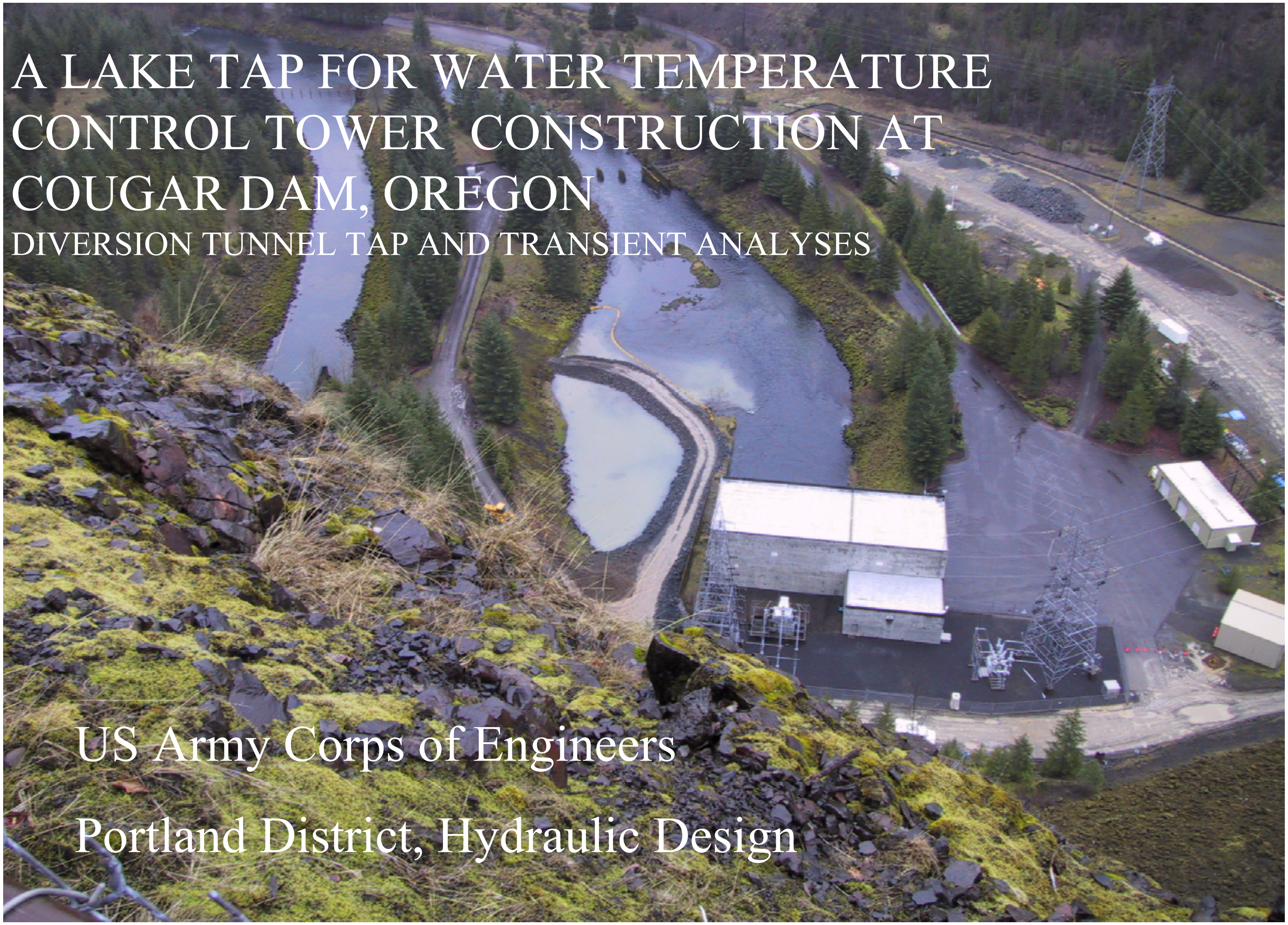
A LAKE TAP FOR WATER TEMPERATURE CONTROL TOWER CONSTRUCTION AT COUGAR DAM, OREGON

