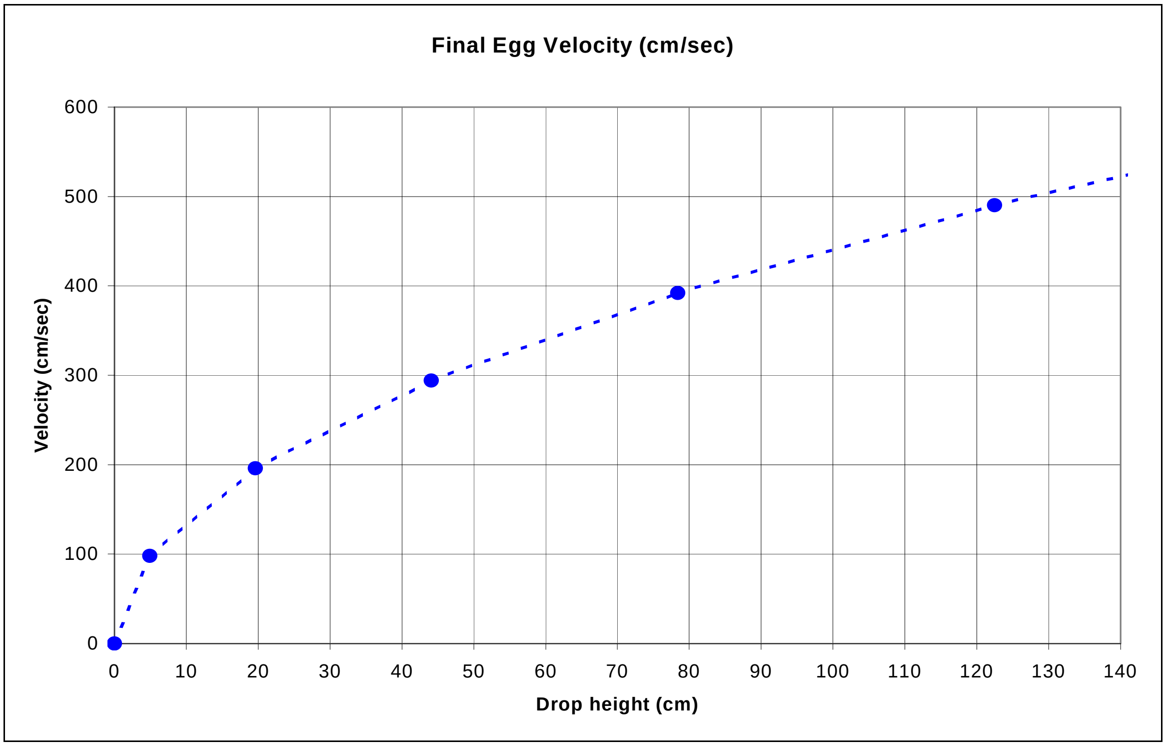

Figure 2. Final velocity (cm/sec) of an egg in relation to drop height (cm).

