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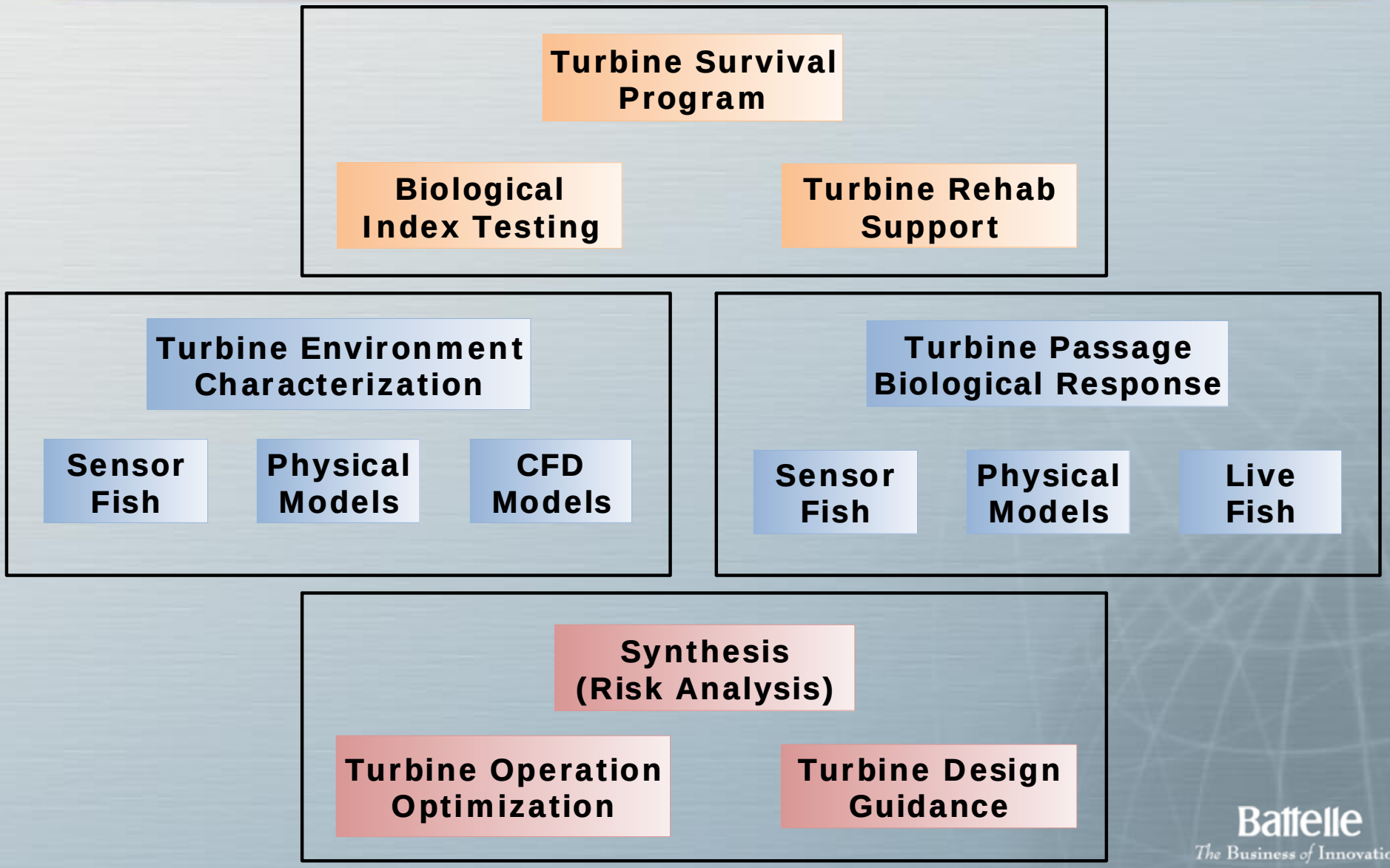
Pressure and Accelerations of Sensor Fish through a Turbine at Ice Harbor Dam

Thomas J. Carlson and Joanne P. Duncan

TSP Elements



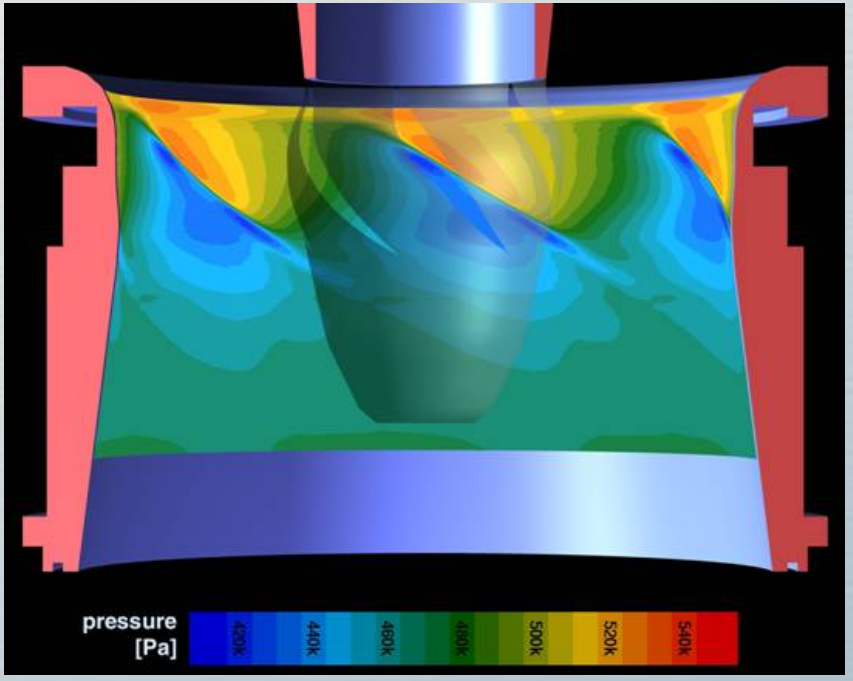
Project Scope

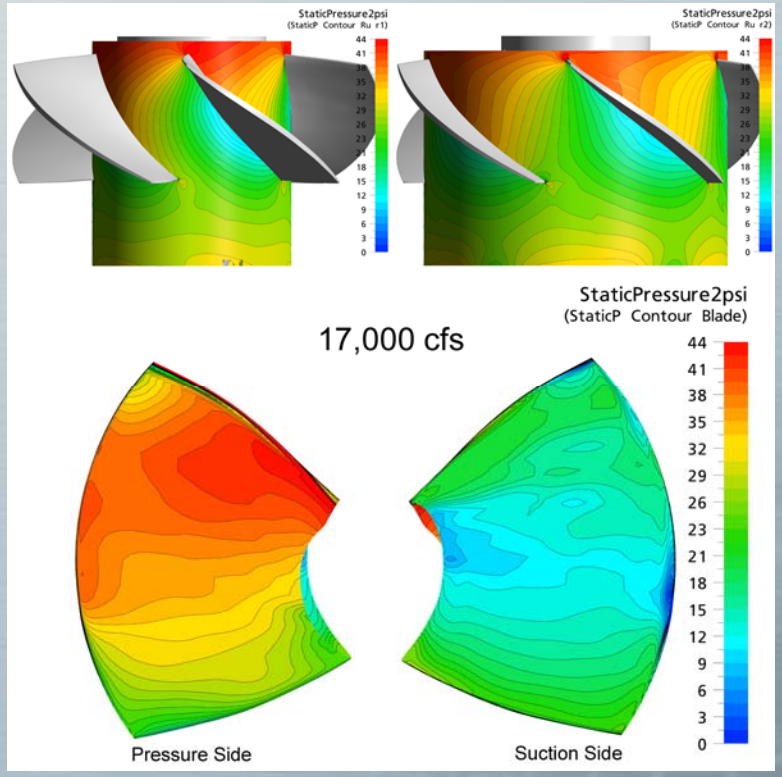
- Objective: Acquire turbine passage data using Sensor Fish Devices for later analysis
  - Pressure, particularly nadir
  - Strike and shear
  - Quality of flow
- Sampled test turbines at:
  - BON2 Unit 16
    - Upper and lower 1% efficiency operations
  - JDA Unit 9
    - Upper and lower 1% plus peak efficiency operations
  - ICH U2
    - Upper and lower 1% efficiency operations
- Used physical turbine models to identify sensor release elevations in downstream intake gate slots

Data Utilization

- Identify Nadir and Pressure Rate of Change Values to Use in Rapid Decompression Studies
- Provide Pressure Time History Data Sets to Aid CFD Modeling
- Compare BON II, ICH, and JDA Turbines

Turbine Pressure Environment



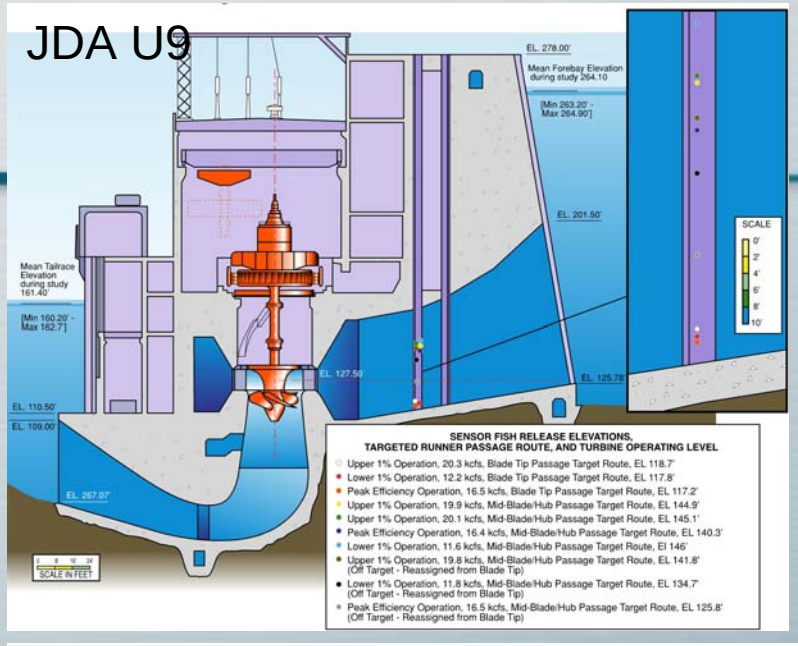


WAN U9 (Voith Hydro CFD)

