Evaluation of Alternatives for Sacramento River Water Temperature Compliance for Winter-Run Chinook Salmon

A requirement in NOAA's National Marine Fisheries Service's reasonable and prudent alternative is to provide water temperatures no greater than a daily average of 56^{o}F in the upper Sacramento River to provide habitat needs for various life history stages of Sacramento River winter-run Chinook salmon. As a result of drought conditions, low storage in Shasta Reservoir, and low snowpack, various alternatives have been proposed for operations of Shasta Reservoir to stretch out the cold water pool. The fish agencies (NMFS, USFWS, and CDFW) have reviewed various alternatives to temperature compliance, including a targeted daily average water temperature from Shasta Dam (*e.g.*, 52^{o}F or 53^{o}F), and increasing the temperature target from 56^{o}F to 58^{o}F at the Sacramento River above Clear Creek CDEC monitoring station (CCR) compliance point[1] after the eggs hatch. As a result of their assessment, the fish agencies do not think that these alternatives would result in negligible impacts and/or little likelihood of adverse impacts to incubating winter-run eggs and alevin in redds compared to a daily average of 56^{o}F.

Targeting a release temperature at Shasta dam, for example, 53^{o}F, does not take into account the warming that occurs between Shasta Dam and CCR due to how fast the water is moving and ambient air temperature. For example, a heat wave in Redding (>105^{o}F) with these operations could lead to elevated temperatures above 56^{o}F at CCR, leading to potentially significant winter-run egg and alevin mortality and sub-lethal effects. Furthermore, the fish agencies do not think Reclamation's Sacramento River water quality temperature modeling accurately reflects increases in water temperature between Keswick Dam and CCR compared with the actual data. Figure 1 shows a consistent difference of about 1.3^{o}F from May through September. This difference is greater than what the temperature model appears to indicate in the monthly 90% exceedance forecast graph (Figure 2).

[1] Bonnyview Bridge (RM 292)

