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Characterization of Fish Passage Conditions through a Francis Turbine and Regulating Outlet at Cougar Dam, Oregon, Using Sensor Fish, 2009–2010

Final Report

JP Duncan

May 2011

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

Fish passage conditions through a Francis turbine and a regulating outlet (RO) at Cougar Dam on the south fork of the McKenzie River in Oregon were evaluated by Pacific Northwest National Laboratory for the U.S. Army Corps of Engineers, Portland District, using Sensor Fish devices. The objective of the study was to describe and compare passage exposure conditions, identifying potential fish injury regions encountered during passage via specific routes. The RO investigation was performed in December 2009 and the turbine evaluation in January 2010, concurrent with HI-Z balloon-tag studies by Normandeau Associates, Inc.

Sensor Fish and live fish for both turbine and RO passage were conveyed through a pipe injection system that terminated at elevations approximately 2 ft above the respective intake midpoints. Release depth and position were established to introduce the fish and sensors into flows of approximately 5 feet per second (fps). Turbine passage through unit 2 was evaluated at minimum wicket gate opening, peak efficiency, and maximum wicket gate opening; RO passage was evaluated through 1.5-ft and 3.7-ft gate openings. Each study was conducted at one operational head.

Sensor Fish data were analyzed to estimate 1) exposure conditions, particularly exposure to severe collision, strike, and shear events by passage route sub-regions; 2) differences in passage conditions between passage routes; and 3) relationships to live-fish injury and mortality data estimates.

For the turbine evaluation, three operational conditions through turbine unit 2 were tested: the minimum wicket gate opening of 13.6 degrees; maximum wicket gate opening of 24.5 degrees; and wicket gates set to the peak efficiency setting of 19.1 degrees. The corresponding turbine discharges were 340 cubic feet per second (cfs), 550 cfs, and 455 cfs, respectively. Sensor Fish were injected into turbine intake flows about 2 ft below the penstock ceiling at an elevation of approximately 1426 ft above mean sea level (MSL), into water velocities of approximately 5 fps.

Sensor Fish experienced at least one significant strike, collision, or shear event during passage through the turbine runner; more than 92% experienced multiple events. The average value for all turbine events was 149.4 g (n = 13). The highest significant event magnitudes (166.2 g) occurred during passage through the maximum wicket gate opening condition followed by those at the minimum and peak efficiency settings (143.2 g and 140.3 g, respectively). Mean pressure nadir values obtained during turbine runner passage at Cougar Dam were the lowest observed to date; mean value observed during the maximum wicket gate opening condition was 3.66 pounds per square inch absolute.

Passage through the RO was evaluated at two test conditions—gate openings of 1.5 ft and 3.7 ft—with corresponding approximate discharges of 440 cfs and 1040 cfs, respectively. The injection system pipe terminus was positioned at approximately elevation 1487.0 ft MSL, 2 ft above the RO centerline elevation.

More than 97% of the Sensor Fish experienced at least one significant collision event during RO passage (n = 35); nearly 86% of the Sensor Fish experienced multiple collision events. The mean acceleration magnitudes for the most severe events observed for the 1.5-ft and 3.7-ft openings were 150.9 g (n = 19) and 135.9 g (n = 16), respectively.

Results from the Sensor Fish passage evaluations at Cougar Dam would likely differ using different fish sizes or species and under other dam operations. Live fish used during the studies were not depth-acclimated. Research has shown that juvenile salmon that are not acclimated to depth as they are in nature do not show the same response to rapid decompression as do fish that are acclimated. The rates of change in pressure as well as the nadir value magnitudes indicate that the injury and mortality rates observed for passage of fish through Cougar turbines are most likely underestimated The same is probably true for RO injury and mortality rate estimates. It is likely that other passage conditions in which rates of change in pressure and nadir magnitudes would be greater and lower, respectively, would lead to increase in injury and mortality rates. Observed injury and mortality rates are not absolute estimates of biological response to passage of juvenile salmon through Cougar Dam turbines or RO but do have utility as estimates of the response of passing fish to mechanical sources of injury. Passage of larger fish through the turbine would result in greater injury and mortality, as blade strike would be likely.

Comparison of the three passage routes evaluated at Cougar Dam indicates that the RO passage route through the 3.7-ft gate opening was relatively the safest route for fish passage under the operating conditions tested; turbine passage was the most deleterious. These observations were supported also by the survival and malady estimates obtained from live-fish testing. Injury rates were highest for turbine passage. Compared to mainstem Columbia River passage routes, none of the Cougar Dam passage routes as tested are safe for juvenile salmonid passage.

Acronyms and Abbreviations

cfs	cubic feet per second
fps	feet per second
ft	foot, feet
g	average acceleration produced by gravity at the Earth's surface (sea level); used in this report as a measure of event magnitude
g	gram(s)
hr	hour(s)
Hz	hertz
in.	inch(es)
min	minute(s)
mm	millimeter(s)
MSL	mean sea level
MW	megawatt(s)
PNNL	Pacific Northwest National Laboratory
psia	pounds per square inch absolute
RO	regulating outlet
s	second(s)
USACE	U.S. Army Corps of Engineers

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1.0 Introduction

The Willamette River provides essential habitat for salmon and trout species. The development of hydropower dams in the upper basin tributaries has impacted conditions throughout the river system, altering the stream ecology and fish survival. Since the construction of Cougar Dam on the McKenzie River, seasonal water temperatures had increased during the fall and decreased over the spring and summer, affecting migration, spawning, and emergence. Construction of a water temperature control tower at Cougar Dam started in 2000 and was completed in December 2004; the tower became operational in 2005. Use of the tower restored water temperatures to levels conducive to fish habitat in the McKenzie River, increasing the productivity and survival of salmonids downstream of the dam. Efforts to further increase salmonid population recovery at Cougar Dam include the development of downstream passage methods for safe emigration.

This report documents investigations of downstream passage research involving regulating outlet (RO) and turbine passage conditions at Cougar Dam in December 2009 and January 2010, respectively. The studies were conducted by Pacific Northwest National Laboratory (PNNL) for the U.S. Army Corps of Engineers (USACE), Portland District, and performed concurrently with HI-Z balloon-tag studies of passage survival for juvenile spring Chinook salmon conducted by Normandeau Associates, Inc.

This study provides information for turbine and RO passage operation alternatives for optimizing downstream temperatures for improved fish survival.

1.1 Objectives

The objectives of this study were

- to describe and compare passage exposure conditions encountered through a turbine penstock into the intake, runner region, draft tube, and tailrace of Francis turbine unit 2 at the minimum wicket gate opening, peak efficiency, and maximum wicket gate opening at one operating head
- to describe passage exposure conditions through a regulating outlet at two gate openings (i.e., RO discharges)
- to describe differences in passage conditions between the passage routes
- to identify regions in all passage routes where passage conditions are potentially injurious to fish.

1.2 Report Overview

Chapter 2 describes the study site, the Sensor Fish device, and the data collection and analysis procedures used in the research. Chapter 3 presents the results of the study, followed by a discussion in Chapter 4. Conclusions are offered in Chapter 5, followed by Chapter 6, the sources cited in this report.

The compact disk included in the pocket on the inside back cover of printed copies of this report contains supplementary details and data in four appendices. Appendix A contains field log data that provide dam operating conditions, release elevations, and deployment and recovery times for each Sensor Fish release. Appendix B provides summary data tables for each Sensor Fish release. Dam operating conditions, exposure event descriptions, pressure at injection, and rates of change in pressure are included in the data tables. Appendices C and D present graphics showing pressure, acceleration magnitude, and of change magnitude time histories for each Sensor Fish release.

2.0 Methods

2.1 Study Site

Cougar Dam is located on the South Fork of the McKenzie River in Lane County, Oregon, approximately 4 mi upstream of the confluence of the mainstem McKenzie River, at river kilometer 406 of the Willamette River (Figure 2.1). It is a storage dam used for flood control, power generation, irrigation, navigation, and recreation. The dam, a rock-fill embankment approximately 452 ft tall and 1500 ft long, has two ROs and an opening leading to the penstock that distributes water to a powerhouse containing two Francis turbine units. The turbines have a hydraulic capacity of 1050 cubic feet per second (cfs) and a total capacity of 25 megawatts (MW) (Figure 2.2). Full pool is 1699.0 ft above mean sea level (MSL); minimum pool is 1532.0 ft MSL. A gated spillway with two spillbays, currently nonoperational, is available for flood control. Downstream fish passage is possible only through the turbines or ROs.

Figure 2.1. Cougar Dam, Oregon.

There are separate intakes for each of the turbine units, merging together into a common 10.5-ft-diameter, 1091-ft-long turbine penstock located at a centerline elevation of 1424.75 ft MSL. The penstock descends to an elevation of 1255.0 ft MSL at the powerhouse (Figure 2.3), where it bifurcates to the two Francis turbines. Each turbine is a 22,100-horsepower unit, operating at 400 revolutions per minute with a maximum discharge of 550 cfs. The runner diameter is 72 in., and runner opening height is 13 in. Each Francis turbine unit has 13 blades and 24 wicket gates. The powerhouse tailrace is a separate channel that merges with the RO channel approximately 0.25 mile downstream. Turbine runners were replaced in 1987 and again in 2004–2005.

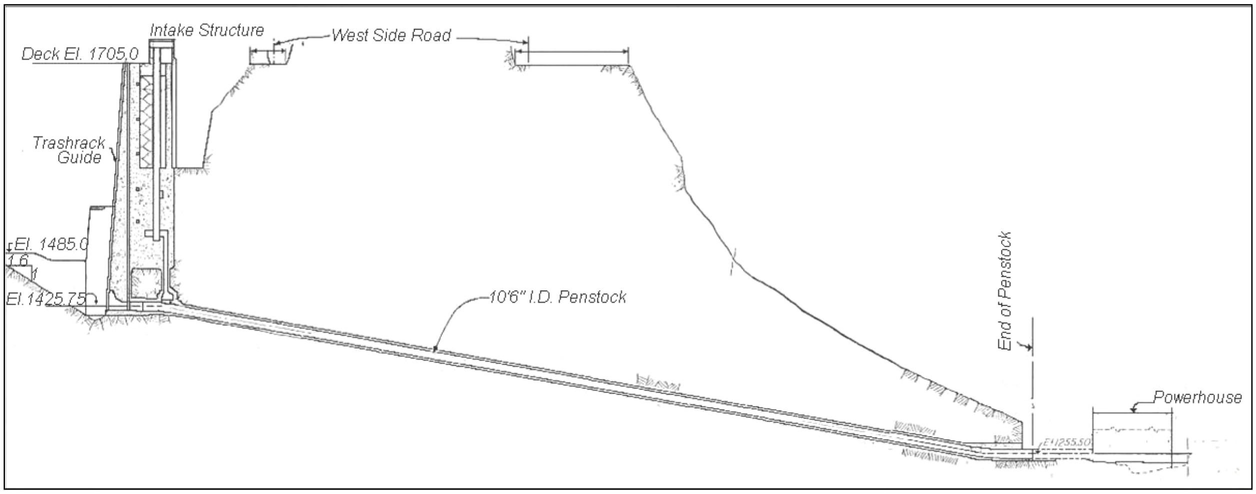


Figure 2.2. Cross section of Cougar Dam penstock.

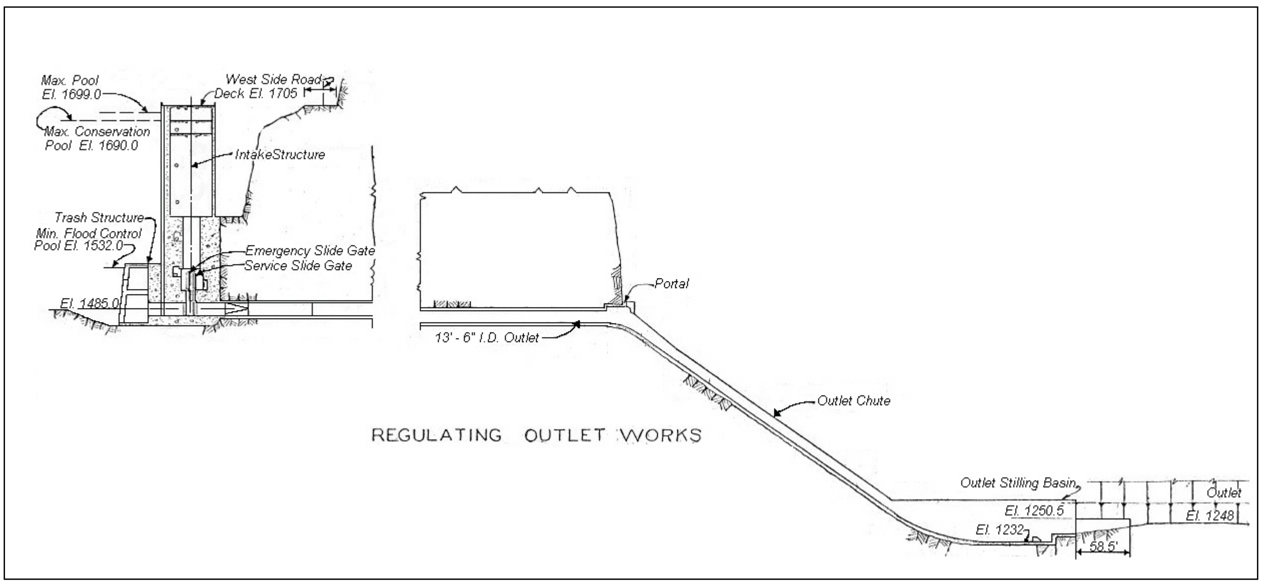


Figure 2.3. Cross section of Cougar Dam regulating outlet works.

The RO intakes are located at a centerline elevation of 1488.5 ft MSL. Approximately 46 ft downstream of the RO intake, hydraulic gates control flow discharge. The two steel-lined entrances, separated by approximately 6.5 ft, are approximately 12.5 ft high and 6.5 ft wide, transitioning to 6.5-ft-diameter pipes before merging as a common 13.5-ft-inner diameter circular steel passageway. The RO tunnel (approximately 1000 ft long) descends to an elevation of 1469.9 ft MSL (floor elevation) before exiting and going down 240 ft via a 20-ft-wide concrete spillway chute with guidewalls to an elevation of 1232 MSL, a total distance of 352 ft. The RO chute transitions to a 50-ft-wide, 205-ft-long stilling basin containing five baffle blocks and an endsill before entering a channel downstream. The RO tailrace merges with the powerhouse tailrace before continuing downstream as the South Fork of the McKenzie River.

2.2 Sensor Fish Device

The Sensor Fish housing is constructed of clear polycarbonate plastic (Figure 2.4). It is 24.5 mm in diameter and 90 mm long and weighs 43 g. The Sensor Fish is nearly neutrally buoyant in fresh water. The Sensor Fish measures the three components of linear acceleration, the three components of angular velocity (these together comprise the six degrees of freedom), absolute pressure, and temperature, at a sampling frequency of 2000 Hz per sensor channel over a recording time of about 4 min.

Figure 2.4. Six-degree-of-freedom Sensor Fish device.

The Sensor Fish consists of modules that charge its internal battery, program the sensor settings, acquire data, and convert from analog signal to digital form. The acquired data are stored in an internal memory card and transferred to computers via a wireless infrared link using an external infrared link modem. Sensor Fish are deployed, acquiring data in response to hydraulic conditions and interaction with structure; units are retrieved; and the data are downloaded, analyzed, and interpreted.

Retrieval of the Sensor Fish is aided by the attachment of a micro-radio transmitter (Advanced Telemetry Systems, Isanti, Minnesota) and HI-Z balloon tags (Normandeau Associates, Inc., Bedford, New Hampshire), which are identical to those used for live test fish (Heisey et al. 1992). HI-Z tags contain a water-soluble capsule filled with a chemical that produces gas when activated with water, a process that takes approximately 3 min following initiation. The balloons inflate sufficiently to bring the Sensor Fish to the surface for recovery, and a directional radio receiver antenna used by boaters in the tailrace homes in on the radio transmitter attached to the Sensor Fish.

2.3 Procedures

Sensor Fish releases were interspersed with releases of HI-Z balloon-tagged live fish through the same release pipes in concurrent studies conducted by Normandeau Associates, Inc. Study plans called for 1 Sensor Fish release for every 10 live-fish treatment releases, when feasible.

2.3.1 Regulating Outlet Evaluation

The RO tests were conducted at two operational flows: 440 cfs and 1040 cfs, equivalent to gate openings of approximately 1.5 ft and 3.7 ft, respectively. Sensor Fish releases were made through an induction system consisting of a large-diameter (4-in.) stainless steel pipe with a flexible hose attachment connected to a frame that was lowered into the RO bulkhead slot. Flexible hosing (4 in. in diameter) connected the head of the steel pipe to the juncture of the modified head tank where live fish and Sensor Fish were introduced into the induction system. The terminus of the pipe system, positioned at a 105-degree angle, was at an elevation of approximately 1487.0 ft MSL, slightly higher than the centerline elevation of the RO (1485.0 ft MSL). Fish and Sensor Fish exited the pipe terminus into flows of approximately 5 feet per second (fps) to ensure entrainment into RO flows.

2.3.2 Penstock/Turbine Passage Evaluation

Three turbine operations through turbine unit 2 were tested—minimum wicket gate opening – 13.6 degrees; maximum wicket gate opening – 24.5 degrees; and wicket gates set to peak efficiency operation – 19.1 degrees. The corresponding turbine discharges were 340 cfs, 550 cfs, and 455 cfs, respectively. Sensor Fish releases were made through an induction system identical to that used for the RO passage evaluation. However, the frame was attached to the penstock bulkhead slot, and the terminus of the pipe system was at an elevation of 1426 ft MSL, slightly higher than the centerline elevation (1424.75 ft MSL) of the penstock entrance. Exit from the pipe terminus occurred into flows of approximately 5 fps, providing guidance into the penstock.

2.4 Data Analysis

Sensor Fish data sets consist of time histories of angular motion (pitch, roll, and yaw), pressure, acceleration (x, y, and z axes), temperature, and battery status extending from the time of release through the period of data acquisition programmed into the Sensor Fish (Deng et al. 2007a). Data time histories contain a data point for each transducer every 0.0005 s. This time interval between digital samples corresponds to a 2000-Hz sampling rate for each of the analog outputs from Sensor Fish acceleration, rotation, and pressure sensors. Sampling of all analog data streams occurs nearly simultaneously within each sampling interval.

Water depth in feet is estimated, when appropriate, from absolute pressure at various points along each Sensor Fish route by subtracting atmospheric pressure, determined at the time of the release of each Sensor Fish, and dividing the resulting gauge pressure by 0.4335, the pressure in pounds per square inch of 12 in. of fresh (distilled) water at 39.2ºF (4ºC). The raw output of the triaxial accelerometers is processed to detect and quantify Sensor Fish response to turbulence, contact with structure (strike or collision), and shear. Triaxial angle rate-of-change data are processed similarly to triaxial acceleration data to provide further information about the response of the Sensor Fish to flow conditions and another measure of quality of flow.

Analysis of the raw data from the Sensor Fish begins with preparation of plots showing absolute pressure, triaxial acceleration, and triaxial rotation. These records are visually inspected to identify prospective collision, strike, and shear events and to obtain a general overview of the passage conditions present for each test treatment. Changes in pressure during passage include consistently present features resulting from the design of passageway structures and the dynamics of water flow through the passageway. These features in the pressure time history permit acceleration and rotation data to be divided into segments corresponding to specific locations (zones) that extend from Sensor Fish injection to exit from the stilling basin. Each region is identified by characteristic features in the Sensor Fish pressure time history and characteristics in triaxial acceleration and rotation data. For each Sensor Fish data set, events of interest, such as rapid pressure changes, collisions, strikes, shear, and severe turbulence, are identified and quantified. Quantification of events includes the time of occurrence, location by zone, and extraction of information describing severity, as well as additional information to separate collisions and strikes from shear exposure.

3.0 Results

Detailed data on which this chapter is based are provided in the appendices. Appendix A contains study data that include the release and recovery times for each Sensor Fish, discharge and other information describing the operation of the passage route for each Sensor Fish release, and other project information for passage through the RO and the penstock and turbine. Appendix B contains tables of observed maximum acceleration magnitudes, pressure rates of change, and turbine pressure nadirs for Sensor Fish releases, as well as dam operations data for the respective studies. Graphs with plots of pressure and acceleration magnitude for each successful Sensor Fish release are located in Appendix C; those of pressure and angular rate-of-change magnitude are in Appendix D.

3.1 Treatment Release Data

Data were acquired from Sensor Fish following passage through the RO and turbine unit 2 at Cougar Dam. Release and recovery information for each route follows.

3.1.1 Regulating Outlet Evaluation

A total of 39 Sensor Fish were released through the RO at Cougar Dam between December 15 and 21, 2010; 35 data sets were acquired (Table 3.1). A successful release requires both the recovery of the unit and successful download of acquired data. All Sensor Fish were recovered successfully. One nonfunctional Sensor Fish was released to evaluate passage retrieval conditions, and three data sets (7.9%) could not be downloaded due to damage to the Sensor Fish during passage. The forebay elevation during the RO evaluation was approximately 167 ft below the maximum pool elevation of 1699 ft MSL.

Table 3.1. Number of Sensor Fish releases by study treatment during the December 2009 regulating outlet evaluation.

Gate Opening (ft)	Mean Forebay Elevation (ft MSL)	Mean Tailwater Elevation (ft MSL)	RO Flow (cfs)	Mean Total Project Flow (cfs)	Total Number Released	Number of Sensor Fish Damaged	Number of Usable Data Sets
1.5	1531.6	1252.0	440	509.0	22[(a)]	2	19
3.7	1533.4	1252.3	1040	1139.0	17	1	16
				Total	**39**	**3**	**35**

(a) One nonfunctional Sensor Fish unit was released.

3.1.2 Penstock/Turbine Evaluation

Thirty-four Sensor Fish were released into the penstock to the turbine at Cougar Dam between January 19 and 21, 2010 (Table 3.2). Three Sensor Fish were not recovered, and five were damaged during transit; the lost units and damage to three of the five Sensor Fish occurred during passage via the maximum flow turbine operation. Data collection through the penstock into the turbine proved to be complicated, as the time required to pass through the penstock was longer than the default Sensor Fish collection time of 2 min. Delay and data collection times were adjusted so that Sensor Fish data would include the turbine region as well as penstock entry and mid-penstock regions. This resulted in fewer data sets containing turbine runner information; however, limited adequate data were collected to characterize turbine passage. The forebay elevation for the turbine passage segment of this study was approximately 158 ft below maximum pool elevation of 1699 ft MSL.

Table 3.2. Number of Sensor Fish releases by study treatment during the January 2010 turbine evaluation.

Turbine Wicket Gate Opening	Mean Forebay Elevation (ft MSL)	Mean Tailwater Elevation (ft MSL)	Mean Turbine Flow (cfs)	Total Number Released	Number of Sensor Fish Damaged/Lost	Number of Usable Data Sets	Sensor Fish with Runner Data
Minimum	1541.5	1252.6	340	16	2	14	5
Maximum	1541.4	1253	550	14	6	8	4
Peak Efficiency	1540.6	1252.9	455	4	0	4	4
			Total	**34**	**8**	**26**	**13**

3.2 Data Analysis

Sensor Fish data analysis included computing absolute and gauge pressure, acceleration magnitudes, and rotational magnitudes and reviewing their time histories. Collision, strike, and/or shear events appear as high-amplitude impulses in acceleration magnitude time histories. To qualify as a significant event, a high-amplitude acceleration impulse must have a peak value equal to or greater than 95 *g*. Significant events frequently also show concurrent high-amplitude pressure and rotation magnitude values, which aid in identifying the location of the event in time and space and in distinguishing collisions and strike events from shear events.

The location of a significant event is determined by the location of the impulse relative to distinctive consistent features observed in the pressure time histories.

3.2.1 Regulating Outlet Passage

Timing marks used to locate significant events and identify regions of RO passage include

1. passage through the RO gate opening
2. passage through the RO outlet
3. passage along the RO concrete chute
4. transition into the stilling basin/tailrace
5. passage through the stilling basin to the tailrace surface.

Examples of pressure timing marks used for the RO study are shown in Figure 3.1. Pressure is highest as the sensor exits the induction pipe and approaches the RO gate. A rapid decrease in pressure (shown by the blue line) occurs as the Sensor Fish passes through the RO gate; pressure is nearly atmospheric during passage through the outlet and down the outlet chute. Pressure increases as the Sensor Fish descends into the stilling basin, then decreases as the sensor rises to the surface in the tailrace. During passage through the 1.5-ft gate opening, one Sensor Fish was observed to have experienced a shear event at the gate and then became caught or trapped for approximately 0.1 s before continuing passage. Passage times from the gate to the stilling basin averaged 41.8 s and 32.6 s for the 1.5-ft and 3.7-ft gate openings, respectively.

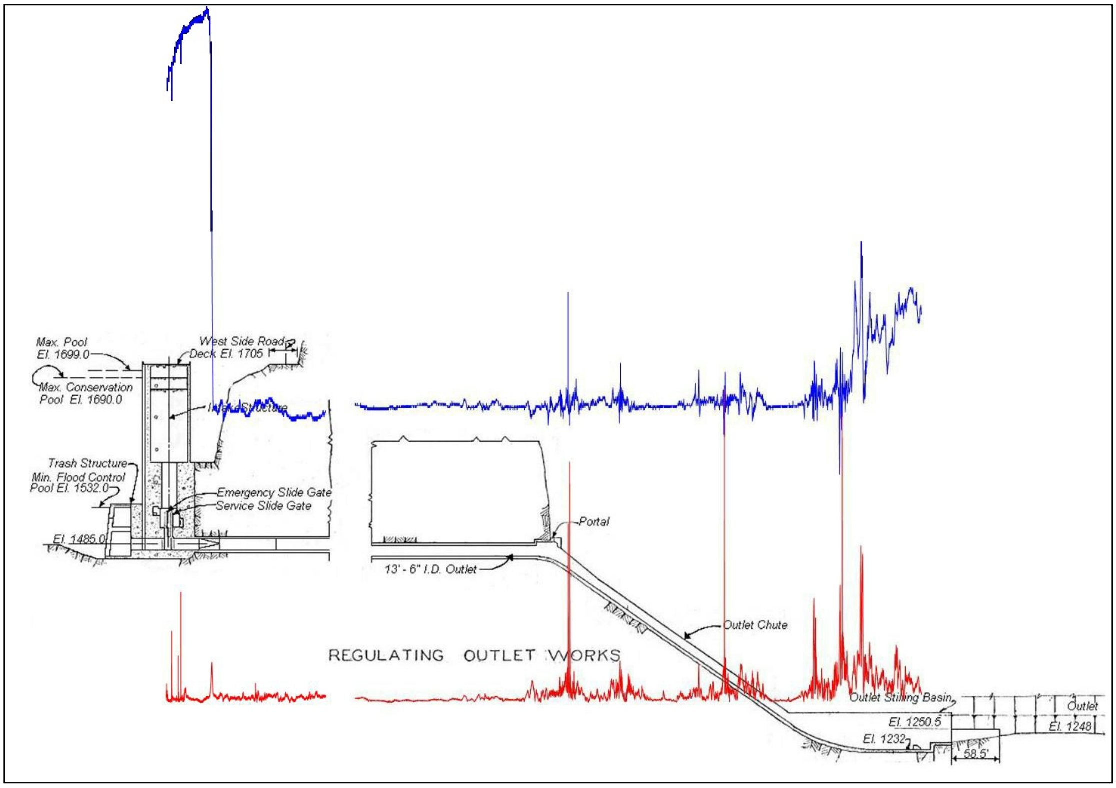


Figure 3.1. Representative Sensor Fish data overlaid on a cross section of the Cougar Dam regulating outlet showing the approximate locations of selected major timing marks. The blue line is pressure; the red line is acceleration vector magnitude in *g*.