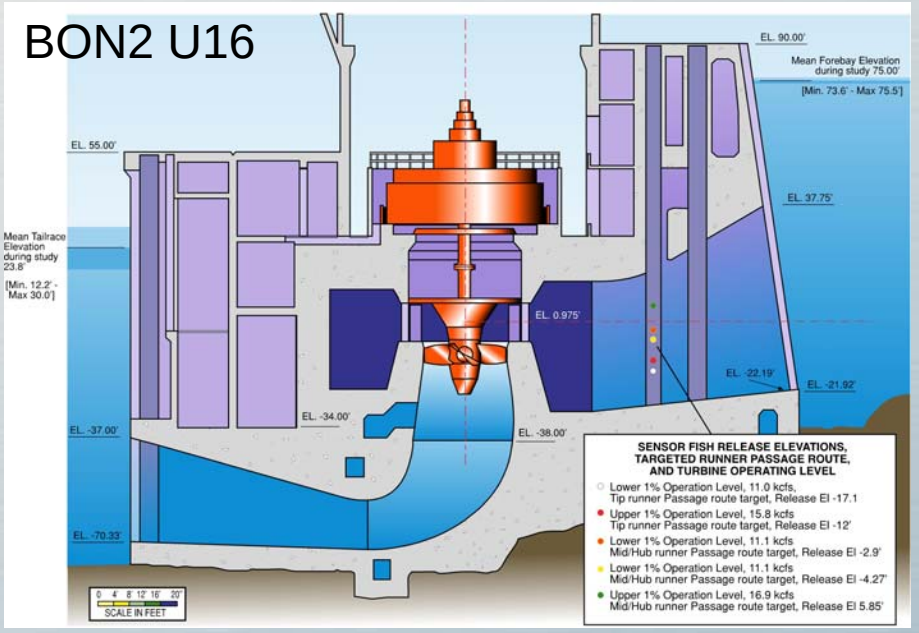
Sensor Fish Releases

Location	Operation	Target Turbine Runner Passage Route	Release Elevation (ft)	Discharge (kcfs)	# of Samples
Ice Harbor	Lower 1%	Blade Tip	321.2	8.3	29
Ice Harbor	Upper 1%	Blade Tip	313.2	13.1	30
Ice Harbor	Upper 1%	Mid-Blade/Hub	325.5	13.5	27
Ice Harbor	Upper 1%	Mid-Blade/Hub	331	13.4	55
Ice Harbor	Lower 1%	Mid-Blade/Hub	326.9	8.1	58
				Total Ice Harbor Releases	**199**
John Day	Upper 1%	Blade Tip	118.7	20.3	23
John Day	Lower 1%	Blade Tip	117.8	12.2	23
John Day	Peak Efficiency	Blade Tip	117.2	16.5	19
John Day	Upper 1%	Mid-Blade/Hub	144.9	19.9	26
John Day	Upper 1%	Mid-Blade/Hub	145.1	20.1	35
John Day	Peak Efficiency	Mid-Blade/Hub	140.3	16.4	66
John Day	Lower 1%	Mid-Blade/Hub	146	11.6	60
John Day	Upper 1%	Blade Tip (off target release elevation by 22.4 ft) - Re-Assigned to Mid-Blade Passage Route for Analysis	141.8	19.8	22
John Day	Lower 1%	Blade Tip (off target release elevation by 15.3 ft) - Re-Assigned to Mid-Blade Passage Route for Analysis	134.7	11.8	22
John Day	Peak Efficiency	Blade Tip (off target release elevation by 7.7 ft) - Re-Assigned to Mid-Blade Passage Route for Analysis	125.8	16.5	20
				Total John Day Releases	**316**
Bonneville 2	Upper 1%	Blade Tip	-12	15.8	21
Bonneville 2	Lower 1%	Blade Tip	-17.1	11	23
Bonneville 2	Lower 1%	Mid-Blade/Hub	-2.9	11.1	51
Bonneville 2	Lower 1%	Mid-Blade/Hub	-4.27	11.1	13
Bonneville 2	Upper 1%	Mid-Blade/Hub	5.85	16.9	66
				Total Bonneville 2 Releases	**174**
				Total Releases	**689**