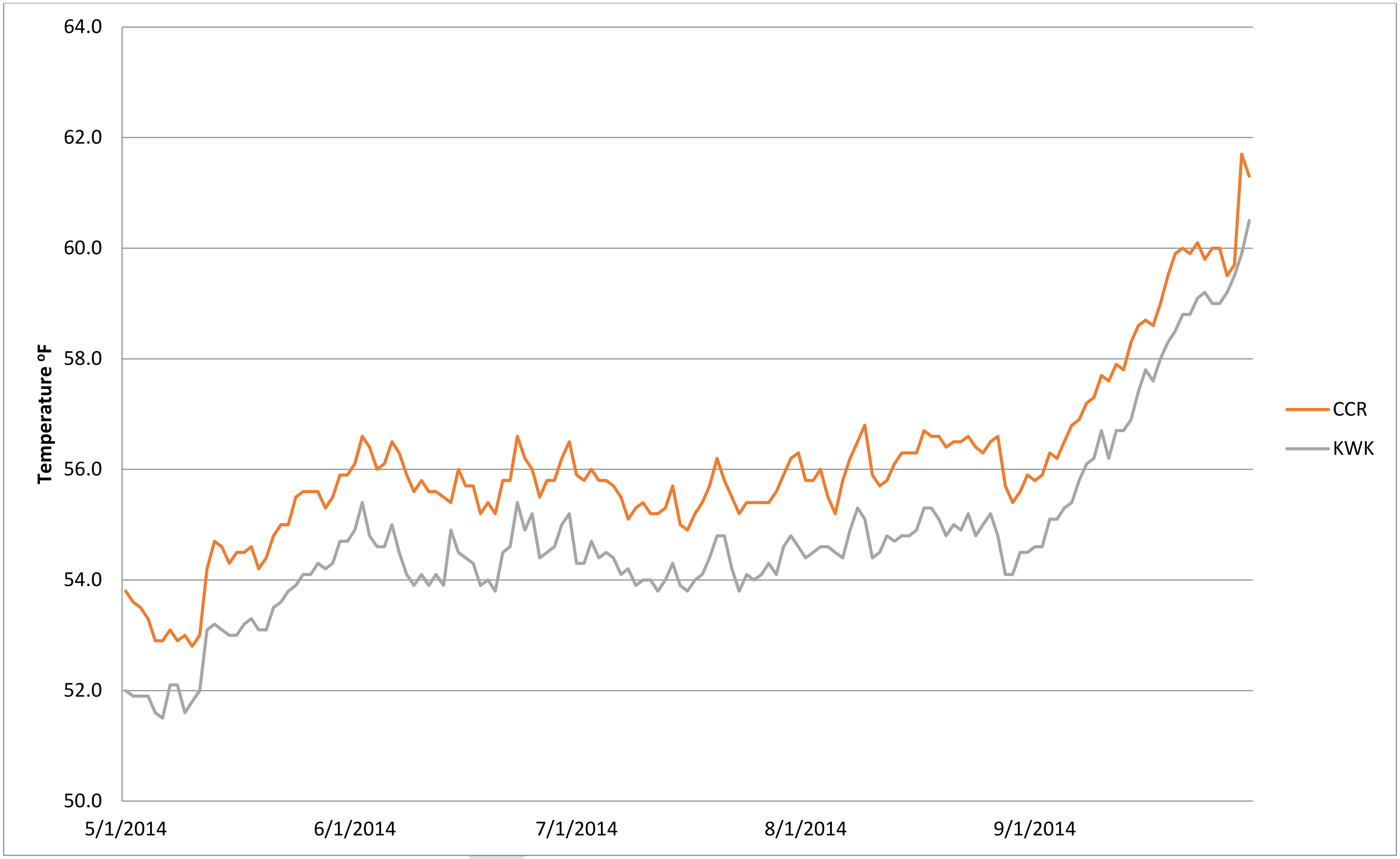

Figure 1. Sacramento River Daily Average Temperature for the Sacramento River above Clear Creek temperature compliance point (CCR) and Keswick Dam release (KWK)