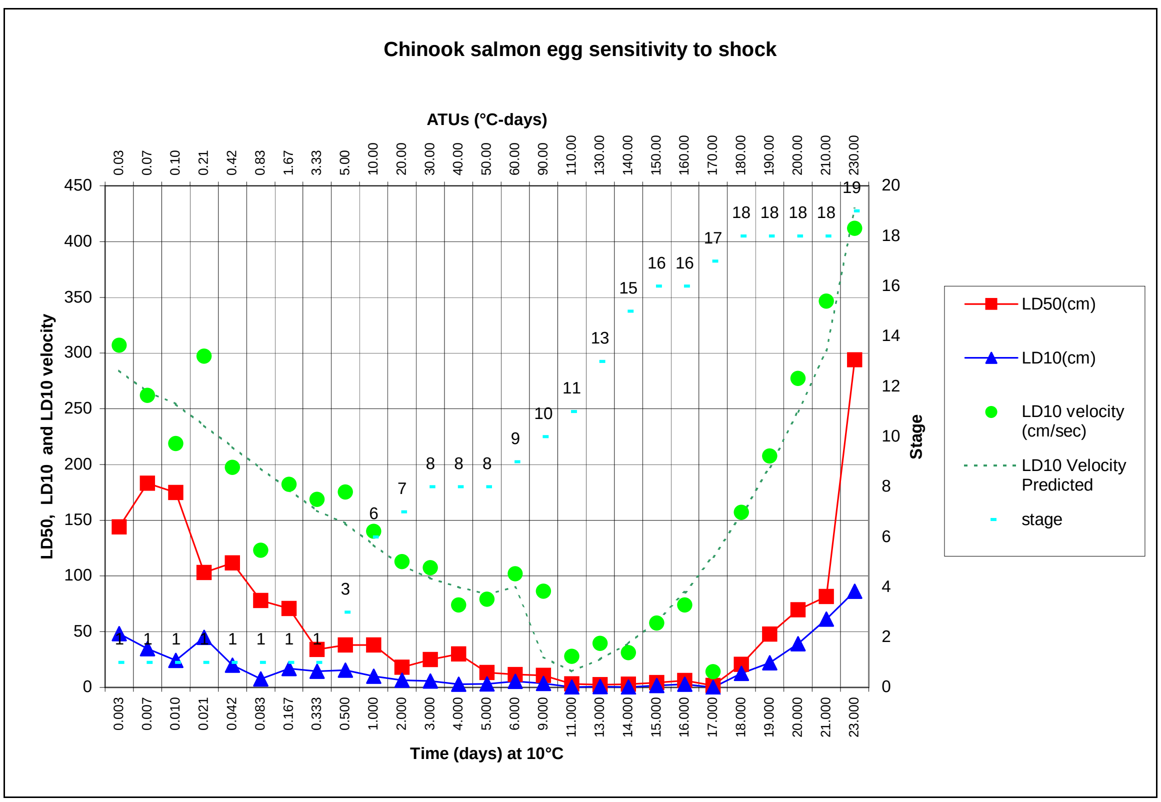

Figure 3. Chinook egg LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (using equation coefficients in Table 8), and embryonic stages (see Table 1) are plotted against days (at 10°C) and ATUs from fertilization.