DIVERSION TUNNEL TAP AND TRANSIENT ANALYSES



US Army Corps of Engineers

Portland District, Hydraulic Design

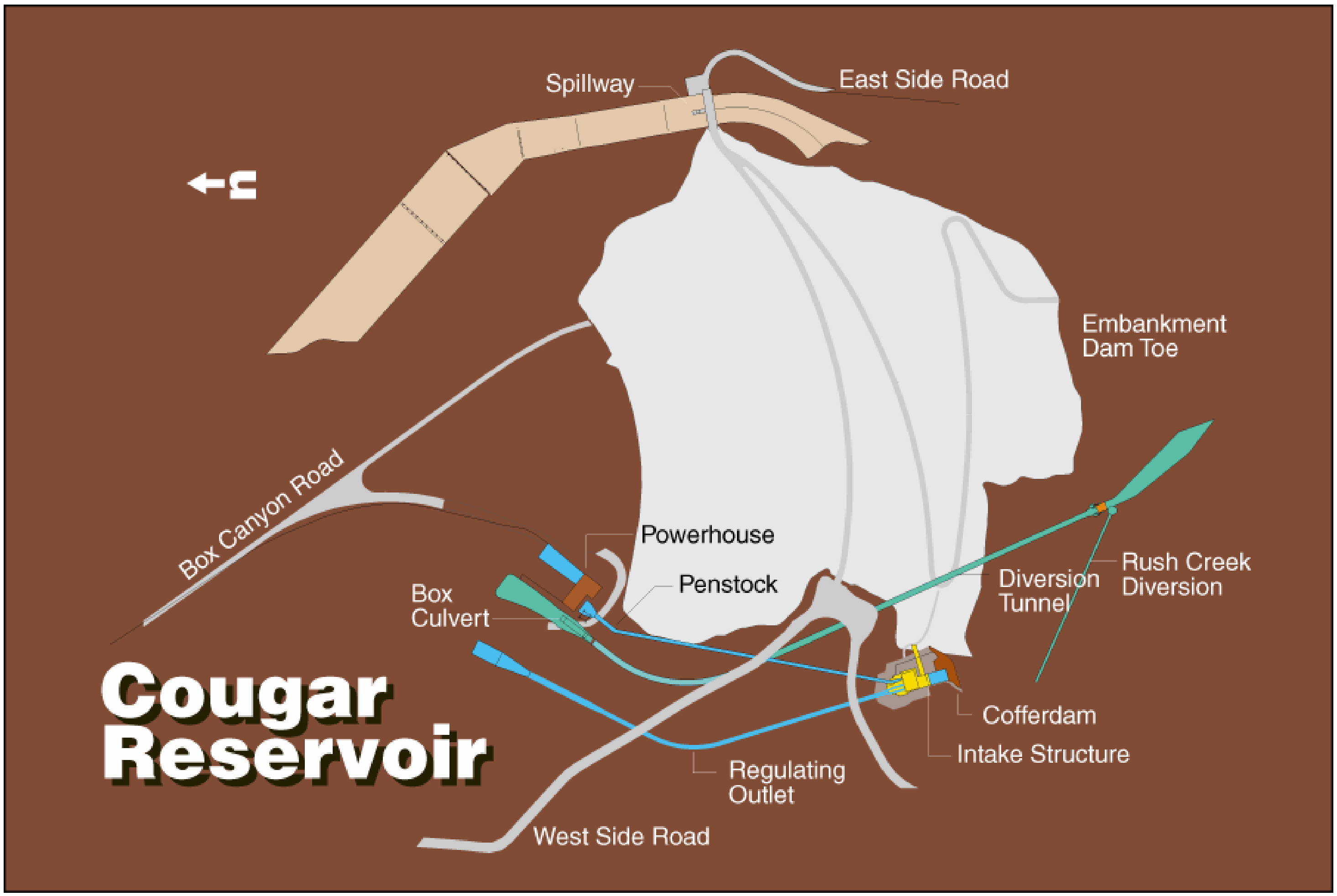
Cougar Dam, Willamette Basin

McKenzie Subbasin, Oregon

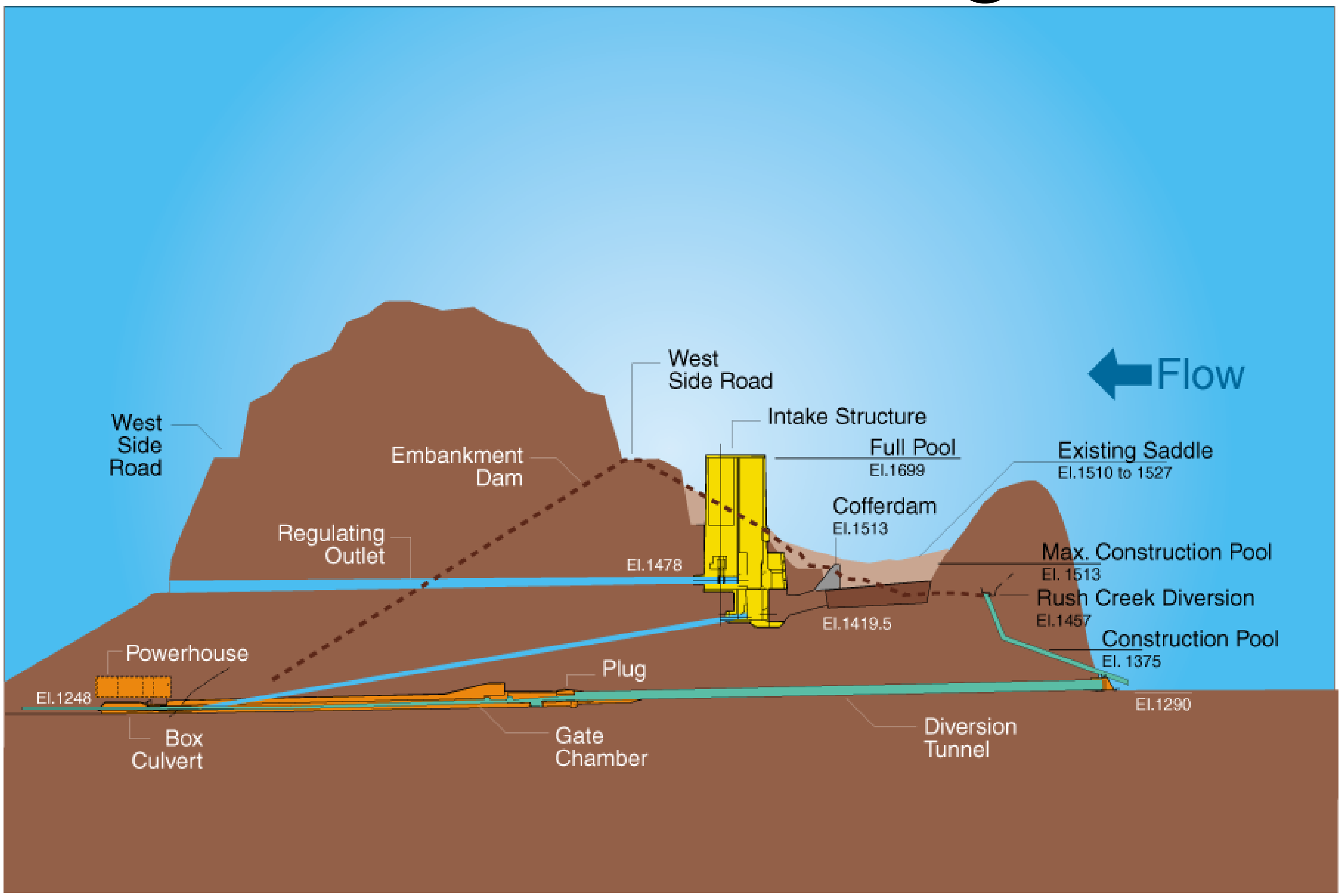
Cougar Dam Specifications

- Year: 1964
- Type: Rockfill
- Cost: $111 Million
- Head: 437 ft
- Height, max: 519 ft
- Height, grn lvl: 435 ft
- Crest Ele: 1705 ft
- Min Power: 1516 ft
- Min Flood: 1532 ft
- Max Pool: 1699 ft
- Store: 219000 ac-ft
- RO Cap: 12 kcfs
- SW Cap: 76 kcfs
- Power: 25MW

Plan View of Cougar Dam



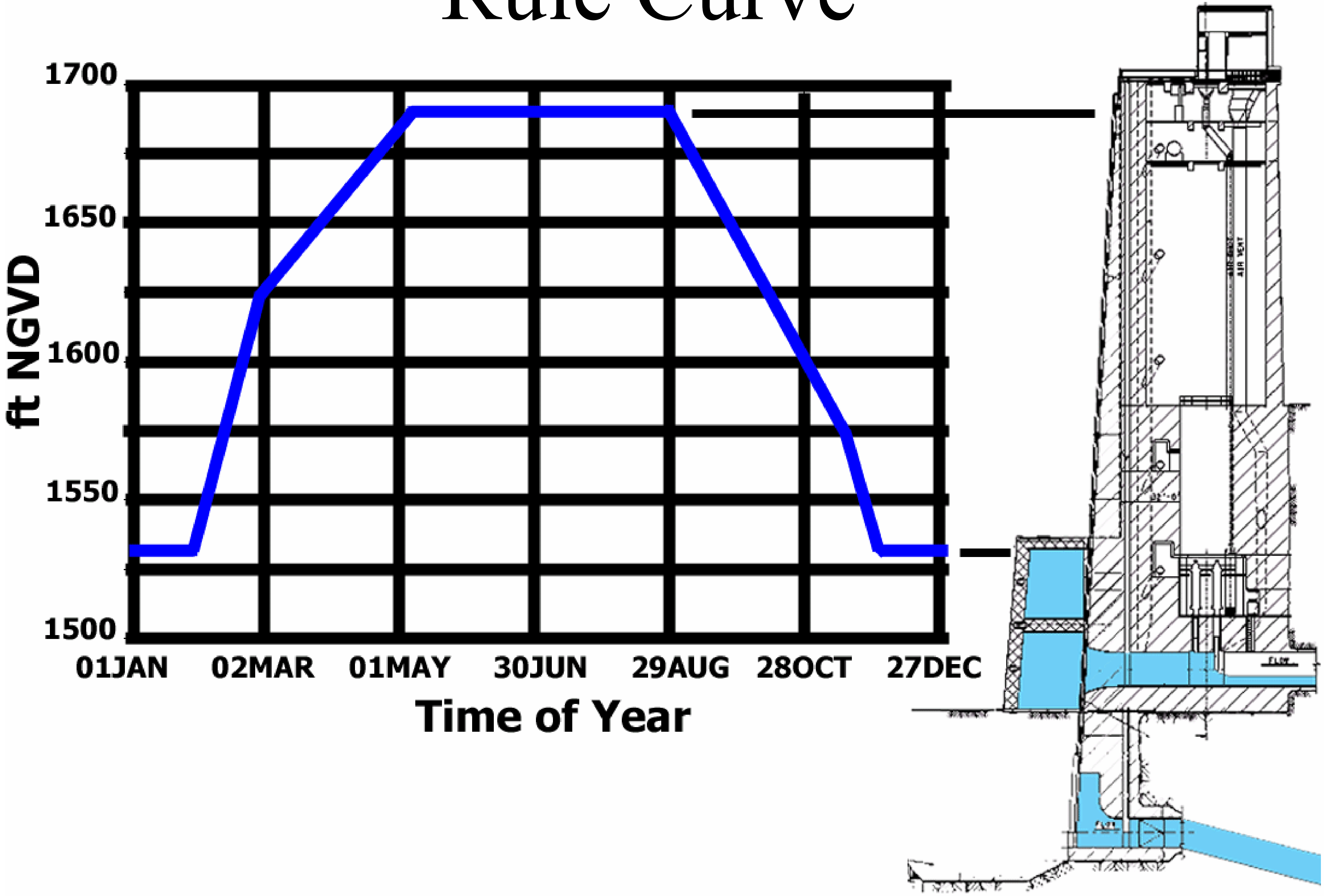
Elevation View of Cougar Dam



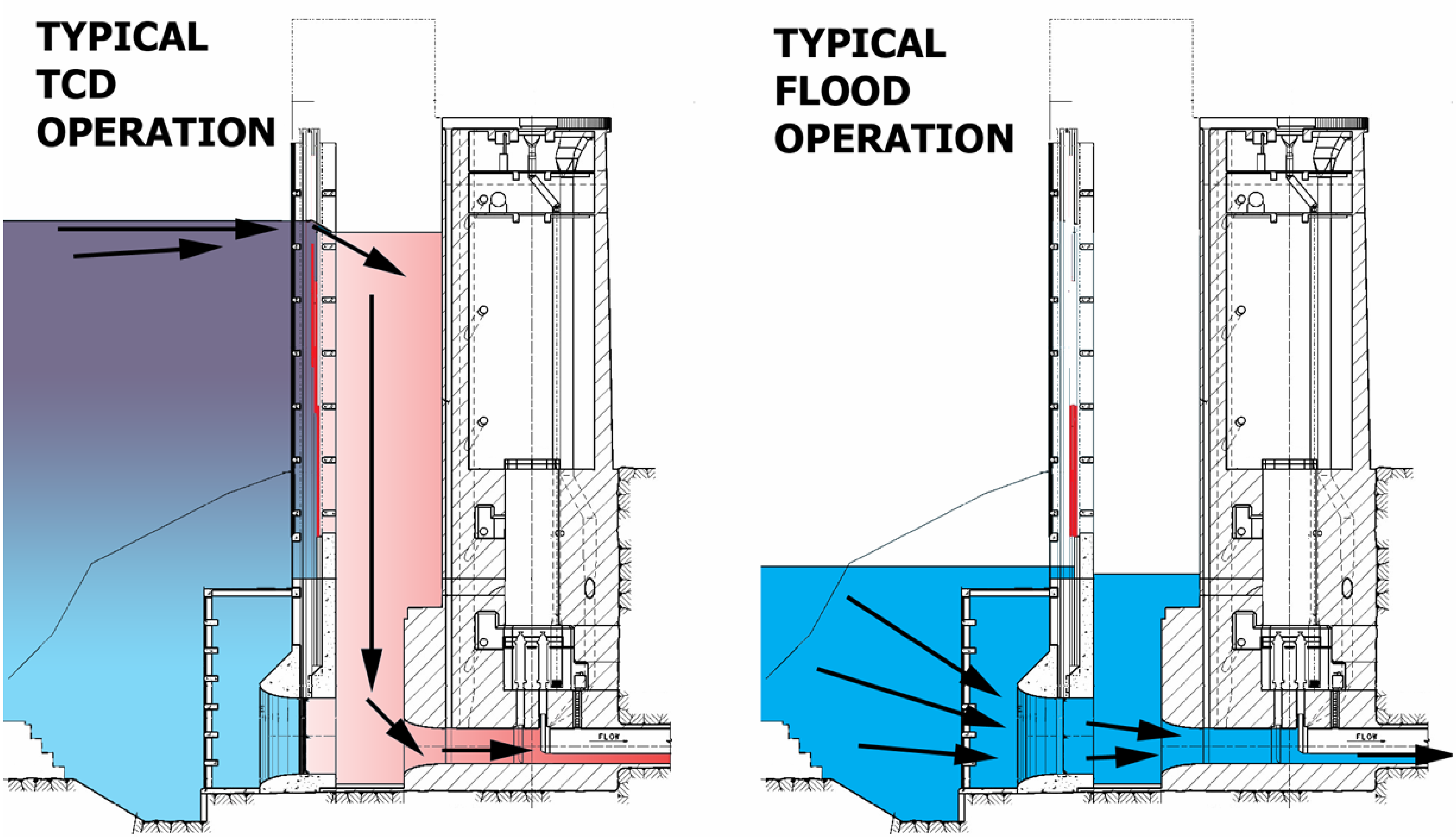
Need for Temperature Control

- Spring/Summer: High Pool, very cold deep water is drawn from bottom intakes of original tower,
  - Causes downstream cold spikes reducing migration of Spring Chinook.
- Fall/Winter: Low Pool, cold reservoir is used up,
  - Water is mixed and warmer than before dam,
  - Causes pre-spawning mortality and premature fry emergence.
- Project objective is to restore natural temperature cycle in MacKenzie River downstream of dam.