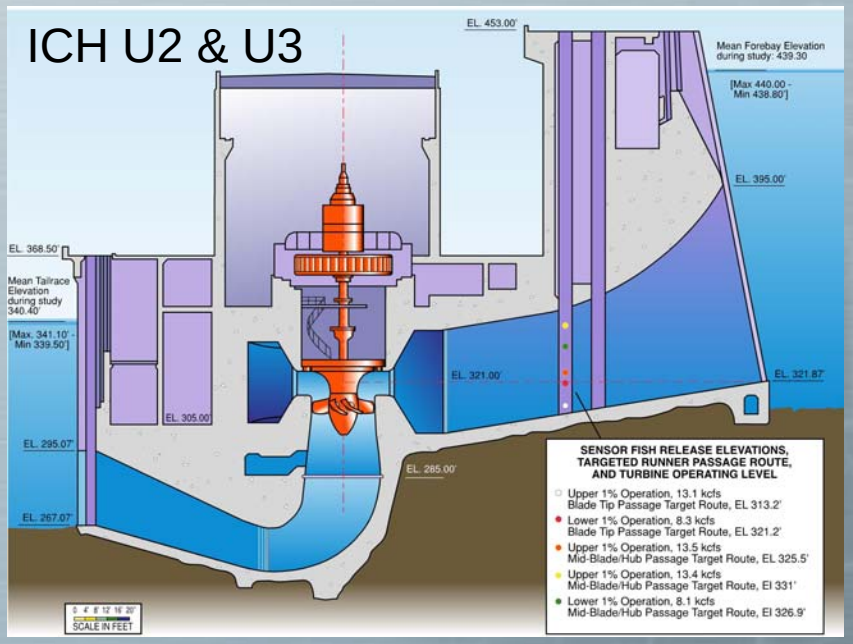
JDA U9



BON2 U16



ICH U2 & U3



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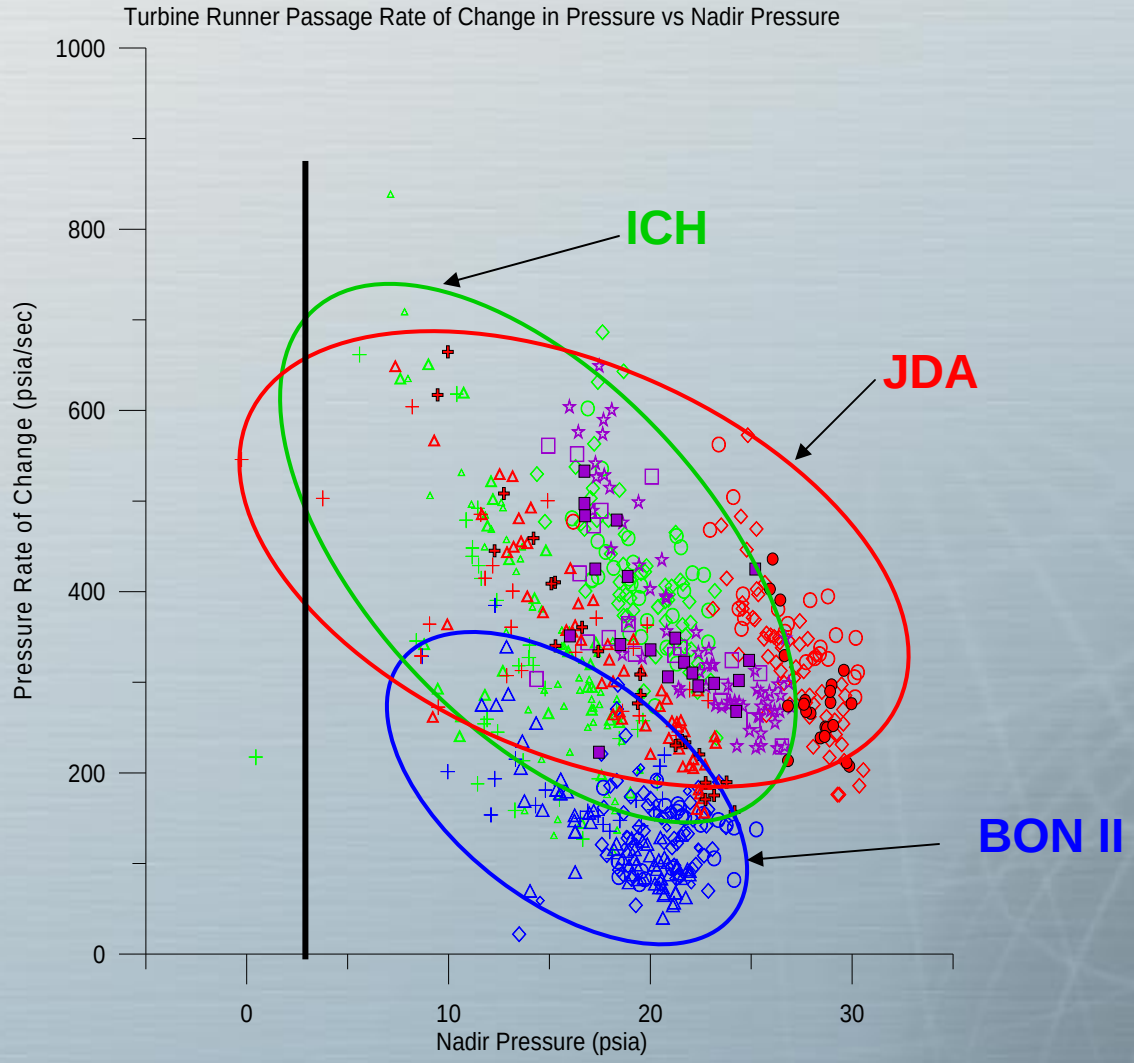
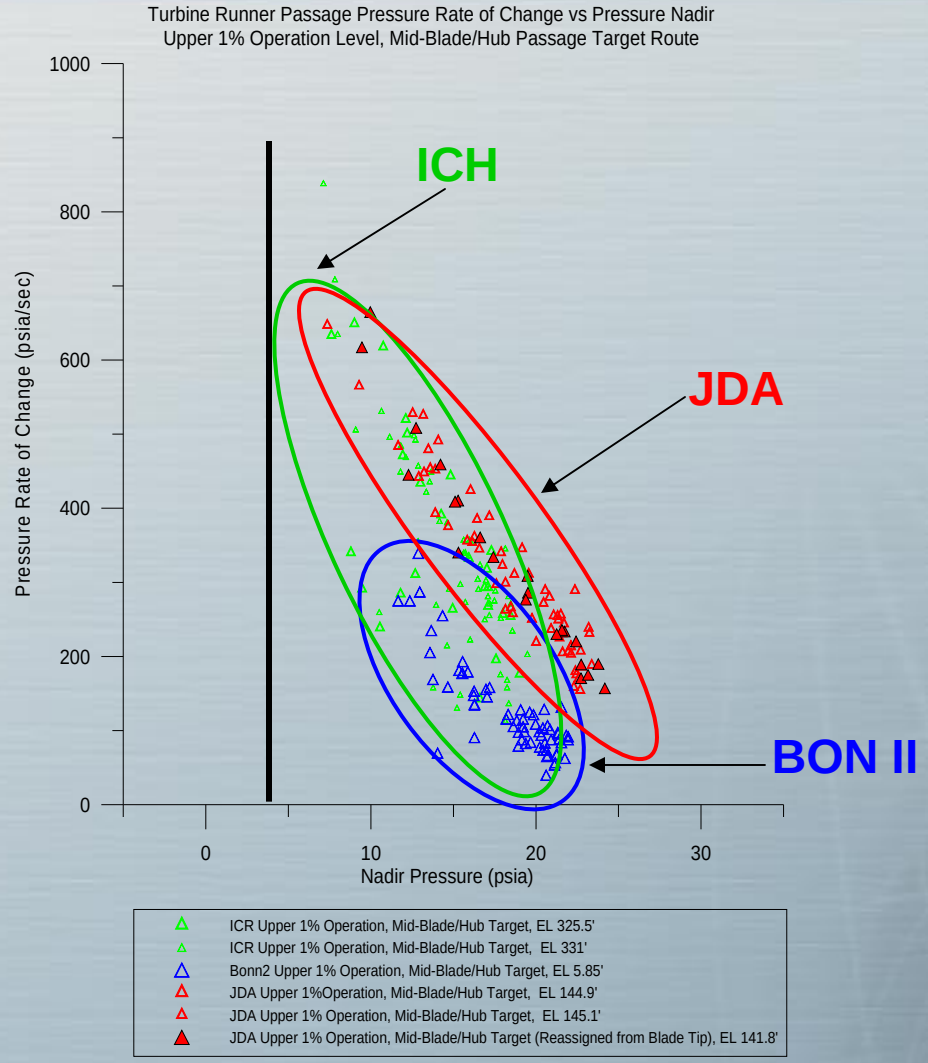
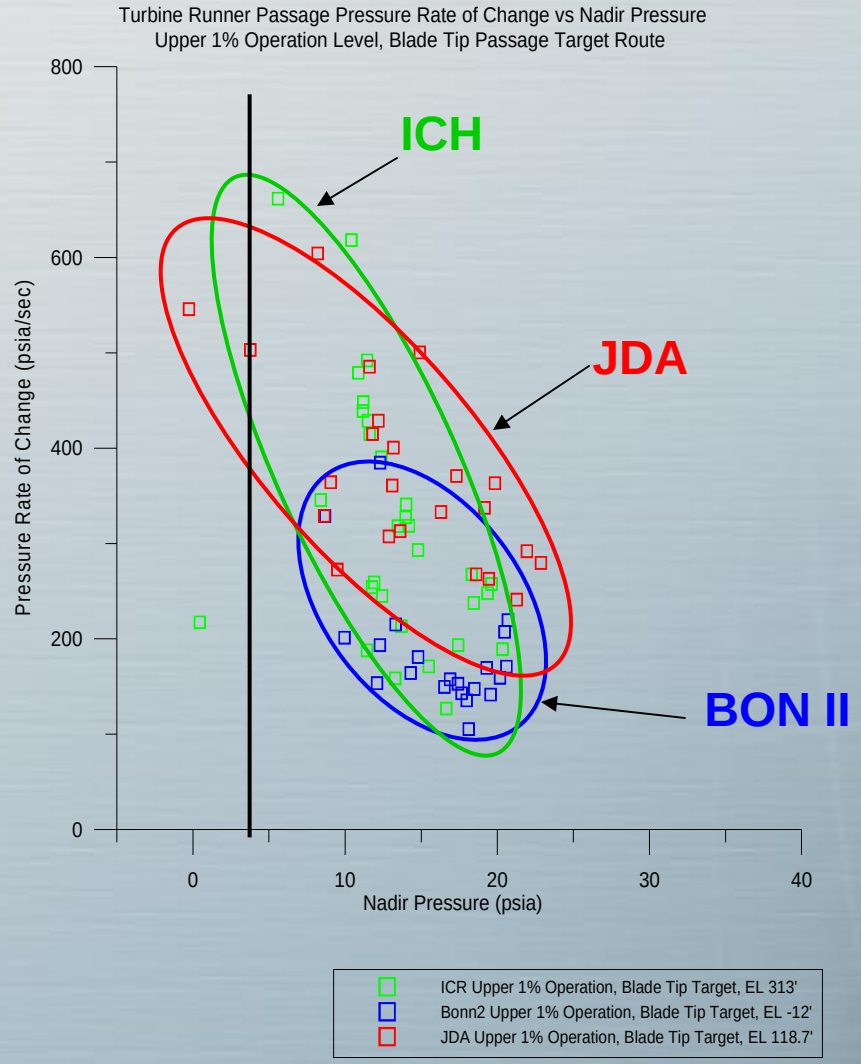
All Nadir Data – BONII, JDA, ICH



Upper 1% - Mid-Blade Route



Upper 1% - Blade Tip Passage



Turbine Characteristics

Metric	BON2	JDA	ICH
Unit No.	16	9	2 & 3
Type	Kaplan	Kaplan	Kaplan
MW	78.30	158.39	106.64
RPM	69.2	90.0	90.0
Number of Blades	5	6	6
Rated Head (ft)	52	94	89
Runner Diameter (in)	330	312	280

Summary

- Selected the following conditions as factors for rapid decompression testing
  - Nadir
    - 3, 6, and 9 psia
  - Pressure Rate of Change
    - 200, 400, and 600 psia/sec

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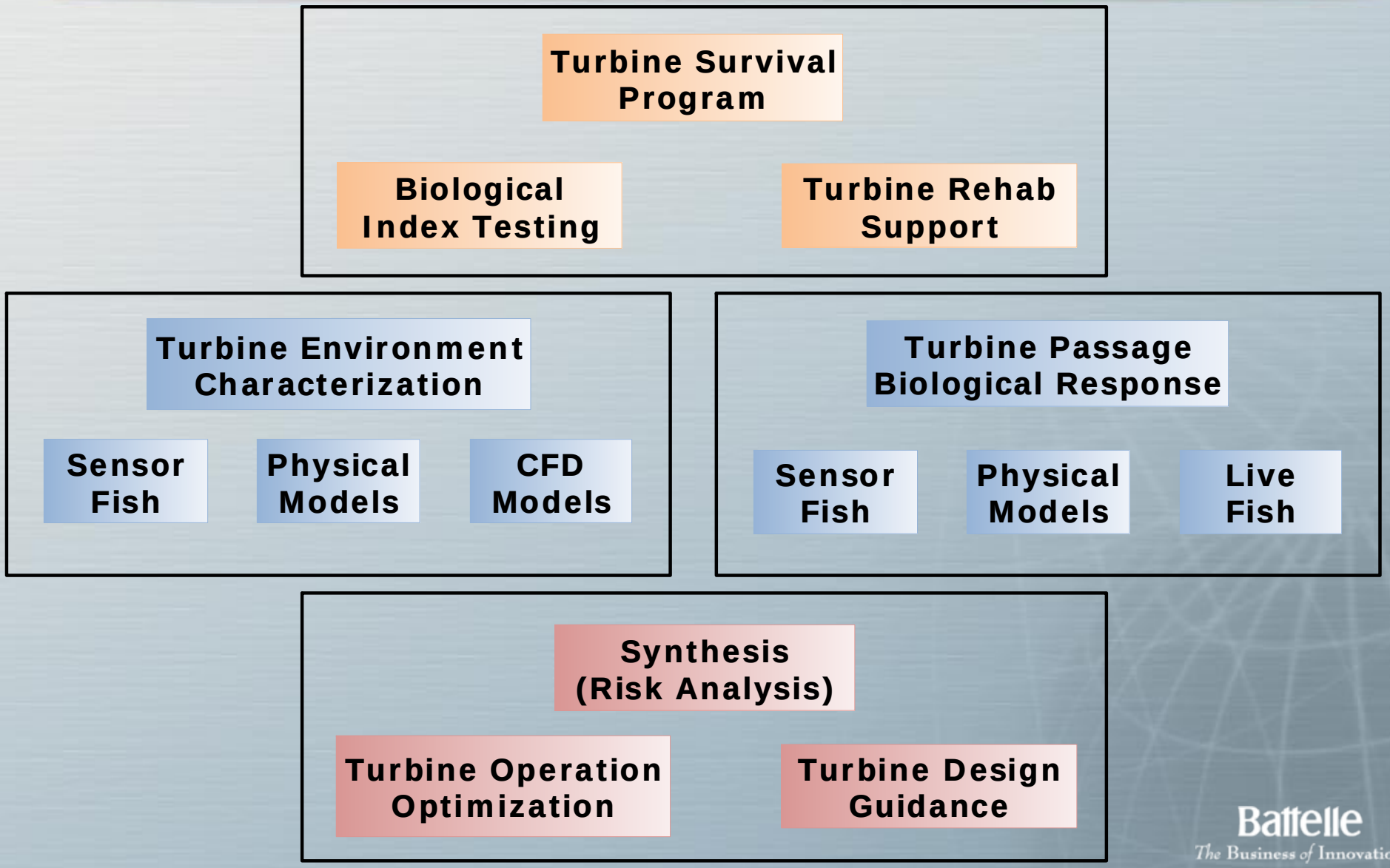
Pressure Acclimation Investigations to Support Biological Index Testing

