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Application of Flexible Curtains to Control Mixing and Enable Selective Withdrawal in Reservoirs

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1. Abstract

The US Bureau of Reclamation (Reclamation) has installed three flexible curtains in two reservoirs in northern California to control mixing and to provide selective withdrawal at a submerged intake. Two surface suspended curtains were installed to control mixing of cold water inflow with epilimnetic water. The curtains have been effective at isolating warm surface water from the mixing or plunge zone. The third curtain was installed to allow selective withdrawal through a low-level intake structure. This 30-m-deep curtain was designed to isolate the intake bay from the main body of the reservoir. The purpose of these curtains is to minimize the temperature gain of water which is conveyed through three reservoirs. This paper will concentrate on the two curtains which were used to control mixing of a plunging inflows. Acoustic Doppler current profilers (ADCPs) and temperature profiles were used to monitor curtain performance. This paper will cover the following topics: engineering design, prototype monitoring, and curtain performance.

2. Background

During the late 1980s, extended drought in northern California created potentially life threatening conditions for endangered salmon species inhabiting the Sacramento River. Summer and early fall river water temperatures threatened to exceed critical levels for sustaining juvenile salmon populations. High release water temperatures from reservoirs, coupled with natural in-stream warming, threatened to make downstream waters too warm for egg incubation and juvenile fish survival. As a result, California's water resources agencies and the National Marine Fisheries Service imposed a maximum temperature of 12EC (56EF) in the upper Sacramento River. To comply with temperature requirements, Reclamation began an aggressive program to construct flexible curtain structures that would yield colder water releases.

3. Description of Reservoir System

Water from the Trinity River Basin is diverted into the Sacramento River Basin through two tunnels and three reservoirs. Trinity River water is diverted from Lewiston Reservoir through Clear Creek Tunnel to the Judge Francis Carr powerplant and discharged into Whiskeytown Reservoir. From there, water flows through the reservoir, into Spring Creek Tunnel and through Spring Creek Powerplant. Spring Creek Powerplant discharges into Keswick Reservoir where it combines with Sacramento River water released from Shasta Dam. Water released from Keswick Dam enters the upper Sacramento River. Over the course of this diversion and prior to curtain installation, Trinity River water temperatures commonly increased 5 to 7EC (10 to 13EF). To provide cold water releases, Reclamation engineers chose to install flexible curtains in Lewiston and Whiskeytown Reservoirs; a total of three curtains were constructed. These curtains permit project operators to manage hydropower operations while controlling the temperature of water releases.

4. Curtain Design

When a reservoir is thermally stratified, water can be selectively withdrawn from distinct horizontal layers. The vertical position and thickness of the withdrawal layer depends on several factors:

- Elevation, placement, size, and orientation of the intake
- Degree of thermal stratification
- Frequency of the withdrawal discharges
- Boundary interference from the reservoir water surface, the dam, or topography near the intake

To develop a strategy for providing selective withdrawal, Reclamation engineers conducted a value engineering (VE) study to develop cost-effective selective withdrawal options. During the VE study, flexible curtains were found to offer potential cost savings compared to traditional structural modifications to existing intakes. Physical model studies were conducted in Reclamation's Water Resources Research Laboratory to determine reservoir responses to curtain installations in Lewiston and Whiskeytown Reservoirs (Johnson and Vermeyen, 1993; Vermeyen 1997).

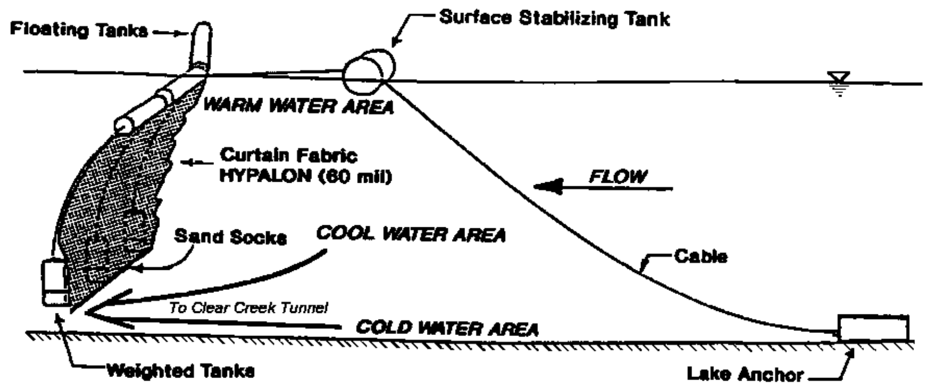

Figure 1. Schematic of the Lewiston Reservoir flexible curtain and its components. This curtain design was also used for both curtains installed in Whiskeytown Reservoir.