3.2.2 Penstock/Turbine Passage

Timing marks used to locate significant events and identify regions of penstock/turbine passage include

1. passage through the penstock
2. passage through the scroll case region
3. runner passage
4. occurrence of nadir during passage through the runner
5. passage through the turbine draft tube
6. passage to the tailrace.

Examples of pressure timing marks used for the turbine study are shown in Figure 3.2. The pressure transducer on the Sensor Fish has a measurement range of 0 to 100 pounds per square inch absolute (psia). The hydraulic head at Cougar Dam was nearly 300 ft during the study period, which when converted to pressure is approximately 132 psia, exceeding the pressure sensor measurement range. At pressures higher than 100 psi, the pressure sensor does not show the actual pressure but reports its maximum value of 100 psia. As the pressure acting on the sensor drops below 100 psi, actual pressures are once again reported by the sensor. However, except where water velocities become high, pressure values can be inferred (as shown on the dotted line in Figure 3.2) by noting the likely time-dependent elevation of the sensor relative to the level of water in the dam forebay.

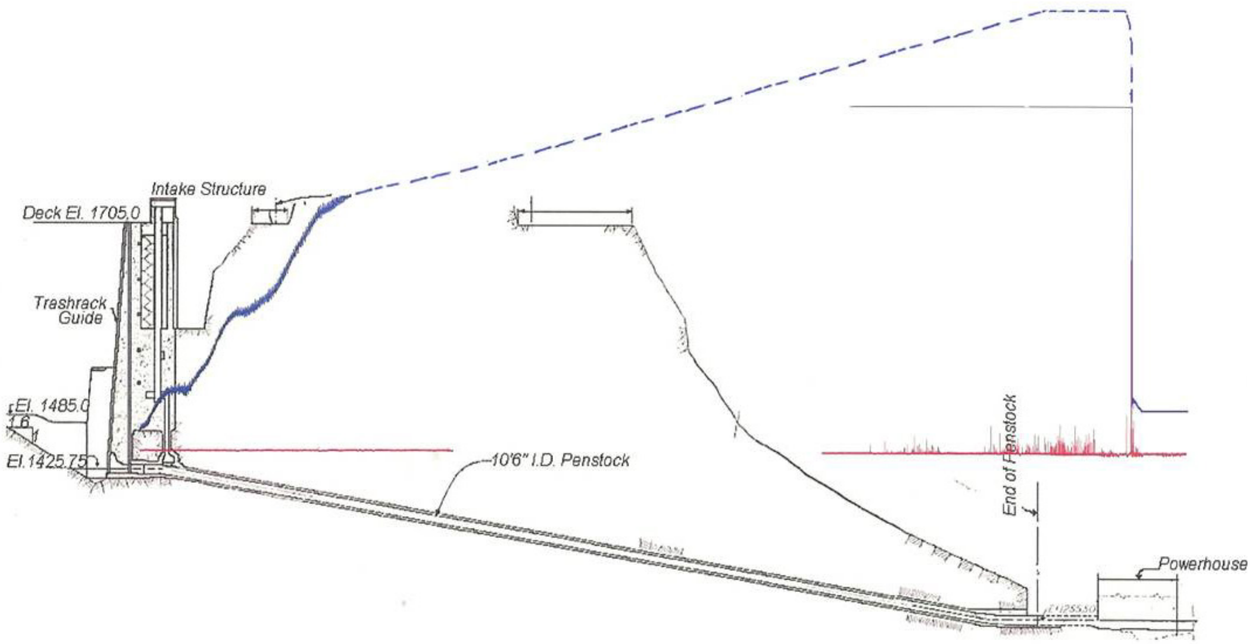


Figure 3.2. Representative Sensor Fish data overlaid on a cross section of the Cougar Dam penstock and turbine region showing the approximate locations of selected major timing marks. The blue line is pressure; the red line is acceleration vector magnitude in *g*.

Pressure rises as the Sensor Fish passes down the induction pipe to the point of injection into the penstock, gradually increasing as the sensor is carried with penstock flow through decreasing elevation of the penstock. As the flow approaches the turbine, a flow transition occurs as the penstock bends, and the pressure remains constant during scroll case passage on approach to the turbine wicket gates. As the Sensor Fish passes through the turbine runner, there is a rapid decrease in pressure. Pressure reaches its lowest point, its nadir, during transit of the suction side of the turbine runner. Following passage through the turbine runner, the Sensor Fish is carried with flow through the turbine draft tube and into the powerhouse tailrace.

Passage times from pipe introduction to the runner averaged 6.4, 4.1, and 4.9 min for minimum, maximum, and peak efficiency operations; time to the tailrace required an additional 12 s for each operating condition.

3.3 Collision, Strike, and Shear Events

The majority of Sensor Fish experienced at least one significant event, regardless of passage route during passage at Cougar Dam. We define a significant event as an impulse in acceleration magnitude greater than or equal to 95 *g*. Significant events are caused by strike, collision with dam structure, or exposure to shear. Overall, 97.9% of the Sensor Fish experienced at least one significant event during passage through all passage routes; 89.4% experienced multiple events.

3.3.1 Regulating Outlet Passage

A total of 97.1% of the Sensor Fish experienced at least one significant event during RO passage; only one had no event. Collision or shear events can occur at the RO gate, within the RO outlet, on the RO chute, or in the stilling basin and tailrace. Nearly 86% of the Sensor Fish experienced more than one significant event during passage through the RO; all passing via the 1.5-ft gate opening experienced multiple events; one Sensor Fish had no event.

Table 3.3 shows the number of analyzed Sensor Fish by release location and type of the most severe significant event. The most severe events were observed primarily as collisions on the outlet chute. Sensor Fish passing through the 1.5-ft gate opening with an estimated flow of 440 cfs had approximately 78% of the most severe events as collisions on the chute. The 3.7-ft gate opening, with an estimated flow of 1140 cfs, had 63% of the most severe events as collisions on the chute. Shear events were rare during RO passage, with only three of the most severe events being of this type.

Table 3.4 summarizes the total number of significant collision and shear events by significant event type and location. Multiple events were most frequent for Sensor Fish passing through the 1.5-ft gate opening, averaging 4.47 events per Sensor Fish release; the 3.7-ft opening averaged approximately 3.2 events per release.

Significant events were observed most frequently on the outlet chute (Figure 3.3). There were no significant events at the gate for Sensor Fish passing through the 3.7-ft gate opening; two significant events were observed at the 1.5-ft opening. Significant event occurrence during passage through the RO outlet passageway and at the flow transition from the outlet chute to the stilling basin was more frequent for Sensor Fish passing through the 3.7-ft gate opening. Sensor Fish passing through the 1.5-ft gate opening experienced a greater percentage of events on the outlet chute and in the stilling basin, presumably due to a more shallow flow depth.

Sensor Fish were more likely to experience shear when passing through the 3.7-ft gate opening (Figure 3.4). Over 90 % of the Sensor Fish had collisions on the spillway chute, regardless of flow or release location.

Sensor Fish passing through the 1.5-ft gate opening had the highest significant event mean magnitude (150.9 *g*); sensors released through the 3.7-ft gate opening experienced an average magnitude of 135.9 *g*. Comparing multiple event values, the differences are small; the 1.5-ft gate opening experienced slightly higher magnitudes (124.9 *g*) than those observed from passage through the 3.7-ft gate opening (123.2 *g*).

Table 3.3. Location, frequency, and type of most severe significant event observed for Sensor Fish releases through the regulating outlet.

Gate Opening (ft)	Number of Releases	Number of Sensor Fish Having at Least 1 Event |a| > 95 *g*	Frequency of Occurrence of the Most Severe Collision or Strike Events by Location					Frequency of Occurrence of the Most Severe Shear Events by Location				
			At Gate	In RO Outlet	On Chute	Transition	In Stilling Basin/ Tailrace	At Gate	In RO Outlet	On Chute	Transition	In Stilling Basin/ Tailrace
1.5	19	18	0	0.06	0.78	0	0.11	0.06	0.00	0	0	0
3.7	16	16	0	0.19	0.63	0.06	0	0	0	0	0.0625	0.06

Gate Opening (ft)	Frequency of Occurrence of the Most Severe Events by Location (Shear and Collision)				
	At Gate	In RO Outlet	On Chute	Transition	In Stilling Basin/Tailrace
1.5	0.06	0.06	0.78	0	0.11
3.7	0	0.19	0.63	0.13	0.06

Table 3.4. Frequency of occurrence of all Sensor Fish significant events by event location and type.

Gate Opening (ft)	Number of Data Sets	No Event	Single Event	>1 Event	Total Number of Events	Average Number Events per Condition	Event Location and Type: Gate		Outlet		Chute		Transition		In Stilling Basin/ Tailrace	
							Collision/ Strike	Shear	Collision/ Strike	Shear	Collision/ Strike	Shear	Collision/ Strike	Shear	Collision/ Strike	Shear
1.5	19	1	0	18	85	4.47	0.01	0.01	0.13	0	0.74	0	0.04	0	0.07	0
3.7	16	0	4	12	51	3.19	0	0	0.20	0	0.65	0	0.10	0.04	0	0.02

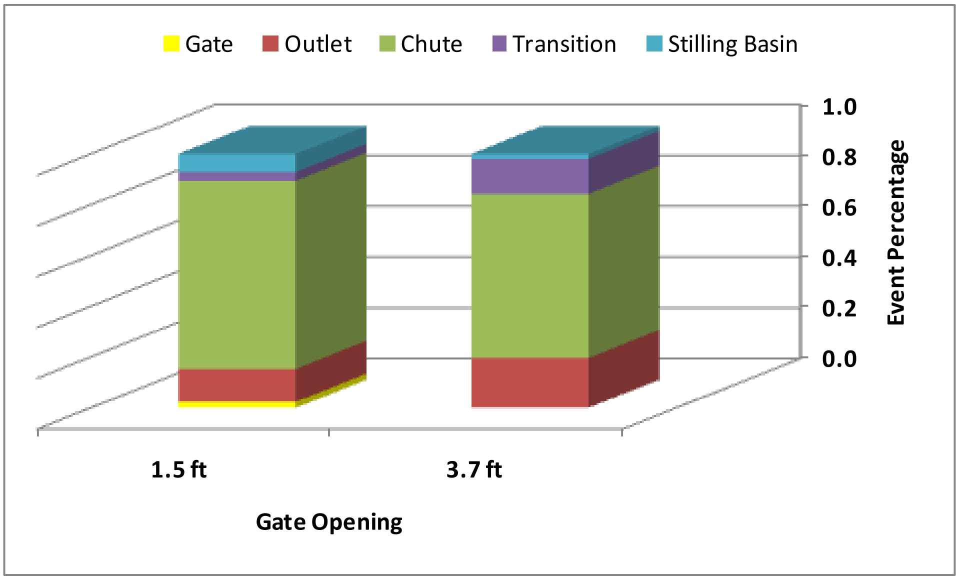


Figure 3.3. Location of all Sensor Fish significant events by passage region.

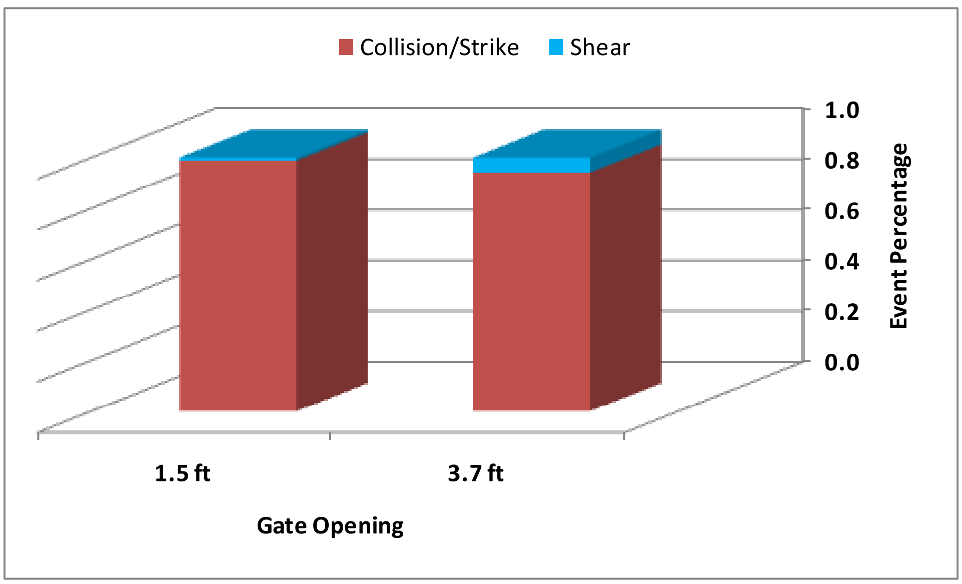


Figure 3.4. Sensor Fish significant event occurrence by type.

The mean acceleration magnitude values for the most severe event per release by event location are shown in Figure 3.5. The highest magnitude was observed for a shear event during Sensor Fish passage under the 1.5-ft gate opening. There were also high magnitude events at the transition of flow from the outlet chute to the stilling basin during passage through the 3.7-ft gate opening. Significant events on the outlet chute, especially at the 1.5-ft gate opening, were frequent due to depth of flow and the resultant distance from structure. The mean acceleration magnitude values for all Sensor Fish significant events by event location are shown in Figure 3.6.

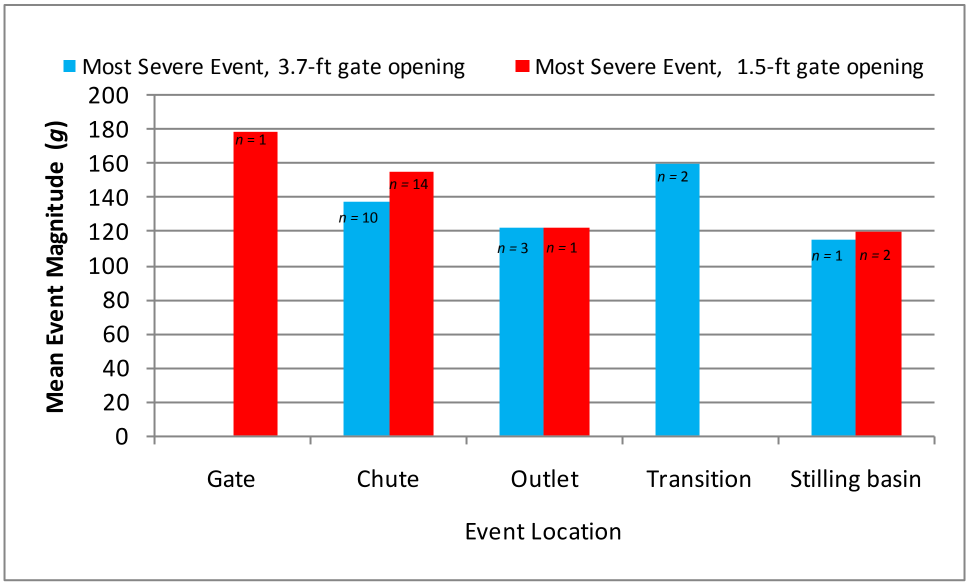


Figure 3.5. Location of the most severe significant events experienced by Sensor Fish during regulating outlet passage.

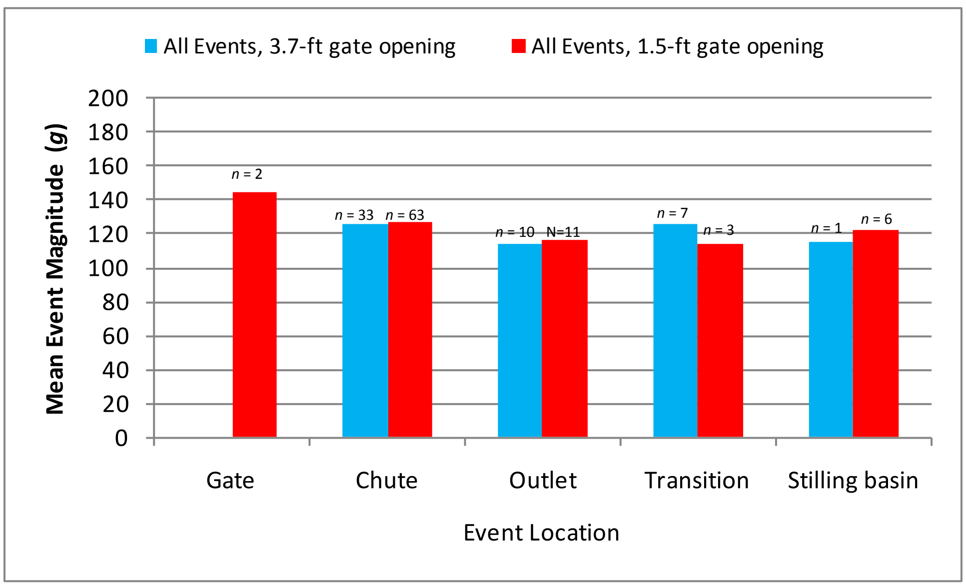


Figure 3.6. Location of all significant events experienced by Sensor Fish during regulating outlet passage.

As the Sensor Fish passes under the RO gate, acceleration increases and pressure decreases. Pressure rate of change under the gate was greatest for the 1.5-ft gate opening (−343.8 psia); rate of change for the 3.7-ft gate opening was −145.9 psia. Maximum acceleration magnitudes during gate passage averaged 30.9 *g* and 10.3 *g* for the 1.5-ft and 3.7-ft RO gate openings, respectively.

3.3.2 Turbine Passage

All Sensor Fish passing through the penstock into turbine unit 2 experienced at least one significant event; all but one experienced multiple events. No events were observed in the penstock. Nearly 24% of the Sensor Fish were damaged or lost during passage through the turbine.

Table 3.5 shows the number of successful Sensor Fish releases and the type and location of the most severe significant event. All of the most severe events occurred in the wicket gate–runner region of the turbine, with 50% of the events classified as shear at maximum and peak efficiency operations; at minimum flow operations, 25% were shear events. The total numbers of events experienced during penstock/turbine passage are summarized in Table 3.6. During maximum and peak efficiency operations, Sensor Fish experienced an average of three significant events per release; slightly fewer (2.8 significant events) occurred during minimum turbine flow operations.

Table 3.5. Sensor Fish turbine releases showing type of most severe significant event observed. All events occurred in the turbine runner region.

Turbine Wicket Gate Opening	Number of Releases	Number of Releases with Runner Data	Number of Sensor Fish Having at Least 1 Event |a| > 95 *g*	Frequency of Occurrence of the Most Severe Event by Type	
				Shear	Collision/Strike
Minimum	16	5	5	0.20	0.80
Maximum	14	4	4	0.50	0.50
Peak Efficiency	4	4	4	0.50	0.50

Table 3.6. Sensor Fish frequency of occurrence of multiple turbine runner events by type.

Turbine Wicket Gate Opening	Number of Data Sets	No Event	Single Event	>1 Event	Total Number of Events	Average Number Events per Condition	Event Type	
							Collision/ Strike	Shear
Minimum	5	0	0	5	14	2.8	0.57	0.43
Maximum	4	0	0	4	12	3	0.58	0.42
Peak Efficiency	4	0	1	3	9	3	0.44	0.56

The significant event magnitude values for the most severe event experienced by Sensor Fish during passage through turbine unit 2 were greatest for the maximum turbine wicket gate opening, averaging 166.2 *g*. Magnitudes were least for peak efficiency turbine passage, 140.3 *g*; mean magnitude for the minimum wicket gate opening was 143.2 *g*. Comparing these values to multiple events per condition, again the highest mean acceleration magnitude was for Sensor Fish passage during maximum load operations (137.5 *g*). Values for peak efficiency and minimum wicket gate openings were 127.8 *g* and 126.7 *g*, respectively.

A rapid pressure decrease occurs during passage through the turbine runner region as the sensor is carried with flow from the pressure to suction sides of the turbine runner. The lowest pressure (nadir) observed during turbine passage occurs as flow passes under the runner blade prior to draft tube entry. The lowest nadir occurred during maximum wicket gate opening, averaging 3.66 psia. Average nadir was highest during peak efficiency operations (9.31 psia); the minimum wicket gate opening averaged 8.74 psia (Figure 3.7).

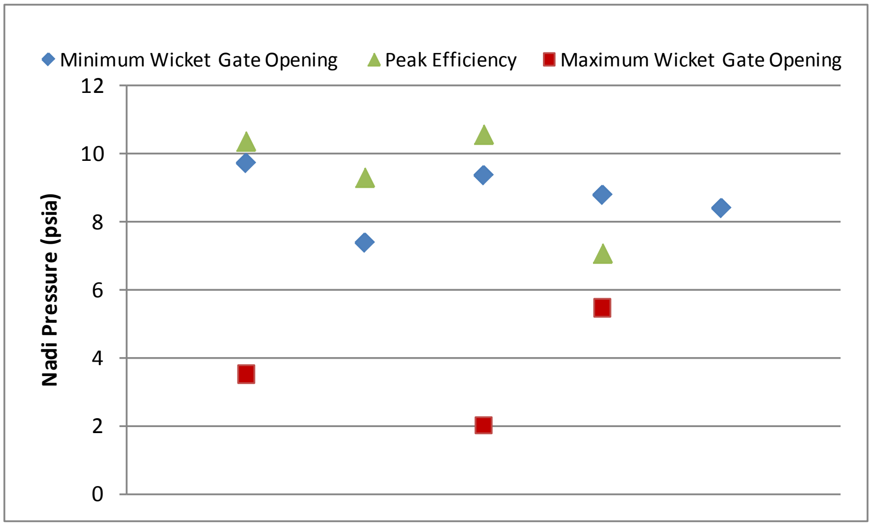


Figure 3.7. Nadir pressure observed during passage through turbine unit 2 as measured by Sensor Fish.

Pressure rate of change differences among turbine operation treatments were associated with turbine flow; i.e., the greater the discharge, the higher the observed pressure rate of change. The average pressure rate of change was greatest for high wicket gate opening releases (−1916.7 psia/s [maximum = −2297; minimum = −1637]). Pressure rate of change during peak efficiency operation was −1348.9 (maximum = –1666; minimum = −1041). Pressure rate of change during passage through the minimum wicket gate opening was −1126.8 (maximum = −1423; minimum = −803) (Figure 3.8). Rapid decompression has been shown to injure or kill fish acclimated to depth (Brown et al. 2007, 2009; Carlson et al. 2010).

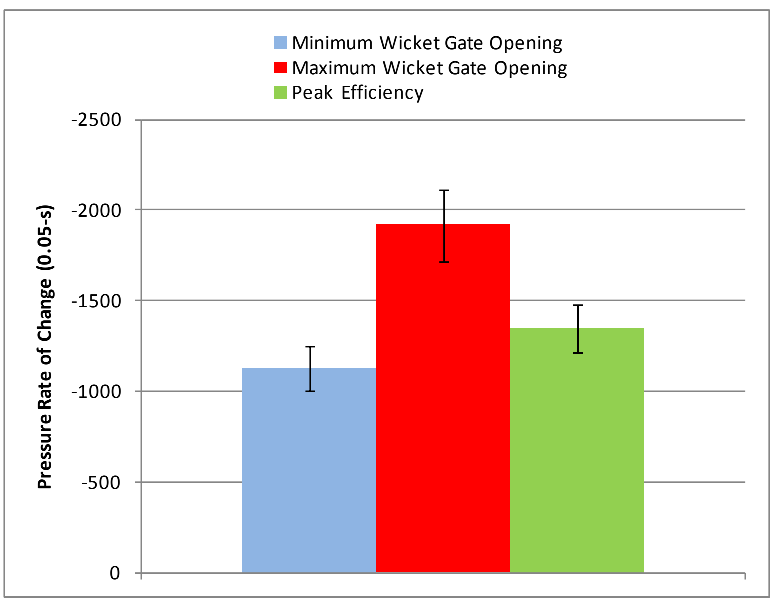


Figure 3.8. Average pressure rate of change for the three passage operations through Cougar Dam turbine unit 2. Error bars represent standard error of the mean.

3.4 Turbulence Index

The turbulence index as it is used here is a subjective measure developed by computing the area (integrating) under the acceleration magnitude and angular rate-of-change magnitude curves for a given period, with the premise that larger area equates to greater turbulence. A 50-s period following gate passage was used for RO passage, and 3 s (1 s prior to the runner nadir and 2 s subsequently) was the period applied for turbine passage. Each time segment encompasses the most turbulent passage interval for all passage treatments. Computed areas were normalized to seconds for evaluation purposes.

The turbulence index value for passage through turbine unit 2 at the minimum wicket gate opening is highest, followed by peak efficiency and maximum wicket gate openings (Table 3.7). Values may be biased due to extended time under the runner and/or in the draft tube region for caught or trapped Sensor Fish, possibly due to balloon inflation as a result of the prolonged penstock route or eddy current entrapment. Eighty percent of the Sensor Fish were caught during the minimum wicket gate opening and 25% during peak efficiency operations. The extent of time trapped varied from approximately 0.5 s to 6 s for the minimum flow and was approximately 1 s for the optimal efficiency flow. Increased turbulence was associated with the ensnared Sensor Fish, indicating that the unit was not in a locked position but was moving in the flow. Using only "standard" passage values (i.e., passage without entrapment) indicates flows with the maximum wicket gate opening were most turbulent, followed by the minimum wicket gate opening and peak efficiency flows.

Table 3.7. Computed area under the curve for angular rate-of-change and acceleration magnitudes per second (turbulence index).

Passage Route and Condition	Area – Acceleration Magnitude per Second	Area – Angular Rate-of-Change Magnitude per Second	Combined Area per Second
RO – 1.5-ft gate opening	1.94	676.00	677.93
RO – 3.7-ft gate opening	2.08	695.70	697.78
Turbine Unit 2 – Maximum	6.01	870.99	876.99
Turbine Unit 2 – Minimum[(a)]	11.05	1187.16	1198.22
Turbine Unit 2 – Minimum[(b)]	6.15	853.22	859.37
Turbine Unit 2 – Peak Efficiency[(a)]	6.85	972.79	979.64
Turbine Unit 2 – Peak Efficiency[(b)]	5.56	810.49	816.06

(a) Includes two sensor units caught under runner/draft tube.
(b) Excludes two sensor units caught under runner/draft tube.

Regulating outlet turbulence index values were lower than those obtained during turbine runner passage. Passage through the 3.7-ft gate opening had a slightly higher turbulence index than that for the 1.5-ft gate opening.

3.5 Comparison of Sensor Fish and Live-Fish Data

Live-fish HI-Z–tag studies were conducted by Normandeau Associates, Inc. concurrently with the Sensor Fish studies at Cougar Dam. Normandeau scientists released live fish through the same injection systems as the Sensor Fish, under the same test conditions. Sensor Fish releases were interspersed with live-fish releases.

A total of 398 juvenile spring Chinook salmon and 39 Sensor Fish were released during the RO evaluation at Cougar Dam in December 2009. Table 3.8 shows fish release and recapture rates, estimated survival rate, and malady-free rate for live fish (Normandeau 2010). In January 2010, 468 juvenile spring Chinook salmon and 34 Sensor Fish were released through the penstock into turbine unit 2 (Table 3.9).

For comparison with Sensor Fish magnitudes, the reciprocal of the malady-free rate is reported as the injury or malady rate; the reciprocal of survival is reported as mortality. Figure 3.9 shows live-fish malady and mortality rates along with the Sensor Fish average significant event magnitudes (± standard error of the mean) for all passage routes. Figure 3.10 illustrates live-fish mortality and malady estimates contrasted with the Sensor Fish turbulence index.