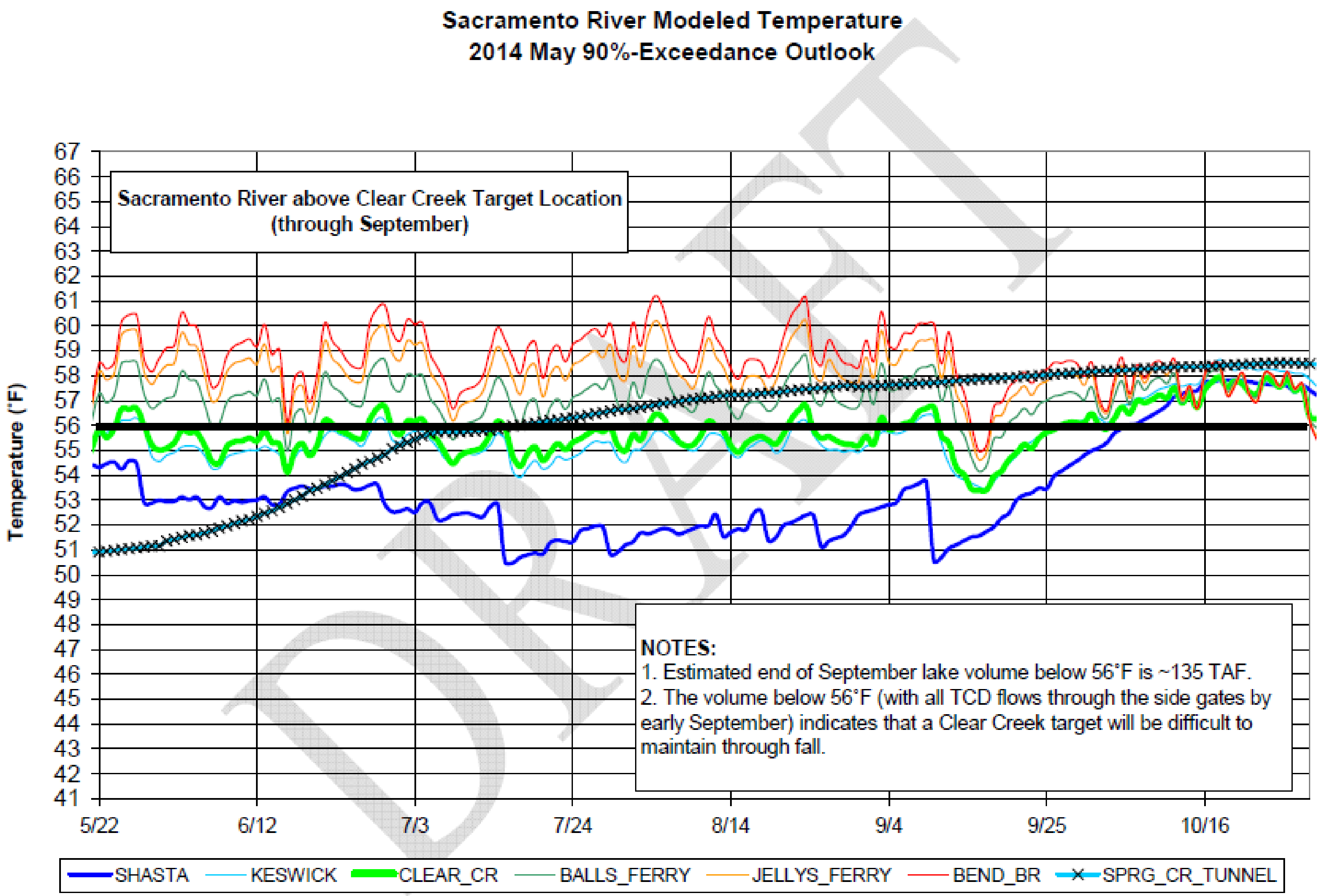

Figure 2. Sacramento River Modeled Temperature 2014 May 90% Exceedance Outlook. KWK modeled water temperatures are in light blue and CCR modeled water temperatures are in green.

In addition, the scientific literature does not support a daily average of 58°F after all eggs have hatched. Providing for optimal protection from fertilization through initial fry development requires that constant or acclimation temperatures be maintained below 48.2-50°F (9-10°C) and that individual daily maximum temperatures generally not exceed 56.3-58.1°F (13.5-14.5°C) (See Appendix A). Myrick and Cech (2004) published a water temperature review, summarizing a number of studies conducted on the Central Valley Chinook salmon. Hinze (1959) found that American River Chinook salmon eggs incubated in water warmer than 16.7°C (62°F) experienced 100% mortality before reaching the eyed stage. Slater (1963) reported that Sacramento River winter-run eggs are limited to 5.6 to 14°C (42 to 57°F). Healey (1979) reported that Sacramento River fall-run Chinook salmon egg mortality rates exceeded 82% at temperatures over 13.9°C (57°F) and that post-hatching mortality was also higher at the elevated temperatures. Healey (1979) also stated that Sacramento River Chinook salmon eggs did not appear to be any more tolerant of elevated water temperatures than eggs from more northern races. US Fish and Wildlife Service (1999) reported that fall-run egg mortality increased at temperatures greater than 12.2°C (54°F) and winter-run egg mortality increased at temperatures over 13.3°C (56°F). Specifically, winter-run Chinook salmon cumulative mortality through rearing nearly doubled from 13.3°C (56°F) to 14.4°C (58°F).

There are water temperatures that may not cause direct mortality to embryos but alevins developed under those temperatures may be subjected to higher mortality at the next developmental stage. Studies indicate that elevated water temperatures earlier in development results in higher mortality, and temperature may also affect the size and weight of alevins and fry (see Appendix B). These sublethal effects do not result in immediate mortality of embryos and alevins, but they can lead to delayed mortality prior to reproduction due to reduced fry and smolt sizes. These effects could result in reduced productivity of a stock and reduced population size. Based on these studies, and on studies of temperature requirements for northern races of Chinook salmon, Myrick and Cech (2004) concluded that temperatures between 6 and 12°C (43 and 54°F) appear best suited to Chinook salmon embryo and alevin development.