The VE team recommended three sites for potential curtain installations. In Lewiston Reservoir, a shallow and weakly stratified impoundment, a curtain was recommended to provide selective withdrawal for a near-surface intake to the Clear Creek Tunnel (figure 1). In Whiskeytown Reservoir, two curtains were recommended: 1) the Carr Powerplant tailrace curtain would minimize interfacial shear mixing which occurs when cold water entering the reservoir plunges below a very warm epilimnion, and 2) a second curtain would enable selective withdrawal at the Spring Creek Tunnel intake.

Model and prototype performance of the Lewiston Reservoir curtain and the Carr powerplant tailrace curtain will be summarized in this paper.

5. Carr Tailrace Curtain Modeling

A 1:72 scale, density-stratified physical model study was conducted to develop a curtain design for Whiskeytown Reservoir that minimized mixing associated with plunging inflows. The model study resulted in a curtain located 1.2 km downstream from the Carr Powerplant which would effectively reduce interfacial shear mixing. The recommended curtain design called for a 183-m-long, 12-m-deep, surface suspended curtain (Vermeyen 1997). A similar study of a 1:120 scale model was done for the Lewiston curtain.

6. Installing the Lewiston and Whiskeytown Curtains

In the summer of 1992, a 250-m-long, 10.7-m-deep flexible curtain was constructed in Lewiston Reservoir (figure 1). Total time for engineering, procurement, and construction of the Lewiston Reservoir curtain was five months. Reclamation's Northern California Area Office was responsible for the design and construction of the curtain. Costs for this curtain totaled $650,000US.

Two flexible curtains were installed in Whiskeytown Reservoir during the summer of 1993. The Carr tailrace curtain was fabricated and installed in one month at a cost of $500,000US. A 30-m-deep, 730-m-long surface suspended curtain which surrounded the Spring Creek Tunnel intake was installed over a four-month period at a cost of $1,800,000US.