Normandeau (2010) also evaluated direct survival and malady-free estimates for larger fish (greater than or equal to 160 mm [6.3 in.] in length) and smaller fish (less than 160 mm) (Table 3.10). Both survival and malady-free estimates were significantly less for larger fish, especially at the 1.5-ft gate opening.

Comparisons of Sensor Fish adjusted turbulence index data to 48-hr mortality and malady estimates based on length of fish are shown in Figure 3.11 and Figure 3.12, respectively. While one would expect data from the 90-mm-long Sensor Fish to correspond more closely with data from live fish less than 160 mm long, the mass of the Sensor Fish may contribute to any discrepancy. The Sensor Fish weighs approximately 43 g. Estimated weight for Chinook salmon less than 160 mm in length is less than 32 g; fish as long as 230 mm could weigh over 50 g.

Table 3.8. Survival and malady-free rates for spring Chinook passage through the regulating outlet at Cougar Dam, December 2009.

	Regulating Outlet			
Gate Opening	1.5 ft	3.7 ft	Combined	Controls
Number released	156	163	319	79
Number recaptured alive	143	151	294	79
	(0.917)	(0.926)	(0.922)	(1.000)
Number recaptured dead	6	0	6	0
	(0.038)	(0.000)	(0.019)	(0.000)
Number assigned dead[(a)]	7	12	19	0
	(0.045)	(0.074)	(0.060)	(0.000)
Dislodged tags	4	11	15	0
	(0.026)	(0.067)	(0.047)	(0.000)
Stationary radio signals	3	1	4	0
	(0.019)	(0.006)	(0.013)	(0.000)
Number undetermined	0	0	0	0
	(0.000)	(0.000)	(0.000)	(0.000)
Number held	143	151	294	79
1-hr survival rate[(b)]	0.917	0.926	0.922	
SE	0.022	0.021	0.015	
95% confidence interval (±)	0.043	0.041	0.029	
Number alive after 48 hr	132	144	276	78
Number died in holding	11	7	18	1
48 hr survival rate[(b)]	0.846	0.883	0.876	
SE	0.029	0.025	0.022	
95% confidence interval (±)	0.057	0.049	0.044	
Number examined for maladies	149	151	300	79
	(0.955)	(0.926)	(0.940)	(1.00)
Number with passage-related maladies	31	32	63	2
	(0.208)	(0.212)	(0.210)	(0.025)
Visible injuries	28	31	59	2
	(0.188)	(0.205)	(0.197)	(0.025)
Loss of equilibrium only	3	1	4	0
	(0.020)	(0.007)	(0.013)	(0.000)
Scale loss only	0	0	0	0
	(0.000)	(0.000)	(0.000)	(0.000)
Number without passage-related maladies	118	119	237	77
	(0.792)	(0.788)	(0.790)	(0.975)
Without passage-related maladies that died	0	0	0	0
Malady-free rate[(b)]	0.813	0.809	0.811	
Standard error	0.037	0.037	0.028	
95% confidence interval (±)	0.073	0.073	0.055	

(a) Includes dislodged tags and stationary signals.
(b) Survival rates not significantly different ($P < 0.10$).

Table 3.9. Survival and malady-free rates for spring Chinook passage through the turbine at Cougar Dam, January 2010.

	Turbine Unit 2				
Operation Level	Minimum	Peak	Maximum	Combined	Controls
Number released	169	40	170	379	89
Number recaptured alive	111 (0.657)	25 (0.625)	99 (0.582)	235 (0.620)	89 (1.000)
Number recaptured dead	27 (0.160)	7 (0.175)	49 (0.288)	83 (0.219)	0 (0.000)
Number assigned dead[a]	31 (0.183)	8 (0.200)	22 (0.129)	61 (0.161)	0 (0.000)
Dislodged tags	26 (0.154)	8 (0.200)	21 (0.124)	55 (0.145)	0 (0.000)
Stationary radio signals	5 (0.030)	0 (0.000)	1 (0.006)	6 (0.016)	0 (0.000)
Number undetermined	0 (0.000)	0 (0.000)	0 (0.000)	0 (0.000)	0 (0.000)
Number held	111	25	99	235	89
1-hr survival rate[b]	0.657	0.625	0.582	0.620	
SE	0.037	0.077	0.038	0.025	
95% confidence interval (±)	0.073	0.151	0.074	0.073	
Number alive after 48 hr	58	14	68	140	84
Number died in holding	53	11	31	95	5
48-hr survival rate[b]	0.364	0.371	0.424	0.391	
SE	0.040	0.081	0.041	0.028	
95% confidence interval (±)	0.078	0.159	0.080	0.055	
Number examined for maladies	138 (0.817)	32 (0.800)	148 (0.871)	318 (0.839)	89 (1.000)
Number with passage-related maladies	90 (0.652)	23 (0.719)	99 (0.669)	212 (0.667)	2 (0.022)
Visible injuries	76 (0.551)	18 (0.563)	81 (0.547)	175 (0.550)	1 (0.011)
Loss of equilibrium only	14 (0.101)	5 (0.156)	18 (0.122)	37 (0.116)	1 (0.011)
Scale loss only	0	0	0	0	0
Number without passage-related maladies	48 (0.348)	9 (0.281)	49 (0.331)	106 (0.333)	87 (0.978)
Without passage-related maladies that died	15 (0.109)	3 (0.094)	8 (0.054)	26 (0.082)	3 (0.034)
Malady-free rate[b]	0.356	0.288	0.339	0.341	
Standard error	0.042	0.081	0.040	0.028	
95% confidence interval (±)	0.082	0.159	0.078	0.054	

(a) Includes dislodged tags and stationary signals.
(b) Survival rates not significantly different ($P < 0.10$).

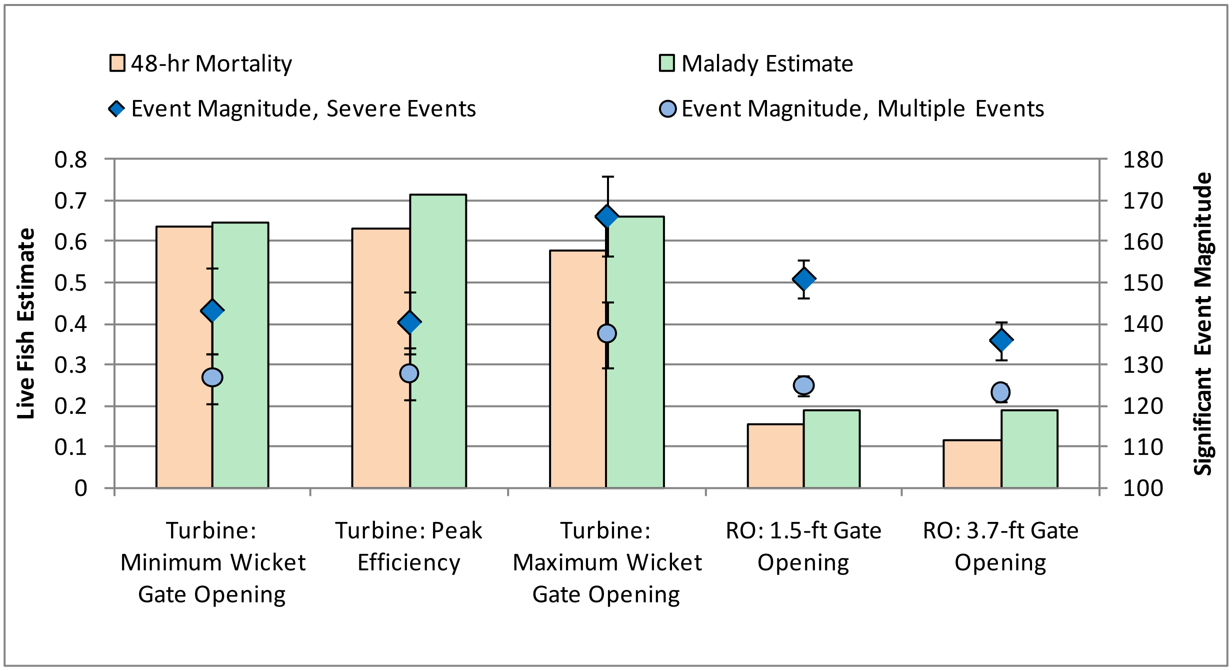


Figure 3.9. Live-fish mortality and malady estimates contrasted with Sensor Fish significant event magnitudes (±standard error of the mean).

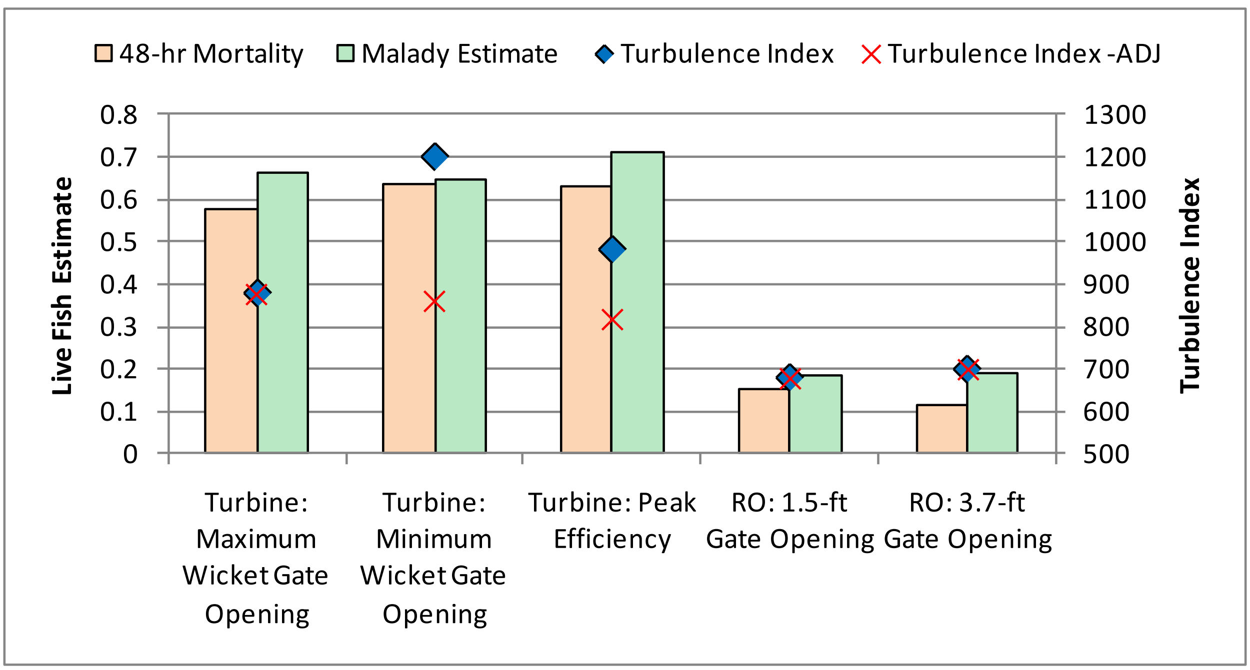
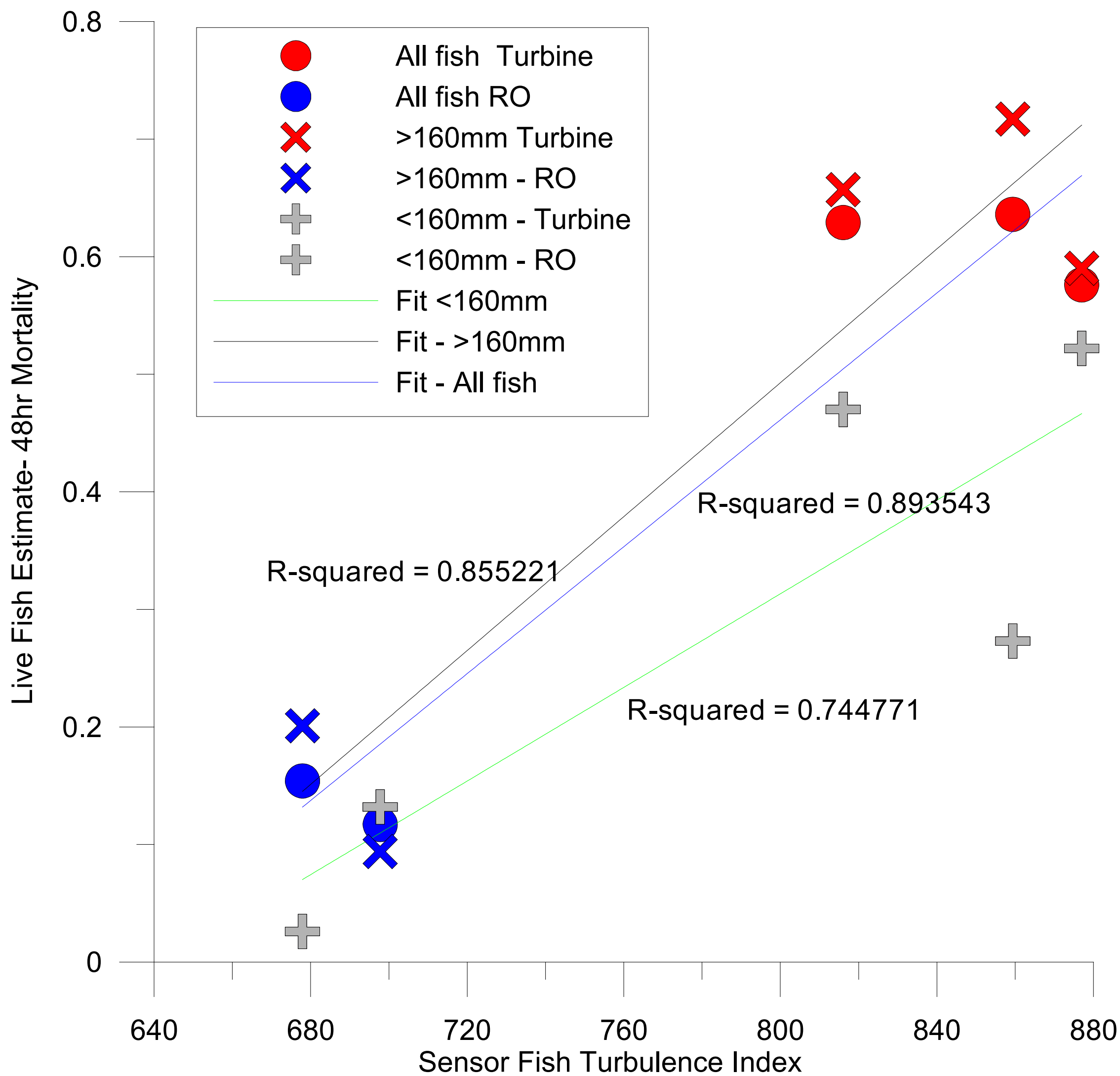


Figure 3.10. Live-fish mortality and malady estimates contrasted with the Sensor Fish turbulence index.

Table 3.10. Comparison of fish length versus 48-hr survival and malady-free estimates (Normandeau 2010).

Operation Level	Fish Size	48-hr Survival	Malady-Free Rate
Minimum	<160 mm	0.727	0.660
	≥160 mm	0.283	0.282
Peak	<160 mm	0.530	0.205
	≥160 mm	0.343	0.303
Maximum	<160 mm	0.478	0.500
	≥160 mm	0.410	0.280
Gate Opening			
1.5 ft	<160 mm	0.974	0.908
	≥160 mm	0.799	0.762
3.7 ft	<160 mm	0.868	0.787
	≥160 mm	0.906	0.817

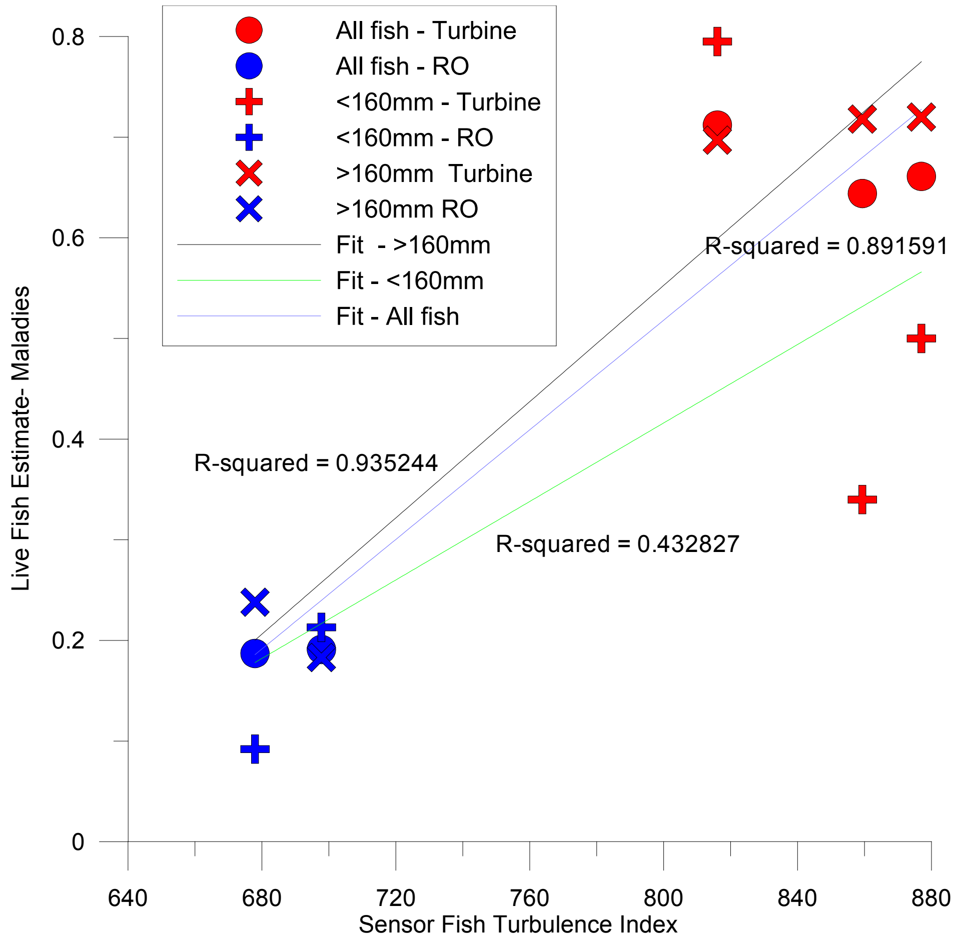


Turbulence Index (Adj) Vs. 48-Hr Mortality <160mm
(green line)
Y = 0.001990538814 * X - 1.279219046
R-squared = 0.744771

Turbulence Index (Adj) Vs. 48-Hr Mortality >160mm
(black line)
Y = 0.002846843478 * X - 1.784754255
R-squared = 0.855221

Turbulence Index (Adj) Vs. 48-Hr Mortality (blue line)
Y = 0.002698042879 * X - 1.697252635
R-squared = 0.893543

Figure 3.11. Fit of linear model between live-fish estimated 48-hr mortality rate and Sensor Fish turbulence index based on length.



Turbulence Index (Adj) Vs. Malady Estimate <160mm
(black line)
Y = 0.002886969631 * X - 1.756878404
R-squared = 0.935244

Turbulence Index (Adj) Vs. Malady Estimate <160mm
(green line)
Y = 0.001949348981 * X - 1.143459242
R-squared = 0.432827

Turbulence Index (Adj) Vs. Malady Estimate (blue line)
Y = 0.002722357063 * X - 1.65975449
R-squared = 0.891591

Figure 3.12. Fit of linear model between live-fish estimated malady rate and Sensor Fish turbulence index based on length.

4.0 Discussion

The objective of this study was to describe and compare passage exposure conditions through the RO and turbine at Cougar Dam using Sensor Fish to identify regions that may potentially cause fish injury or mortality.

4.1 Regulating Outlet Passage

Sensor Fish were used to evaluate the RO at two gate openings, 1.5 ft and 3.7 ft, corresponding to discharge flow rates of 440 cfs and 1040 cfs, respectively, at an approximate forebay elevation of 1533 ft MSL. The RO is a gravity-fed passageway controlled by a hydraulic gate. The 1000-ft-long passageway runs through the dam and rock formations before exiting down a concrete chute with guidewalls into a concrete-enclosed stilling basin (Figure 4.1). The velocity of the RO discharge jet at entry into the stilling basin was estimated to be approximately 125 fps.

Figure 4.1. Regulating outlet flow discharge exits down a concrete chute into the stilling basin.

All Sensor Fish passing through the RO at the 3.7-ft gate opening experienced at least one significant event. One Sensor Fish experienced no event during passage at the 1.5-ft gate opening; the others experienced multiple events per release. The highest-magnitude events (150.9 *g*) were observed at the lower gate opening, and more Sensor Fish were damaged during passage at this treatment (42.9% vs. 12.5% for the higher gate opening).

During passage at the 1.5-ft gate opening, one Sensor Fish experienced a significant shear event; a second had a collision with the gate. None of the Sensor Fish passing through the 3.7-ft gate opening collided with the gate or experienced significant shear during passage under the gate. The average acceleration magnitude of the Sensor Fish during passage under the control gate at an opening of 1.5 ft was nearly 3 times that observed during passage when the gate was open 3.7 ft. At least one Sensor Fish was caught behind the gate during passage at the 1.5-ft gate opening (Figure 4.2). More than 12 s were required for the trapped Sensor Fish to pass from the pipe exit to the gate, compared to an average time of less than 6 s.

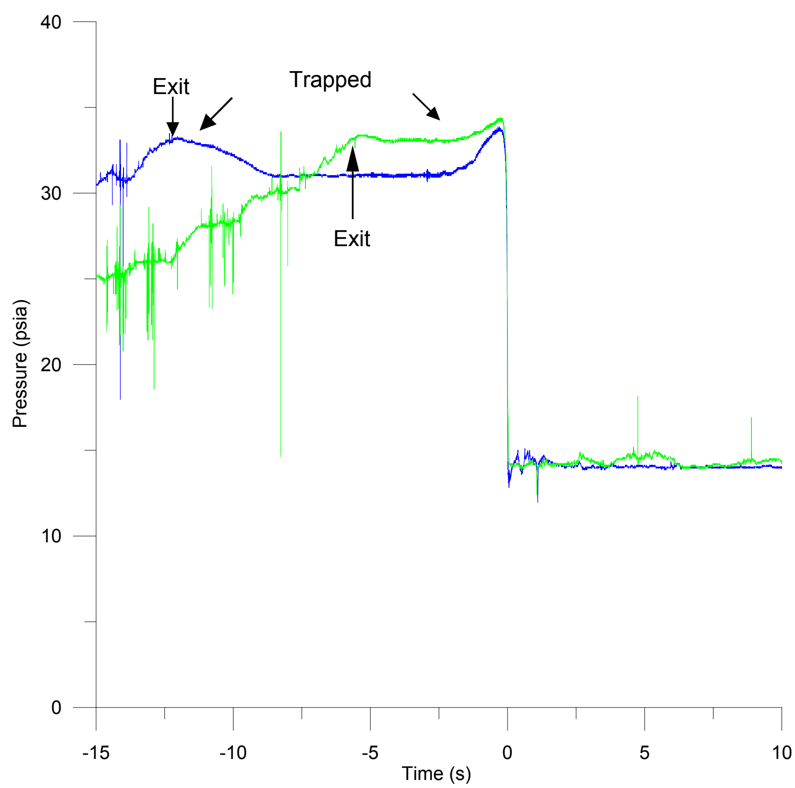


Figure 4.2. Pressure time histories for two Sensor Fish from injection pipe exit to regulating outlet passageway showing one sensor trapped prior to the gate at the 1.5-ft gate opening.

The route through the RO passageway was similar for both gate openings, with approximately 45% of the Sensor Fish experiencing at least one significant event. Event magnitudes for this region were also similar, averaging approximately 116 *g*. The majority of all observed events were collisions on the RO chute; significant event magnitude averaged approximately 126 *g* for both gate openings. A greater percentage of significant events (44%) occurred following passage through the 3.7-ft gate opening than the 1.5-ft gate opening (16%) in the transition region from the RO chute to the stilling basin; average event magnitude was also greater (126.2 *g* versus 113.8 *g* for the 3.7-ft and 1.5-ft gate openings, respectively). Approximately 29% of the significant events observed in the transition region following passage through the 3.7-ft gate opening were shear; no shear was observed in this region after passage through the 1.5-ft gate opening. Collisions in the stilling basin were more frequent following passage through the 1.5-ft gate opening; there were no significant event collisions in the stilling basin after 3.7-ft gate passage and only one shear event.

The pressure reported by Sensor Fish decreased rapidly to near atmospheric following passage under the RO gate for both the 1.5-ft and 3.7-ft gate openings. Pressure rate of change during passage under the RO gate averaged −343.8 psia/s for Sensor Fish at the 1.5-ft gate opening; at the 3.7-ft gate opening, pressure rate of change averaged −145.9 psia/s. Observed differences are an indication of the change in acceleration as the flow passes under the gate at the two openings and are a function of operational head. Values observed at Cougar Dam are considerably less than those observed during RO passage through a 1-ft opening at Detroit Dam (−945.5 psia/s) but comparable to that observed through the Detroit 5-ft gate opening (−271.7 psia/s) (Duncan and Carlson 2011). The operational head during the Cougar RO evaluation was 280 ft; the Detroit Dam RO evaluation operational head was approximately 239 ft. However, the pressure behind the respective gates would have been much greater at Detroit, as the head behind the gate was approximately 98 ft; the head behind the Cougar RO gate was approximately 45 ft. This 53-ft difference would translate into an additional 23 psi pressure based on water depth. The gate opening at Detroit was 6 in. lower, and flow was 20 cfs greater than that at Cougar.

A linear model fit to the live-fish 48-hr mortality estimates and Sensor Fish turbulence index values for turbine passage at Cougar and Detroit dams based on fish length showed that for operating conditions tested, the turbulence index is a fairly good predictor for 48-hr mortality for fish less than 160 mm in length (Figure 4.3).

The RO is usually used to aid in temperature control when the forebay levels are higher. During the RO study, head was approximately 280 ft, which is typical of conditions during winter drawdown of the dam reservoir. During the spring and summer when the dam reservoir would be nearly full, the RO operating head could be as high as 448 ft. It is likely that fish passage conditions would deteriorate at all gate openings, particularly small gate openings, over those observed in this study as RO operating head increases.