The information presented above come from laboratory studies under constant temperature conditions that allow both acclimation and exposure temperatures to be precisely controlled. Acclimation and exposure temperatures can be made either constant or fluctuating, and if fluctuating, they can conform to precise, repeatable cyclic patterns. However, laboratory studies have limited use because of unrealistic conditions. For example, in natural stream systems, temperatures fluctuate hourly with a maximum temperature in late afternoon and a minimum temperature in early morning. From day to day, these values change, resulting in continually changing conditions in the stream. Fluctuating temperature conditions make it difficult to predict thermal effects. In addition, embryos and alevins are also affected by other factors, including dissolved oxygen and the size of substrate particles. These combined effects during thermal acclimation and exposure would likely result in greater mortality under field conditions than in laboratory settings, in which multiple stresses are limited. Further research is needed to understand the effects of variable temperature regimes using sensitive life stages. Understanding the sublethal effects associated with the upper thermal tolerance limits for salmonids is essential for managing these fishes in such highly altered habitats (Deas *et al.* 2008).

Even though State Water Resources Control Board Orders 90-5 and 91-1 require Reclamation to operate Keswick and Shasta dams to meet a daily average temperature of 56°F at Red Bluff Diversion Dam (RBDD) [or at a temperature compliance point (TCP) modified when the objective cannot be met at RBDD based on Reclamation's other operational commitments including those to water contractors, D-1641 regulations and criteria, and projected end of September storage volume], nearly every year, Reclamation has exceeded the TCP at some point throughout the temperature control season. Especially last year, 100% of winter-run brood year 2014 redds were exposed to temperatures above 56°F degrees at the CCR TCP at some time period during the water year (see Figure 3). Of significant concern were those redds exposed to the consistently-elevated temperatures throughout August and September. This led to one of the lowest egg to fry survival rates to RBDD estimated by the USFWS Juvenile Production Index. Based upon history, it is likely that a proposed 58°F TCP at CCR for the alevin stage would be exceeded throughout the temperature compliance season and would in fact have significantly more adverse effects to winter-run alevin survival.

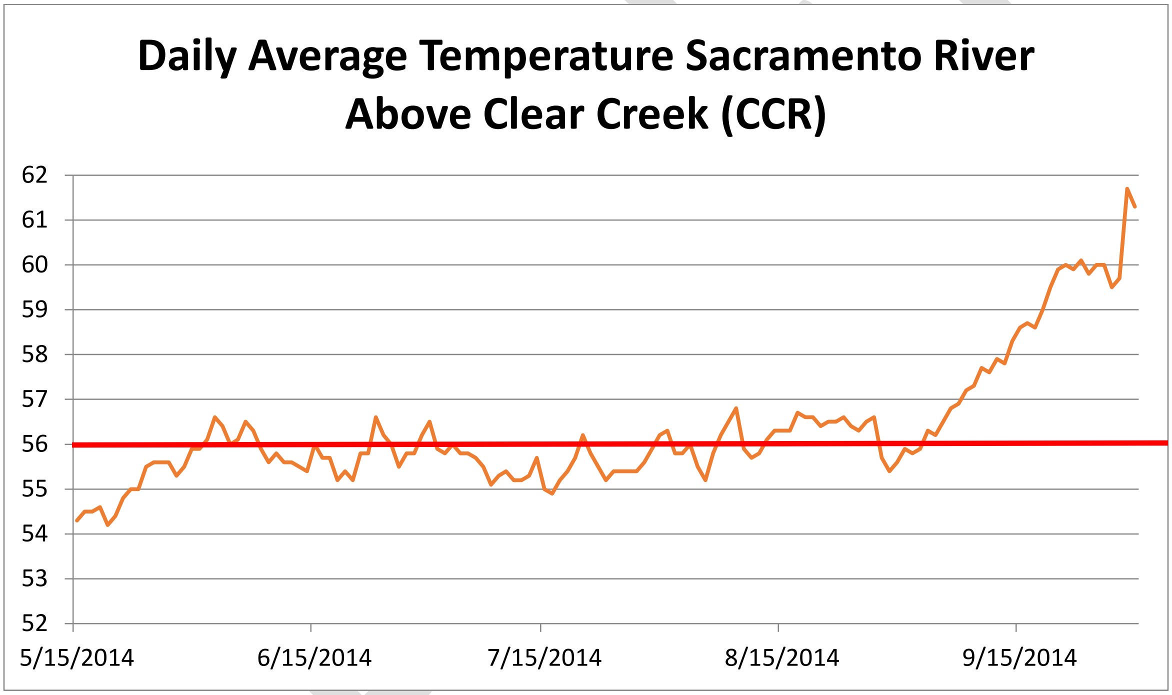

Figure 3. Daily average temperature Sacramento River at the CDEC Temperature Monitoring Station at the Clear Creek Temperature Compliance Point (CCR), May 15 through September 30, 2014.