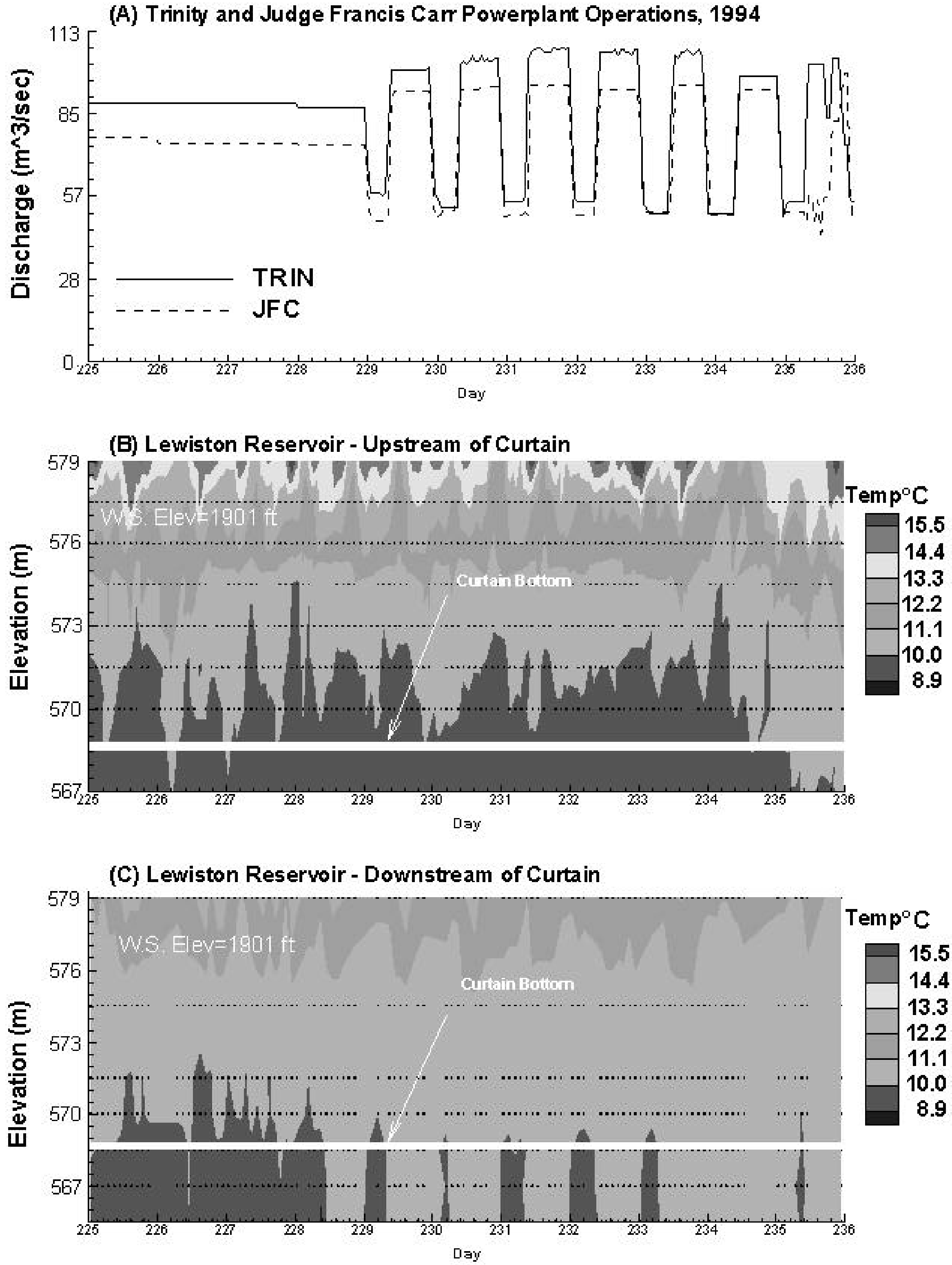

Figure 2. (a) Lewiston Reservoir operations where Trinity and Judge Francis Carr Powerplants represent inflow and outflow, respectively. (b and c) Continuous temperature profile data collected at hourly intervals on both sides of the Lewiston Reservoir curtain for the period of August 12 through 23, 1994 (calendar days 225-236). The black dots on figures B and C are the measurement locations.

7. Lewiston Reservoir Curtain Performance

Lewiston curtain performance was evaluated by analyzing temperature data collected in the Clear Creek Tunnel intake. In 1992, data collected before and after curtain installation indicated that for similar operational conditions the average temperature of water entering the Clear Creek Tunnel was reduced by about 1.4EC (2.5EF) after the curtain installation.

Continuous temperature profile data collected at hourly intervals on both sides of the Lewiston Reservoir curtain for August 12 through 23, 1994 (calendar days 225 to 236), are shown on figures 2B and 2C. These plots of temperature contours (isotherms) illustrate the modification to the temperature stratification generated by the curtain for two power generation schemes as shown in figure 2A. For both these operational scenarios, the temperature profiles collected downstream from the curtain are very uniform in the 10 to 12EC range. The temperature profiles collected upstream from the curtain show periods of variable thermal stratification caused by diurnal fluctuations in the amount of insolation (solar heating). Figures 2B and 1C illustrate that the curtain was effective at isolating the Clear Creek Tunnel intake structure from the thermally stratified reservoir. When power plant operations were switched to partial peaking, greater fluctuations in temperatures occurred upstream from the curtain, because flow fluctuations caused periods of increased and reduced mixing. Intense mixing occurred during peaking that would begin to break down the stratification in the upstream pool. Conversely, peaking had little effect downstream from the curtain, except that less cold water would be passed under the curtain. Partial peaking operations had little or no impact on the downstream pool because the intake continuously withdraws surface water, so warm water was unable to accumulate. Unfortunately, no temperature profile data were available for full peaking operations, which went into effect on calendar day 243 (see figure 3).