Thomas J. Carlson, Richard S. Brown &

Craig A. McKinstry - PNNL

John R. Skalski & Richard L. Townsend - UW

TSP Elements

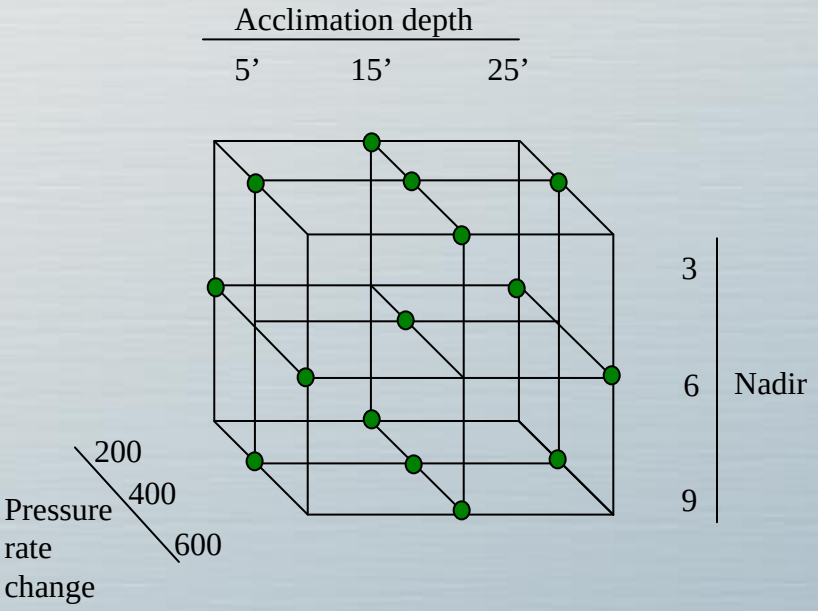


Physical Processes with Biological Consequences

- Boyles Law
  - $p_1V_1 = p_2V_2$
  - As pressure decreases gas bubble volume increases
  - Swimbladder and other gas bubbles become larger as pressure decreases
  - Consequences: swimbladder rupture & pressure damage to organs and other tissue
- Henry's Law
  - $C_1/p_1 = C_2/p_2$
  - As pressure decreases gas solubility also decreases
  - Dissolved gas in the blood leaves solution as pressure decreases
  - Consequences: Bubbles occlude gills and heart & rupture vessels

The ratio of initial and final pressure is critical – not the absolute difference between pressures. Ex. The change in volume and gas solubility are the same for a pressure change from 12 psia to 6 psia as for a pressure change from 4 psia to 2 psia. -- As a result it is the lower range of nadir pressures that are most critical when investigating barotrauma to fish during turbine passage.

Initial Experimental Design



- Goal: Identify onset of effect threshold(s)
- Treatment Factors
  - Fish Age
    - Subs and Yearling
  - Fish Physiological State or Origin
    - Hatchery and ROR
  - Acclimation Depth
    - 5’, 15’, 25’
    - 16.9, 21.2, 25.5 psia
  - Total Dissolved Gas
    - 115%, 120%, 125%
  - Nadir Pressure
    - 3, 6, & 9 psia
  - Pressure Rate of Change
    - 200, 400, & 600 psia/s
  - 2 X 2 X 3 X 3 X 3 X 3 = 324 Possible Combinations of Treatment Factors
  - Selected within these treatments for those most “realistic”

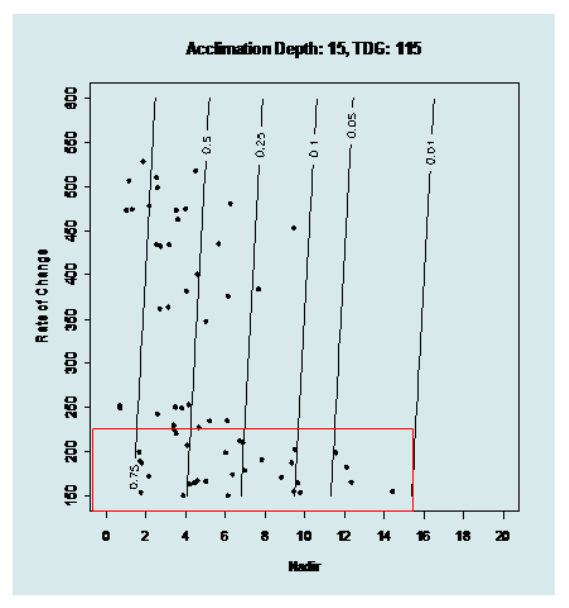
Mortal Injury Metric

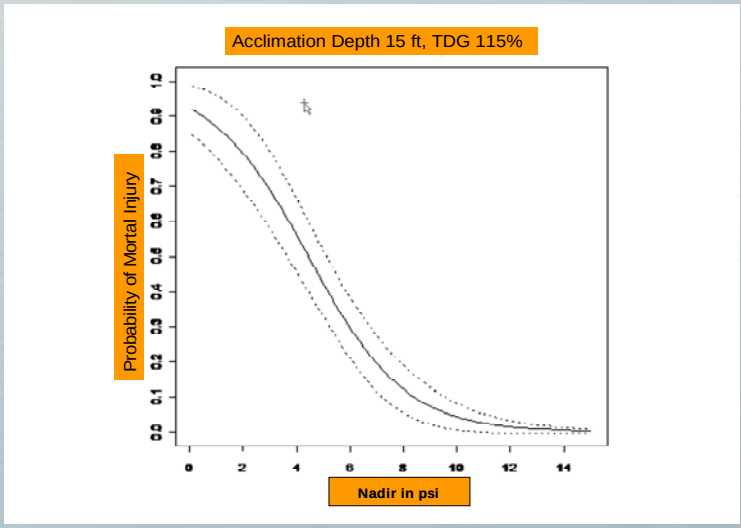
- Endpoint of exposure is completion of simulated turbine passage
  - Test fish were not held but were immediately necropsied
- Analyzed data from previous experiments when fish were held following exposure and identified the subset of injuries observed during necropsy that were most predictive of injury
- Ending list was:
  - Hemorrhaging in the pericardium
  - Hemorrhaging in the liver
  - Hemorrhaging in the kidney
  - Ruptured swim bladder
  - Exothalmia (eye-pop)
  - Blood or bile secretions from the vent
  - Emboli in the gills
  - Emboli in the pelvic fins.

Initial Experimental Design

- Problem
  - Could not consistently achieve nadir and rate of change
- Analysis of acquired data suggested an alternative approach that might provide more generally useful results

Current Experimental Design





- Consider Nadir a continuous rather than discrete variable
- Set all treatment factors with exception of Nadir then:
  - Sample Nadirs within range of 0 to 15 psia
- Progressively analyze data and identify range of Nadirs where additional data is required
- When an acceptable result is achieved, select another set of treatment factors (selection driven by acclimation depth) and repeat the experimental process described above