Based on upon the scientific literature and uncertainly in Reclamation's Sacramento River temperature modeling, the fish agencies cannot support proposals to target daily average water temperature releases from Shasta Dam or 58°F water at the CCR compliance point after the eggs hatch, and do not think that these alternatives would result in negligible impacts and/or little likelihood of adverse impacts to incubating winter-run eggs and alevins in redds than the current requirement of 56°F daily water temperature at CCR.

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Appendix A: Additional Information

The U.S. Environmental Protection Agency (US EPA) published 5 volumes of issue papers on the effects of water temperature on salmonids for various freshwater life stages. The following data summary is adopted from the issue paper 5 (US EPA 2001). Original citations are retained but no relevant references are listed.

Once spawning has taken place, the eggs of Chinook salmon hatch in about 2 months and the young remain in the gravel for 2-3 weeks before emerging. Many researchers have tested incubation survival at constant exposure to various test temperatures. Complete mortality (100%) has been noted at incubation temperatures from 57 to 66.9°F (13.9-19.4°C) (Donaldson 1955; Garling and Masterson 1985; Seymour 1956; Eddy 1972, as cited in Raleigh *et al*. 1986). Significant mortality (over 50%) has been noted at constant incubation temperatures from 49.8 to 62°F (9.9-16.7°C) (Donaldson 1955; Seymour 1956; Burrows 1963; Bailey and Evans 1971, as cited in Alderdice and Velsen 1978; Hinze 1959, as cited in Healy 1979). A constant incubation temperature of 46.4°F (8°C) produced more robust alevin and fry survival than constant exposure to either 39.2 or 53.6°F (4 or 12°C) in a study by Murray and Beacham (1986), and Velsen (1987) compiled data showing that the best survival (>92.9%) occurred between 44.9 and 49.2°F (7.2 and 9.6°C).

Heming (1982) found good survival at both 50 and 53.6°F (10 and 12°C). Heming tested survival in both incubation trays and artificial redds. Survival rates declined as the temperatures increased from 42.8 to 46.4, 50, and 53.6°F (6-8, 10, and 12°C). The greatest survival (91.7%-98%) occurred at 42.8 and 46.4°F (6 and 8°C), respectively, but it was still very good (90.2%-95.9%) at 50°F (10°C). Incubation at 53.6°F (12°C) consistently had the lowest survival (84.6%-89.3%). Heming also tested survival rates from incubation to hatching against survival rates from hatching through complete yolk absorption. His work suggests higher incubation temperatures may create a metabolic energy deficit for pre-emergent salmon that increases mortality. Once alevin have hatched and absorbed their yolk sacs they will need to make a transition to active feeding. Heming and McInery (1982) found that temperatures of 42.8, 46.4, and 50°F (6, 8, and 10°C) resulted in an average survival of 98.4% during this transitional period, while 53.6°F (12°C) was associated with a decrease in survival to 89.2%. The maximum conversion of yolk to tissue weight was reported by Heming (1982, as cited by Beacham and Murray 1986) to occur at 42.8°F (6°C) or below. Seymour (1956) noted a nine fold increase in abnormalities in fry incubated at 60°F (15.6°C) and higher when compared with those incubated between 39.9 and 55°F (4.4-12.8°C). Seymour also noted that fry incubated at 39.9°F (4.4°C) emerged at a larger size than those reared at higher temperatures; however, subsequent fry growth was maximized at 55°F (12.8°C).

Considered together, the work of the authors cited above strongly suggests that constant temperatures above 48.2-50°F (9-10°C) and below 41°F (5°C) may reduce the survival of Chinook salmon embryos and alevins. Although constant temperatures of 51.8-53.6°F (11-12°C) can still result in good success, the results are consistently less than what is produced at lower temperatures. As discussed previously in this paper, constant laboratory test temperatures of 48.2-50°F (9-10°C) should be considered roughly equivalent to naturally-fluctuating stream temperatures with daily maximums of 51.8-53.6°F (11-12°C).