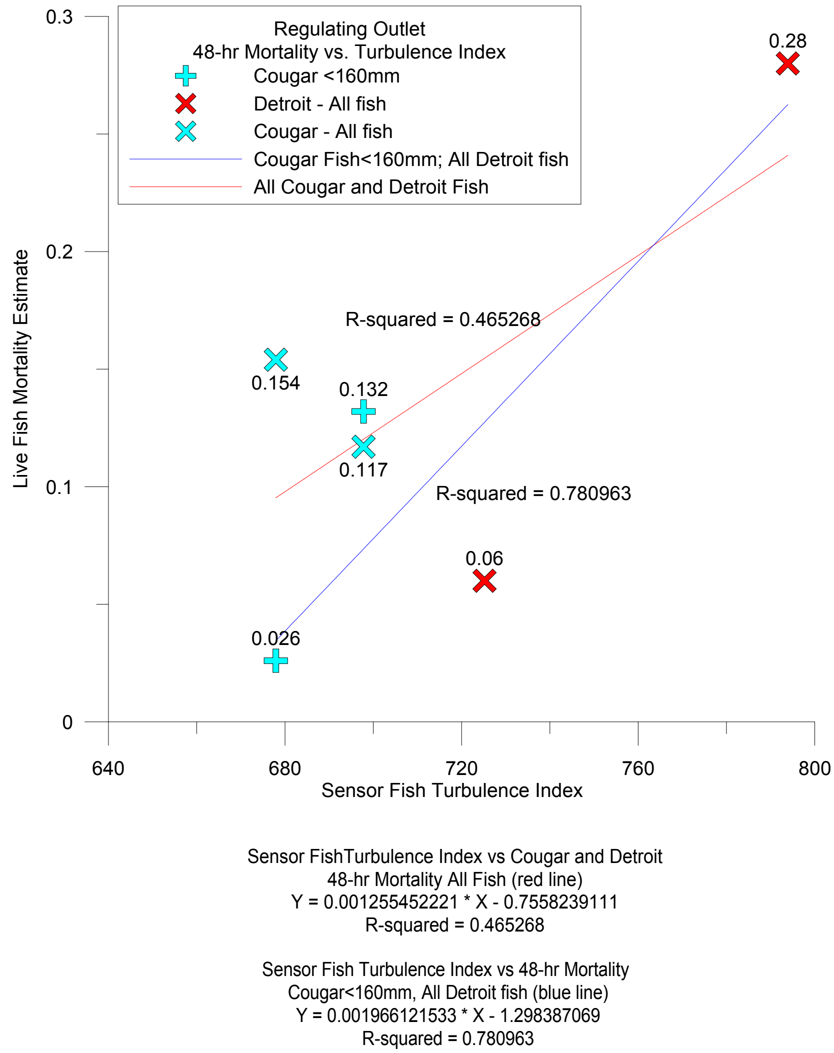


Figure 4.3. Fit of linear model between live fish estimated 48-hr mortality and Sensor Fish turbulence index for Cougar and Detroit regulating outlet evaluations based on fish length.

4.2 Penstock/Turbine Passage

Exposure to changes in pressure, shear, turbulence, collisions, strike, cavitation, and grinding may occur during turbine passage and can cause injuries and mortality to fish. Fish are most vulnerable during passage through the wicket gates and runner, where they may collide on structure, be struck by runner blades, exposed to rapid changes in pressure, and exposed to turbulence and shear in the wake of wicket gates and runner blades. All Sensor Fish experienced at least one significant event during runner passage; all but one experienced multiple events per release. No significant events were observed during penstock passage or in the draft tube. Highest significant magnitude events were observed during passage at maximum wicket gate opening (166.2 *g*), followed by minimum wicket gate opening (143.2 *g*) and peak efficiency operation (140.3 *g*). Nearly 43% of the maximum wicket gate opening treatment sensors, 12.5% of those for the minimum wicket gate opening treatment, and none of those for the peak efficiency wicket gate opening treatment were either damaged or lost during turbine transit.

Transport time through the penstock into the turbine was longer than observed at other projects—more than 6 min for minimum wicket gate opening flows, approximately 5 min for peak efficiency flows, and over 4 min for maximum wicket gate opening flows. HI-Z balloon tags typically begin inflation approximately 4 min after injection. During the low-flow treatment scenario, 80% of the Sensor Fish were observed to be "caught" either under the runner or at the draft tube entrance. These fish were apparently temporarily hung up in an eddy area or became caught on some structure within the passage region prior to draft tube exit (Figure 4.4). Data indicate that the Sensor Fish did not become stationary but were in motion. This phenomenon was also observed in 25% of the peak efficiency treatment but for a shorter time increment. Inflation of the HI-Z tags likely contributed to this period of entrapment and could potentially contribute to injury and/or mortality if fish are exposed to high extreme flows or collide repeatedly with structure while caught. Figure 4.5 shows typical passage for comparison.

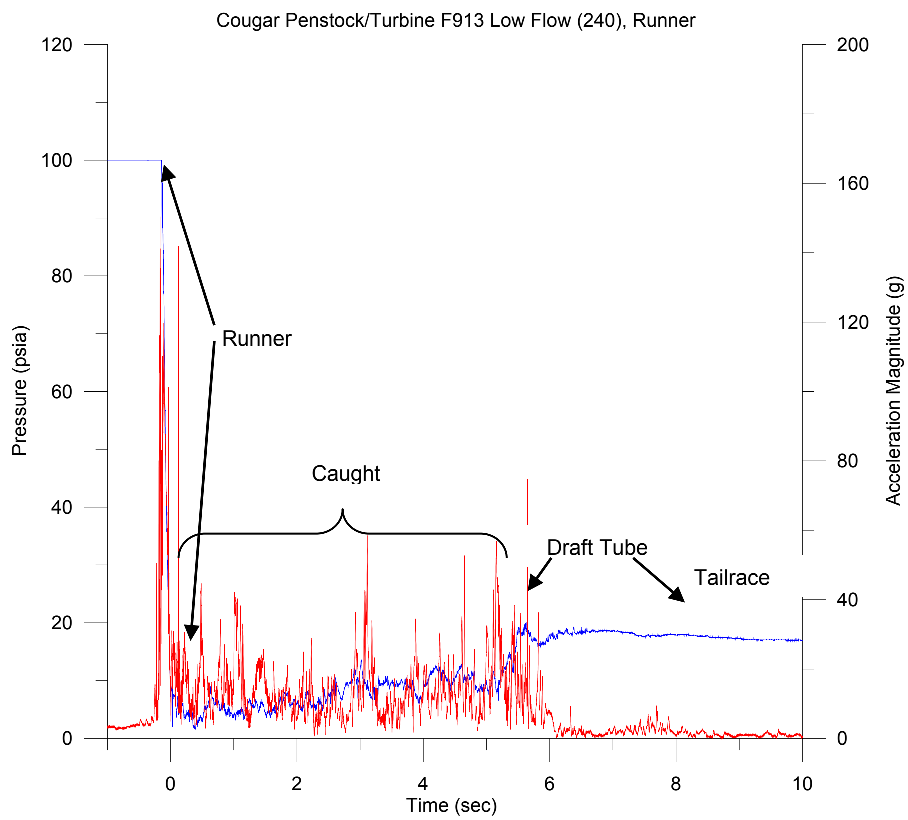


Figure 4.4. Pressure and acceleration magnitude time histories for passage through the runner, draft tube, and into the tailrace. Sensor Fish were caught under the runner for more than 5 s.

The Francis turbine at Cougar Dam operates at 22,100 horsepower and 400 revolutions per minute. The runner diameter is 72 in., and the runner opening height is 13 in. Maximum discharge is 550 cfs, and there are 13 blades and 24 wicket gates. Turbines at Cougar Dam operate almost daily, based on Bonneville Power Administration load demands. During the summer, water depth above the penstocks is approximately 270 ft. Winter drawdown lowers the submergence of the penstock to approximately 115 ft. The submergence depth of the penstock influences the probability of fish entry into the turbines.

Computational fluid dynamics analyses of turbine unit 2 were conducted to evaluate the test conditions examined at Cougar Dam during January 2010. The stay vane–to–wicket gate region of the turbine was modeled to determine the effects of the different operating conditions using a 288-ft operating head. Areas of shear, high velocity, and pressure were evaluated, as well as areas of strike in the stay vane to wicket gate region (Keil 2010). At low operating flows (340 fps) with a wicket gate opening of 13.5 degrees, the maximum wicket gate spacing was determined to be 3.22 in., corresponding to the area between the leading edge of one wicket gate to the trailing edge of the adjacent gate, producing a greater possibility of strike along the leading edge of the stay vane or on the wicket gate. At maximum operating flows for 288 ft of head (540 fps), the wicket gates are open approximately 23 degrees and the maximum wicket gate spacing is 4.96 in. With increased head (greater than 300 ft), the wicket gates can be opened to their maximum opening of 28 degrees.

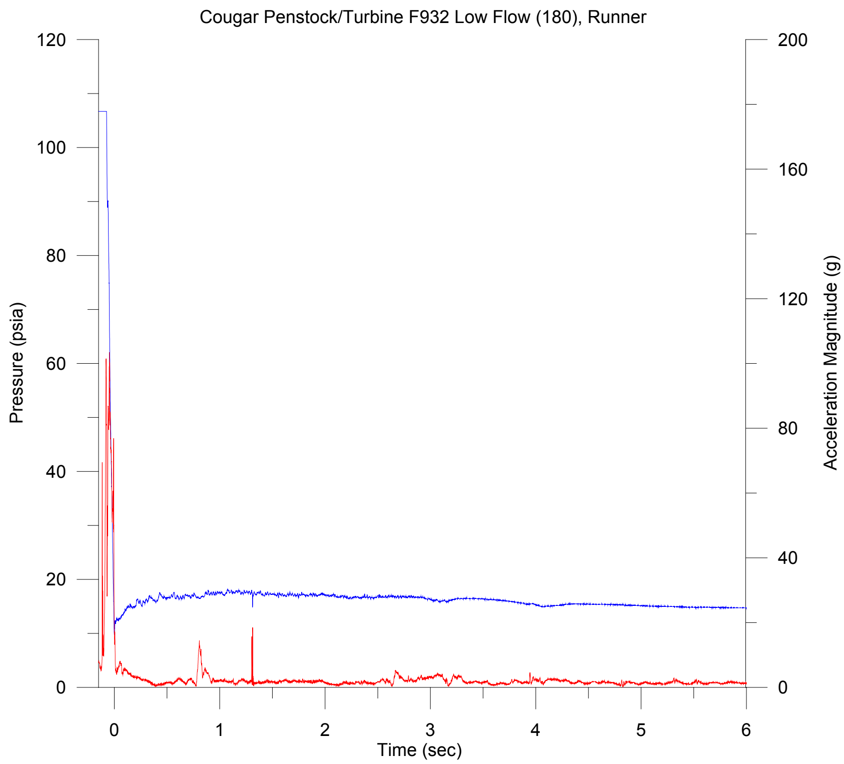


Figure 4.5. Pressure and acceleration magnitude time histories for typical passage through the runner, draft tube, and into the tailrace.

During turbine operations with the minimum wicket gate opening, Sensor Fish were more likely to experience a collision or strike event; 80% of the most severe significant events were of this type. During maximum and peak efficiency operations, significant shear events were more prevalent (50%). The Sensor Fish measures 3.54 in. and would be expected to collide with or be struck by a wicket gate or stay vane during minimum load operations (low operating flows), as the maximum wicket gate opening is 3.22 in.

The probability of a fish being struck by a turbine runner blade (bucket) during passage through one of the Francis turbines at Cougar Dam was estimated as a function of fish length. The method used by Deng et al. (2007b) to estimate the probability of blade-strike for fish passing through Kaplan turbines was adapted for Francis turbines to account for the entry of fish into the turbine runner at the periphery of the runner rather than along the blade from hub to tip. As is the case for Kaplan runners, it was expected that the probability of strike during runner passage would be a function of the attitude of the fish in the pitch plane relative to the horizontal plane passing through the centerline of the turbine distributor.

Two pitch ranges, 0° to ±22.5° and 0° to ±45°, and two turbine discharges, 340 cfs and 550 cfs, were modeled. The pitch range distributions were assumed to be uniform. The analysis model was stochastic and was performed using @RISK[1] spreadsheet overlay software. The discharges modeled were the lowest and highest evaluated during the Sensor Fish and live-fish study.

The estimates of probability of blade strike for fish over the size range from 5 to 300 mm for the two discharges, and pitch angle ranges are shown in Figure 4.6 and Table 4.1. As expected, the probability of blade strike increased with fish size, with a greater rate of increase for the lower discharge and for the 0° to ±22.5° pitch range. Because the radial velocity of the runner is constant with discharge, at higher discharge the fish are carried with flow more rapidly into the runner past the periphery of the runner blades, therefore experiencing a lesser probability of blade strike. The lower probability of blade strike with increasing pitch range results from the shorter effective length of fish (the projection of the fish length onto the horizontal axis) as pitch angle increases.

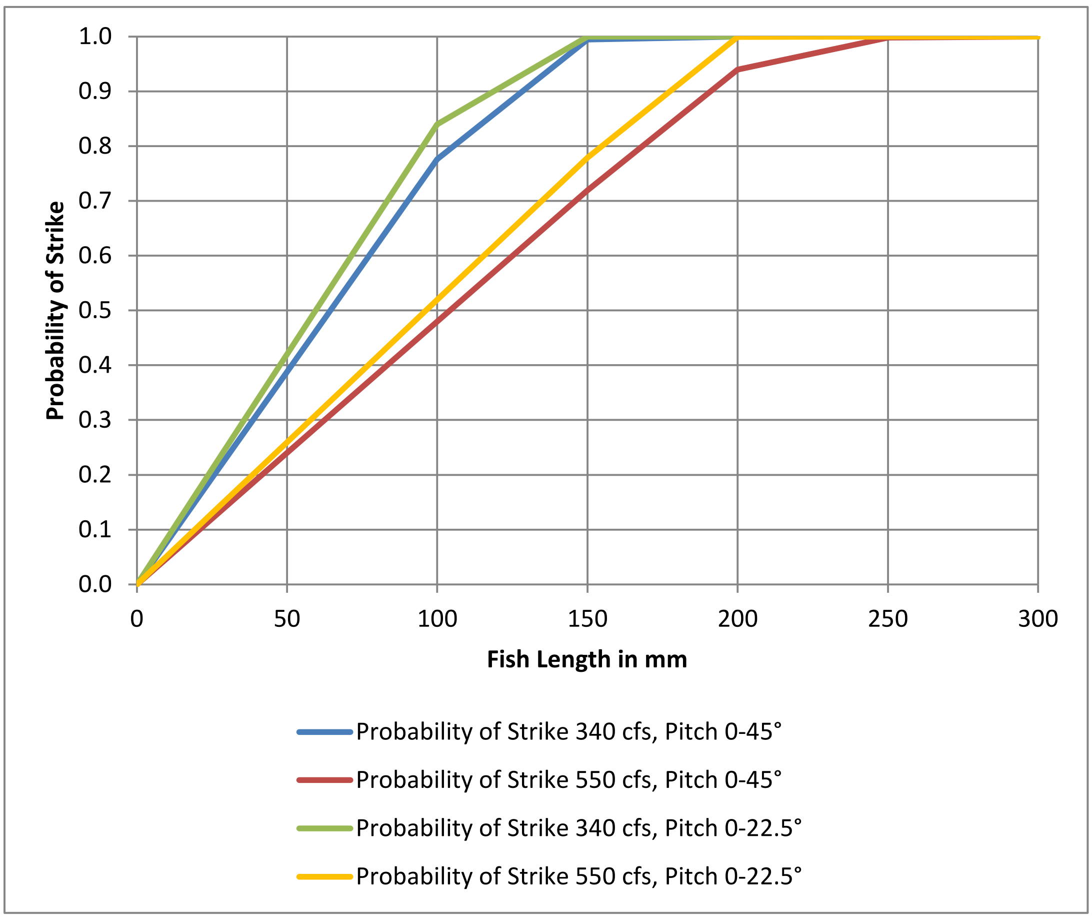


Figure 4.6. Probability of blade strike based on fish length, discharge, and blade pitch.

[1] Palisade Corporation, Ithaca, New York.

Table 4.1. Probability of blade strike for fish ranging from 0 to 300 mm in length at two discharges and two blade pitch angles.

	Discharge, 340 cfs		Discharge, 550 cfs		Discharge, 340 cfs		Discharge, 550 cfs	
Fish Length (mm)	Probability of Strike (340 cfs, Pitch 0–45º)	Standard Deviation	Probability of Strike (550 cfs, Pitch 0–45º)	Standard Deviation	Probability of Strike (340 cfs, Pitch 0–22.5º)	Standard Deviation	Probability of Strike (550 cfs, Pitch 0–22.5º)	Standard Deviation
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0388	0.0038	0.0240	0.0023	0.0420	0.0010	0.0260	0.0006
10	0.0776	0.0076	0.0480	0.0047	0.0840	0.0020	0.0519	0.0012
25	0.1940	0.0190	0.1199	0.0117	0.2099	0.0049	0.1298	0.0030
50	0.3879	0.0379	0.2398	0.0234	0.4199	0.0098	0.2596	0.0061
100	0.7759	0.0758	0.4796	0.0469	0.8398	0.0196	0.5191	0.0121
150	0.9947	0.0166	0.7194	0.0703	1.0000	0.0000	0.7787	0.0182
200	1.0000	0.0000	0.9397	0.0761	1.0000	0.0000	0.9992	0.0028
250	1.0000	0.0000	0.9977	0.0092	1.0000	0.0000	1.0000	0.0000
300	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000

The model results indicate that for equivalent pitch angle ranges, fish are less likely to experience blade-strike at higher discharge. However, because of the size, operating characteristics, and design features of the Cougar Dam Francis turbines, it is unlikely that fish greater than 150 mm can pass without being struck at low discharge and greater than 200 mm at high discharge.

Bull trout were listed as a threatened species under the *Endangered Species Act of 1973* in 1999 (64 FR 17110–17125). In September 2010, the McKenzie River and Cougar Reservoir were designated as bull trout critical habitat,[1] providing regulatory protection to the geographic areas essential for the conservation the species. Bull trout sub-adults range in size from approximately 250 to 400 mm in length; adults are generally greater than 400 mm in length. The fish evaluated during the current studies were Chinook salmon, ranging from 124 to 230 mm in length. Passage conditions through the turbine for larger fish, including bull trout, would likely be worse, as the probability of blade strike would be greater.

The live balloon-tagged fish released into the RO and turbine at Cougar Dam were not pressure-acclimated. Because of the nature of the balloon-tagging process and handling requirements at placement into injection systems, test fish could not be released in a natural state of neutral buoyancy. Research has clearly shown that physostomous juvenile salmon that are not neutrally buoyant when exposed to rapid decompression do not show the same barotrauma injury and mortality response as fish exposed when in a neutrally buoyant physiological condition (Brown et al. 2009). Therefore, any method that cannot ensure acclimation to depth (pressure) prior to exposure to rapid decompression does not test the response of the fish to the change in pressure that all turbine passed fish experience. We now know that the barotrauma response of juvenile salmon to rapid decompression is a function of species, size, and age, as well as turbine design, operation parameters, and passage location. Given this information, it is clear that the mortality and malady rates reported for live test fish following passage through Cougar Dam Francis turbines are underestimated and underreport the rates that are likely for acclimated fish that pass through these units. A similar concern is warranted for RO passage, given the rapid changes in pressure observed at control gate passage. However, mortality and malady rates attributable to pressure effects would be less than those for the Francis turbine units because the nadir values are approximately atmospheric, 14.7 psia, compared to the much lower nadir values for turbine passage.

The lowest pressure (nadir) that occurs in the water path from the penstock entrance through draft tube exit occurs on the underside of turbine runner blades, which is called the suction side of the turbine runner. The mean of nadir pressures observed for Sensor Fish passage through the Francis turbine at all operating conditions was 7.66 psia; pressures were lowest for the high flow (ranging from 2.0 to 5.5 psia; mean value 3.7 psia). The observed nadir values for the Cougar Dam Francis turbine are much lower than those observed for Kaplan turbines installed in the mainstem Columbia and Snake river dams. Mainstem Kaplan turbine mean nadir pressures ranged from approximately 14 to 27 psia depending upon variables such as discharge and trajectory through the turbine runner (Carlson and Duncan 2002; Dauble et al. 2007; Carlson et al. 2008). Table 4.2 shows nadir values obtained at low-head dams on the Columbia and Snake rivers along with those observed during the Cougar study.

Using Sensor Fish, the mean rate of change in pressure for all treatments through the Cougar Dam Francis turbine was –1398.3 psia/s, observed at approach to the nadir. The mean rate of change in pressure was greatest for passage during the largest wicket gate opening (−1916.7 psia/s); lowest rate of change was observed at the minimum wicket gate opening (−1126.8 psia/s). These values are much

[1] http://www.fws.gov/pacific/bulltrout/CriticalHabitat.html.

higher than those observed for passage through Kaplan turbines at mainstem Columbia and Snake river projects, which varied between –125 to –413 psia/s (Table 4.3) (Carlson et al. 2008).

A linear model fit to the live-fish 48-hr mortality estimates and Sensor Fish turbulence index values for turbine passage at Cougar and Detroit dams (Duncan and Carlson 2011) based on fish length showed that for operating conditions tested, the turbulence index is a good predictor for 48-hr mortality for fish greater than 160 mm in length (Figure 4.7). Live fish less than 160 mm in length are more likely to survive higher turbulence indices, according to model results. This fit is contrary to the assumption that a higher turbulence index is indicative of higher mortality for smaller fish. The mass of the Sensor Fish or conditions encountered in the Francis turbine may contribute to this observation.

Table 4.2. Pressure nadirs observed in Sensor Fish data during turbine passage at USACE hydropower projects.

Project	Flow (kcfs)	Mean Pressure Nadir (psia)	Maximum Pressure Nadir (psia)	Minimum Pressure Nadir (psia)
Ice Harbor	8.3	19.60	23.28	14.38
	13.1	13.19	20.35	0.45
	13.45	15.00	19.48	7.13
	14.1	14.99	19.54	6.33
John Day	11.6	27.05	30.55	23.1
	19.9	19.07	23.38	9.22
	16.5	22.53	27.02	15.99
	20.3	13.87	22.87	0.26
Bonneville	11.1	20.30	23.75	13.5
	15.8	16.27	20.7	8.69
	16.9	18.45	21.95	11.65
Cougar	**0.34**	**8.88**	**9.74**	**8.07**
	0.455	**9.31**	**10.54**	**7.06**
	0.55	**4.04**	**5.46**	**2.0**
Detroit	2.2	6.32	10.23	0.93

Table 4.3. Pressure rates of change observed from Sensor Fish turbine passage at USACE hydropower projects.

Project	Flow (kcfs)	Mean Pressure Rate of Change (psia/s)	Maximum Pressure Rate of Change (psia/s)	Minimum Pressure Rate of Change (psia/s)
Ice Harbor	8.3	–413.4	–686.4	–238.6
	13.1	–318.1	–661.6	–127
	13.45	–336.3	–838.8	–113.4
	14.1	–374.4	–637.8	–193.2
John Day	11.6	–320.1	–572.6	–176
	16.5	–351.1	–649	–227.2
	19.9	–304.1	–525.6	–175.4
	20.3	–373	–604.2	–241.2
Bonneville	11.1	–139.7	–297.2	–22
	15.8	–184.9	–384.8	–105.4
	16.9	–125.8	–339.4	–40
Cougar	**0.34**	**–1126.8**	**–1423.4**	**–803.6**
	0.455	**–1348.9**	**–1666.5**	**–1041.2**
	0.55	**–1916.7**	**–2297.1**	**–1637.2**
Detroit	2.2	–1112.5	–1654.6	–678

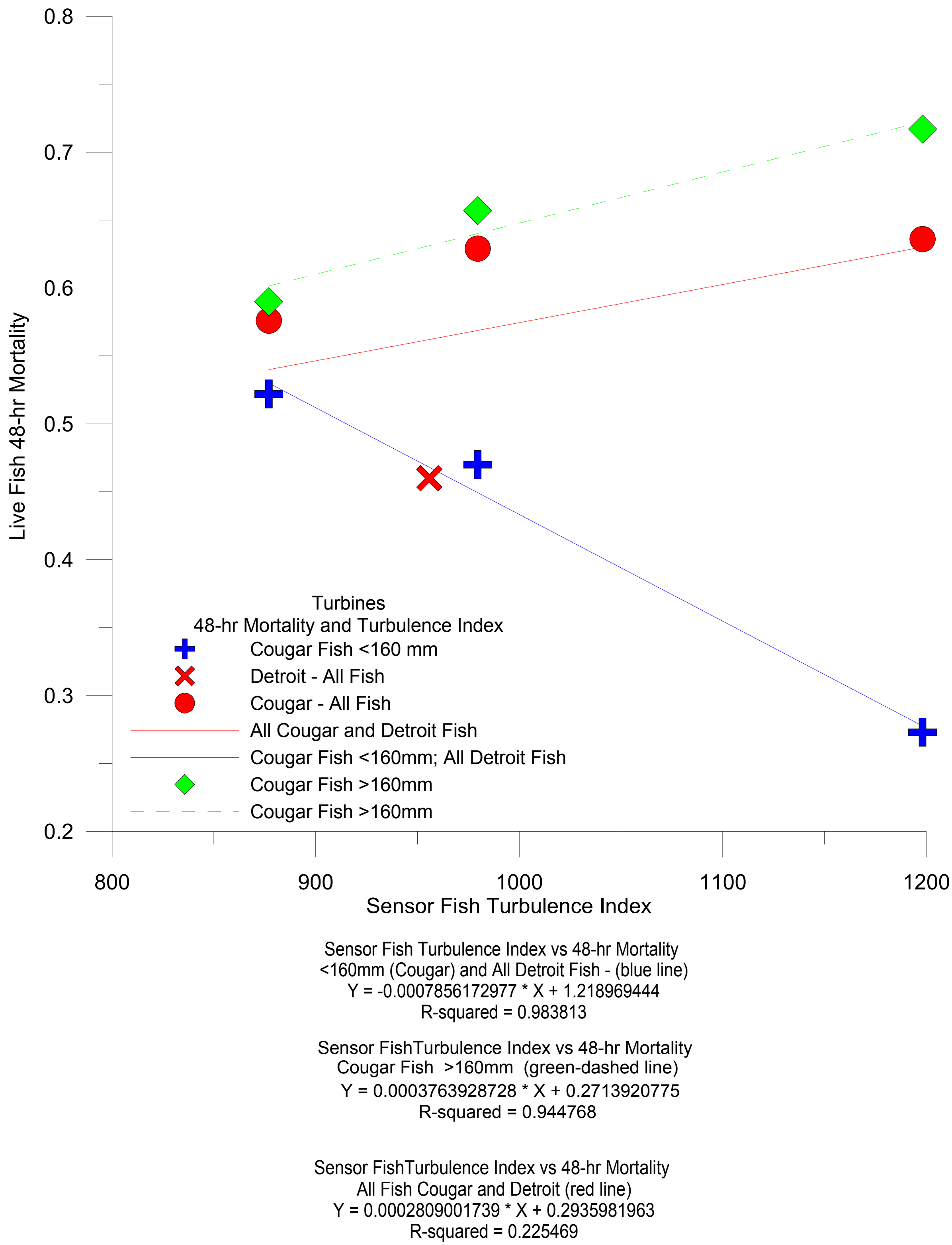


Figure 4.7. Fit of linear model between live fish estimated 48-hr mortality and Sensor Fish turbulence index for Cougar and Detroit turbine evaluations based on fish length.

4.3 All Passage Routes

The passage routes tested during this study are considerably less safe for fish passage than Columbia River passage routes that have been evaluated. The turbine passage route was most detrimental, with damage and losses to more than 23% of the Sensor Fish; RO damage was nearly 8%. All Sensor Fish experienced a significant event during turbine passage; highest values were seen for the maximum wicket gate opening condition (166.2 *g*; maximum 188.4 *g*). However, these values were less than those observed for Sensor Fish passage through Detroit Dam Francis turbine unit 2, which was 176.5 *g* with a maximum value of 234.8 *g* (Duncan and Carlson 2011).

Sensor Fish and live-fish data indicate that the RO provided the best fish passage conditions of the routes tested. Sensor Fish passage through the 3.7-ft gate opening had the lowest severe event magnitudes, and few sensors were damaged during passage. Turbulence index was low for both RO discharges.

Testing was conducted during the winter when operational heads are lowest, with heads of 280 ft and 288 ft for the RO and turbine study, respectively. The results reported here are for these conditions and should not be extrapolated to higher operational heads that would be encountered during the summer, nor should the results be extended to include fish that were larger than those evaluated.

5.0 Conclusions

Results from Sensor Fish data for RO passage at Cougar Dam indicate the 1.5-ft gate opening produced more severe conditions for fish passage. All but one Sensor Fish passing via the 1.5-ft gate opening experienced at least one significant collision or shear event; 100% of those having an event were subjected to multiple events. Of the Sensor Fish passing through the 3.7-ft gate opening, 25% had a single significant event and 75% experienced multiple events. On average, there were 4.5 events per release for Sensor Fish passage through the 1.5-ft gate opening and 3.2 events per release for the 3.7-ft gate opening. Two Sensor Fish were damaged during passage at the 1.5-ft gate opening; one was damaged during passage at the 3.7-ft gate opening.