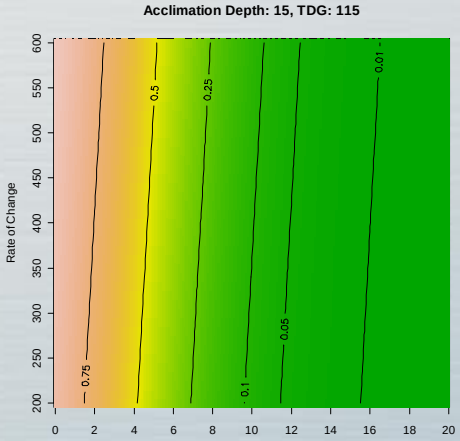
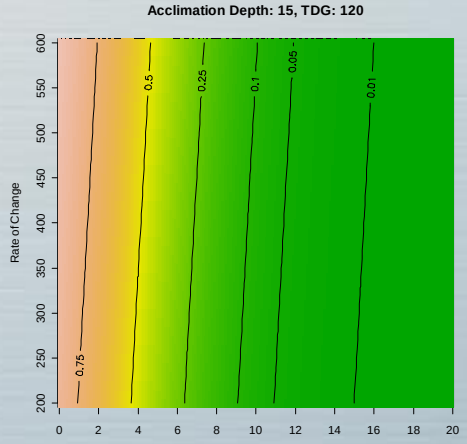
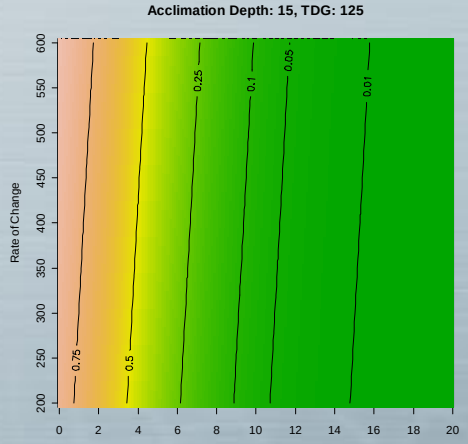
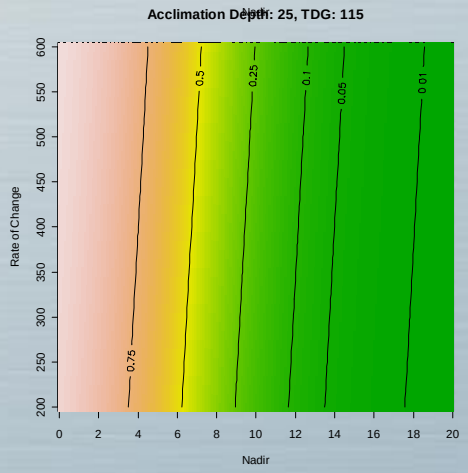
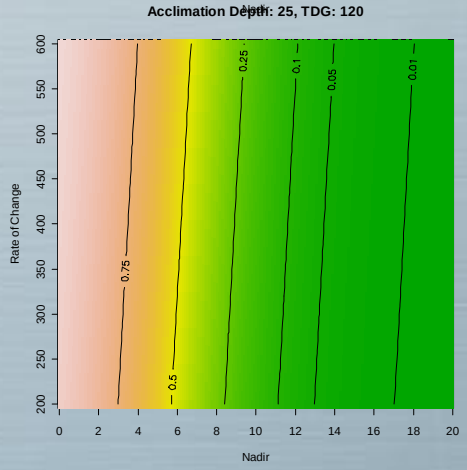
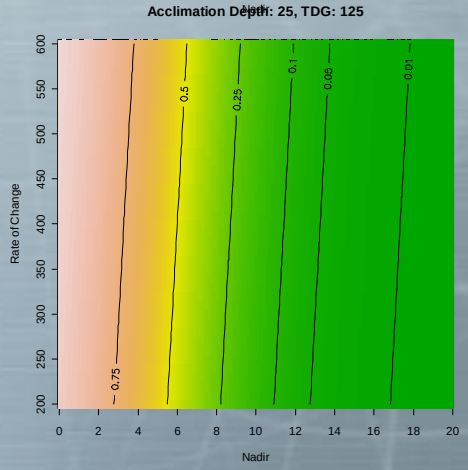
Initial regression model

- Hatchery yearling Chinook salmon
- Response variable: probability of mortality

4 Main effects were significant

1. Nadir
2. Rate of Change
3. Acclimation depth
4. TDG

Initial Results

Acclimation Depth	TDG 115%	120%	125%
15 feet			
25 feet			

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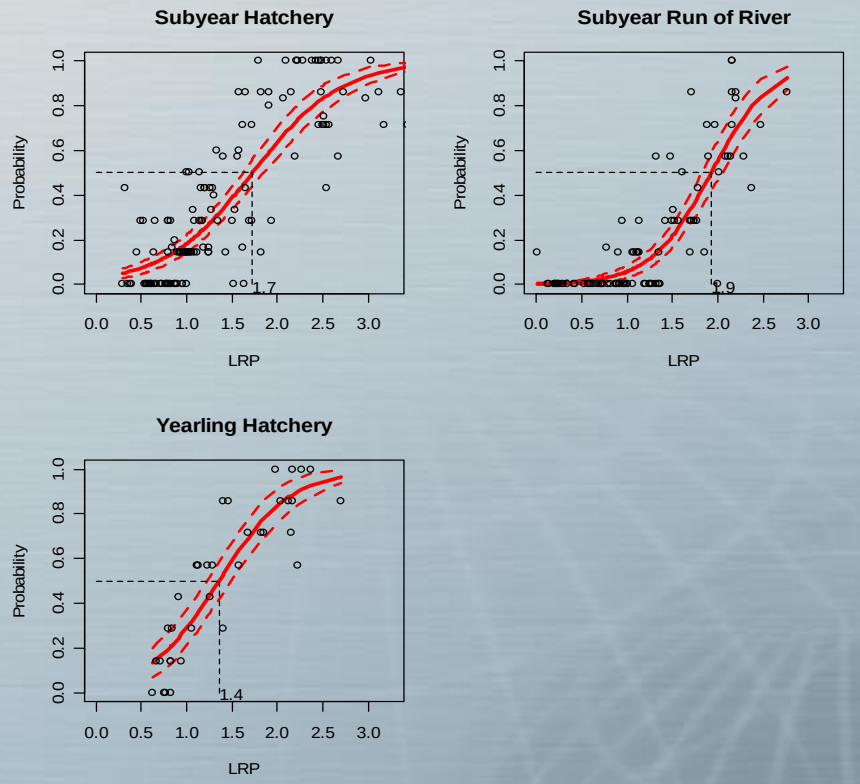
Ln Ratio (Acclimation P/Nadir P)

- Pressure Ratio: Ln (P_A/ P_N)
- Physically and biologically sound
- Example: Pressure change of 15 psia
  - 30 psia/15 psia = 2
    - Bubble volume and gas solubility change by factor of 2
  - 18 psia/3 psia = 6
    - Bubble volume and gas solubility change by several factors of 2
      - 18 psia to 9 psia (X2)
      - 9 psia to 4.5 psia (X2)
      - 4.5 psia to 3 psia (X1.5)
      - 2 x 2 x 1.5 = 6



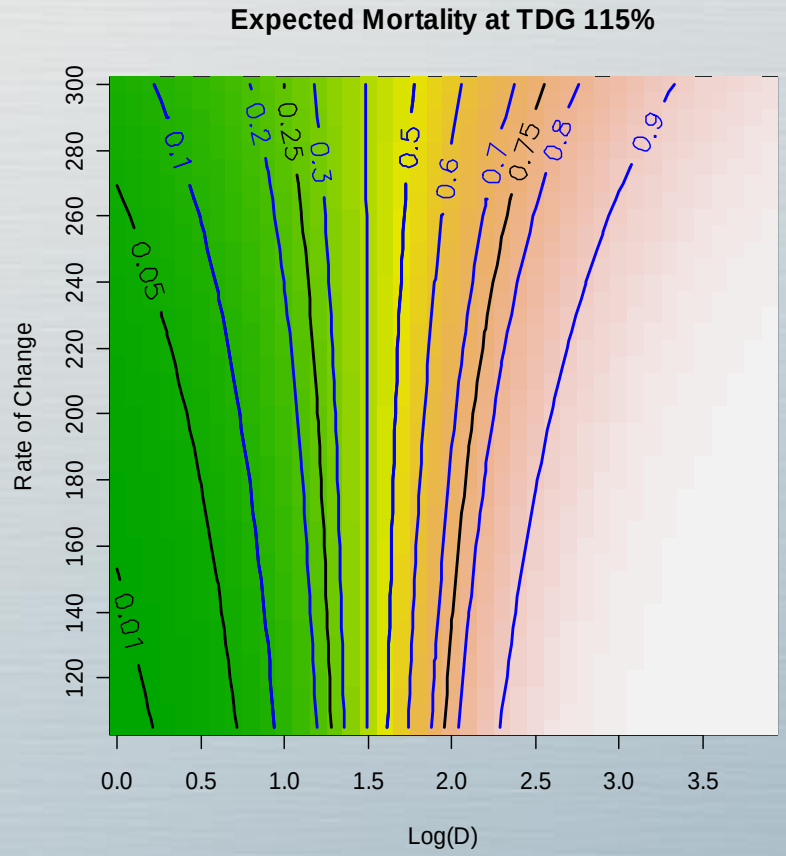
Updated, LRP, regression model

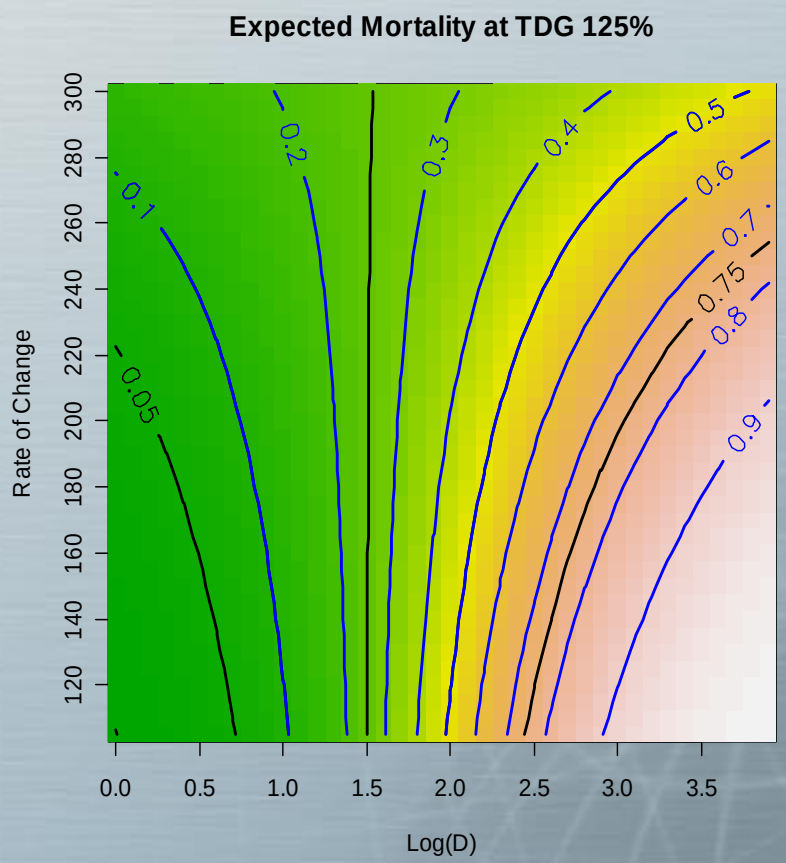
- Hatchery subyearling Chinook salmon
- Response variable: Ln (acclimation pressure/nadir)