During August and September 1994, Lewiston inflow and outflow temperatures were compared for three types of power operations at Trinity and Carr Powerplants (see figure 3A): 1) during days 220 through 228, baseload power releases were held constant at 90 m^3/s; 2) days 229 through 243 had partial peaking power operations, during which flows fluctuated between 50 and 90 m^3/s; 3) days 244 through 250 were strictly peaking power operations when one and occasionally two turbines operated for 10 to 12 hour periods. A comparison of Trinity Dam outflow and Clear Creek Tunnel intake temperatures showed a consistent 2EC temperature gain through the reservoir for days 220 through 243 regardless of the operations (figure 3B). However, when peaking operations were implemented on day 244, a steady increase in outflow temperature was observed. After day 254, temperature gain through Lewiston Reservoir had stabilized at 3.6EC. This 1.6EC temperature gain occurred because warm water accumulated upstream and downstream from the curtain during no-flow periods.

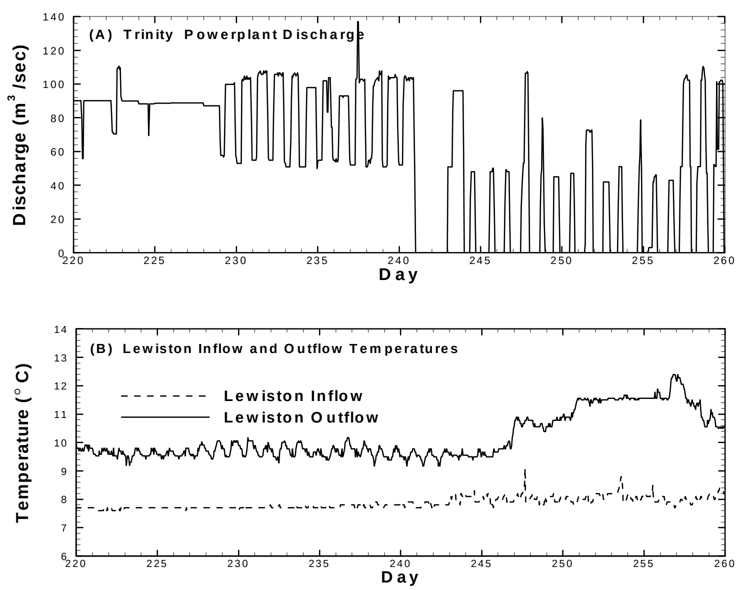

Figure 3. (a) Lewiston Reservoir operations along with (b) inflow and outflow temperatures for August 8 - September 17, 1994. These data illustrate the temperature gain of Trinity River water diverted through the reservoir for a three different power generation schemes.