The mean acceleration magnitudes for significant events observed during RO passage were 150.9 *g* and 135.9 *g* for the 1.5-ft and 3.7-ft gate openings, respectively. Of the most severe events observed following passage through the 1.5-ft gate opening, 78% occurred on the chute of the RO outlet; 63% of the most severe events observed following passage through the 3.7-ft gate opening occurred in the same region. One shear event was observed at the 1.5-ft gate opening, occurring during passage under the gate; the remaining events were collisions. At the 3.7-ft gate opening, shear was observed at the chute–to–stilling basin transition and in the stilling basin; all other events were collisions.

Exposure conditions for passage through the turbine proved particularly hazardous to both live fish and Sensor Fish. All Sensor Fish released into the turbine experienced more than one significant collision or shear event, and all events occurred in the runner region. Significant event magnitude was greatest for turbine operation at the maximum wicket gate opening (166.2 *g*) and least for the peak efficiency operations (140.3 *g*). Collisions or strikes were observed most frequently during the minimum wicket gate opening, most likely due to the maximum wicket gate spacing of 3.22 in. Shear events occurred most often during maximum wicket gate opening and peak efficiency operations.

Mean pressure nadir values obtained during turbine runner passage were lowest for turbine operations with a maximum wicket gate opening, averaging 3.66 psia, the lowest observed to date. Mean nadir values observed for the minimum wicket gate opening and peak efficiency operations were 8.74 psia and 9.31 psia, respectively. Associated pressure rate-of-change values were greatest for the maximum wicket gate openings as well, averaging −1633.3 psia/s; average pressure rate-of-change values for the minimum wicket gate opening and peak efficiency operations were −874.8 psia/s and −1042.7 psia/s, respectively. Detroit Dam turbine nadir values averaged 6.32 psia; pressure rate of change was −1000.5 psia/s.

Results from the Sensor Fish and live-fish passage evaluations at Cougar Dam would likely be different with other fish sizes, changes in dam operations, or for the same operations but with forebay elevations different from those tested. The effect of higher operating heads on changes in the magnitude and rates of change in pressure would likely contribute to greater mortality and injury rates. Because test fish used during the Cougar Dam passage evaluations were not acclimated (i.e., not neutrally buoyant) to pressure, it is very likely the malady and mortality rates observed are underestimated. Should bull trout adults or sub-adults be exposed to the turbine conditions tested, the likelihood of blade strike would be 100%.

Sensor Fish and live fish study results indicate that the RO passage route with a control gate opening of 3.7 ft was the safest route for fish passage of the routes, operating conditions, and fish size tested.

6.0 References

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Appendix A

Field Log Data Sheets

Appendix A contains field log data sheets showing dam operating conditions, release locations, deployment and recovery times for each Sensor Fish release, and other project information for each study period.

Regulating Outlet Passage

Test Date	Test Condition	Fish ID	Tag Number	Deployment Time	Recovery Time	File Name	Barometric Pressure (in Hg)	Notes	Barometric Pressure (psi)	Forebay Elevation (ft)	Tailwater Elevation (ft)
12/15/2009	1.5-ft opening	723	8 281	1518	1521		27.99	"Dummy" SF – no data	13.75		
		923	8 851	1526	1532	f923_1_1t	27.99	Pinch valve	13.75		
		913	8 821								
		121	8 341	1536	1540	f121_1_2t	27.99	No pinch valve – slow to go	13.75		
		912	8 891	1618	1621	f912_1_3t	28.00	No pinch valve	13.75		
12/16/2009	1.5-ft opening	923	8 851	819	831	f923_1_1	28.21		13.86	1530.83	1251.47
		914	8 931	825	831	f914_1_2	28.20		13.85	1530.83	1251.47
		927	8 081	843	949	f927_1_3	28.21	Screw connection popped	13.86	1530.83	1251.47
		109	8 681	919	924	f109_1_4	28.22		13.86	1530.90	1251.43
		930	8 841	947	951	f930_1_5	28.23		13.87	1530.90	1251.43
		931	8 371	1010	1015		28.24	Data interrupt	13.87	1530.99	1251.43
		913	8 821	1032	1036	f913_1_7	28.24		13.87	1530.99	1251.43
		932	8 351	1105	1109	f932_1_6	28.23		13.87	1531.09	1251.43
		912	8 891	1148	1153	f912_1_8	28.22		13.86	1531.09	1251.43
		121	8 341	1205	1210	f121_1_9	28.22		13.86	1531.12	1251.43
		103	8 911	1232	1237	f103_1_10	28.21		13.86	1531.12	1251.43
		908	8 831	1250	1254		28.20	DEAD	13.85	1531.12	1251.43
		912	8 891	1528	1532	f912_1_11	28.22		13.86	1531.36	1251.43
12/17/2009	1.5-ft opening	930	8 841	833	837	f930_1_12	28.39		13.94	1532.97	1253.38
		914	8 931	853	856	f914_1_13	28.40		13.95	1532.97	1253.38
		923	8 851	919	928	f923_1_14	28.41		13.95	1533.00	1253.35
		109	8 681	939	944	f109_1_15	28.40		13.95	1533.00	1253.35
		926	8 371	959	1007	f926_1_16	28.40		13.95	1533.01	1253.37

Test Date	Test Condition	Fish ID	Tag Number	Deployment Time	Recovery Time	File Name	Barometric Pressure (in Hg)	Notes	Barometric Pressure (psi)	Forebay Elevation (ft)	Tailwater Elevation (ft)
12/17/2009	3.68-ft opening	929	8 281	1220	1252	f929_3_1	28.39	Stuck in whitewater – retrieved with crab ring	13.94	1533.07	1252.29
		932	8 351	1303	1305	f932_3_2	28.38		13.94	1533.12	1252.27
		912	8 891	1335	1345		28.36	Data interrupt	13.93	1533.12	1252.27
		913	8 821	1406	1409	f913_3_3	28.36		13.93	1533.15	1252.27
		103	8 911	1432	1435	f103_3_4	28.36		13.93	1533.15	1252.27
		926	8 371	1508	1511	f926_3_5	28.37		13.93	1533.19	1252.28
		923	8 851	1526	1533	f923_3_6	28.37		13.93	1533.19	1252.28
12/18/2009	3.68-ft opening	103	8 911	830	836	f103_3_7	28.39		13.94	1533.61	1252.29
		901	8 831	850	852	f901_3_8	28.39		13.94	1533.61	1252.29
		121	8 341	901	904	f121_3_10	28.40		13.95	1533.61	1252.29
		930	8 841	917	934	f930_3_9	28.40		13.95	1533.61	1252.29
		914	8 931	944	948	f914_3_11	28.39		13.94	1533.61	1252.29
		923	8 851	1020	1023	f923_3_12	28.38		13.94	1533.62	1252.28
		109	8 681	1044	1047	f109_3_14	28.38		13.94	1533.62	1252.28
		932	8 351	1109	1111	f932_3_13	28.37		13.93	1533.62	1252.30
		929	8 281	1155	1158	f929_3_15	28.37		13.93	1533.62	1252.30
		913	8 821	1220	1222	f913_3_16	28.35		13.92	1533.64	1252.29

Turbine Passage

Test Date	Test Condition	Fish ID	Tag	Deployment Time	Recovery Time	File Name	Barometric Pressure (in Hg)	Notes	Barometric Pressure (psia)	Total Turbine Flow (cfs)	Unit 2 Turbine Flow	Forebay (ft)	Tailwater (ft)
1/19	High flow	729	9 164	9:09	9:13		27.3	Wouldn't download	13.4	1030	550	1541.91	1252.96
		923	9 740	9:39	9:45	f923_H_1		Tried to adjust timing by setting delay and extending recording but was unsuccessful		1030	550	1541.91	1252.96
		909	9 720	10:04	10:10	f909_H_2		Pressure/timing		550	550	1541.88	1252.94
		121	9 800	10:35	10:41	f121_H_3	27.28	Timing	13.4	550	550	1541.88	1252.94
		913	9 341	11:07	11:13	f913_H_4		Timing		550	550	1541.86	1252.95
	Low flow	103	9 124	13:27	13:36	f103_L_15	27.26	No delay	13.4	540	550	1541.83	1252.93
		932	9 014	13:27	13:34	f932_L_180		180-sec delay		540	550	1541.83	1252.93
		914	9 085	13:28	13:34	f914_L_90		Tried 90-sec delay – didn't hold		540	550	1541.83	1252.93
		926	9 531	14:23	14:31	f926_L_15		15-sec delay – 90 second?		340	340	1541.82	1252.69
		901	9 671	14:25	14:31	f901_L_180		180-sec delay		340	340	1541.82	1252.69
		109	9 381	14:50	14:58	f109_L_15	27.25	15-sec delay	13.4	340	340	1541.82	1252.69
		929	9 095	14:51	15:00	f929_L_180		Tried 180-sec delay – didn't hold		340	340	1541.82	1252.69
		913	9 341	15:19	15:27	f913_L_240	27.27	240-sec delay	13.4	340	340	1541.79	1252.68
		121	9 800	15:19	15:31	f121_L_240		240-sec delay		340	340	1541.79	1252.68
		923	9 740	15:47	15:54		27.61	Wouldn't download	13.6	340	340	1541.79	1252.68
1/20	Low flow	121	9 800	9:14	9:24	f121_L_300	27.28	300-sec delay – *x*-axis offset	13.4	1120	550	1541.5	1253.91
		103	9 124	9:15	10:45	f103_L_300		Stuck in pipe – no good data		1120	550	1541.5	1253.91
1/20	Low flow	914	9 085	9:46	9:53	DEAD	27.27	120-sec delay	13.4	1120	550	1541.5	1253.91
		901	9 671	9:47	9:54	f901_L_120		120-sec delay		1120	550	1541.5	1253.91
		930	9 164	10:17	11:05	f930_L_300	27.26	Stuck in pipe – no good data	13.4	400	340	1541.48	1252.63
		109	9 381	11:07	11:15	f109_L_300	27.23	300-sec delay	13.4	400	340	1541.46	1252.61
	High flow	913	9 341	13:54	13:59	f913_H_150	27.13	150-sec delay	13.3	340	340	1541.39	1252.62
		929	9 095	13:54	14:00	f929_H_150		150-sec delay		340	340	1541.39	1252.62

Test Date	Test Condition	Fish ID	Tag	Deployment Time	Recovery Time	File Name	Barometric Pressure (in Hg)	Notes	Barometric Pressure (psia)	Total Turbine Flow (cfs)	Unit 2 Turbine Flow	Forebay (ft)	Tailwater (ft)
		103	9 124	14:35	14:49	DEAD	27.12	Came back blinking red	13.3	520	550	1541.35	1252.94
		121	9 800	14:36	14:49	f121_H_150		150-sec delay – recovered with one tag only		520	550	1541.35	1252.94
		930	9 164	14:57	15:02	f930_H_150	27.11	150-sec delay	13.3	540	550	1541.33	1252.93
1/21	High flow	913	9 341	8:46	8:50	DEAD	27.27	DEAD	13.4	1120	550	1540.88	1253.81
		909	9 720	9:04				Lost in boil – PIECES?		760	550	1540.88	1253.07
		109	9 381	9:22				Lost in boil – pieces?		760	550	1540.88	1253.07
		932	9 014	9:43				Lost in boil – pieces?		760	550	1540.88	1253.07
	Maximum efficiency	930	9 164	13:57	14:05	f930_ME_200	27.22	200-sec delay	13.4	380	455	1540.63	1252.91
		926	9 531	13:58	14:03	f926_ME_200		200-sec delay		380	455	1540.63	1252.91
		930	9 164	15:07	15:14	f930_ME_200_2		200-sec delay		400	455	1540.63	1252.91
		926	9 531	15:08	15:14	f926_ME_200_2		200-sec delay		400	455	1540.63	1252.91

Appendix B

Data Summary Tables for Each Sensor Fish Release

Regulating Outlet Passage

Significant Events

File	Time	AdjTime	Magnitude	Event Type	Location
f923_1_1t	65.1855	36.288	158.7	Collision	Chute
	68.333	39.4355	139.9	Collision	Chute
	66.9565	38.059	124.6	Collision	Chute
	70.8795	41.982	122.6	Collision	Transition
f121_1_2t	71.673	18.9	122.4	Collision	Outlet
	69.349	16.576	111.5	Collision	Outlet
	92.07	39.297	111	Collision	Chute
f912_1_3t	71.6655	42.5165	124.2	Collision	SB
	66.261	37.112	122	Collision	Chute
	71.92	42.771	113.8	Collision	SB
	44.187	15.038	107.3	Collision	Outlet
	66.8345	37.6855	106.8	Collision	Chute
	67.233	38.084	103.4	Collision	Chute
	70.6175	41.4685	102.2	Collision	Chute
f923_1_1	64.222	37.7105	174.1	Collision	Chute
	62.7035	36.192	128.2	Collision	Chute
	60.3095	33.798	117.2	Collision	Chute
	61.5485	35.0355	102.9	Collision	Chute
f914_1_2	30.0135	0.0075	177.9	Shear	Gate
	67.6885	37.6825	151.4	Collision	Chute
	67.0335	37.0285	112	Collision	Chute
	66.0685	36.0625	101.4	Collision	Chute
f927_1_3					
f109_1_4	73.271	45.459	154.1	Collision	Chute
	71.135	43.323	147.9	Collision	Chute
	70.136	42.324	146.5	Collision	Chute
	75.4395	47.6275	141.3	Collision	SB
	73.8295	46.0175	136.5	Collision	Chute
	75.362	47.55	117.8	Collision	SB
	72.5685	44.7565	107.2	Collision	Chute
f930_1_5	69.9435	41.0925	172.5	Collision	Chute
	67.1655	38.3145	139.4	Collision	Chute
	66.2885	37.4375	123.1	Collision	Chute
f913_1_7	74.641	42.897	150.1	Collision	Chute
	73.2525	41.5085	138.1	Collision	Chute
	75.5985	43.8545	137	Collision	Chute
	77.0575	45.3135	123.3	Collision	Chute
	77.9385	46.1945	121.3	Collision	Chute
	74.8895	43.1455	106.8	Collision	Chute

File	Time	AdjTime	Magnitude	Event Type	Location
f932_1_6	91.6475	40.7045	143.8	Collision	Chute
	90.3805	39.4375	126.3	Collision	Chute
	89.0205	38.0775	124.9	Collision	Chute
	87.3855	36.4425	110.5	Collision	Chute
	60.7215	9.7785	109.7	Collision	Outlet
	51.9565	1.0135	107	Collision	Outlet
f912_1_8	67.8685	36.965	165.1	Collision	Chute
	69.7125	38.809	143.2	Collision	Chute
	68.878	37.9745	136	Collision	Chute
	50.607	19.7035	113.9	Collision	Outlet
	69.426	38.5225	111.1	Collision	Chute
f121_1_9	63.575	38.642	181.3	Collision	Chute
	61.927	36.994	144	Collision	Chute
	66.614	41.681	114	Collision	Chute
	66.7035	41.7705	112.1	Collision	Chute
	27.441	2.508	110.9	Collision	Outlet
	62.929	37.996	110	Collision	Chute
	62.6875	37.7545	103.8	Collision	Chute
	63.1595	38.2265	95.5	Collision	Chute
f103_1_10	69.7885	37.8635	162.7	Collision	Chute
	37.2065	5.2815	146.3	Collision	Outlet
	72.9365	41.0115	134.8	Collision	Chute
	66.04	34.115	119.4	Collision	Chute
	73.2335	41.3085	104.2	Collision	Transition
	68.8545	36.9295	96.5	Collision	Chute
f912_1_11	64.7655	37.048	127.9	Collision	Chute
	67.863	40.1455	114.7	Collision	Transition
	67.2355	39.518	104.4	Collision	Chute
	64.266	36.5485	103.1	Collision	Chute
	50.852	23.1345	100.8	Collision	Outlet
f930_1_12	82.044	45.831	114.7	Collision	SB
	36.237	0.024	112	Collision	Gate
	77.786	41.573	107.4	Collision	Chute
	76.3355	40.1225	97.2	Collision	Chute
f914_1_13	64.505	36.414	145.9	Collision	Chute
	59.9685	31.8775	129.6	Collision	Chute
	66.5435	38.4525	112.3	Collision	Chute
f923_1_14	79.9205	38.9985	133.5	Collision	Chute
	78.7	37.778	100.4	Collision	Chute
	81.557	40.635	95.7	Collision	Chute

File	Time	AdjTime	Magnitude	Event Type	Location
f109_1_15	70.434	37.479	159.4	Collision	Chute
	36.049	3.094	123.9	Collision	Outlet
	78.7685	45.8135	124.2	Collision	SB
	69.575	36.62	97.4	Collision	Chute
f926_1_16	67.0665	38.786	147.6	Collision	Chute
	31.23	2.9495	123.4	Collision	Outlet
	67.8815	39.601	119.8	Collision	Chute
Most Severe:	**Mean**	**150.88**	**All Events:**	**Mean**	**124.95**
	Maximum	**181.3**		**Maximum**	**181.30**
	Minimum	**114.7**		**Minimum**	**95.50**
	SD	**20.14**		**SD**	**20.98**
	SE	**4.75**		**SE**	**2.28**
f929_3_1	55.323	27.3795	126.5	Collision	Chute
	60.237	32.2935	109.8	Collision	Transition
	56.725	28.7815	106.7	Collision	Chute
f932_3_2	34.845	5.2745	109.6	Collision	Outlet
f913_3_3	59.3325	30.962	115.7	Shear	SB
f103_3_4	54.281	26.901	161	Collision	Chute
	54.9825	27.6045	113.9	Collision	Chute
	53.5535	26.1755	113.1	Collision	Chute
	54.0585	26.6805	102.6	Collision	Chute
	54.362	26.984	99	Collision	Chute
f926_3_5	31.805	6.605	133.9	Collision	Outlet
f923_3_6	53.2495	27.4105	115.4	Collision	Chute
	39.512	13.673	111.3	Collision	Outlet
f103_3_7	56.8295	33.1175	163.7	Shear	Transition
	53.5105	29.7985	123.5	Collision	Chute
f901_3_8	57.9615	30.772	157.8	Collision	Chute
	55.0335	27.844	151.6	Collision	Chute
	56.2845	29.095	128.3	Collision	Chute
	55.1955	28.006	126.8	Collision	Chute
	58.437	31.2475	115.5	Collision	Chute
f121_3_10	37.0995	13.8715	122.2	Collision	Outlet
	53.973	30.745	113	Collision	Chute
	57.546	34.318	106.8	Shear	Transition
f930_3_9	55.6635	29.669	123.9	Collision	Chute
	55.446	29.4515	119.5	Collision	Chute
	56.7785	30.784	110.7	Collision	Chute

File	Time	AdjTime	Magnitude	Event Type	Location
f914_3_11	57.3905	31.474	155.4	Collision	Transition
	56.0735	30.157	136.4	Collision	Chute
	57.539	31.6225	131.6	Collision	Transition
	33.331	7.4145	107.6	Collision	Outlet
	30.2855	4.369	105.2	Collision	Outlet
f923_3_12	54.186	28.134	134.7	Collision	Chute
f109_3_14	57.7205	29.543	145	Collision	Chute
	61.1425	32.965	127.8	Collision	Chute
	61.1795	33.002	126.7	Collision	Chute
	58.809	30.6315	125.7	Collision	Chute
	61.0875	32.91	118	Collision	Chute
f932_3_13	54.44	29.566	119.9	Collision	Chute
	55.895	31.021	110.9	Collision	Transition
	35.7785	10.9045	105.4	Collision	Outlet
f929_3_15	60.256	33.305	142.8	Collision	Chute
	64.5845	37.6335	135.4	Collision	Chute
	62.2475	35.2965	126.7	Collision	Chute
	64.141	37.19	126.7	Collision	Chute
	40.1835	13.2325	125.6	Collision	Outlet
	44.1145	17.1635	118.5	Collision	Outlet
	40.3465	13.3955	104.1	Collision	Outlet
	60.8965	33.9455	100.9	Collision	Chute
f913_3_16	52.1165	27.199	147.6	Collision	Chute
	53.682	28.7645	118.3	Collision	Chute
	56.521	31.6035	105.1	Collision	Transition
Most Severe:	**Mean**	**135.94**	**All Events:**	**Mean**	**123.21**
	Maximum	**163.7**		**Maximum**	**163.70**
	Minimum	**109.6**		**Minimum**	**99.00**
	SD	**17.76**		**SD**	**16.33**
	SE	**4.44**		**SE**	**2.29**

Dam Operations

File Name	Elevations (ft)			Turbine				RO (cfs)
				Unit 1		Unit 2		
	Forebay	Tailwater	Head	MW	Discharge	MW	Discharge	
f923_1_1t								
f121_1_2t								
f912_1_3t								
f923_1_1	1530.83	1251.47	279.4	0	0	0	100	440
f914_1_2	1530.83	1251.47	279.4	0	0	0	100	440
f927_1_3	1530.83	1251.47	279.4	0	0	0	100	440
f109_1_4	1530.90	1251.43	279.5	0	0	0	100	440
f930_1_5	1530.90	1251.43	279.5	0	0	0	100	440
f913_1_7	1530.99	1251.43	279.6	0	0	0	100	440
f932_1_6	1531.09	1251.43	279.7	0	0	0	100	440
f912_1_8	1531.09	1251.43	279.7	0	0	0	100	440
f121_1_9	1531.12	1251.43	279.7	0	0	0	100	440
f103_1_10	1531.12	1251.43	279.7	0	0	0	100	440
f912_1_11	1531.36	1251.43	279.9	0	0	0	100	440
f930_1_12	1532.97	1253.38	279.6	8		7.25		440
f914_1_13	1532.97	1253.38	279.6	8		7.25		440
f923_1_14	1533.00	1253.35	279.7	8		7.25		440
f109_1_15	1533.00	1253.35	279.7	8		7.25		440
f926_1_16	1533.01	1253.37	279.6	8		7.25		440
f929_3_1	1533.07	1252.29	280.8	0	0	0	100	1020
f932_3_2	1533.12	1252.27	280.9	0	0	0	100	1040
f913_3_3	1533.15	1252.27	280.9	0	0	0	100	1040
f103_3_4	1533.15	1252.27	280.9	0	0	0	100	1040
f926_3_5	1533.19	1252.28	280.9	0	0	0	100	1040
f923_3_6	1533.19	1252.28	280.9	0	0	0	100	1040
f103_3_7	1533.61	1252.29	281.3	0	0	0	100	1040
f901_3_8	1533.61	1252.29	281.3	0	0	0	100	1040
f121_3_10	1533.61	1252.29	281.3	0	0	0	100	1040
f930_3_9	1533.61	1252.29	281.3	0	0	0	100	1040
f914_3_11	1533.61	1252.29	281.3	0	0	0	100	1040
f923_3_12	1533.62	1252.28	281.3	0	0	0	100	1040
f109_3_14	1533.62	1252.28	281.3	0	0	0	100	1040
f932_3_13	1533.62	1252.30	281.3	0	0	0	100	1040
f929_3_15	1533.62	1252.30	281.3	0	0	0	100	1040
f913_3_16	1533.64	1252.29	281.4	0	0	0	100	1040

Pressure Rate of Change and Acceleration Magnitude under the RO Gate

File Name	Acceleration Magnitude under Gate (g)	Pressure Rate of Change (psia/s)
f923_1_1t	19.4	–266.67
f121_1_2t	19.8	–269.00
f912_1_3t	33.5	–325.67
f923_1_1	19.3	–289.67
f914_1_2	49.6	–628.67
f927_1_3	31.3	–374.67
f109_1_4	17	–288.33
f930_1_5	44.1	–376.00
f913_1_7	19.7	–288.00
f932_1_6	19.9	–287.67
f912_1_8	42.1	–344.67
f121_1_9	26.9	–302.33
f103_1_10	18.5	–264.00
f912_1_11	55.1	–431.00
f930_1_12	50.9	–420.33
f914_1_13	48.8	–420.33
f923_1_14	25.4	–332.33
f109_1_15	16.4	–278.67
f926_1_16	29.2	–345.00
Mean	**30.89**	**–343.84**
Maximum	**55.1**	**–628.67**
Minimum	**16.4**	**–264.00**
SD	**13.3**	**87.90**
SE	**3.06**	**20.16**
f929_3_1	9.1	–142.67
f932_3_2	8.9	–142.00
f913_3_3	8.0	–132.00
f103_3_4	15.5	–153.33
f926_3_5	8.2	–135.33
f923_3_6	10.9	–145.00
f103_3_7	9.3	–140.00
f901_3_8	9.6	–152.33
f121_3_10	9.2	–133.00
f930_3_9	8.2	–135.67
f914_3_11	13.7	–182.67
f923_3_12	10	–138.33
f109_3_14	9.8	–144.33
f932_3_13	10.1	–138.67
f929_3_15	9.6	–142.67
f913_3_16	15	–177.00
Mean	**10.32**	**–145.94**
Maximum	**15.5**	**–182.67**
Minimum	**8.0**	**–132.00**
SD	**2.34**	**14.55**
SE	**0.58**	**3.64**

Turbine Passage

Significant Events

File Name	Number of Events	Data Collection Region	Data Collection Time (s)	Trigger Delay Time (s)	Event Magnitude (g)	Time of Event (s)	Type of Event	Event Location
f103_L_15		Entrance	120	15				
f932_L_180	2	Runner	233	180	103.4	198.0215	Strike	Runner
					101.5	197.99	Shear	Runner
f914_L_90		Entrance	120	15				
f926_L_15		Penstock	233	180				
f901_L_180		Entrance	233	15				
f109_L_15		Entrance	233	15				
f929_L_180		Entrance	120	15				
f913_L_240	4	Runner	233	240	150.4	126.072	Strike	Runner
					141.8	126.365	Strike	Runner
					110.3	126.1105	Strike	Runner
					101.2	126.2105	Strike	Runner
f121_L_240	2	Runner	233	240	163.1	160.409	Strike	Runner
					143.7	160.3765	Shear	Runner
f121_L_300	2	Runner	233	300	156.4	108.1985	Shear	Runner
					125.8	108.237	Shear	Runner
f901_L_120		Penstock	233	120				
f109_L_300	4	Runner	233	300	142.5	79.8345	Strike	Runner
					123.8	79.7775	Strike	Runner
					113.6	79.733	Shear	Runner
					96.9	79.673	Shear	Runner
			Most Severe Events:	**Mean**	**143.2**	**All Events:**	**Mean**	**126.7**
				Maximum	**163.1**		**Maximum**	**163.1**
				Minimum	**103.4**		**Minimum**	**96.9**
				SD	**23.5**		**SD**	**22.7**
				SE	**10.5**		**SE**	**6.1**
f923_H_1	0	Entrance	120	15				
f909_H_2	0	Entrance	120	15				
f121_H_3	0	Entrance	120	15				
f913_H_4	0	Entrance	120	15				
f913_H_150	2	Runner	233	150	188.4	95.9455	Shear	Runner
					136.6	95.972	Strike	Runner
f929_H_150	4	Runner	233	150	176.2	98.937	Strike	Runner
					155.8	98.881	Strike	Runner
					116.1	98.8145	Strike	Runner
					114.5	96.024	Strike	Runner
f121_H_150	4	Runner	233	150	152.2	110.4855	Strike	Runner
					134.7	110.327	Strike	Runner
					124.2	110.5325	Shear	Runner
					105.5	110.518	Shear	Runner
f930_H_150	2	Runner	233	150	148	84.634	Shear	Runner
					97.4	84.6745	Shear	Runner