Analysis of Deviance: Full Model

Source	Df	Deviance	P(> c^2)
Totalc	284	1220.29	
Log(D)	1	550.28	1.09×10^{-121}
ROC*	1	0.23	0.63
TDG	1	45.89	1.25×10^{-11}
Log(D):ROC	1	10.76	1.04×10^{-03}
Log(D):TDG	1	19.61	9.52×10^{-06}
ROC:TDG	1	0.02	0.87
Log(D):ROC:TDG	1	1.81	0.18
Error	277	591.69	

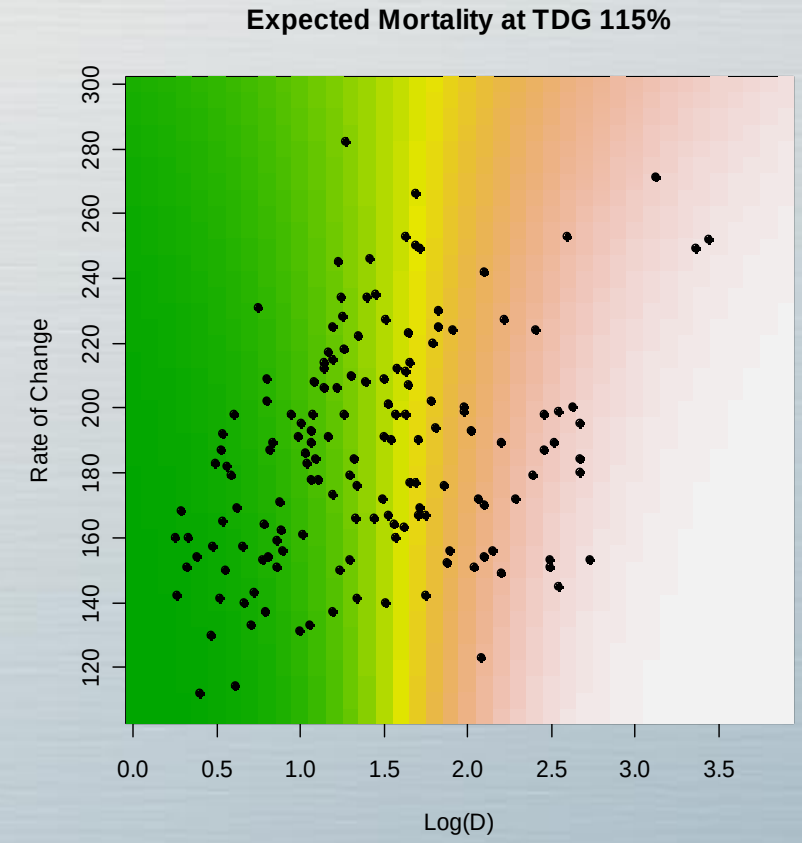
Updated 3-d results

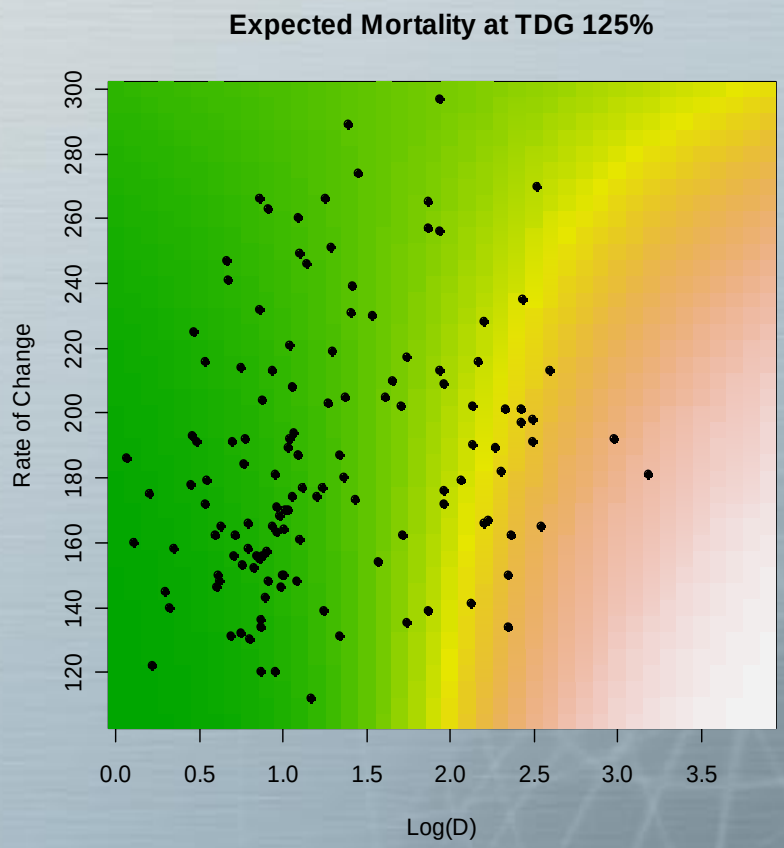




R	2	4	6	8	10	12	14	16	18	20
Ln	0.7	1.4	1.8	2.1	2.3	2.5	2.6	2.7	2.8	3.0

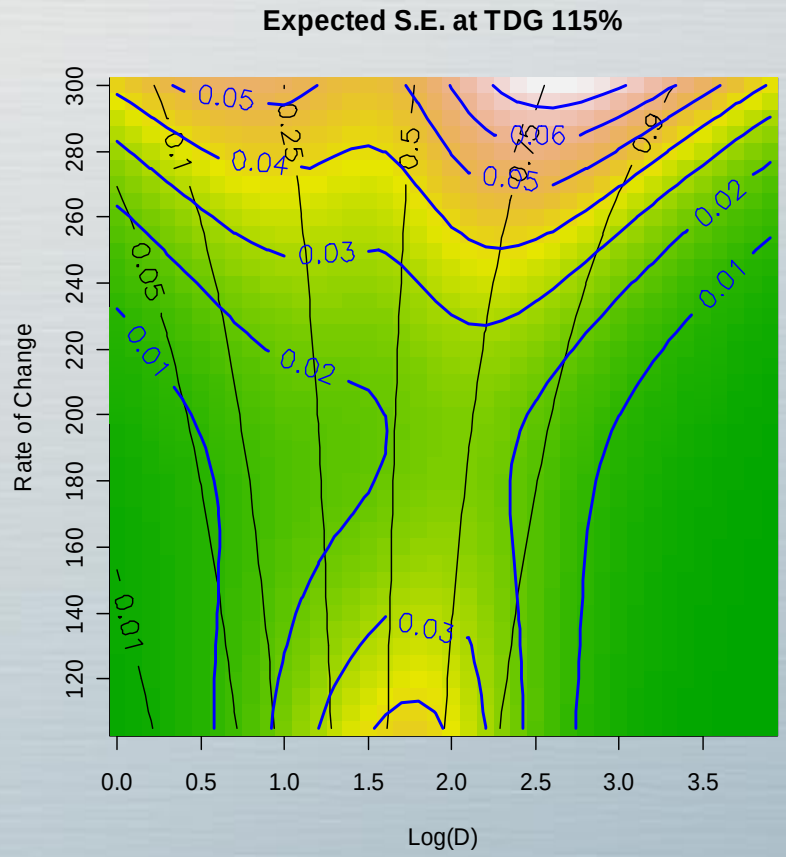
Tested combinations to date