Rule Curve


1700
1650
1600
1550
1500
ft NGVD
01JAN
02MAR
01MAY
30JUN
29AUG
28OCT
27DEC
Time of Year

Operating Diagram



Old Tower vs. New Tower

Reason for Lake Tap

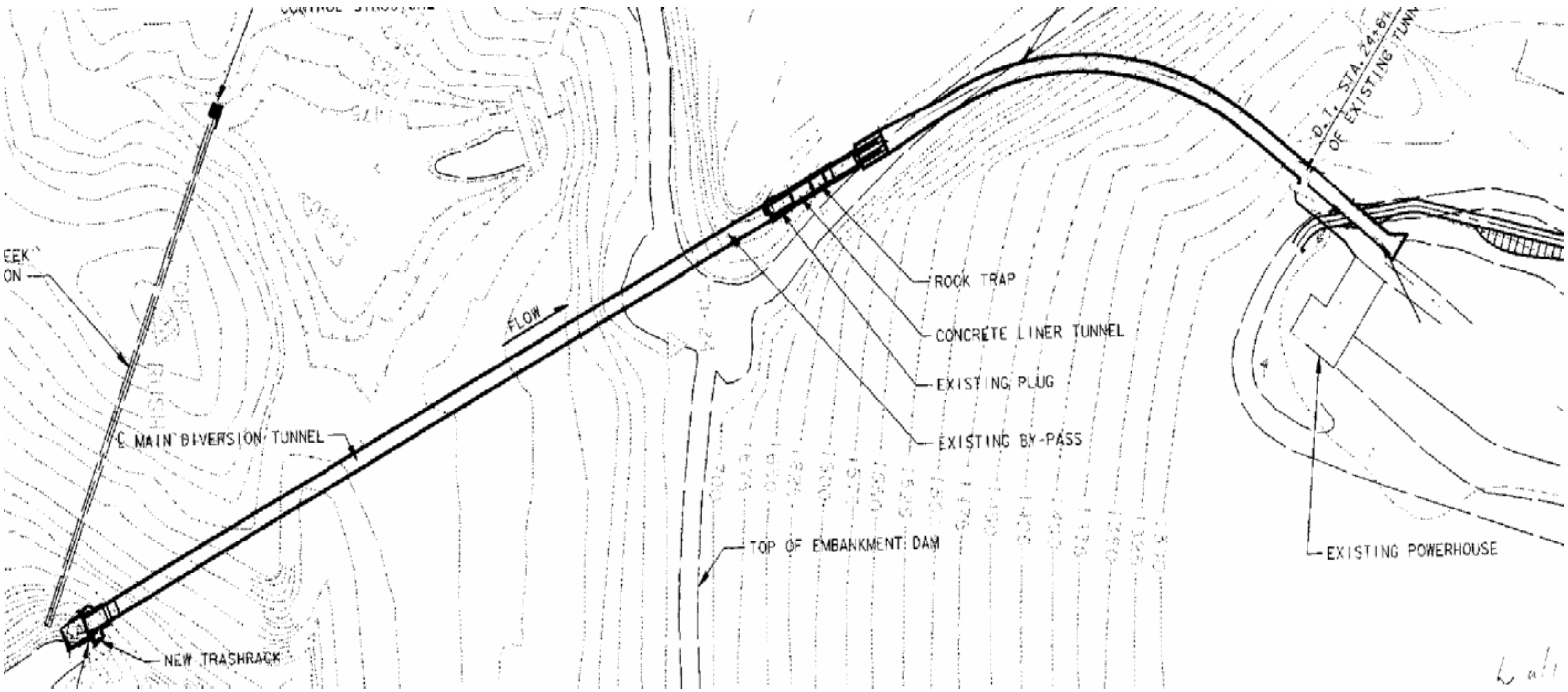
- Reservoir level must be drawn below invert elevation in Reservoir Outlet Intake Tower to construct tower modifications
- Intake to original Diversion Tunnel is lower.
- Diversion Tunnel was plugged after dam construction.
- Plug must be blasted open to operate tunnel and control reservoir outflow during construction of new tower.
  - Lake Tap performed in Feb 2002
  - Tower Construction Completed in 2005

Cougar Diversion Tunnel

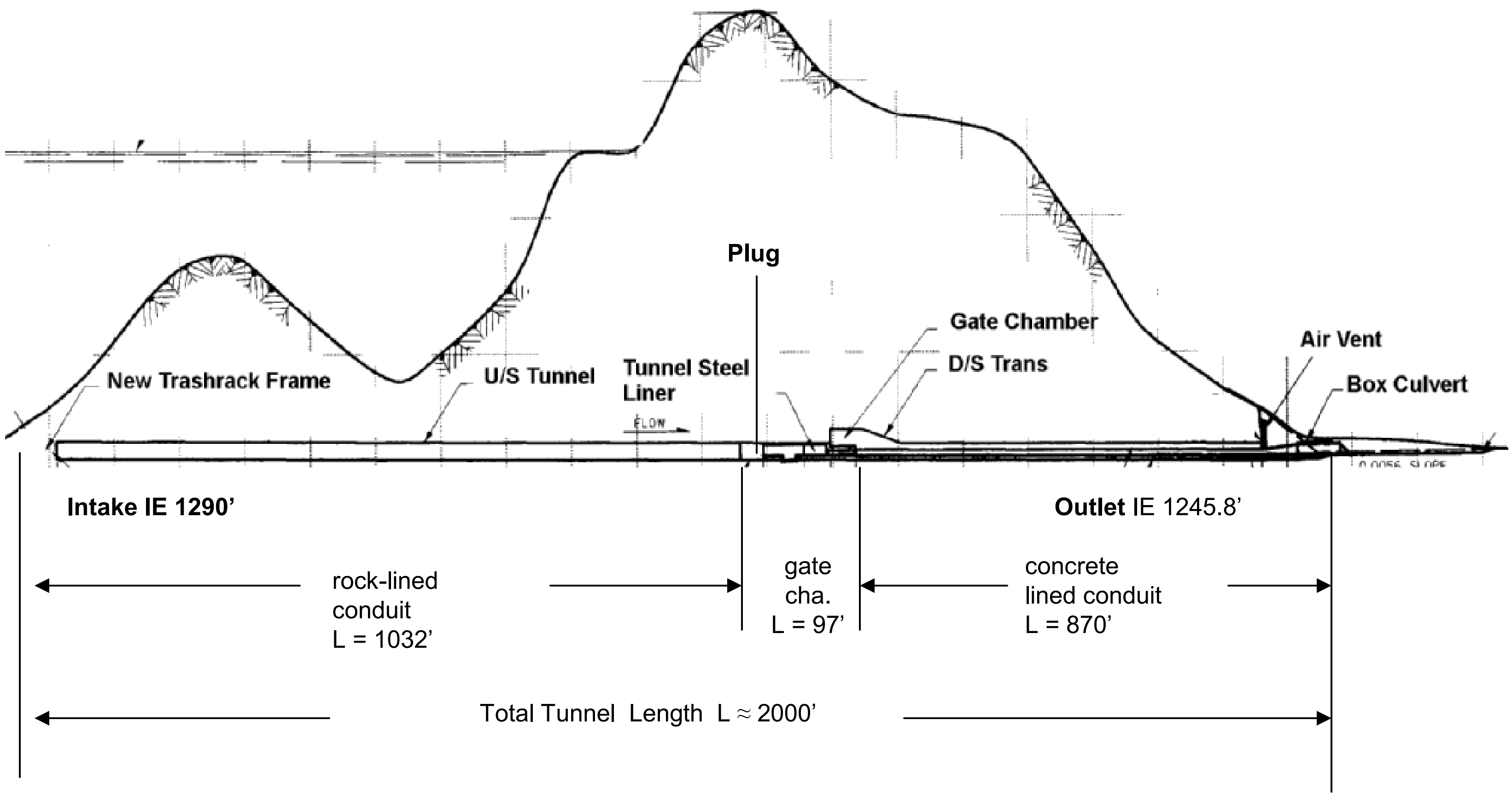
- 2000-foot long, rock-lined horseshoe tunnel
  - Built for river diversion during original dam construction
  - Tunnel plugged after dam completion
- Tunnel Reopened for construction of Water Temperature Tower
- Features Added for Tunnel Flow Control
  - New Control gate chamber in middle of tunnel
  - Lower half of tunnel lined with high velocity concrete