File Name	Number of Events	Data Collection Region	Data Collection Time (s)	Trigger Delay Time (s)	Event Magnitude (g)	Time of Event (s)	Type of Event	Event Location
			Most Severe Events:	**Mean**	**166.2**	**All Events:**	**Mean**	**137.5**
				Maximum	**188.4**		**Maximum**	**188.4**
				Minimum	**148.0**		**Minimum**	**97.4**
				SD	**19.3**		**SD**	**27.9**
				SE	**9.7**		**SE**	**8.1**
f930_ME_200	3	Runner	233	200	118.3	100.971	Shear	Runner
					109	100.9465	Shear	Runner
					98.9	100.924	Shear	Runner
f926_ME_200	3	Runner	233	200	153.1	91.91	Collision/ strike	Runner
					140.3	92.1225	Shear	Runner
					116.6	91.929	Collision/ strike	Runner
f930_ME_200_2	1	Runner	233	200	145.7	82.816	Collision/ strike	Runner
f926_ME_200_2	2	Runner	233	200	144.2	108.521	Shear	Runner
					123.9	108.58	Collision/ strike	Runner
			Most Severe Event:	**Mean**	**140.3**	**All Events:**	**Mean**	**127.8**
				Maximum	**153.1**		**Maximum**	**153.1**
				Minimum	**118.3**		**Minimum**	**98.9**
				SD	**15.2**		**SD**	**18.7**
				SE	**7.6**		**SE**	**6.2**

Dam Operations

File Name	Deployment Time (s)	Recovery Time (s)	Data Collection Location	Elevations (ft)			Turbine				RO
							Unit 1		Unit 2		
				Forebay	Tailwater	Head	MW	cfs	MW	cfs	cfs
f923_H_1	9:39	9:45	Entrance	1541.91	1252.96	289.0	0	0	11.5	550	660
f909_H_2	10:04	10:10	Entrance	1541.88	1252.94	288.9	0	0	11.5	550	660
f121_H_3	10:35	10:41	Entrance	1541.88	1252.94	288.9	0	0	11.5	550	660
f913_H_4	11:07	11:13	Entrance	1541.90	1252.92	289.0	0	0	11.5	550	660
f913_H_150	13:54	13:59	Runner	1541.39	1252.62	288.8	0	0	11.5	550	840
f929_H_150	13:54	14:00	Runner	1541.39	1252.62	288.8	0	0	11.5	550	840
f121_H_150	14:36	14:49	Runner	1541.35	1252.94	288.4	0	0	11.5	550	660
f930_H_150	14:57	15:02	Runner	1541.35	1252.94	288.4	0	0	11.5	550	660
f103_L_15	13:27	13:36	Entrance	1541.83	1252.93	288.9	0	0	7.1	340	900
f932_L_180	13:27	13:34	Runner	1541.83	1252.93	288.9	0	0	7.1	340	900
f914_L_90	13:28	13:34	Entrance	1541.83	1252.93	288.9	0	0	7.1	340	900
f926_L_15	14:23	14:31	Penstock	1541.82	1252.68	289.1	0	0	7.1	340	900
f901_L_180	14:25	14:31	Entrance	1541.82	1252.68	289.1	0	0	7.1	340	900
f109_L_15	14:50	14:58	Entrance	1541.82	1252.68	289.1	0	0	7.1	340	900
f929_L_180	14:51	15:00	Entrance	1541.82	1252.68	289.1	0	0	7.1	340	900
f913_L_240	15:19	15:27	Runner	1541.79	1252.69	289.1	0	0	7.0	340	900
f121_L_240	15:19	15:31	Runner	1541.79	1252.69	289.1	0	0	7.0	340	900
f121_L_300	9:14	9:24	Runner	1541.50	1253.91	287.6	0	0	7.0	340	0
f901_L_120	9:47	9:54	Penstock	1541.50	1253.91	287.6	0	0	7.0	340	0
f109_L_300	11:07	11:15	Runner	1541.46	1252.61	288.9	0	0	7.0	340	840
f930_ME_200	13:57	14:05	Runner	1540.63	1252.91	287.7	0	0	9.7	455	840
f926_ME_200	13:58	14:03	Runner	1540.63	1252.91	287.7	0	0	9.7	455	840
f930_ME_200_2	15:07	15:14	Runner	1540.59	1252.93	287.7	0	0	9.7	455	840
f926_ME_200_2	15:08	15:14	Runner	1540.59	1252.93	287.7	0	0	9.7	455	840

Pressure Rate of Change and Nadir

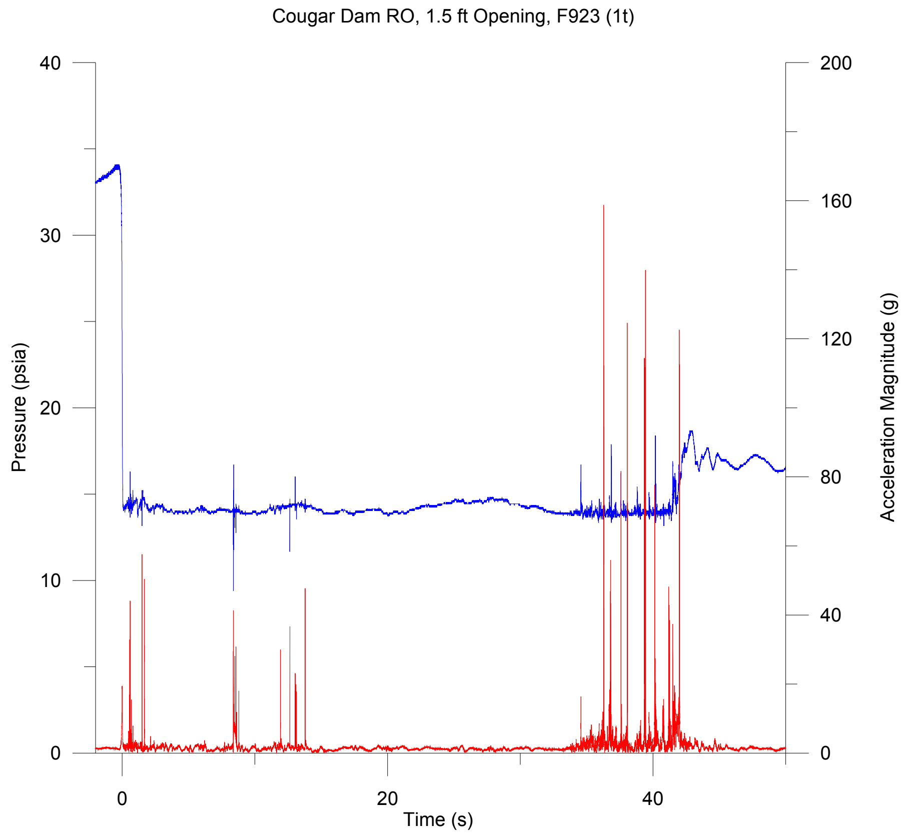
File Name		Rate of Change (psia/s)	Nadir (psia)
f932_L_180		–1423.4	9.74
f913_L_240		–892.6	7.39
f121_L_240		–1312.0	9.38
f121_L_300		–1202.4	8.8
f109_L_300		–803.6	8.41
	Mean	**–1126.8**	**8.74**
	Max	**–803.6**	**9.74**
	Min	**–1423.4**	**7.39**
	SD	**268.0**	**0.91**
	SE	**119.9**	**0.41**
f913_H_150		–2297.14	3.52
f929_H_150			
f121_H_150		–1637.2	2
f930_H_150		–1815.6	5.46
	Mean	**–1916.6**	**3.66**
	Max	**–1637.20**	**5.46**
	Min	**–2297.1**	**2.00**
	SD	**341.4**	**1.73**
	SE	**197.1**	**1.00**
f930_ME_200		–1041.2	10.34
f926_ME_200		–1396.6	9.28
f930_ME_200_2		–1291.2	10.54
f926_ME_200_2		–1666.5	7.06
	Mean	**–1348.9**	**9.31**
	Max	**–1041.2**	**10.54**
	Min	**–1666.5**	**7.06**
	SD	**259.0**	**1.60**
	SE	**129.5**	**0.80**

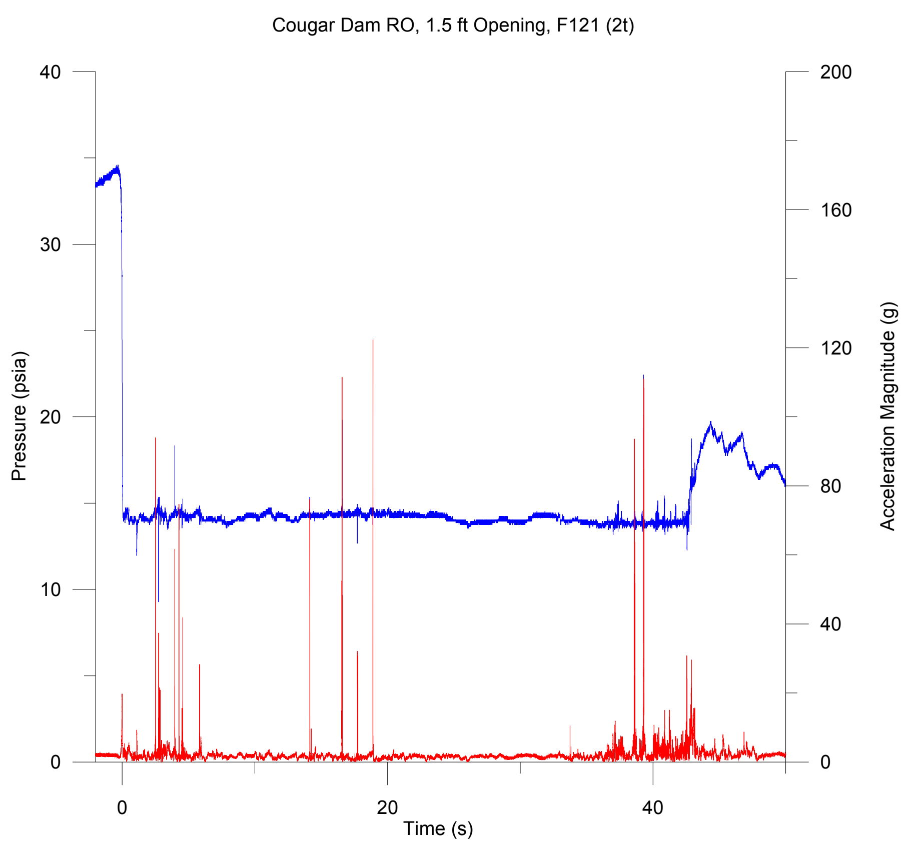
Appendix C

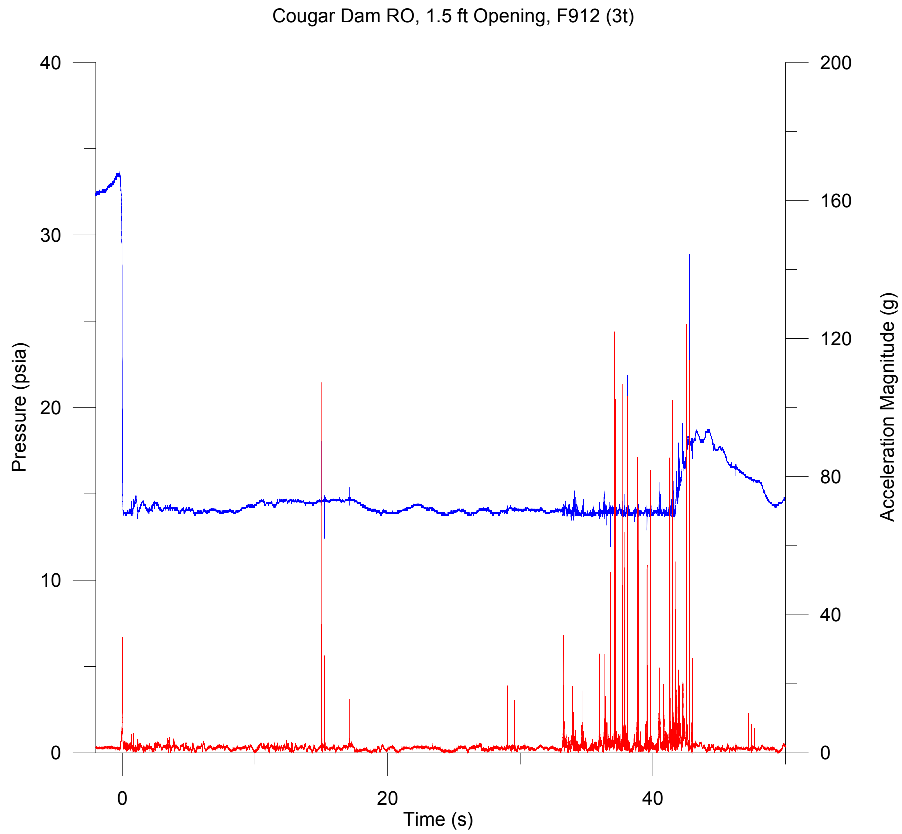
Pressure and Acceleration Magnitude Time Histories of Each Sensor Fish Release

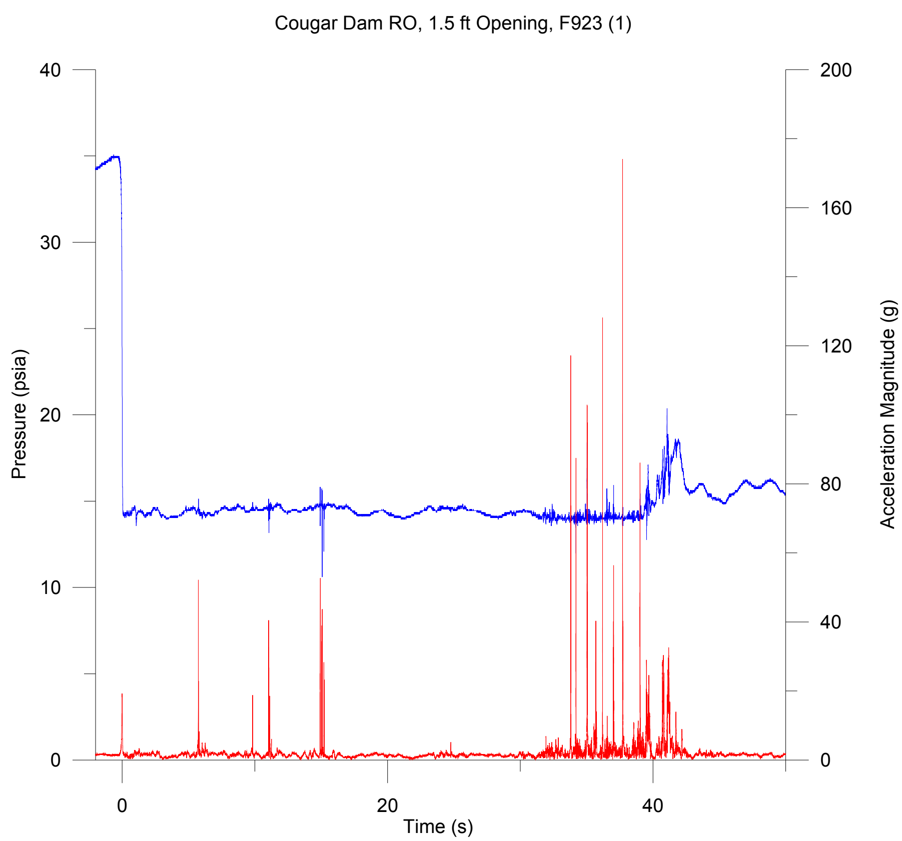
Cougar Dam Regulating Outlet

1.5-ft Gate Opening

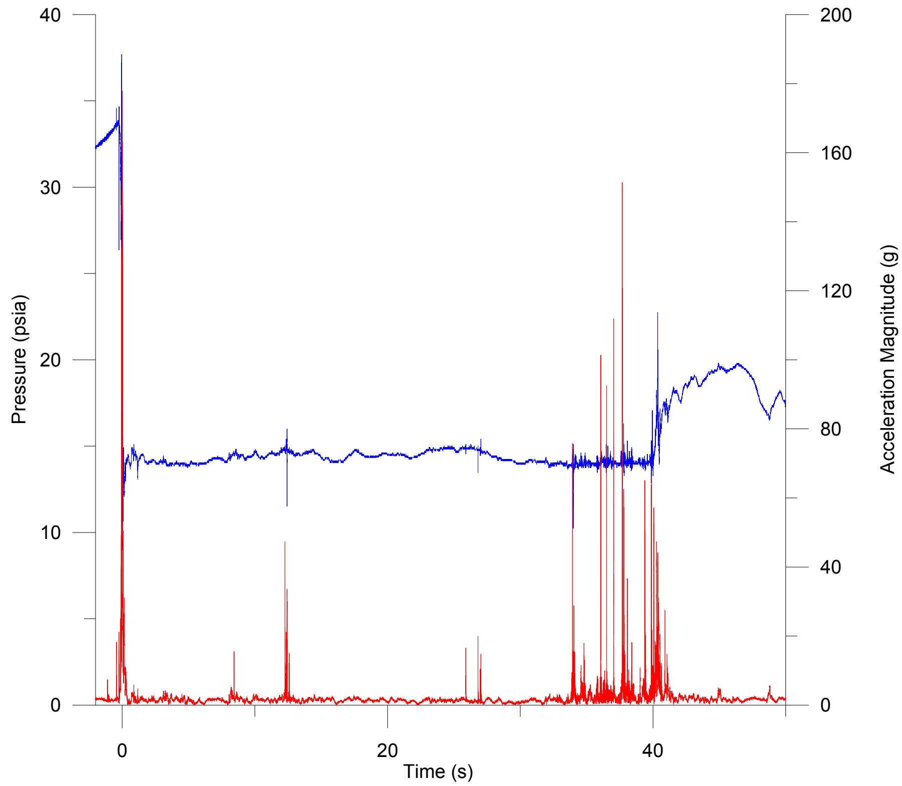

Cougar Dam RO, 1.5 ft Opening, F923 (1t)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40


Cougar Dam RO, 1.5 ft Opening, F121 (2t)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

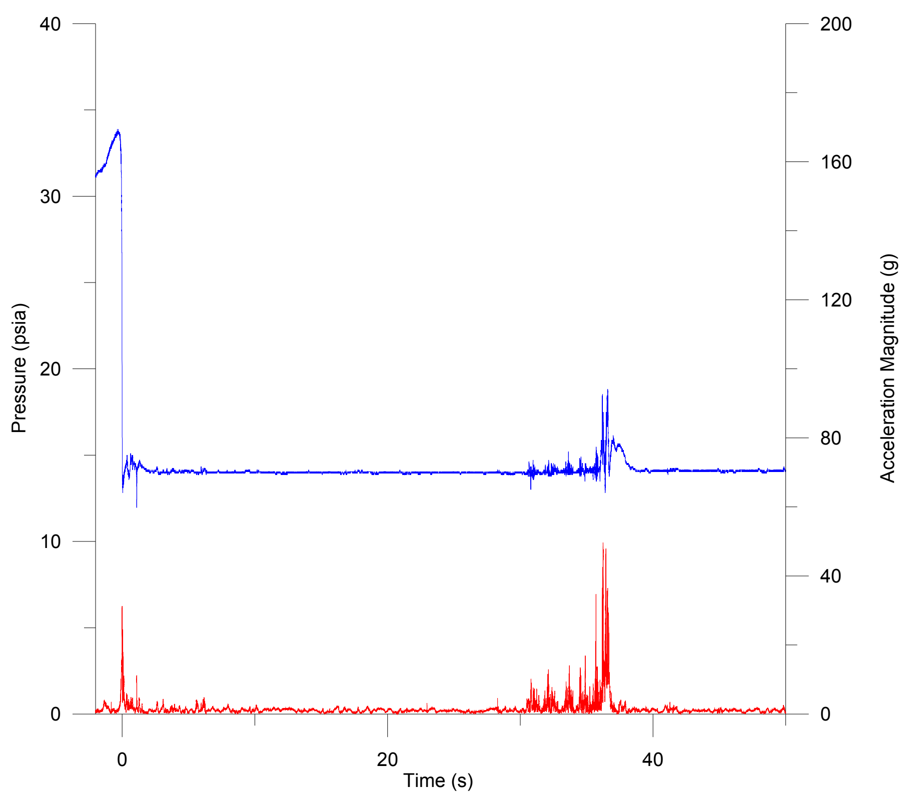

Cougar Dam RO, 1.5 ft Opening, F912 (3t)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

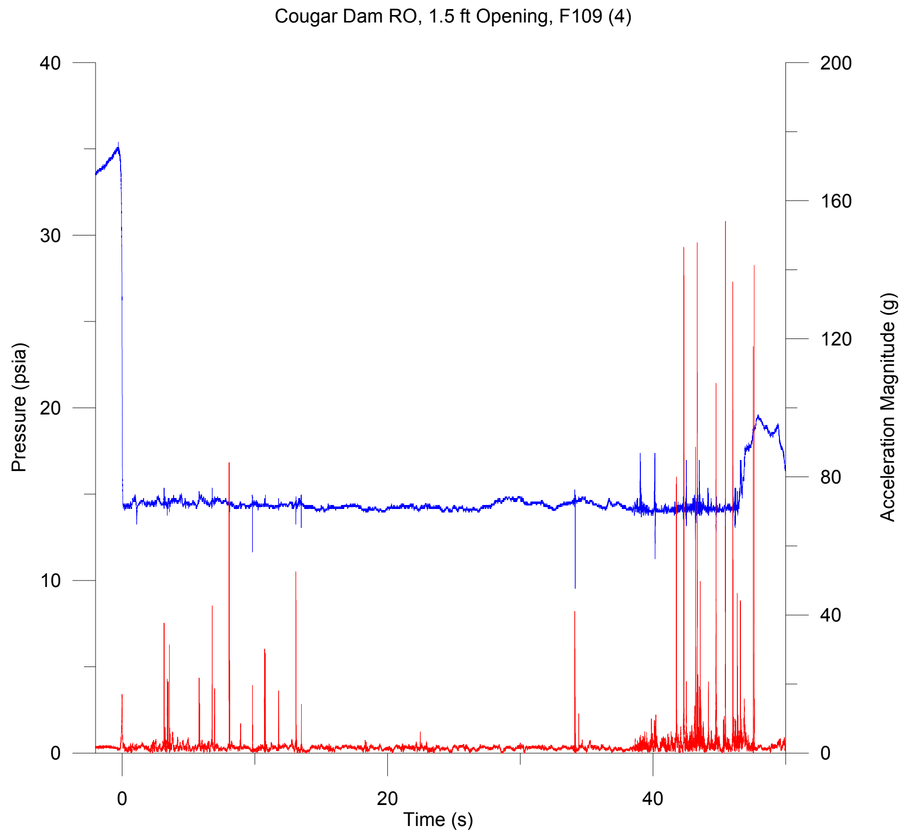

Cougar Dam RO, 1.5 ft Opening, F923 (1)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

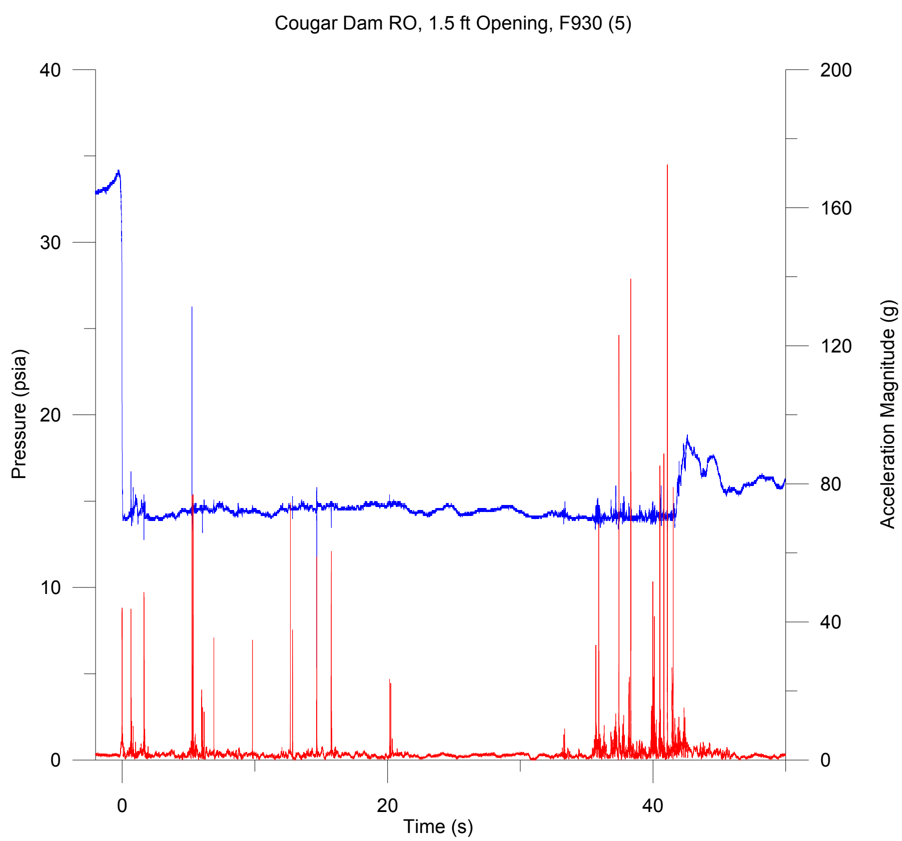
Cougar Dam RO, 1.5 ft Opening, F914 (2)



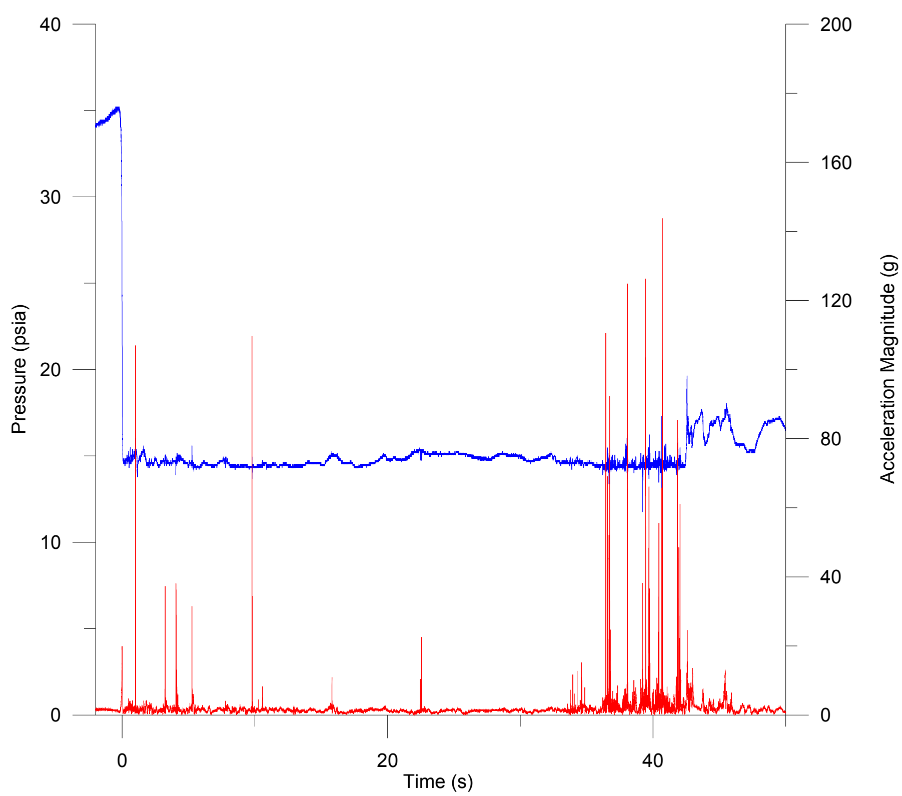
Cougar Dam RO, 1.5 ft Opening, F927 (3)