Some researchers have tried to mimic the naturally-fluctuating and falling temperatures actually experienced by incubating eggs, or have stepwise reduced the incubation temperatures as incubation progressed. Initial incubation temperatures from 60 to 62°F (15.6-16.7°C) have been associated with significant to total losses of young fish through the incubation to early fry development phase [Healy 1979, Johnson and Brice 1953, California Department of Water Resources (CDWR) 1988, and Jewett 1970 as cited in CDWR 1988]. Rice (1960) found that source waters declining from 60 to 46.9°F (15.6-8.3°C) resulted in satisfactory egg development, although he did not provide survival rates or clearly consider survival through to the fry stage. Johnson and Brice (1953) found survival often exceeded 90% where initial water temperatures (as a daily mean) were below 53.9°F (12.2°C).

Healy (1979) found that highest survival (97%) occurred in creek water where the daily maximum reached 55°F (12.8°C) only a few times during the first 2 week of development, but also noted that survival was still very good (90%-94%) where the initial temperatures were between 55 and 57.5°F (12.8 and 14.2°C). Olson and Nakatani (1969) found 53.7%-88% survival in egg lots started at 54.5°F (12.5°C), experiencing a brief increase to 58.4°F (14.7°C) in the first week, and then quickly dropping back to 53.6-54.5°F (12-12.5°C) and assuming a seasonal downward trend in temperature (test water paralleled both diel and seasonal fluctuations). Olson and Foster (1955) found the greatest survival of 92.2% at an initial test temperature of 52.8°F (11.6°C), but reported no appreciable differences in survival rates at initial test temperatures of 56.8, 59, and 60.8°F (13.8, 15, and 16°C) (89.9%-83.9%) (test water paralleled seasonal daily average temperatures).

Seymour (1956) tested four geographically distinct stocks of Chinook salmon. Taking into consideration both mortality and growth rate, the optimum temperature was estimated as 52°F (11.1°C) for eggs and fry. The mortality rate was considered low at all stages of development for lots reared between 39.9 and 55°F (4.4-12.8°C). Lots with initial temperatures of 64.9°F (18.3°C) had the highest mortality (11%, 24%, 40%, and 100%). In the cyclic and fluctuating temperature tests reviewed here, temperatures at the beginning of incubation that are below 51.8-55°F (11-12.8°C) are typically associated with optimal survival rates. This compares well with the adjusted optimal range of 52.7-54.5°F (11.5-12.5°C) suggested above based on examining the constant temperature exposure studies. This range also compares well with the optimal temperature range of 46.4-53.6°F (8-12°C) recommended by the Independent Scientific Group (1996) study.

Donaldson (1955) transferred eggs to more optimal 50-55°F (10-12.8°C) incubation temperatures after various periods of exposure to higher temperatures. He found that tolerance to temperature exposure varies with the stage of development. He also found 20% mortality could be induced by exposing eggs to 66.9°F (19.4°C) for 1 day, 64.9°F (18.3°C) for 3 days, and 62.9°F (17.2°C) for less than 10 days. Donaldson's work lends further support to the observations made by others such as Jewett (1970, as cited in CDWR 1988) that the latent effects of holding eggs at higher than optimal temperatures continues through the period of absorption of the yolk sac; thus, using mortality estimates at the time of hatching underestimates the total temperature-induced mortality.

Donaldson found the developmental stages associated with the greatest percentages of temperature induced mortality were: (1) the time up until the closure of the blastopore [200 temperature units (T.U.)]; (2) the period just previous to and during hatching; and (3) when fry are adapting themselves to feeding. He also found that when eggs were exposed to test temperatures 62.9, 64.9, and 66.9°F (17.2, 18.3, and 19.4°C) past the eye pigmentation stage (350 T.U.), the time necessary for complete hatching doubled, and the frequency of common abnormalities increased with both the higher temperatures and longer exposures.