Plan View Diversion Tunnel

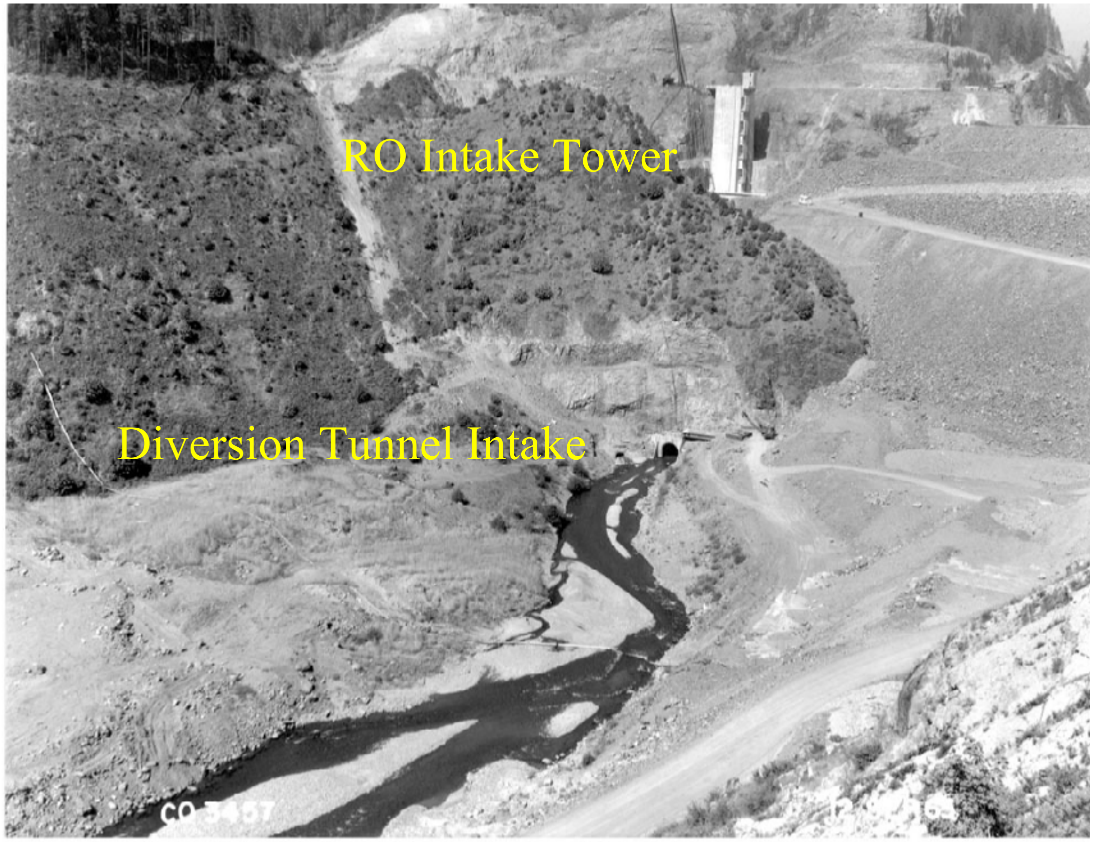
2000 feet long *19.5 feet wide horseshoe tunnel*



Diversion Tunnel Profile



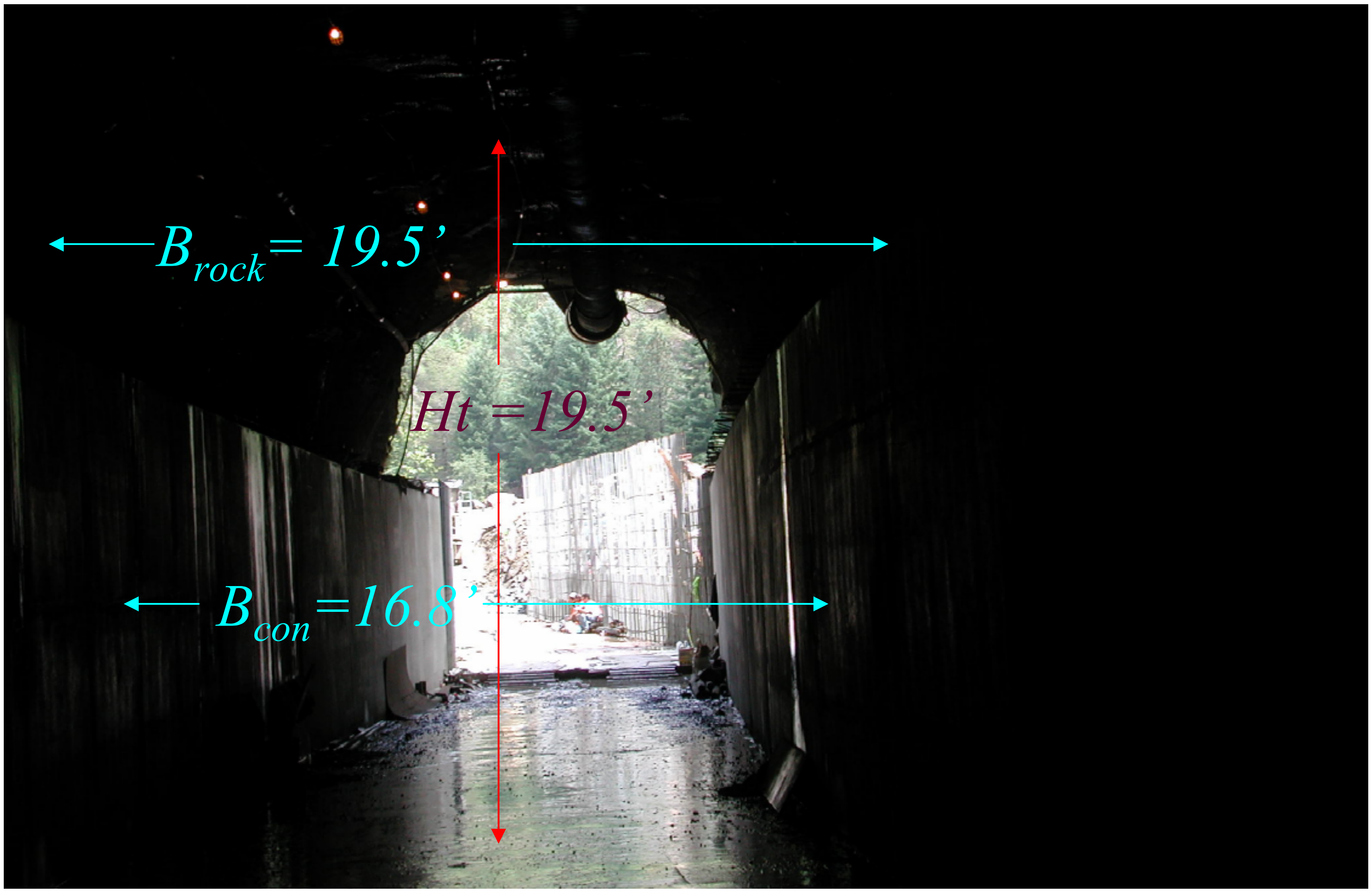
Diversion Tunnel Intake & RO Tower (Old Photo)



Construction photo, McKenzie River flowing into diversion, intake tower in background, Cougar Dam.

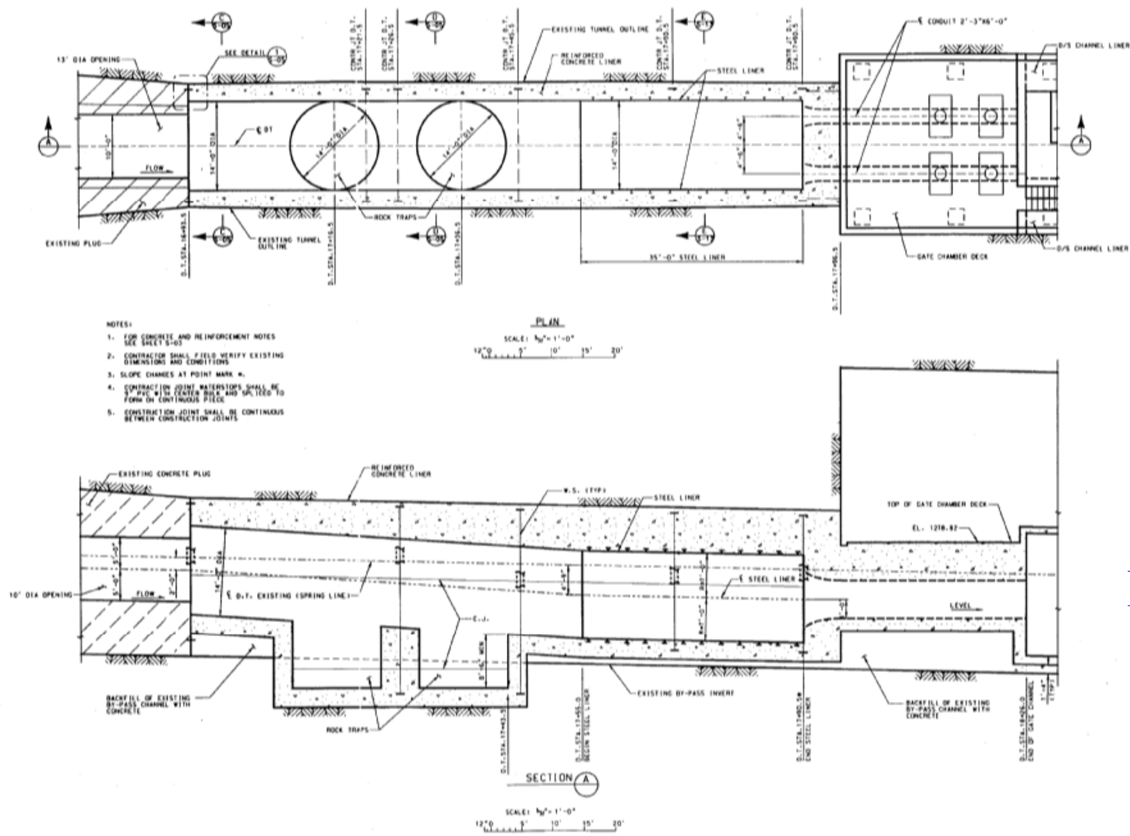
RIVER CHANNEL AND LEFT BANK. Pictures taken progressively from Borrow Area to toe of Dam. Camera on East Side Road. Merritt-Chapman & Scott Corp., Cont. 59-270.