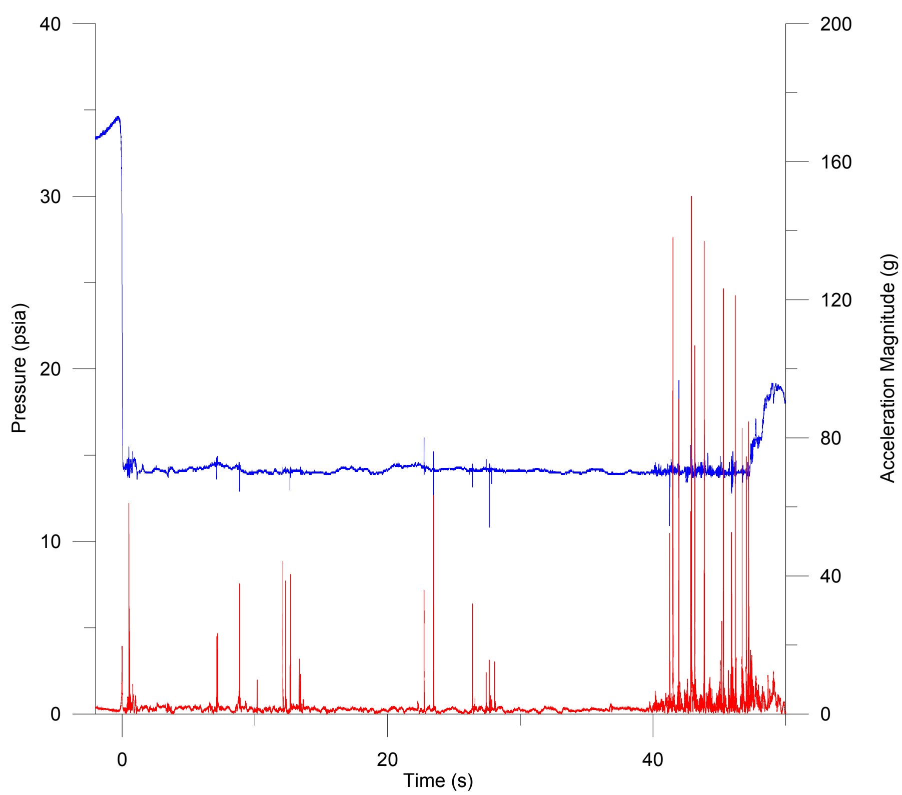

Cougar Dam RO, 1.5 ft Opening, F109 (4)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40


Cougar Dam RO, 1.5 ft Opening, F930 (5)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

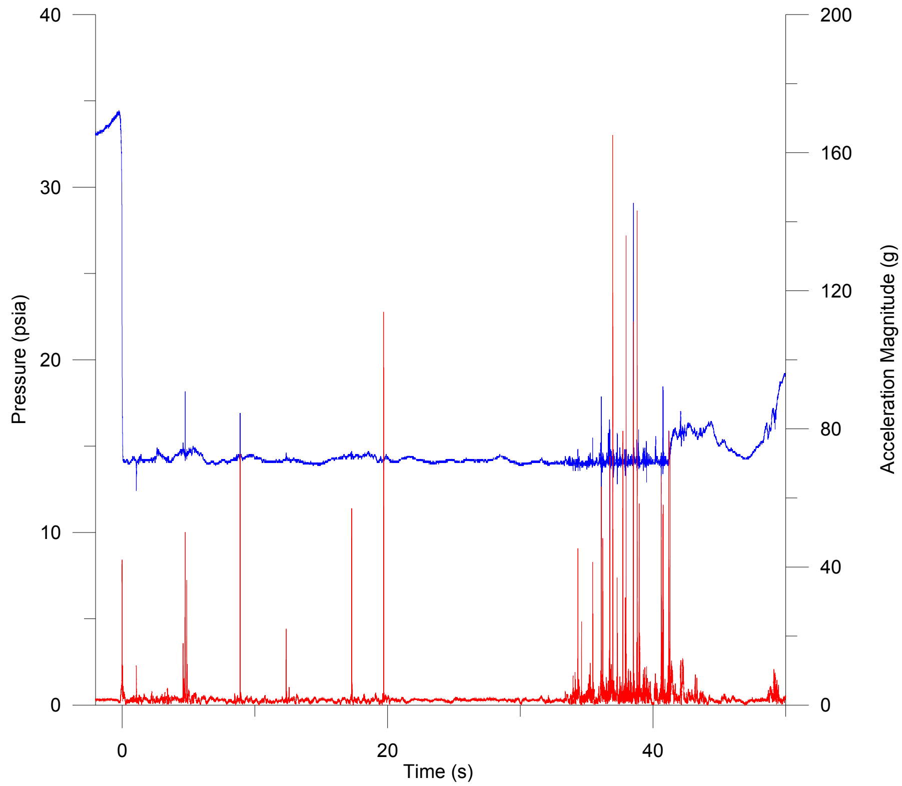
Cougar Dam RO, 1.5 ft Opening, F932 (6)



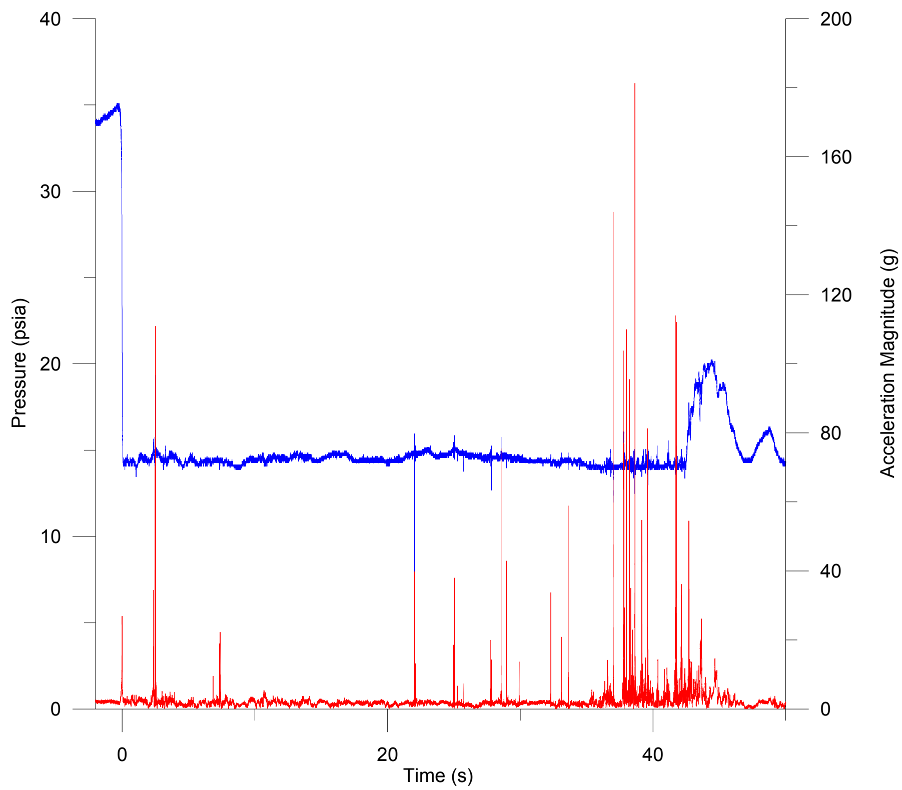
Cougar Dam RO, 1.5 ft Opening, F913 (7)

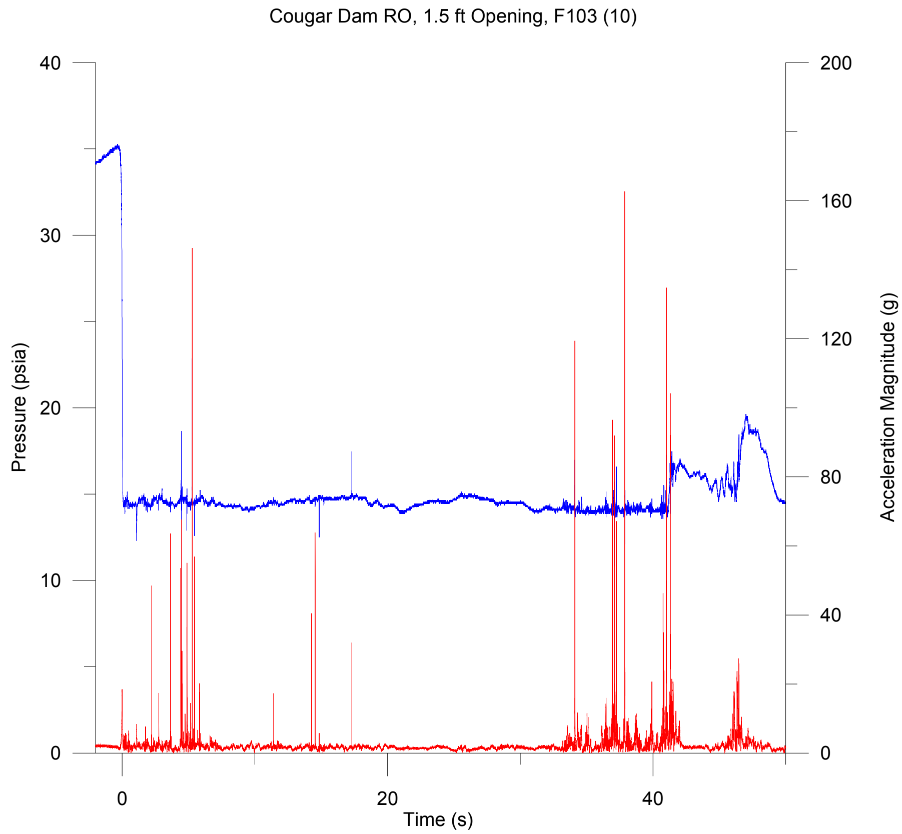


Cougar Dam RO, 1.5 ft Opening, F912 (8)

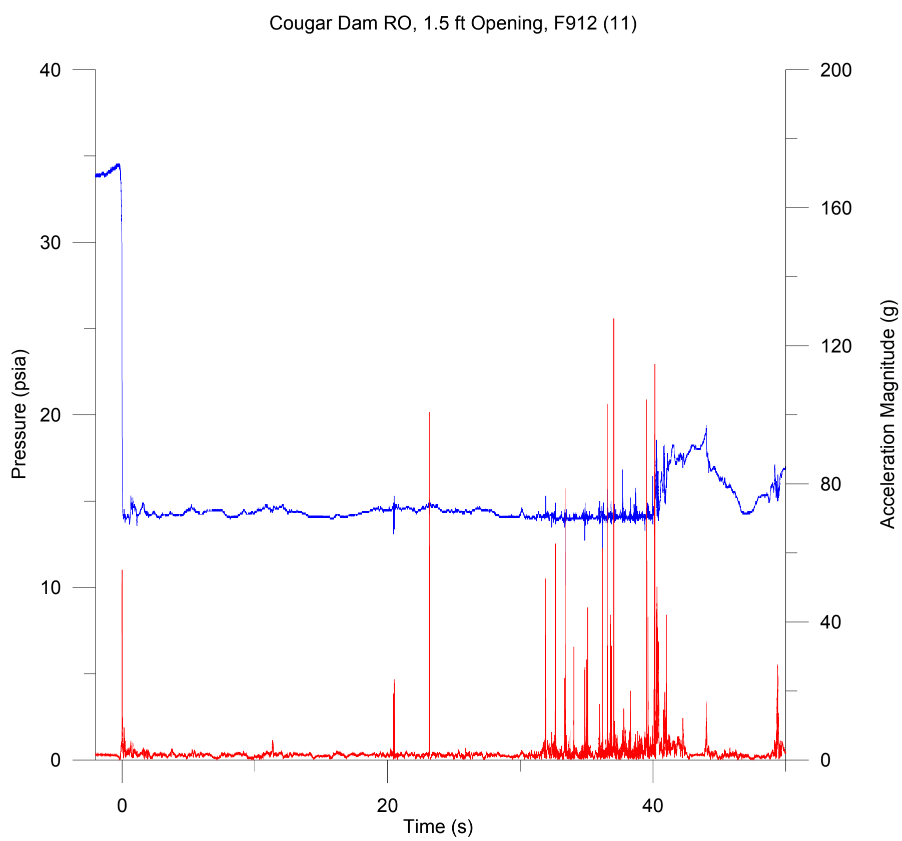


Cougar Dam RO, 1.5 ft Opening, F121 (9)

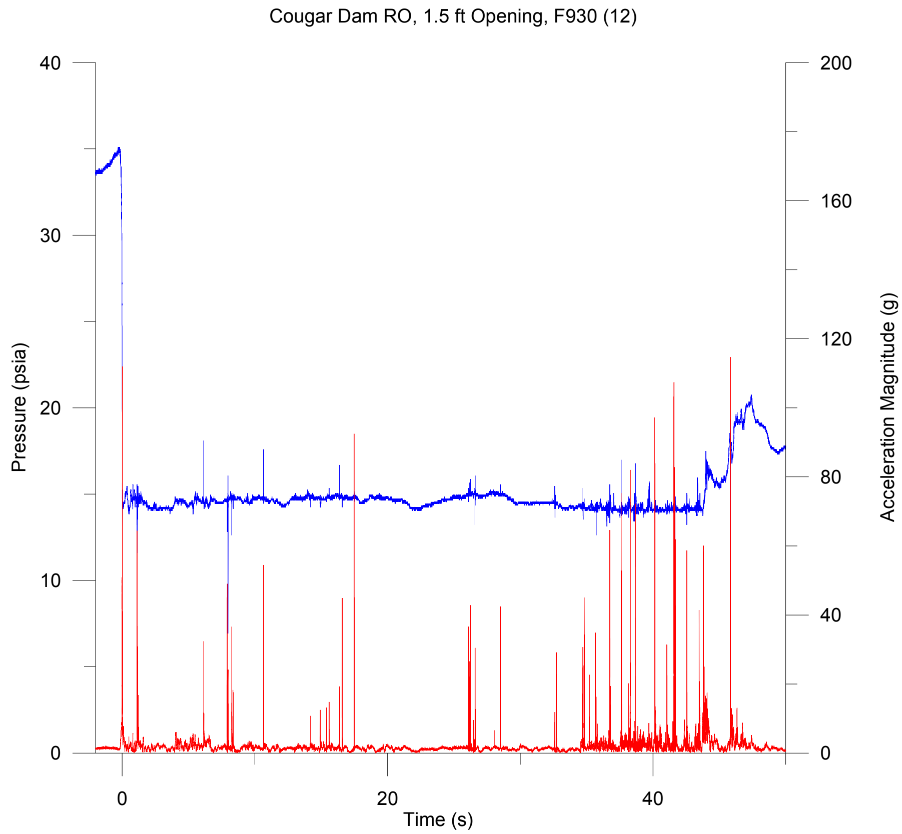




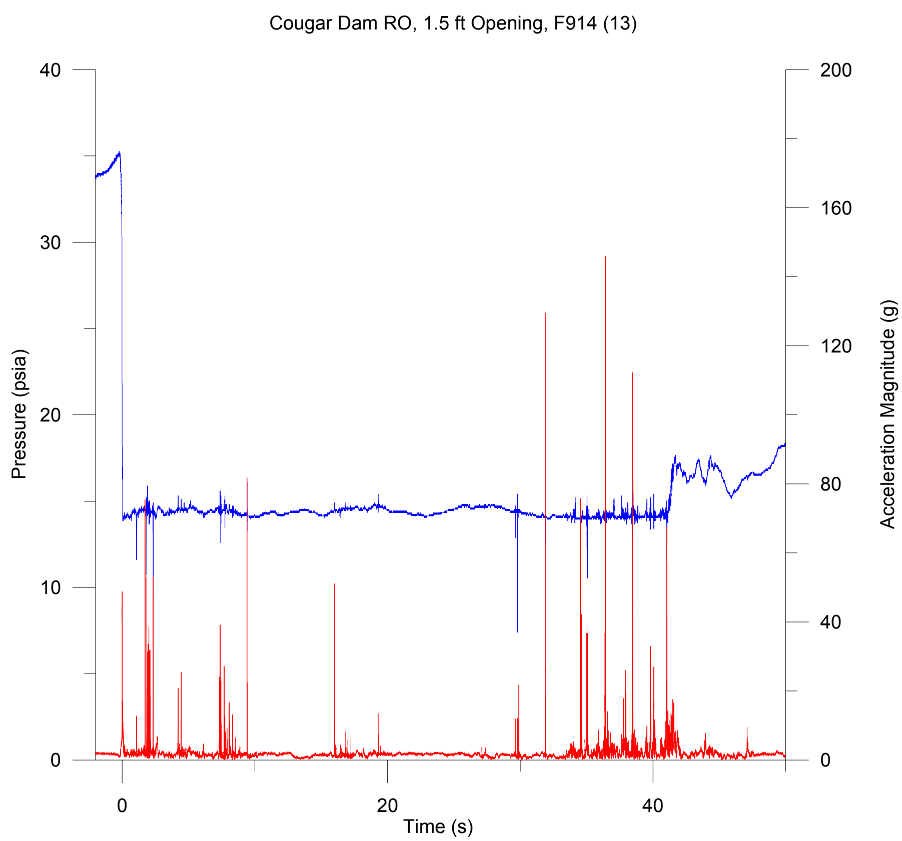
Cougar Dam RO, 1.5 ft Opening, F103 (10)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40



Cougar Dam RO, 1.5 ft Opening, F912 (11)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

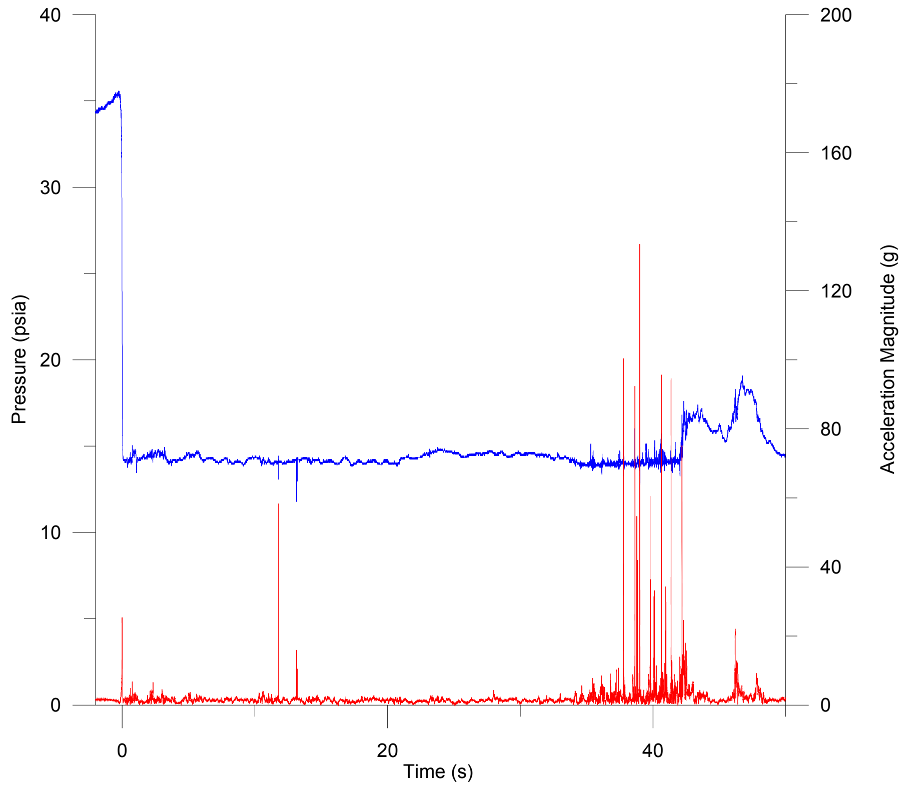


Cougar Dam RO, 1.5 ft Opening, F930 (12)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

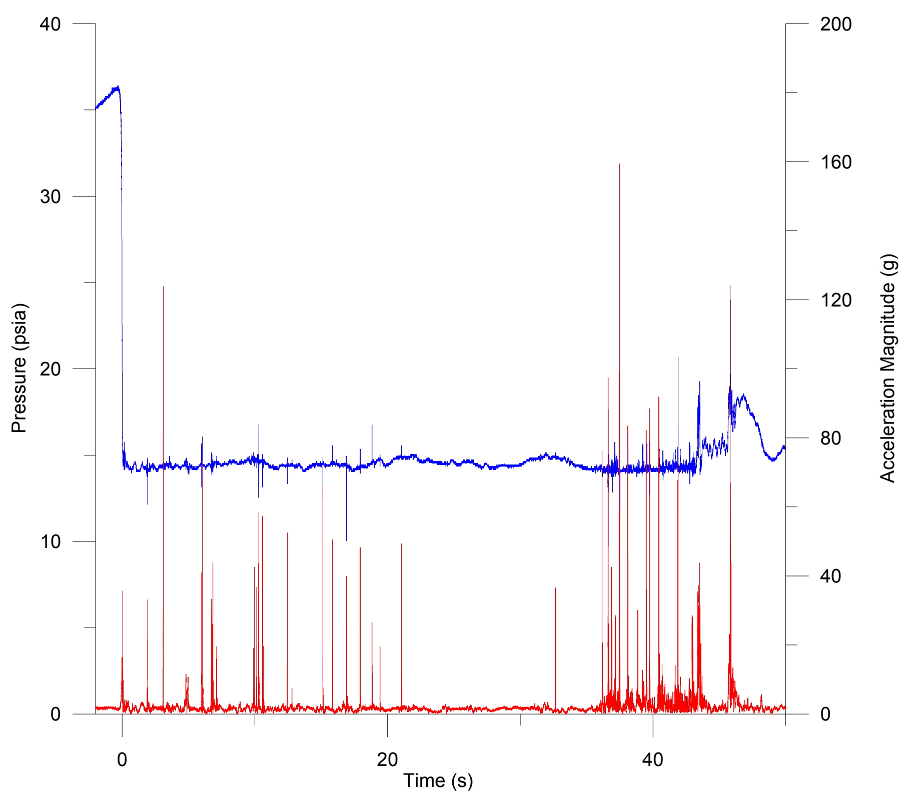


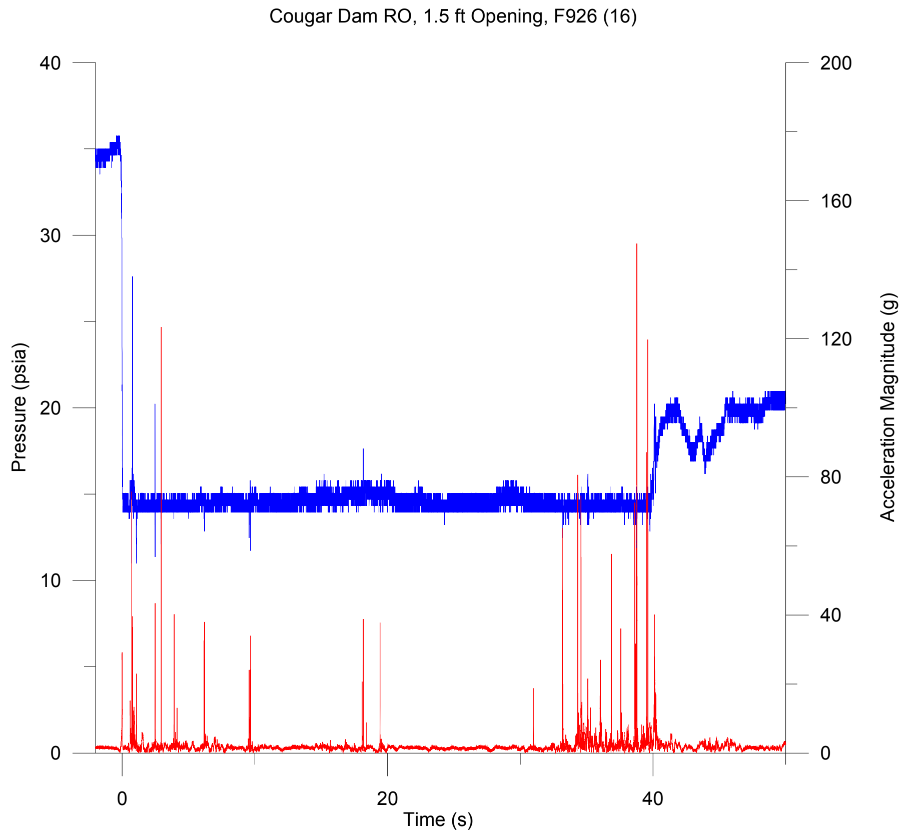
Cougar Dam RO, 1.5 ft Opening, F914 (13)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

Cougar Dam RO, 1.5 ft Opening, F923 (14)



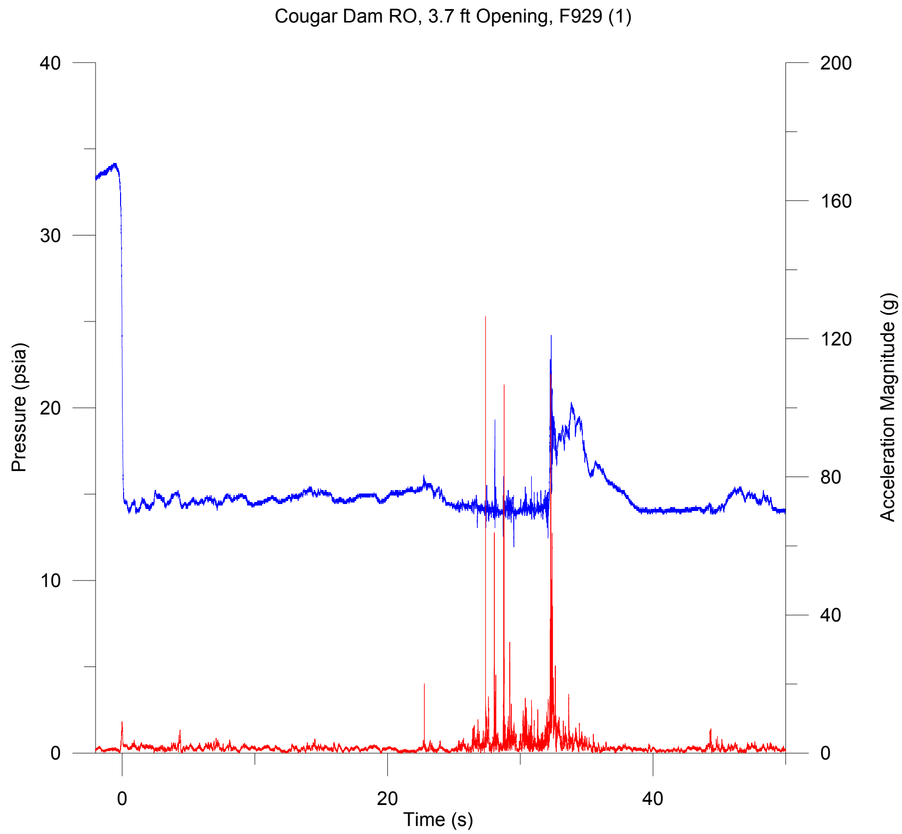
Cougar Dam RO, 1.5 ft Opening, F109 (15)