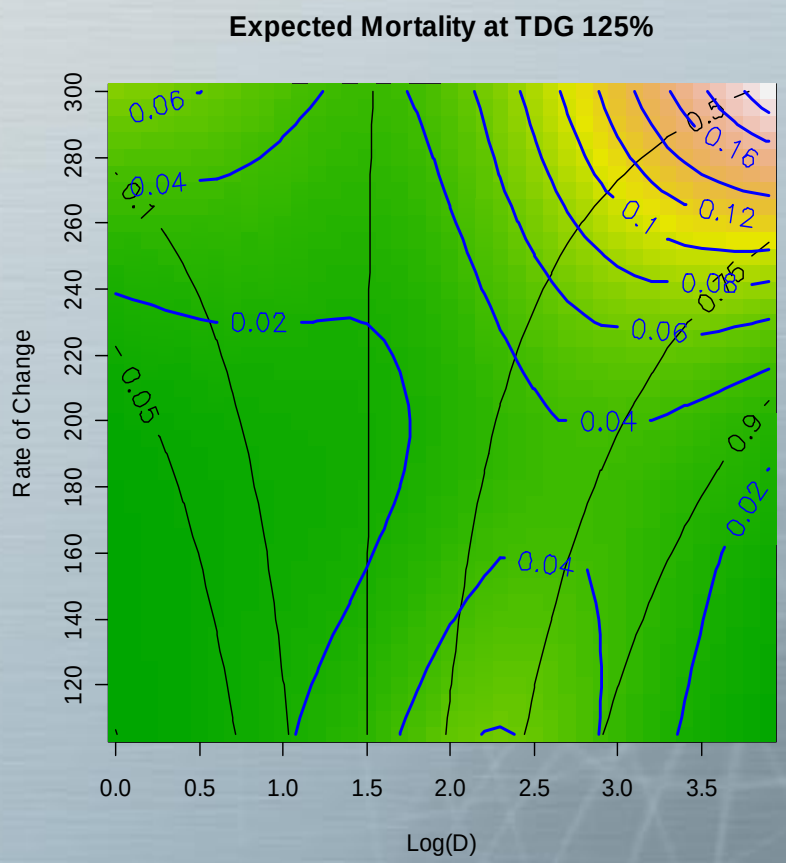




R	2	4	6	8	10	12	14	16	18	20
Ln	0.7	1.4	1.8	2.1	2.3	2.5	2.6	2.7	2.8	3.0

Expected s.e. on prediction

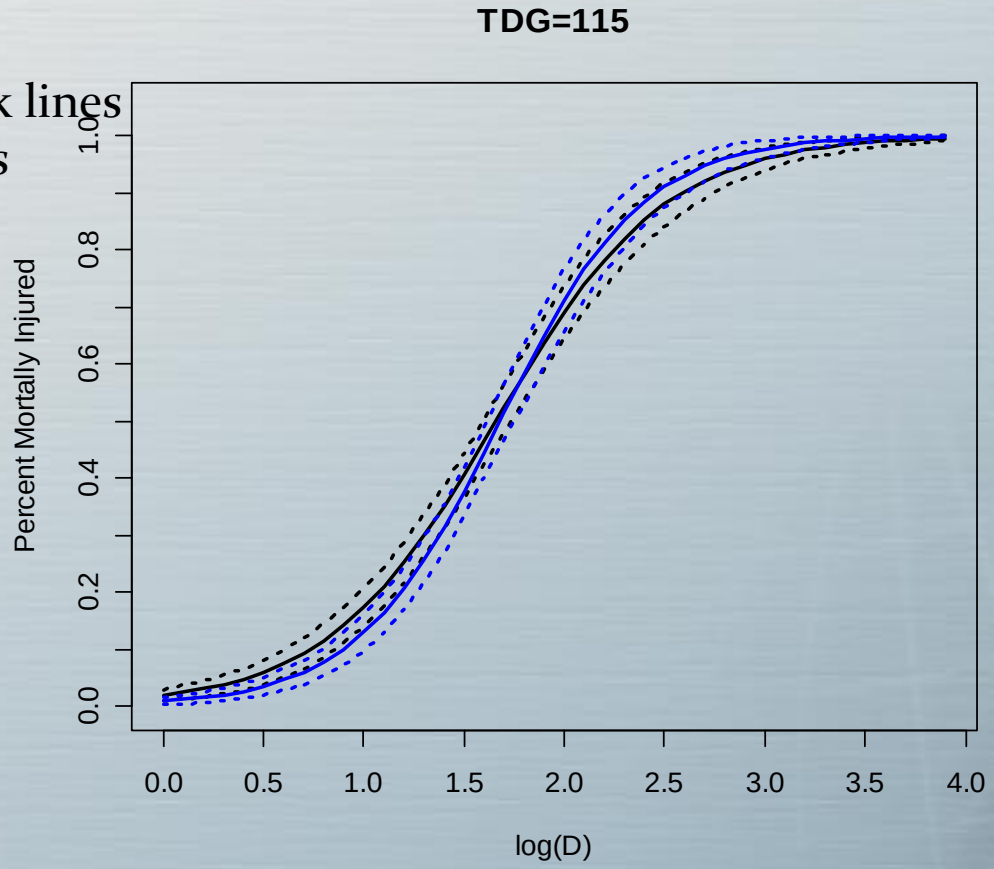




R	2	4	6	8	10	12	14	16	18	20
Ln	0.7	1.4	1.8	2.1	2.3	2.5	2.6	2.7	2.8	3.0

Hatchery vs. ROR subyearling

Hatchery: black lines
ROR: blue lines



95% c.i. on predicted mortality: dashed lines

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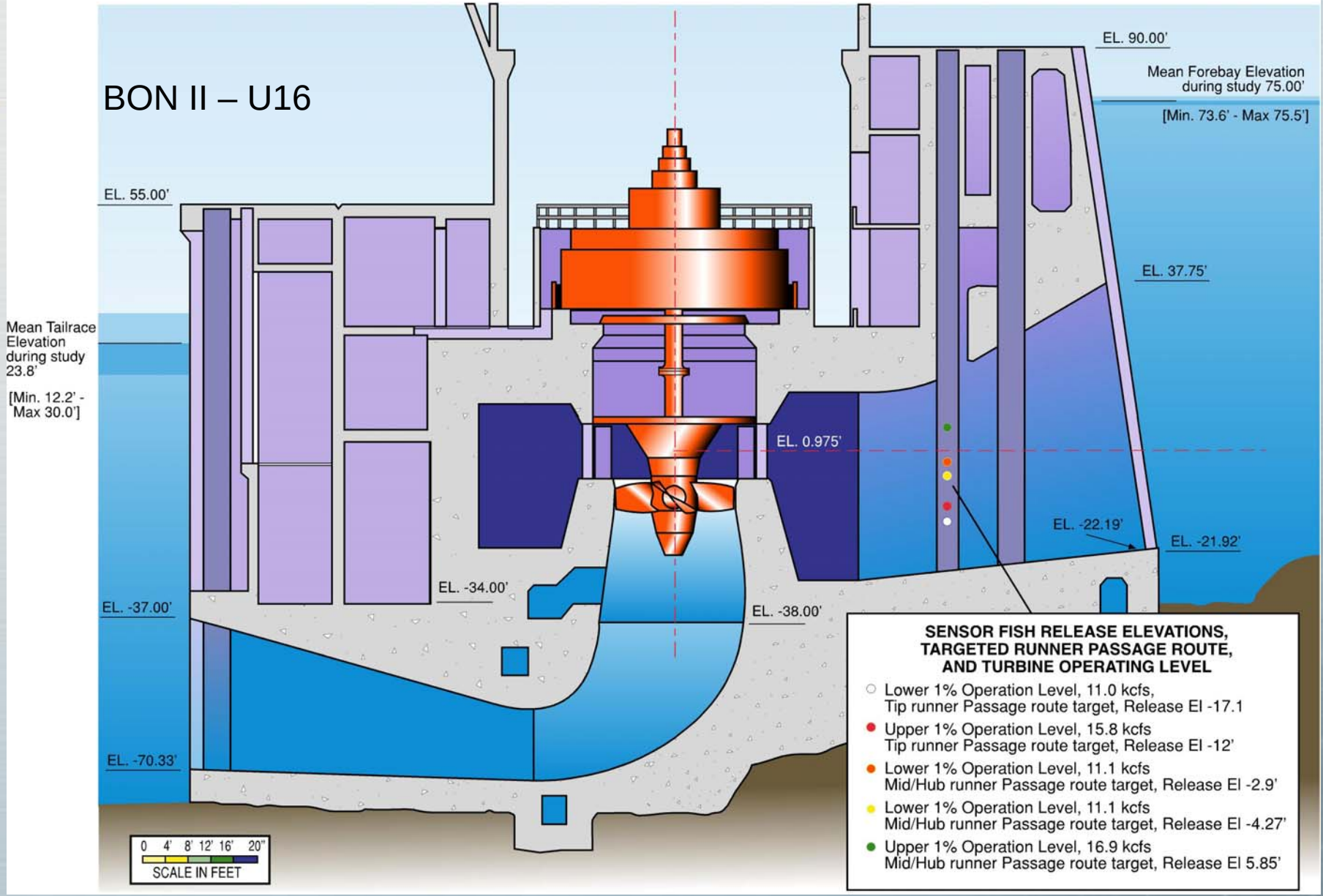
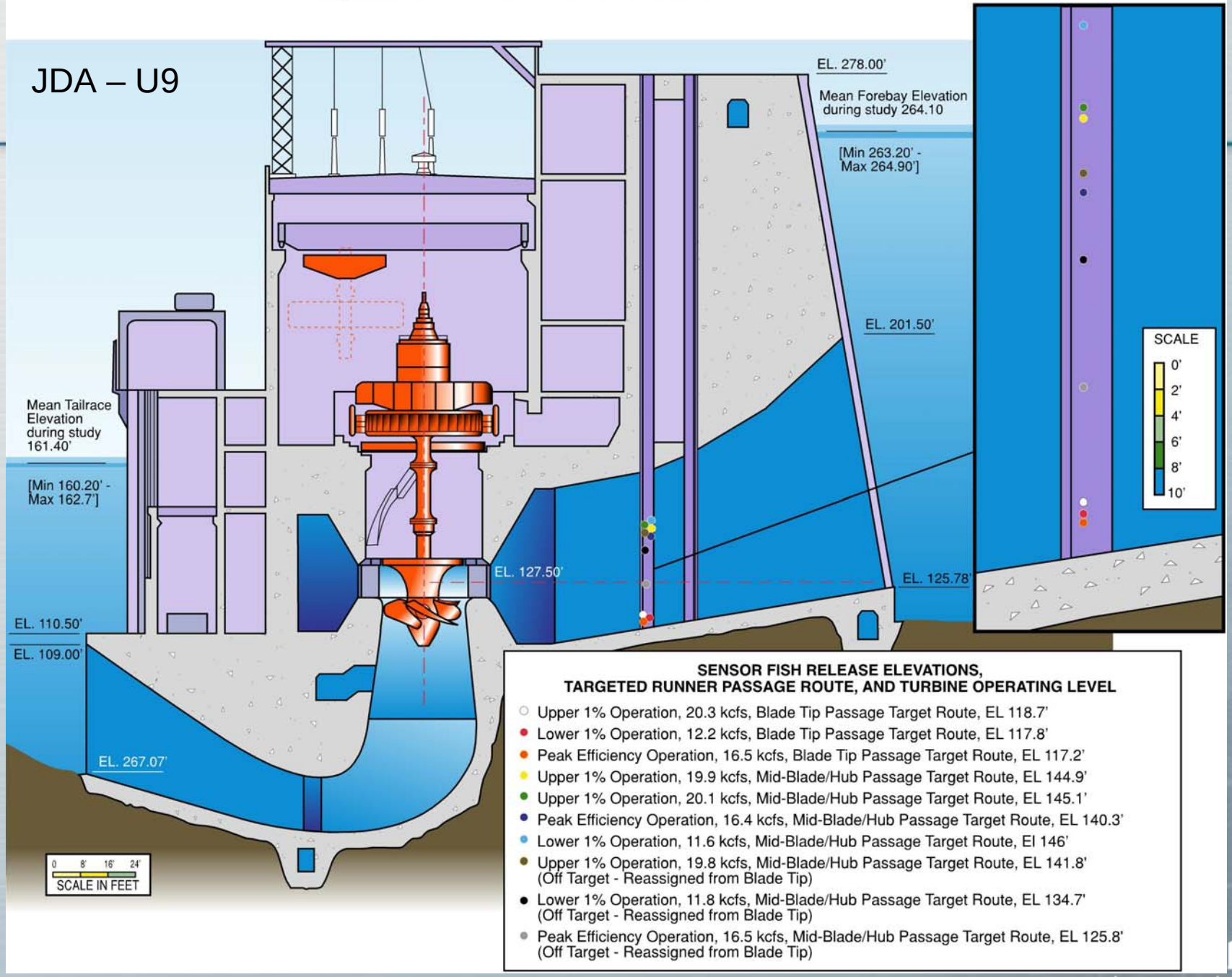
Summary