D/S End of Diversion Tunnel Under Construction



Tunnel Plug & Gate Chamber

97'



Plan View

Elev. View

Lake Tap Analysis History

- 1:20 scale model at ENSR Lab, Seattle WA, during DM Phase
  - Recommended two phased opening
  - Feasibility ruled out by Blasting Contractor during construction phase (no wet charges)
- Rigid body slug flow analyses with closed gate:
  - Ht (Max Tap Head) = 12 * HR (Reservoir Head)
- FORTRAN SIMULATION using Method of Characteristics:
  - Closed Gate Ht = 6 HR
  - Open Gate Ht = 3 HR

Solutions for Transient Analyses

- Basic Water hammer: $$\Delta H = -a \cdot \frac{\Delta V}{g}$$
- Wave Speed a ~ 4600 ft/s
- Gate chamber air compression & evacuation
  - Perfect gas law (P/r = RT); $(P/\rho)^k$
  - Air outflow= f(Cd,A, RT, Pb, Pi) *Streeter & Wiley*
  - Air chamber continuity
  - Secant method used to solve for pressure head in chamber
- Method of Characteristics
  - Simultaneous solutions of momentum and continuity
- FORTRAN program developed for analyses
  - *References: Streeter & Wiley; Tullis*

Governing Equations for Water Hammer

Water Hammer Equation

$$\Delta H = -a \cdot \frac{\Delta V}{g}$$

In which:
ΔH = change in pressure head at location of changed velocity
a = acoustic wave speed in water (maximum = 4,671 ft/s at T = 40 degrees)
ΔV = incremental change in velocity
g = gravity

Wave Speed (a)

For Water Temperatute = 40 degrees:

K = bulk modulus of elasticity of water (= 294,000 psi)

$K := 294 \cdot 10^3 \cdot psi$

ρ = water density (= 1.94 slugs per cubic foot) (slug = lb force * sec ^{2}/feet)

$\rho := 1.94 \cdot \frac{slug}{ft^3}$

d = equivalent diameter of pipe (about 17 feet)

$d := 17 \cdot ft$

E = bulk modulus of elasticity of pipe material
Rock lined, assume 4000 psi concrete

$E := 57000 \cdot \sqrt{4000} \cdot psi$

$E = 3.605 \cdot 10^6 \cdot psi$

e = thickness of pipe wall (asssume 100 feet)

$e := 100 \cdot ft$

Wave Speed:

1. $$a := \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1 + \frac{K \cdot d}{E \cdot e}}}$$

$a = 4.639 \cdot 10^3 \cdot ft \cdot sec^{-1}$

AIR CHAMBER EQUATIONS

Perfect Gas Law

I. PERFECT GAS

2. $\frac{P}{\rho_a} = R \cdot T$ >>>>> $P \cdot Vol = mass \cdot R \cdot T$

In which:
P = absolute air pressure
ρ_a = air density
R = gas constant (= 1715 ft-lb/slug/deg R
T = absolute air temperature (degrees Rankine)

In which:
Vol = air volume (ft^3)
mass = air mass (slugs)

3. $\left(\frac{P}{\rho_a}\right)^k = constant$ >>>>> $RT_i = RT_b \cdot \frac{(P_i)^{\left(\frac{k-1}{k}\right)}}{(P_b)^{\left(\frac{k-1}{k}\right)}}$

In which :
k = specific heat ratio (use k = 1.2)
subscript i refers to conditions at current time step
subscript b refers to barometric pressure conditions

AIR OUTFLOW (mass rate)

4. Subsonic Flow (Wiley page 131):

IF : $\frac{P_b}{0.53} > P_i > P_b$

THEN:

$$\frac{dm}{dt} = C \cdot A \cdot P_i \cdot \sqrt{\frac{7}{RT_i} \cdot \left[\left(\frac{P_b}{P_i}\right)^{1.4286} - \left(\frac{P_b}{P_i}\right)^{1.714} \right]}$$

In which:

dm/dt = rate of air mass outflow from chamber

C = Coefficien of discharge through gates

P_b = barometric pressure (= 2028 lbs/ft ^{2})

P_i = pressure at current time step

AIR CHAMBER CONTINUITY

5. Open Chamber Gates

$$P_2 \cdot \left[Vol_1 + \frac{\Delta t}{2} \cdot \left(Qin_1 - Qout_1 + Qin_2 - Qout_2 \right) \right] = \left[m_1 + \frac{\Delta t}{2} \cdot \left(\frac{dm}{dt_1} + \frac{dm}{dt_2} \right) \right] \cdot RT_2$$

In which

Qin = water inflow rate to chamber

Qout = volumetric air outflow rate from chmaber through open gates

Δt = time step interval used in calculations

m = mass of trapped air in chamber

Vol = volume of air in chamber

Subscrpt 1 refers to beginning time step

Subscript 2 refers to end of time step

6. Closed Gates (simplified EQ)

$$P_2 \cdot \left[Vol_1 + \frac{\Delta t}{2} \cdot \left(Qin_1 + Qin_2 \right) \right] = m_1 \cdot RT_2$$

SECANT METHOD
to Solve for Pressure Head in Chamber

Solved for Head (P) in chamber using the
Secant (Newton) method

7. $$F = P\cdot\left[Vol + \frac{\Delta t}{2}\cdot\left(Qin_1 + Qin_2\right)\right] - m_1\cdot RT_2$$

Want F to go to zero

Guess P and solve iteratively until |F| < very small number

8. Secant Method

$$P_{i+1} = P_i - \frac{F_i}{\left(\frac{F_i - F_{i-1}}{P_i - P_{i-1}}\right)}$$

Method of Characteristics

- Solves Equations for momentum and continuity simultaneously
- Uses finite differences to solve for conditions at each node
- Nodes evenly spaced along pipeline based on the interval distance:

  $dx = a/dt$
- Incorporates conduit friction and change in water density
- Boundary conditions set at:
    - Upstream end: Constant Reservoir head
    - Downstream end:
        - Plug opening area (as function of time)
        - Gate area (open or closed)
        - Initial mass & volume of air in chamber
- **FORTRAN program developed for analyses**

Method of Characteristics Equations solved

METHOD of CHARACTERISTICS: for $\Delta x/\Delta t = a$

9. C+ Equation

$$\frac{g}{a}\cdot\frac{\Delta H}{\Delta t}+\frac{\Delta V}{\Delta t}+\frac{f\cdot v\cdot|V|}{2D}=0$$

from knowns at d/s node

10. C- Equation

$$\frac{g}{a}\cdot\frac{\Delta H}{\Delta t}-\frac{\Delta V}{\Delta t}-\frac{f\cdot v\cdot|V|}{2D}=0$$

from knowns at u/s node

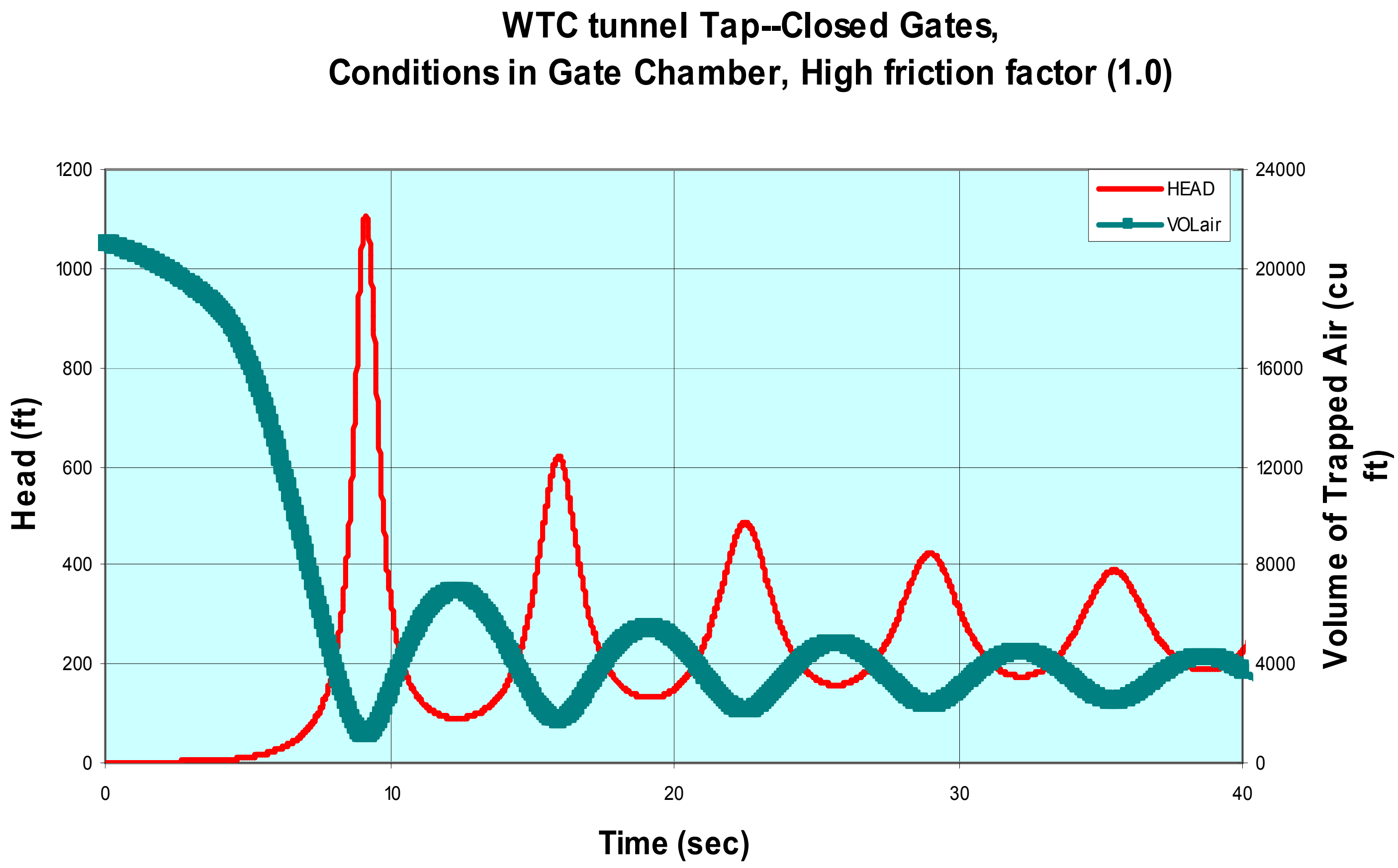
Tunnel Tap Strategies

- <u>Closed Gates</u> (*assumptions below*)
  - Perfect Gas Law
    - $P/\rho = RT$; $(P/\rho)^{\kappa} = \text{constant}$; k = 1.2
  - No change in mass of trapped air after tunnel tap.