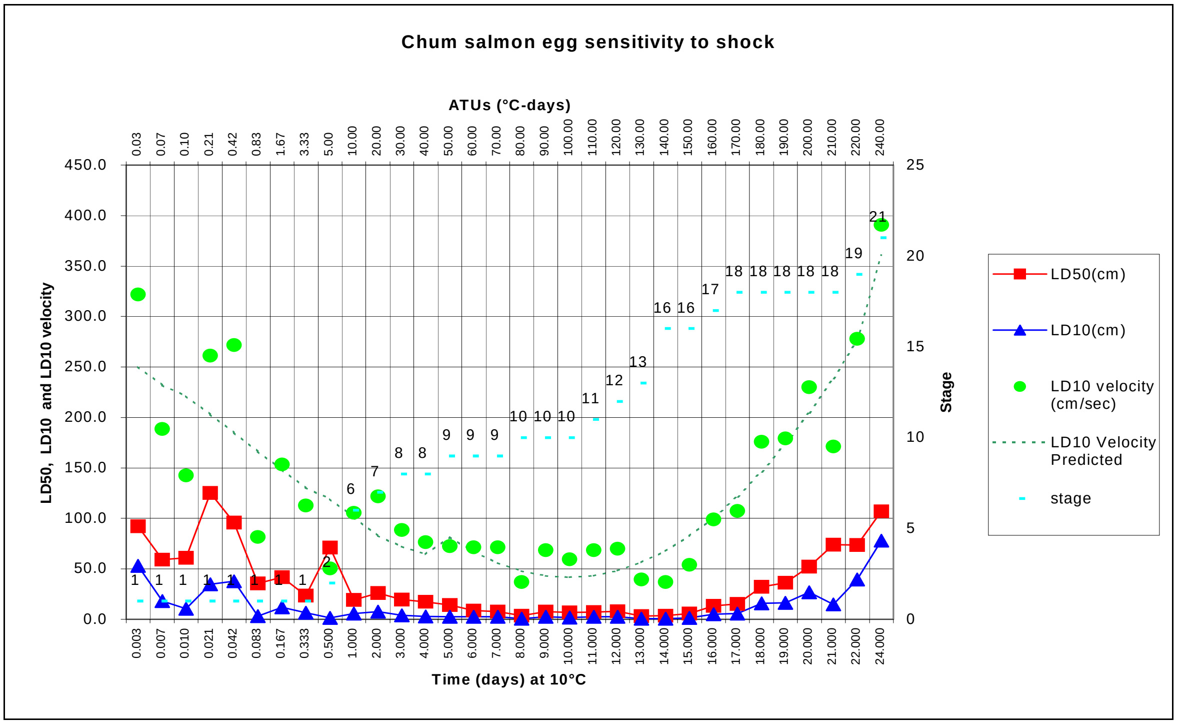

Figure 4. Chum egg LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (using equation coefficients in Table 8), and embryonic stages (see Table 1) are plotted against days (at 10°C) and ATUs from fertilization.

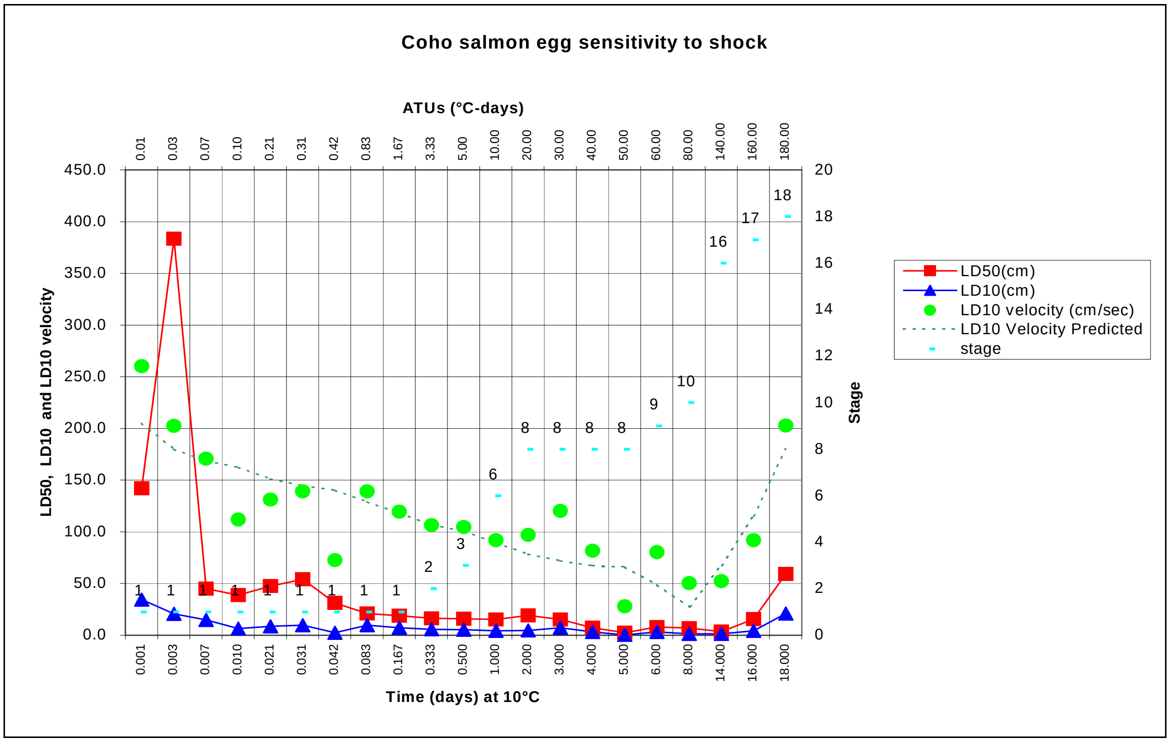

Figure 5. Coho egg LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (using equation coefficients in Table 8), and embryonic stages (see Table 1) are plotted against days (at 10°C) and ATUs from fertilization.