Murray and Beacham (1986) found that initial incubation at 39.2°F (4°C) reduced survival even with later transfer (at completion of epiboly) to warmer waters 46.4 and 53.6°F (8 and 12°C). Transfers after epiboly or completion of eye pigmentation from 39.2 to 53.6°F (4-12°C) and from 53.6 to 39.2°F (12-4°C) also caused an increase in alevin mortality. The authors also found that decreasing temperature produced longer and heavier alevins and fry. Combs (1965) found that eggs developed to the 128-cell stage at 42.4°F (5.8°C) could then tolerate 35°F (1.7°C) for the remainder of the incubation period with only moderate losses. Mortality of 14.5% was observed with a transfer time of 72 hours, whereas only 3.3% mortality occurred with a transfer at 144 hours. These three works together suggest that the effects of suboptimal initial incubation temperatures may not be nullified by later changes in the temperature regime to more optimal levels; that sudden changes in temperature at either early or later stages of development, regardless of the direction of that change, can be harmful to pre-emergent life stages; and that initial incubation at optimal temperatures may condition eggs and embryos such that they can withstand very low winter temperature regimes.

In addition to Donaldson (1955), Neitzel and Becker (1985) conducted work on the effects of short-term increases in temperature that can be used to support daily maximum temperature criteria. Neitzel and Becker used Chinook salmon to determine the effects of short-term dewatering of redds by hydropower facilities. Neitzel and Becker found that sudden increases in temperatures from 50°F to above 71.6°F (10-22°C) for 1-8 hours significantly reduced survival of cleavage eggs in Chinook salmon. Controls held at 50°F (10°C) had very low mortalities (less than 2%). Mortality in treatment groups was 8%-10% at 71.6°F (22°C) after a 2-hour exposure, and was 22% after a 1-hour exposure at 74.3°F (23.5°C). They further found that decreasing the temperature from 50°F (10°C) to near freezing 32°F (0°C) for up to 24 hours did not increase mortality in eggs, embryos, or alevin. Considering the work of Neitzel and Becker, it would appear that Chinook salmon eggs and embryos are relatively tolerant of short-term increases in temperature up to 71.6°F (22°C). However, because Donaldson (1955) found that 66.9°F (19.4°C) produced 20% mortality in 1 day and 64.9°F (18.3°C) produced 20% mortality in 3 days, setting a more restrictive single daily maximum temperature limit is certainly warranted. Furthermore, as described above, incubation conditions where daily maximum temperatures were in the range of 57.9-60.8°F (14.4-15.6°C) produced reduced survival rates, so further caution may be warranted in allowing daily maximum temperatures to exceed 56.3-58.1°F (13.5-14.5°C) during incubation.

Appendix B Sub-lethal Effects

USFWS (1999) found that the subsequent alevin survival rate was 80% when fall-run Chinook embryos were incubated at 52^{o}F (11.1^{o}C), but the alevin survival rate decreased to 51% when the embryos were incubated at 56^{o}F (13.3^{o}C), and decreased further to 17% when incubated at 60^{o}F (15.6^{o}C). Seymour (1956) found that high egg mortality and 100% sac-fry mortality occurred at 15.6^{o}C and 17^{o}C. Although there was low egg mortality (12.8% and 14.2%, respectively), subsequent sac-fry mortality exceeded 50%. USFWS (1999) observed that the embryo survival rate was 79% when fall-run Chinook embryos were incubated initially at 56^{o}F (13.3^{o}C) for about 40 days and then at 60^{o}F (15.6^{o}C), but the rate decreased to 55% when the embryos were incubated initially at 56^{o}F (13.3^{o}C) for only 20 days and then at 60^{o}F (15.6^{o}C). Beacham and Murray (1990) reported study results for Chinook salmon at water temperatures 39.2^{o}F (4°C), 46.4^{o}F (8°C), and 53.6^{o}F (12°C). Water temperature and egg size both contributed significantly to describing variation in alevin and fry size. Temperature variation had the greatest effect on alevin length and some effect on fry length, while egg size had the more important factor for alevin weight. On average, Chinook alevin length was reduced by 5% and fry weight reduced by 44.6^{o}F (7%) at 53.6^{o}F (12^{o}C) comparing to 39.2^{o}F (4^{o}C) or 46.4^{o}F (8^{o}C).

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