OR

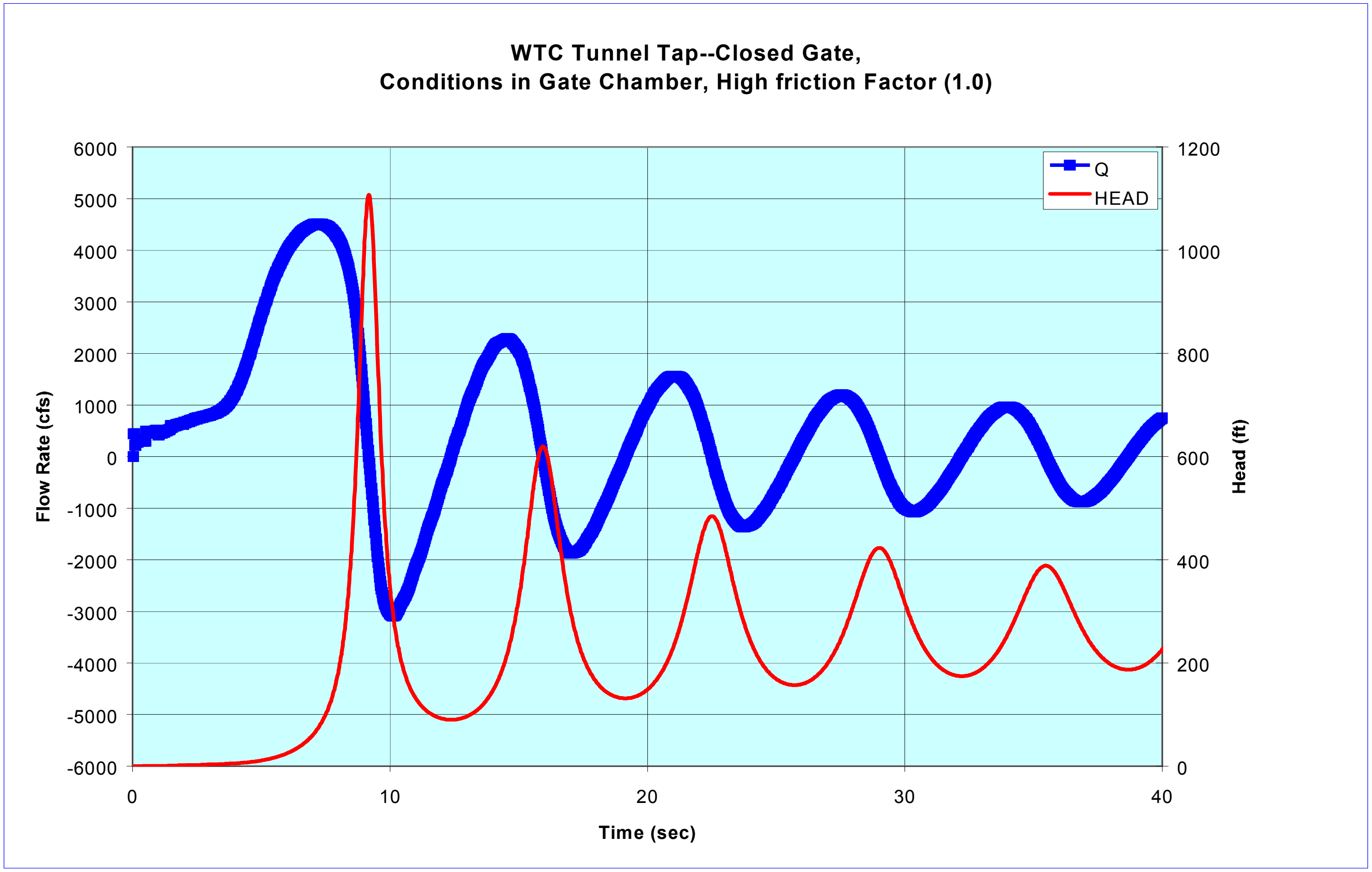
- <u>Open Gates</u> (*assumptions below*)
  - Perfect Gas Law
  - Continuity equation for air volume and mass change
  - Outflow Through Gates
    - When trapped air volume > 0; all outflow is air
    - When Trapped air Volume = 0; all outflow is water