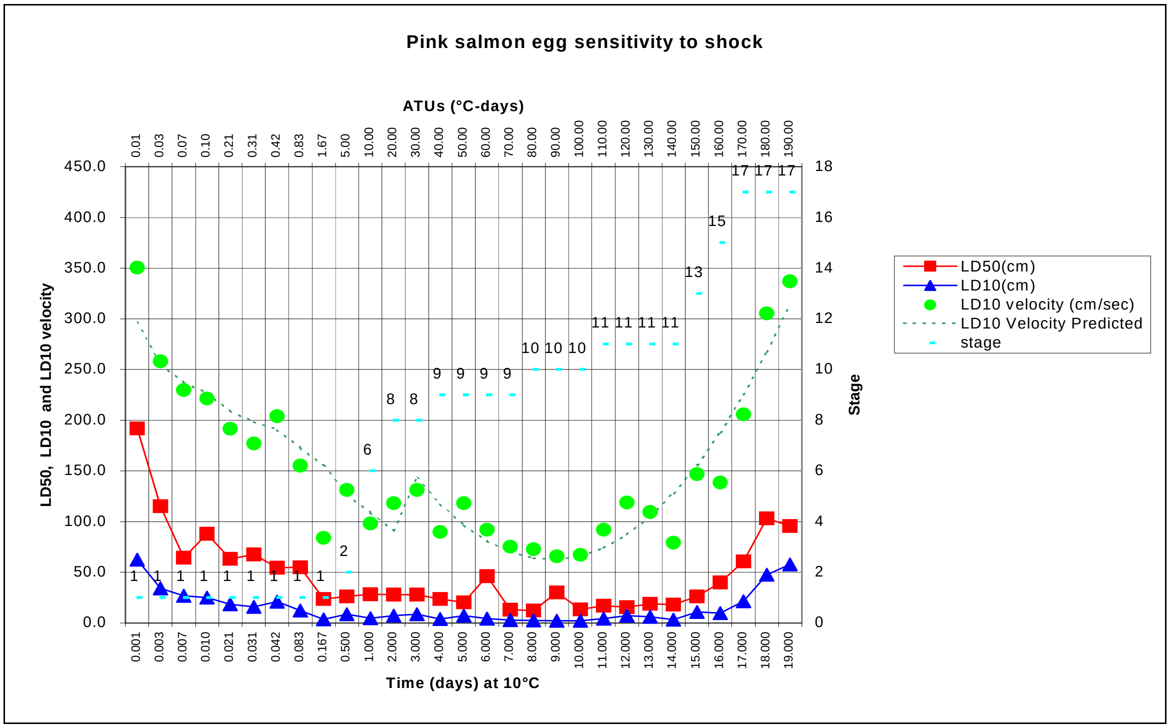

Figure 6. Pink egg LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (using equation coefficients in Table 8), and embryonic stages (see Table 1) are plotted against days (at 10°C) and ATUs from fertilization.