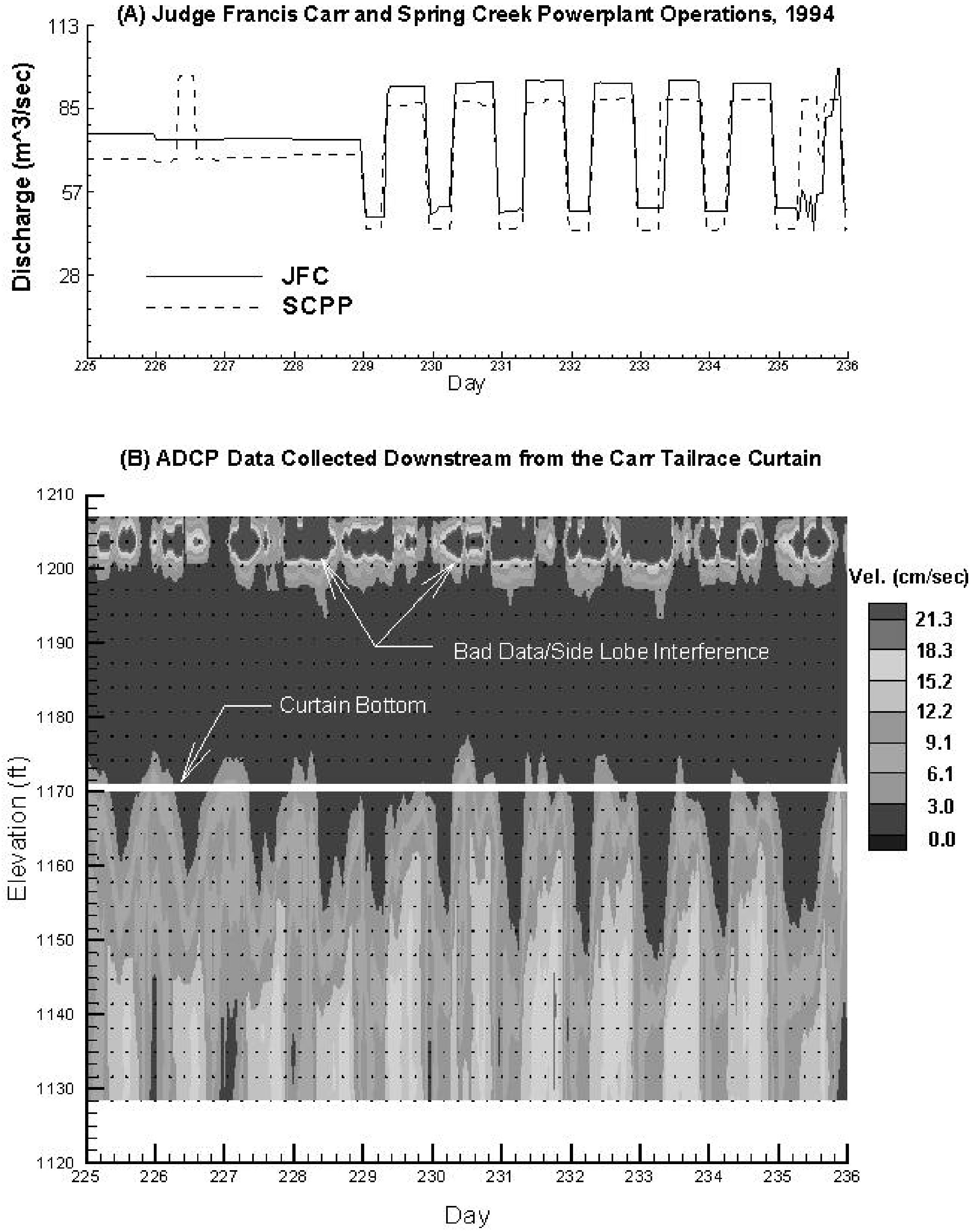

Figure 4. (a) Whiskeytown Reservoir operations, (b) ADCP isovels collected downstream from the Carr Powerplant tailrace curtain. Both plots cover the period from August 13 to August 24, 1994. Note: the black dots represent ADCP depth cell locations.

8. Carr Tailrace Curtain Performance

Curtain performance was evaluated by analyzing temperature data collected in the tailrace below Carr Powerplant and temperature profiles collected downstream from the curtain. The main objective was to determine the reduction of inflow warming attributed to the curtain. In May 1994, temperature profiles collected before and after curtain installation showed dramatic modifications to the reservoir stratification. After curtain installation, the temperature of water flowing into the hypolimnion was reduced from 13.3 to 11.7EC. The upstream epilimnion was reduced to a depth of 3 to 4.5 m, and the downstream epilimnion expanded to a depth of 6 to 7.6 m. In August 1994, the two curtains reduced the overall temperature gain of water routed through Whiskeytown Reservoir by 2.2EC compared to pre-curtain temperatures collected in August 1988. The majority of the temperature reduction was attributed to the Carr tailrace curtain.

Plots in figure 4 illustrate the hydraulic performance of the Carr tailrace curtain. These data were collected over an 11-day period when the power operations were baseload for 4 days and partial peaking for 7 days (figure 4a). Figure 4b shows ADCP data collected 50 m downstream from the curtain. For baseload operations, velocities varied with diurnal fluctuations in underflow temperatures. On days 225 and 227 the underflow detached from the bottom and became an interflow. Likewise, there were periods during each day when the curtain did not hydraulically control the underflow, and water was flowing into the hypolimnion as a density current.

9. Conclusions

! For seven consecutive years, flexible curtains have been successfully used to control reservoir mixing and permit selective withdrawal at Lewiston and Whiskeytown Reservoirs in northern California.

! Curtains have reduced temperature gains of Trinity River water diversions by 2 to 3EC during late summer and early fall.

! Hydro-power operations have a strong influence on curtain performance. Peaking power operations increased temperature gains in Lewiston Reservoir by 1.6EC when compared to baseload operations.

! Thermally-stratified physical models were valuable tools for developing effective curtain designs.

! Continuous temperature monitoring and ADCP data were used to document curtain performance and hydraulic characteristics for a wide range of operations.

10. References

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