Closed Gate Results
Head & Air Volume VS Time



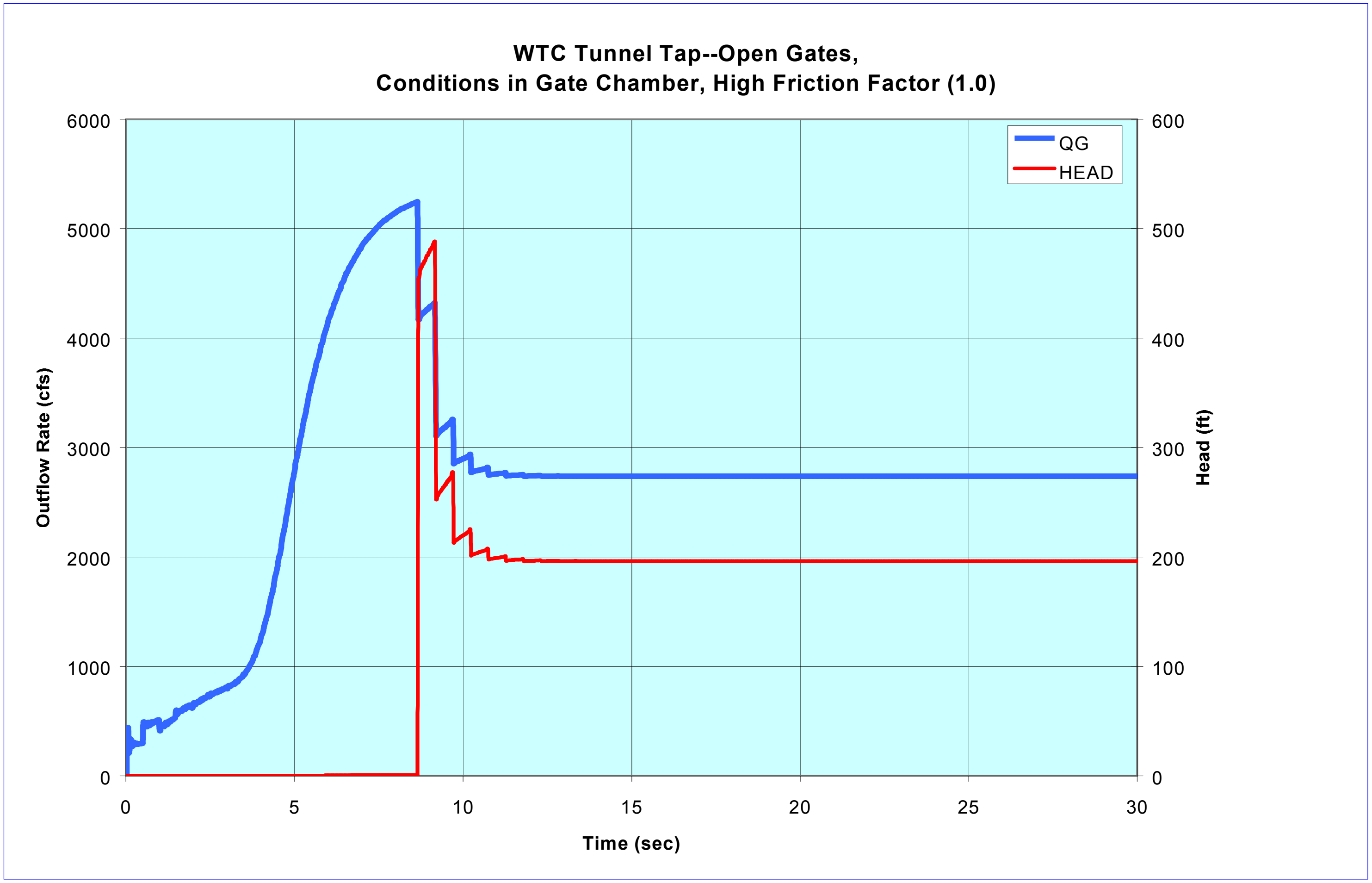
Closed Gate Results

Water Inflow & Head VS Time



Open Gate Results

Water Inflow & Head VS Time

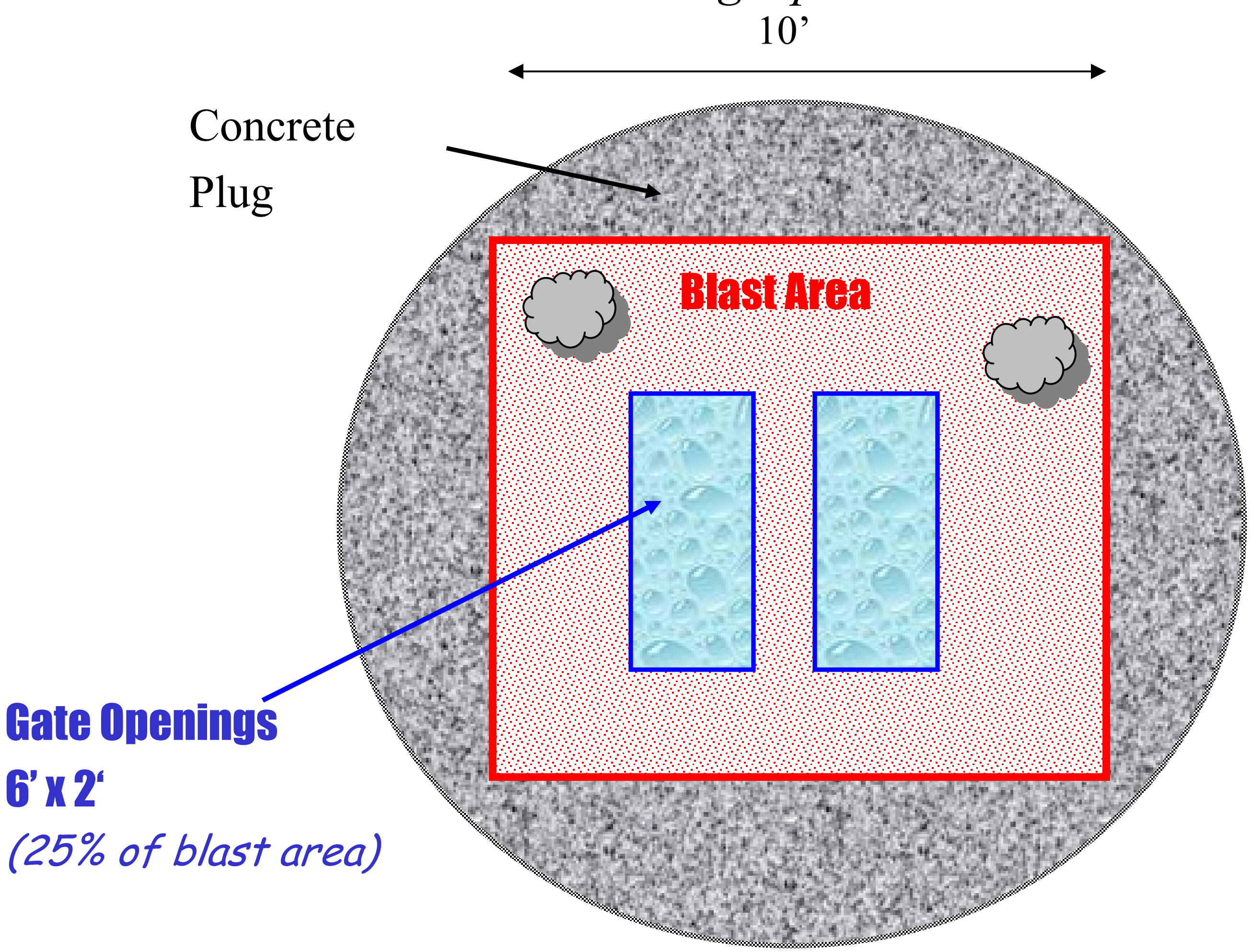


Tunnel Tap—02/23/2003

- Concrete Plug: 35’ long
  - *New 10-feet square hole*
- Most material mechanically mined before tap
- Tunnel Tap
  - *Tap conducted under 270 feet of reservoir head*
  - *Control gates open during tap*
  - *0.4 second long controlled blasting sequence starting from interior of cross-section*
  - *Rock trap to catch debris*