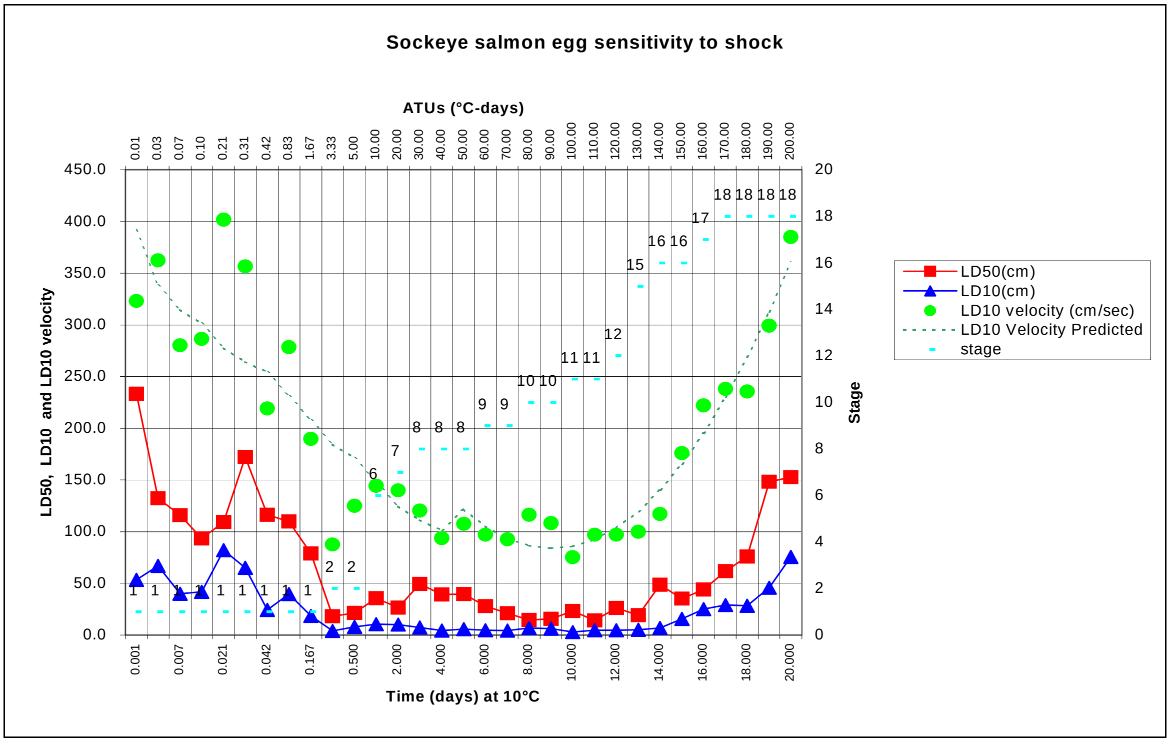

Figure 7. Sockeye egg LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (using equation coefficients in Table 8), and embryonic stages (see Table 1) are plotted against days (at 10°C) and ATUs from fertilization.

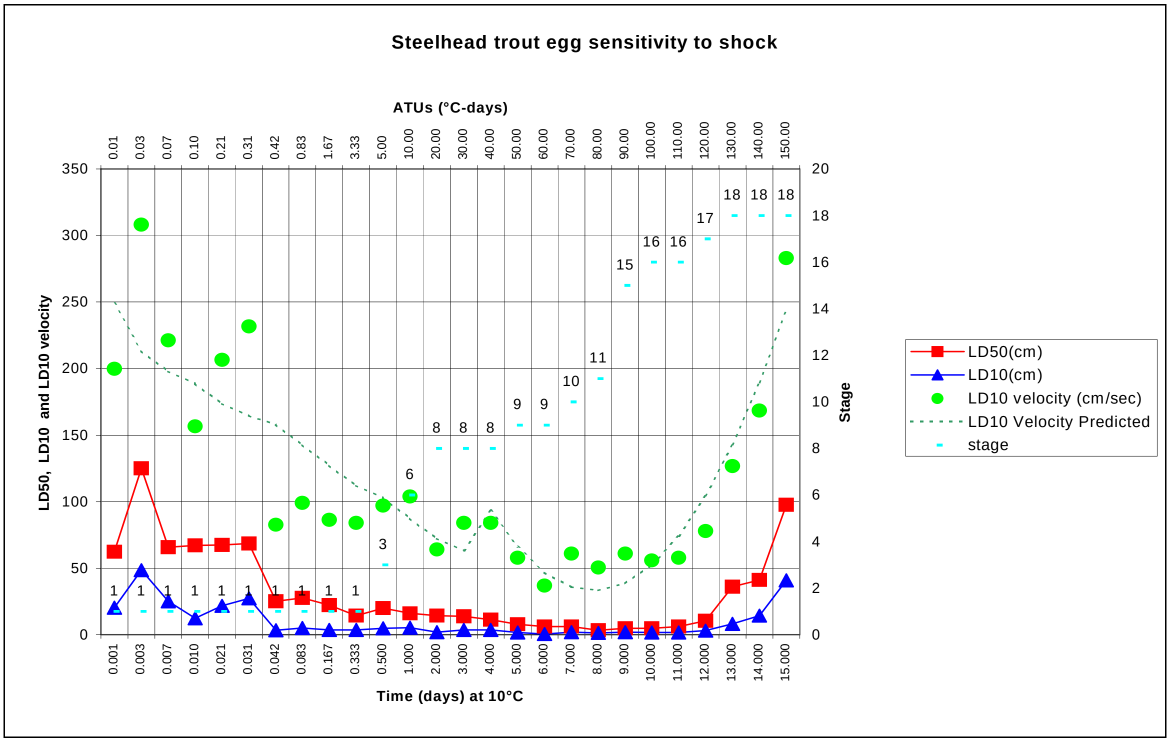

Figure 8. Steelhead egg LD50 and LD10 drop heights, LD10 velocities, predicted LD10 velocities (using equation coefficients in Table 8), and embryonic stages (see Table 1) are plotted against days (at 10°C) and ATUs from fertilization.