- The study is not yet complete – however
- It appears that the assumption of surrogacy of hatchery for ROR subyearling chinook is acceptable
- Dominant exposure factors for mortal injury are the ratio of acclimation and nadir pressures and TDG
- ROC does not appear to be very important over rates considered
- Trends in mortal injury with increases in TDG are different than expected. Exposure and nadir pressures may have to be “unbundled” from LRP to understand the data.

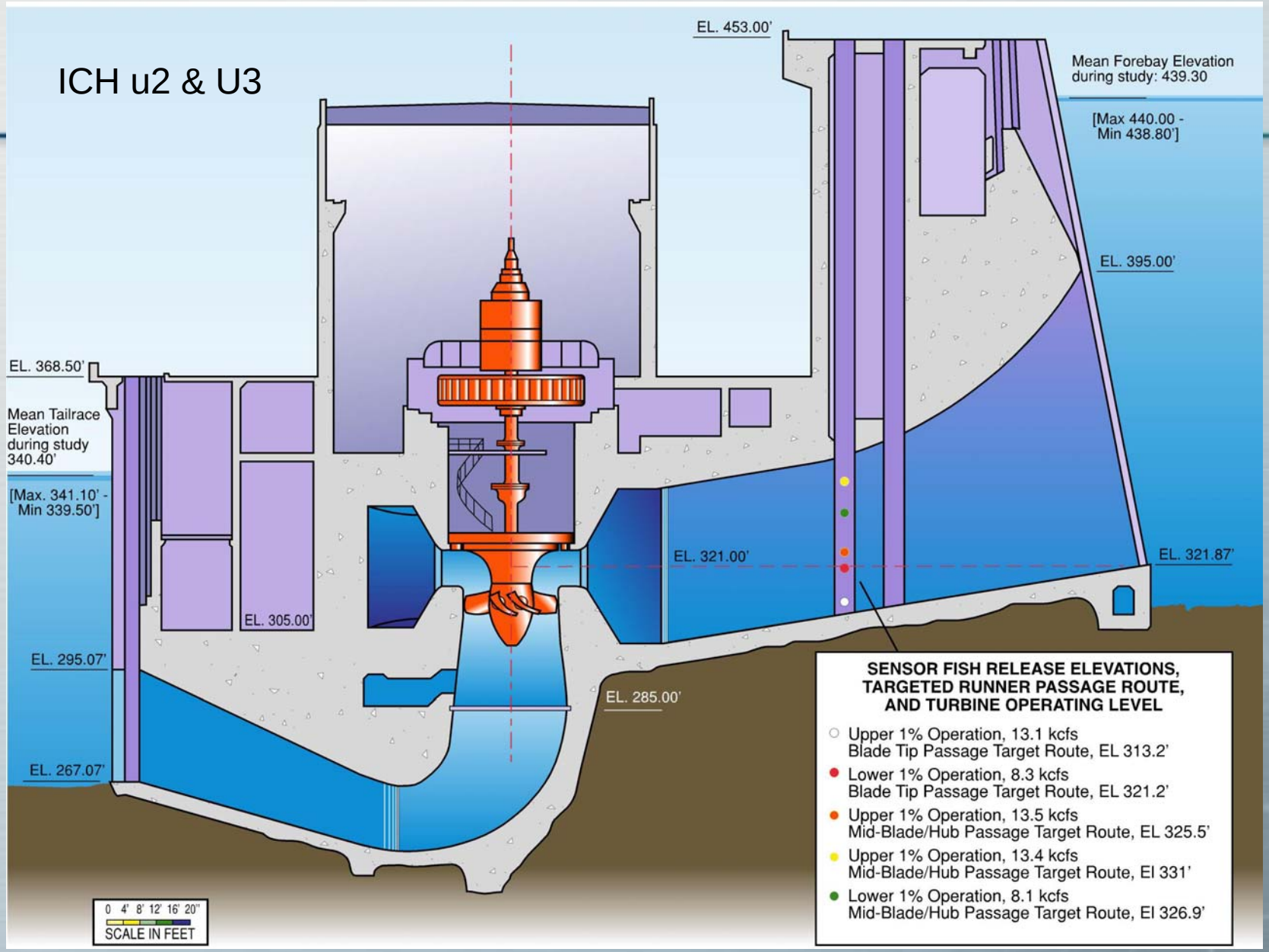
BON II – U16


EL. 90.00'
Mean Forebay Elevation during study 75.00'
[Min. 73.6' - Max 75.5']
EL. 55.00'
EL. 37.75'
Mean Tailrace Elevation during study 23.8'
[Min. 12.2' - Max 30.0']
EL. 0.975'
EL. -22.19'
EL. -21.92'
EL. -34.00'
EL. -38.00'
EL. -37.00'
EL. -70.33'
0 4' 8' 12' 16' 20"
SCALE IN FEET
SENSOR FISH RELEASE ELEVATIONS, TARGETED RUNNER PASSAGE ROUTE, AND TURBINE OPERATING LEVEL
Lower 1% Operation Level, 11.0 kcfs, Tip runner Passage route target, Release El -17.1
Upper 1% Operation Level, 15.8 kcfs Tip runner Passage route target, Release El -12'
Lower 1% Operation Level, 11.1 kcfs Mid/Hub runner Passage route target, Release El -2.9'
Lower 1% Operation Level, 11.1 kcfs Mid/Hub runner Passage route target, Release El -4.27'
Upper 1% Operation Level, 16.9 kcfs Mid/Hub runner Passage route target, Release El 5.85'

JDA – U9


EL. 278.00'
Mean Forebay Elevation during study 264.10
[Min 263.20' - Max 264.90']
EL. 201.50'
SCALE
0'
2'
4'
6'
8'
10'
Mean Tailrace Elevation during study 161.40'
[Min 160.20' - Max 162.7']
EL. 127.50'
EL. 125.78'
EL. 110.50'
EL. 109.00'
EL. 267.07'
0 8' 16' 24'
SCALE IN FEET
SENSOR FISH RELEASE ELEVATIONS,
TARGETED RUNNER PASSAGE ROUTE, AND TURBINE OPERATING LEVEL
Upper 1% Operation, 20.3 kcfs, Blade Tip Passage Target Route, EL 118.7'
Lower 1% Operation, 12.2 kcfs, Blade Tip Passage Target Route, EL 117.8'
Peak Efficiency Operation, 16.5 kcfs, Blade Tip Passage Target Route, EL 117.2'
Upper 1% Operation, 19.9 kcfs, Mid-Blade/Hub Passage Target Route, EL 144.9'
Upper 1% Operation, 20.1 kcfs, Mid-Blade/Hub Passage Target Route, EL 145.1'
Peak Efficiency Operation, 16.4 kcfs, Mid-Blade/Hub Passage Target Route, EL 140.3'
Lower 1% Operation, 11.6 kcfs, Mid-Blade/Hub Passage Target Route, El 146'
Upper 1% Operation, 19.8 kcfs, Mid-Blade/Hub Passage Target Route, EL 141.8'
(Off Target - Reassigned from Blade Tip)
Lower 1% Operation, 11.8 kcfs, Mid-Blade/Hub Passage Target Route, EL 134.7'
(Off Target - Reassigned from Blade Tip)
Peak Efficiency Operation, 16.5 kcfs, Mid-Blade/Hub Passage Target Route, EL 125.8'
(Off Target - Reassigned from Blade Tip)

ICH u2 & U3


EL. 453.00'
Mean Forebay Elevation during study: 439.30
[Max 440.00 - Min 438.80']
EL. 395.00'
EL. 368.50'
Mean Tailrace Elevation during study 340.40'
[Max. 341.10' - Min 339.50']
EL. 321.00'
EL. 321.87'
EL. 305.00'
EL. 295.07'
EL. 285.00'
EL. 267.07'
0 4' 8' 12' 16' 20'
SCALE IN FEET
SENSOR FISH RELEASE ELEVATIONS, TARGETED RUNNER PASSAGE ROUTE, AND TURBINE OPERATING LEVEL
Upper 1% Operation, 13.1 kcfs
Blade Tip Passage Target Route, EL 313.2'
Lower 1% Operation, 8.3 kcfs
Blade Tip Passage Target Route, EL 321.2'
Upper 1% Operation, 13.5 kcfs
Mid-Blade/Hub Passage Target Route, EL 325.5'
Upper 1% Operation, 13.4 kcfs
Mid-Blade/Hub Passage Target Route, El 331'
Lower 1% Operation, 8.1 kcfs
Mid-Blade/Hub Passage Target Route, El 326.9'