Cross-sections of Blast Area and Gate Openings

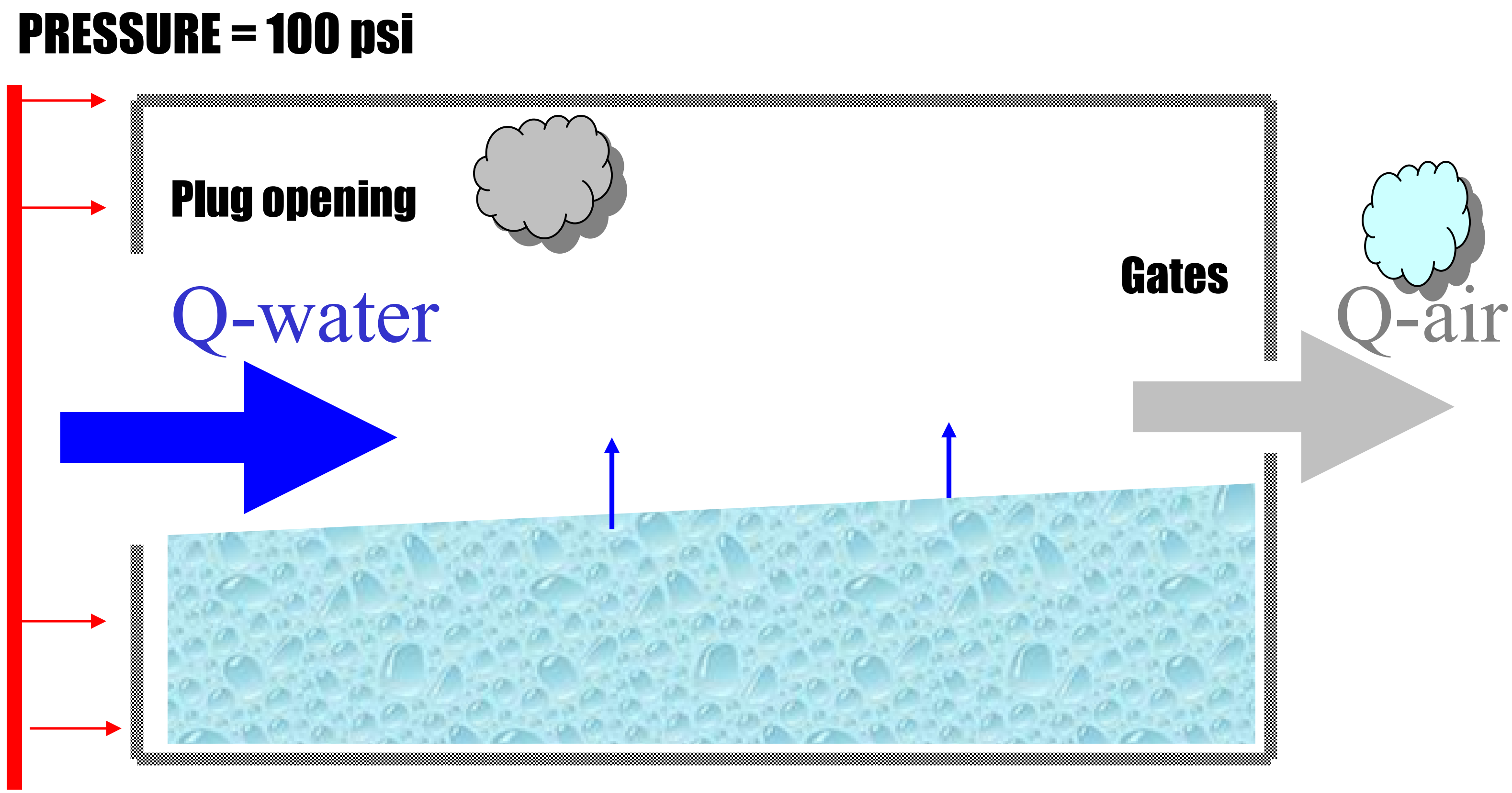
Looking Upstream



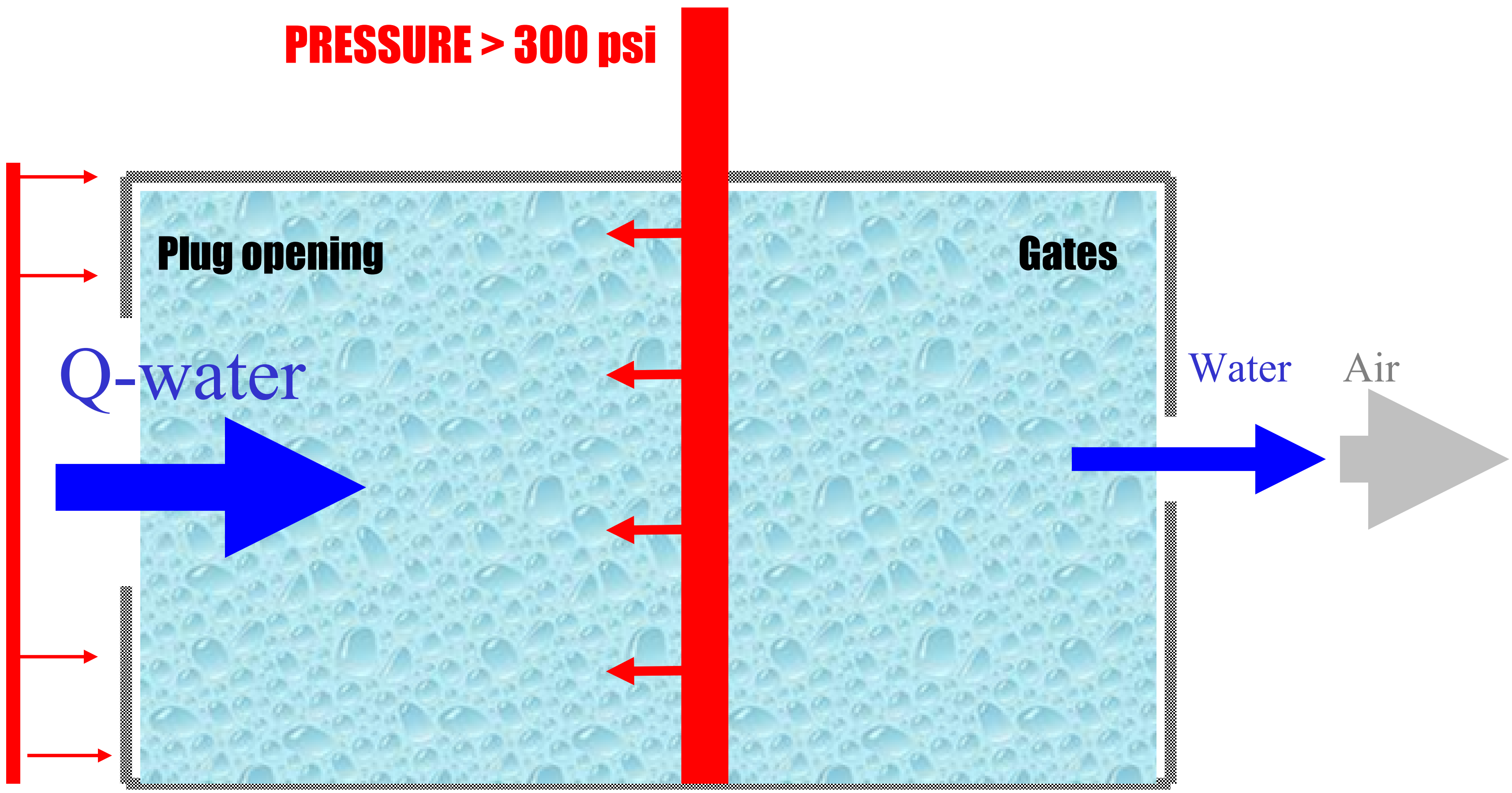
Tunnel Tap Transient Issues

- Tap conducted under 270 feet of reservoir head
- High initial discharge (5000 - 6000 cfs)
- Potentially high transient pressure head
  - *inevitable drops in discharge lead to pressure rises*
  - *3 times ambient reservoir head*
- First studied in 1:20 physical model (ENSR)
- FORTRAN program used for final analyses
  - *Evaluated alternative tap strategies*
  - *Refined blasting procedures*
  - *Estimated actual pressure and discharges during tap*

Gate Chamber Filling Right After Plug Opening

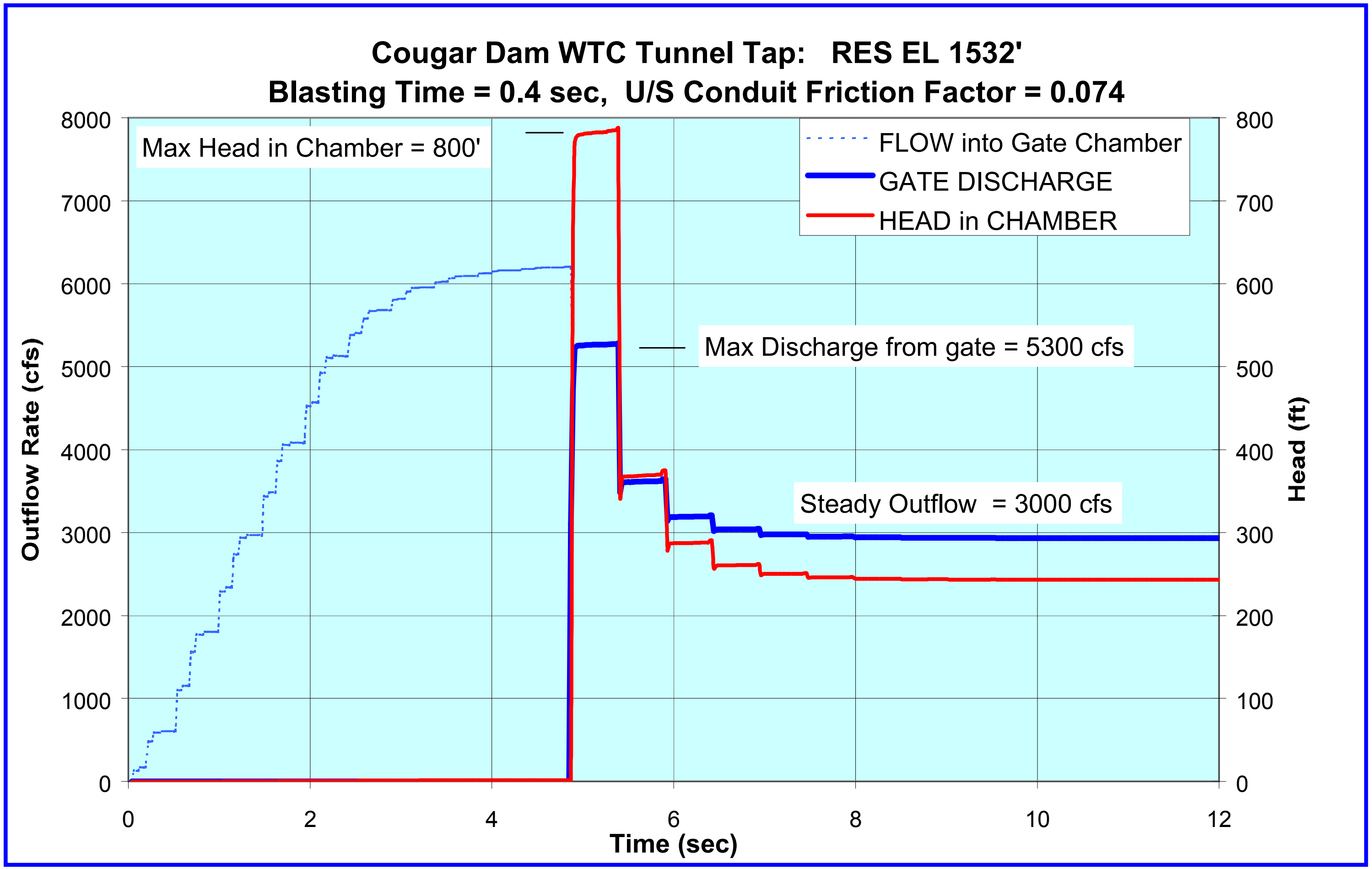


Gate Chamber Right After Filling With Water

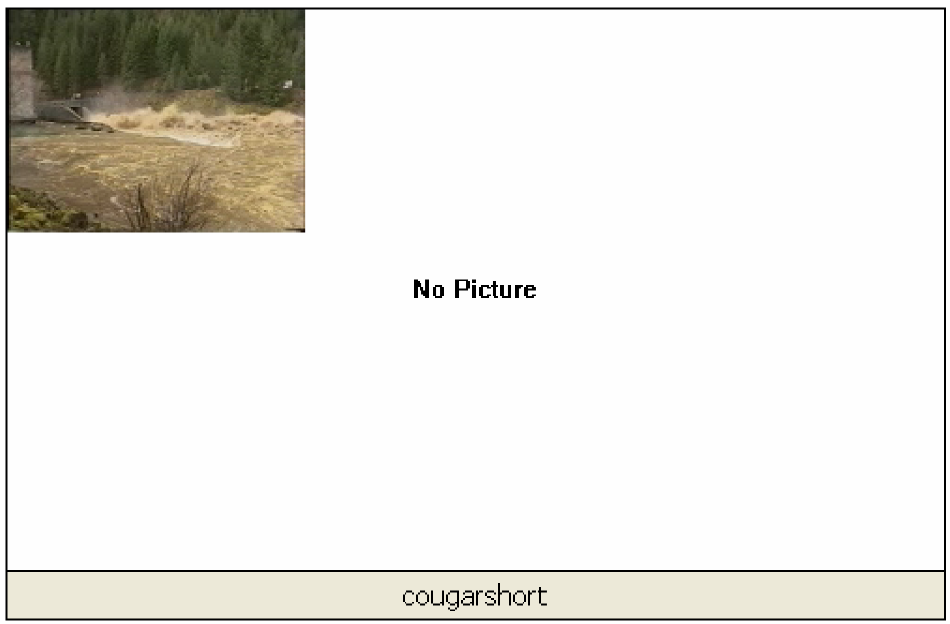


Open Gate Results-Contractors Proposal

Water Inflow & Head VS Time



80 second Tunnel Tap Video



Tap Photos:

Downstream End of Tunnel Before Tap

Tunnel Tap: Peak Outflow

Tunnel Tap: Steady Outflow (Later)

Tunnel Tap, D/S Channel (Early)

Tunnel Tap, D/S Channel (Later)

LESSONS LEARNED

- Provide more distance between plug and gates in design phase
  - Distance and volume will reduce potential pressure rise.
- Coordinate with Blasting Contractors while developing lake tap plan
- Obtain pressure transducers with capacities greater than estimated pressures.
- Use both physical and numerical models to predict maximum potential tap pressures and refine procedures.

Conclusions on Tunnel Tap

- Successful tap
  - *no apparent structural damage in tunnel or in downstream channel*
  - *Downstream erosion minimized*
  - *Great coordination between Construction, Cougar Project, NWD Reservoir Control Center, Blasting Contractor, & NWP Design team*
- Predictions
  - *Pressure transducers did not work*
  - *Timing of exit discharge conformed to transient results*
  - *Water level rise at d/s USGS gage < 1 foot (predicted)*

END

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