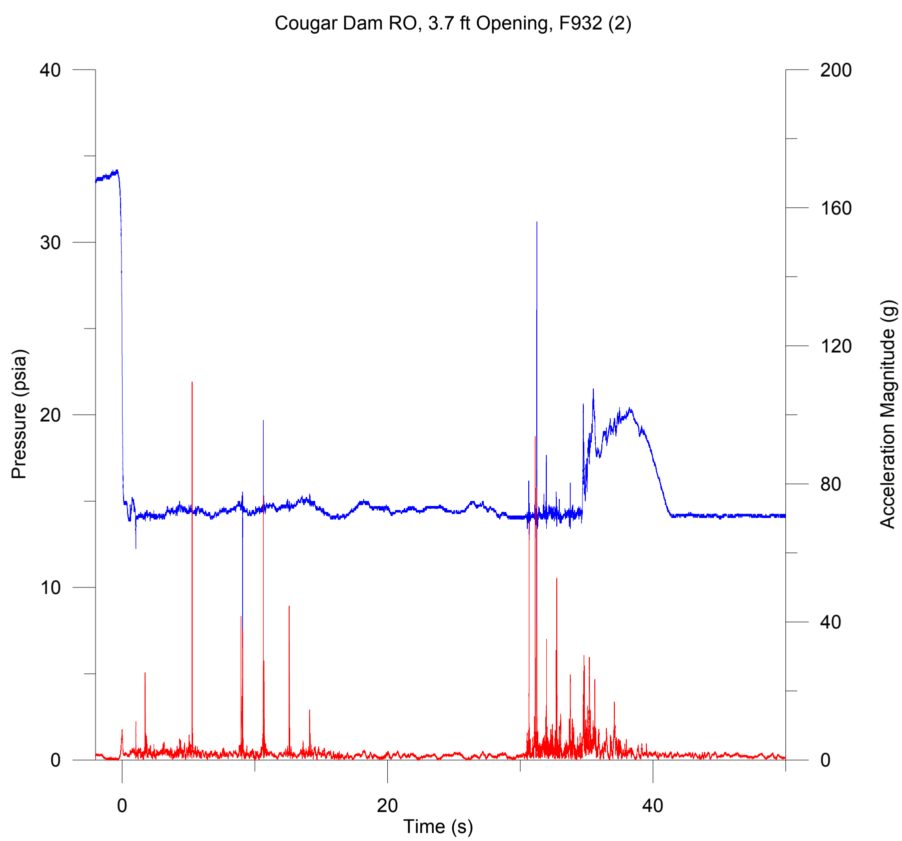


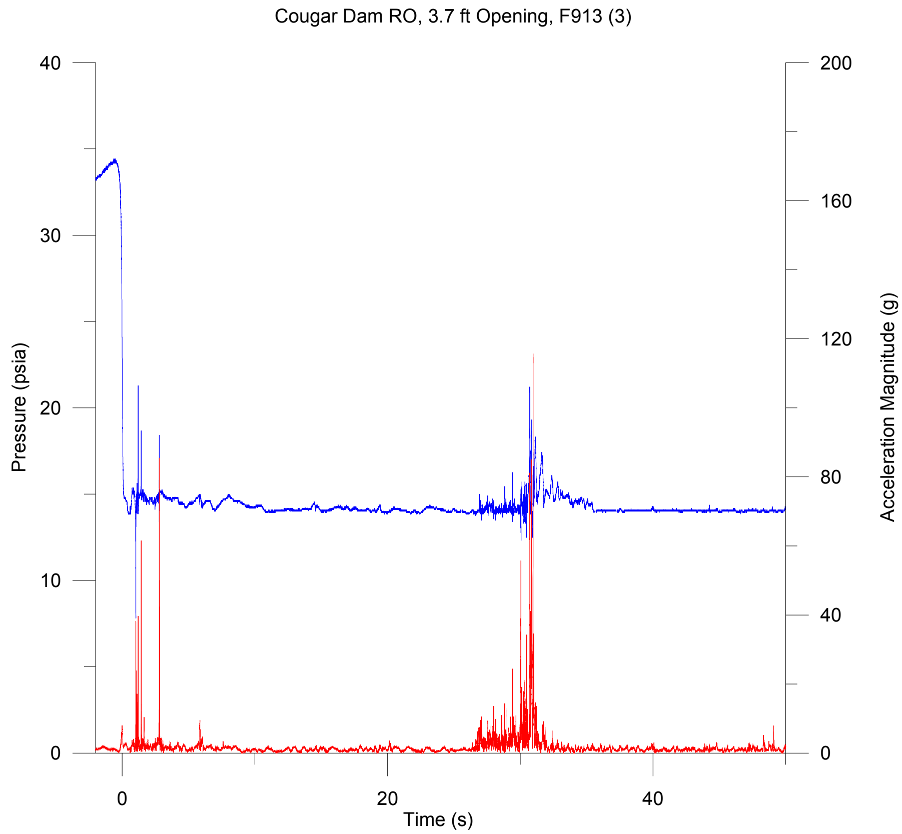

Cougar Dam RO, 1.5 ft Opening, F926 (16)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

Cougar Dam Regulating Outlet

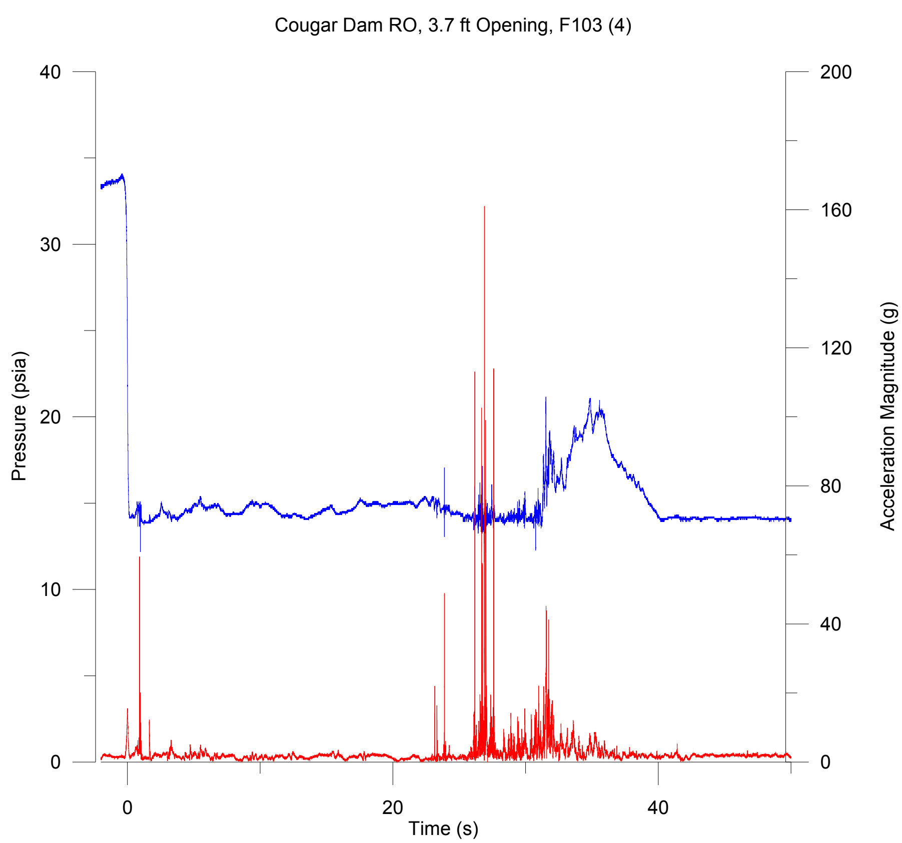
3.7-ft Gate Opening


Cougar Dam RO, 3.7 ft Opening, F929 (1)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

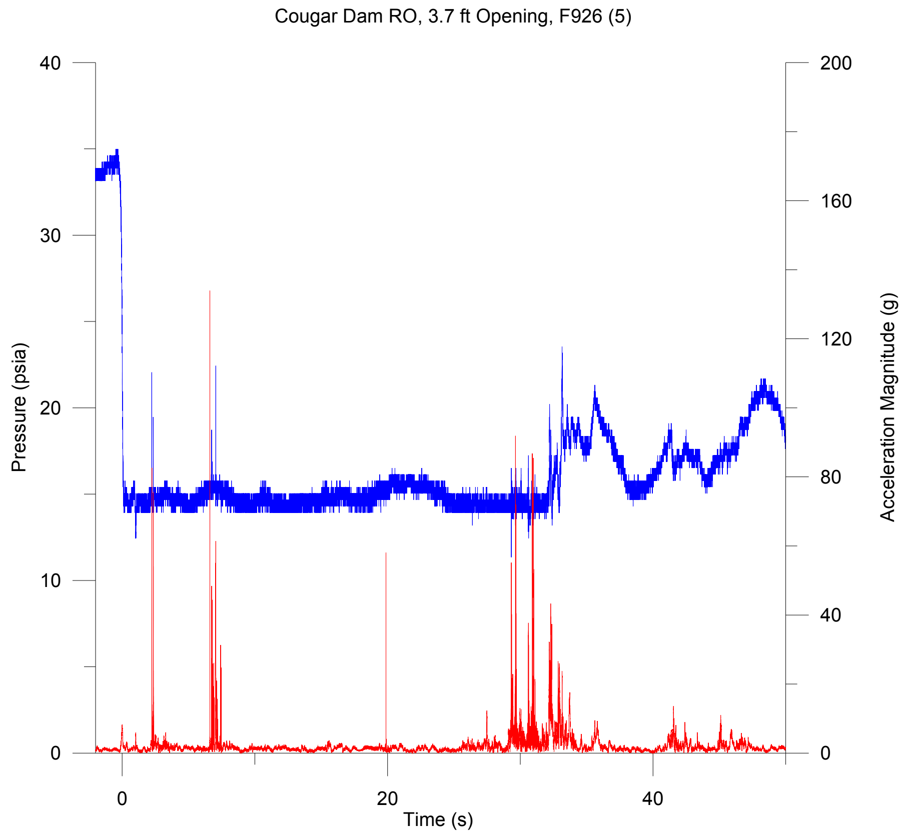

Cougar Dam RO, 3.7 ft Opening, F932 (2)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

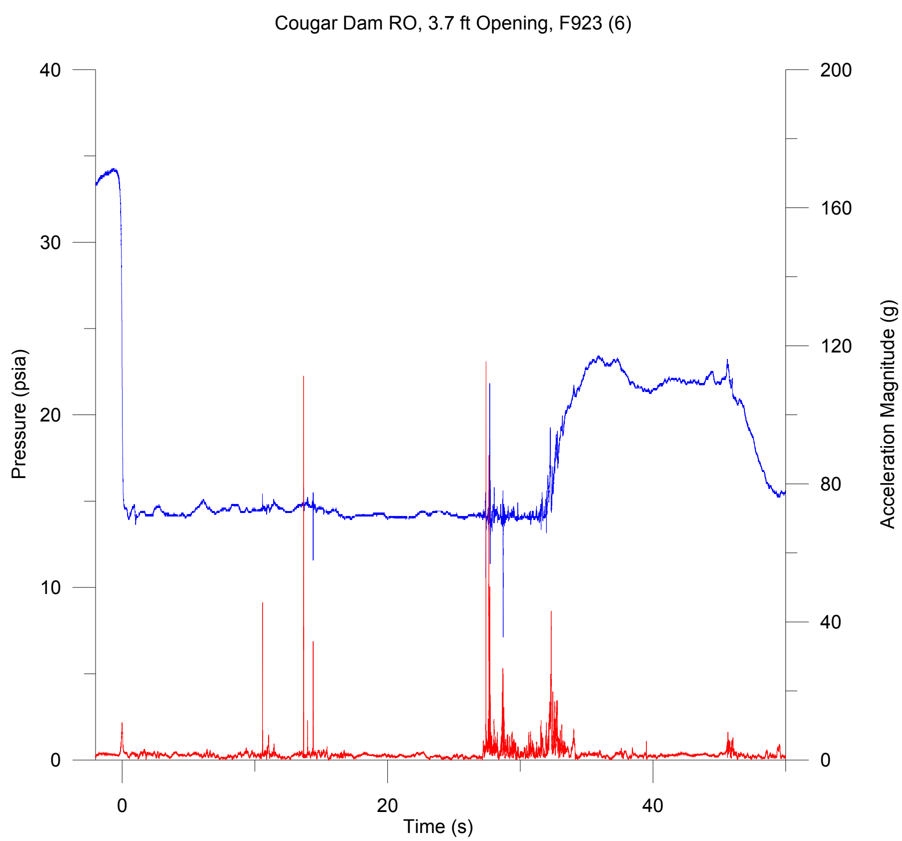


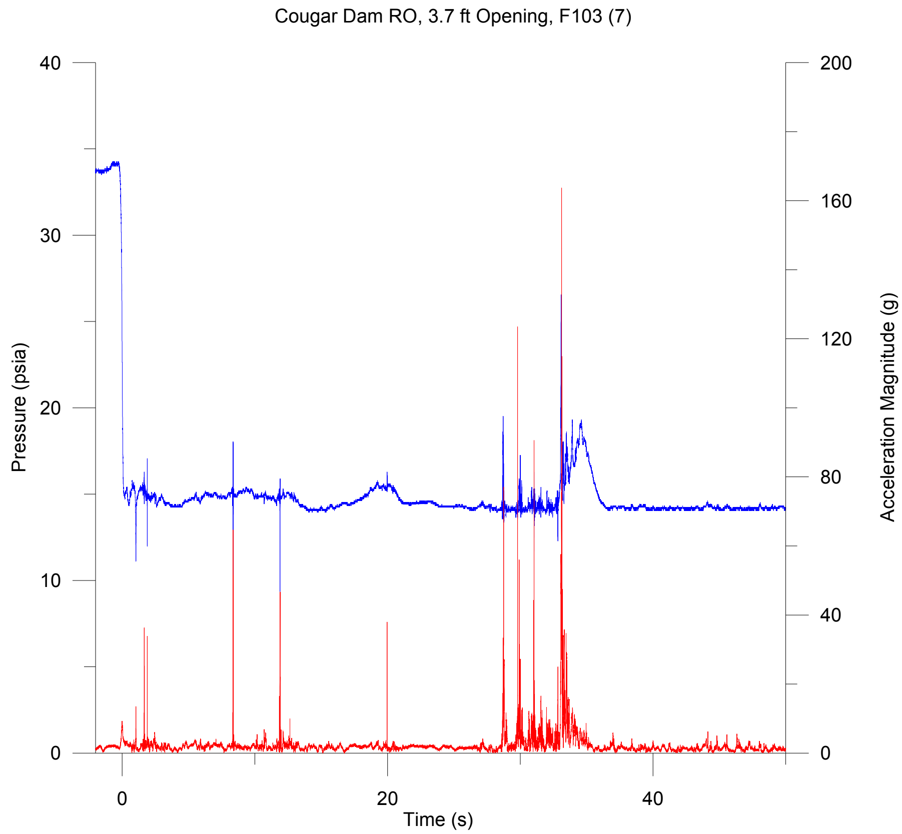
Cougar Dam RO, 3.7 ft Opening, F913 (3)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

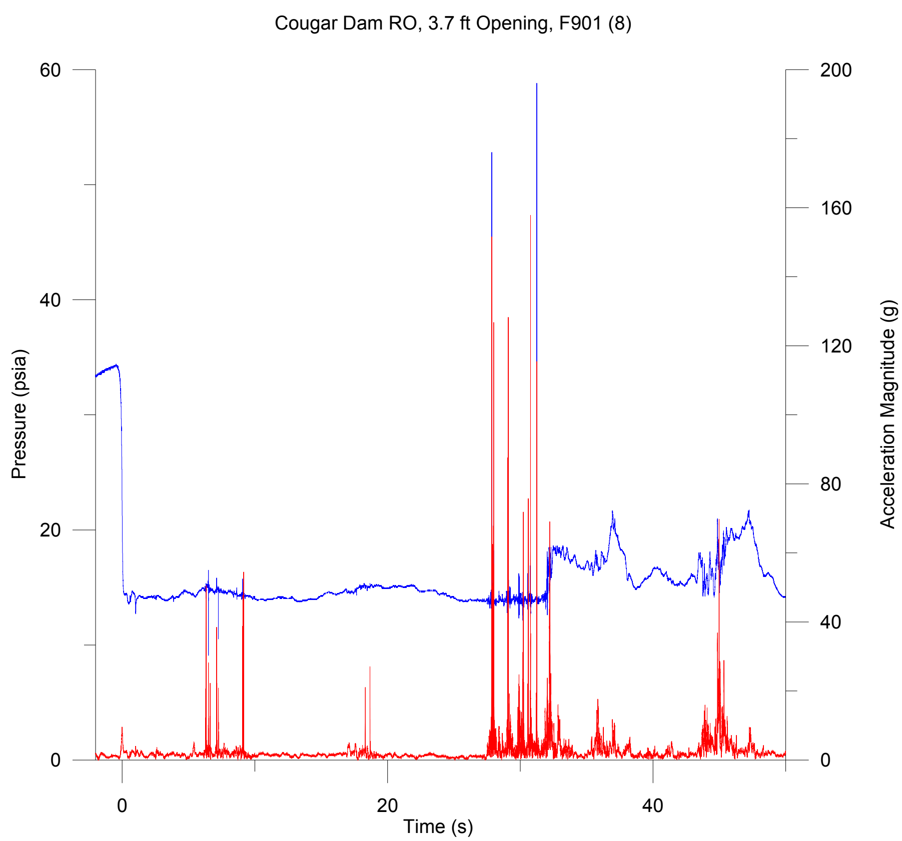


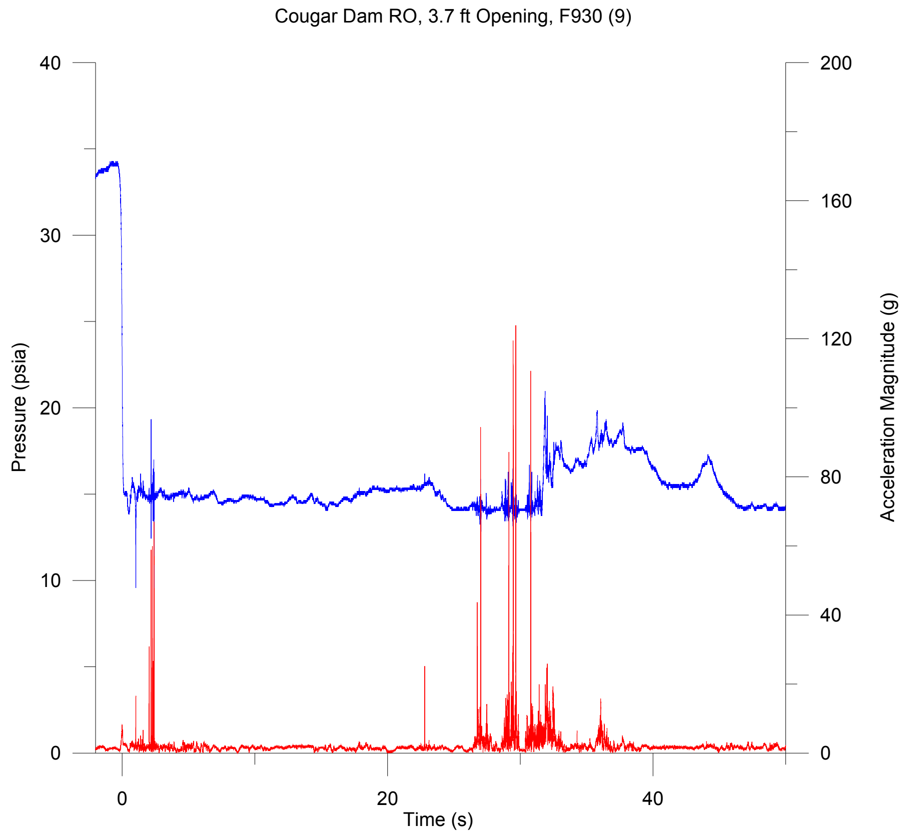
Cougar Dam RO, 3.7 ft Opening, F103 (4)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200
0
20
40

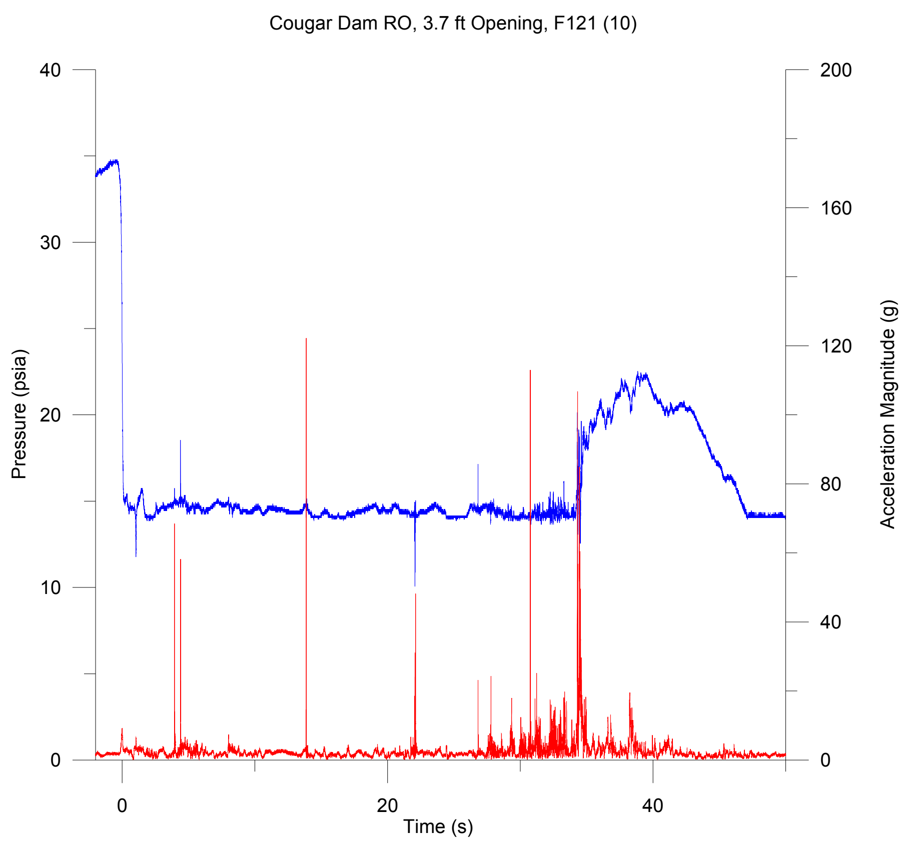

Cougar Dam RO, 3.7 ft Opening, F926 (5)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200

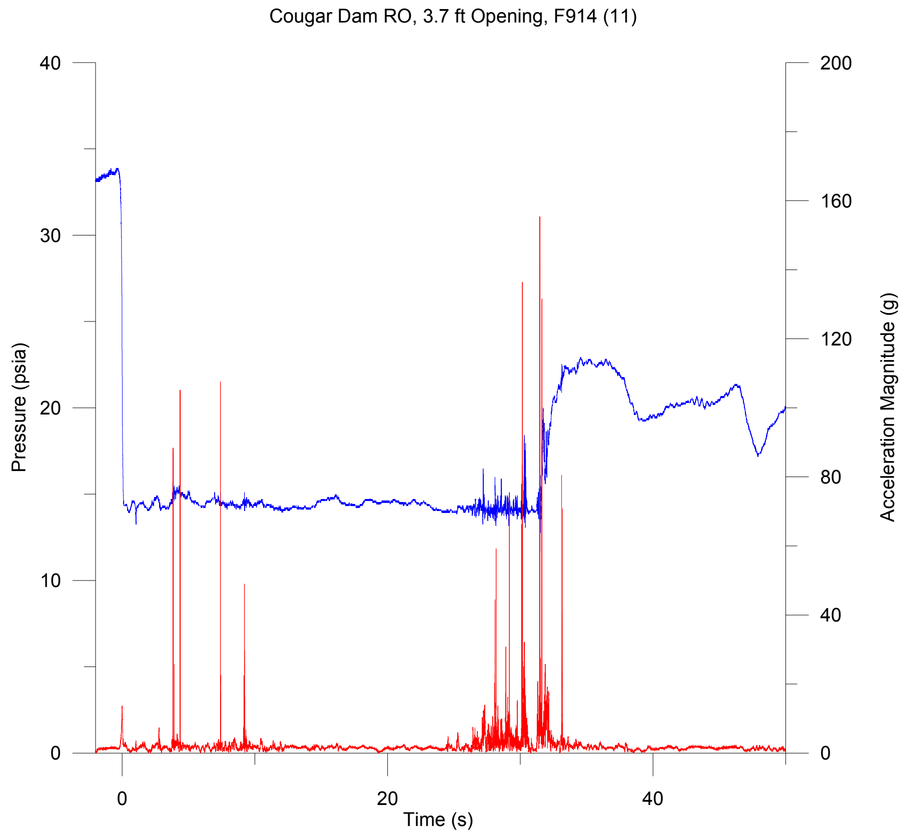

Cougar Dam RO, 3.7 ft Opening, F923 (6)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200


Cougar Dam RO, 3.7 ft Opening, F103 (7)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
40
30
20
10
0
200
160
120
80
40
0
0
20
40

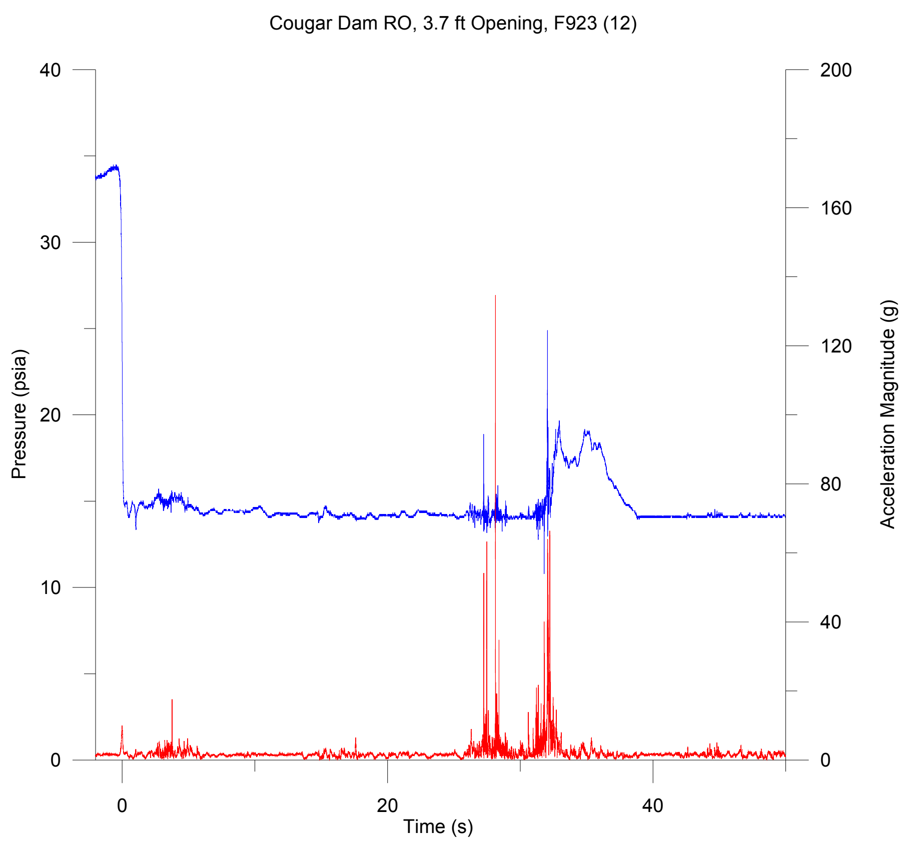

Cougar Dam RO, 3.7 ft Opening, F901 (8)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
60
40
20
0
200
160
120
80
40
0
0
20
40


Cougar Dam RO, 3.7 ft Opening, F930 (9)
40
30
20
10
0
Pressure (psia)
200
160
120
80
40
0
Acceleration Magnitude (g)
0
20
40
Time (s)

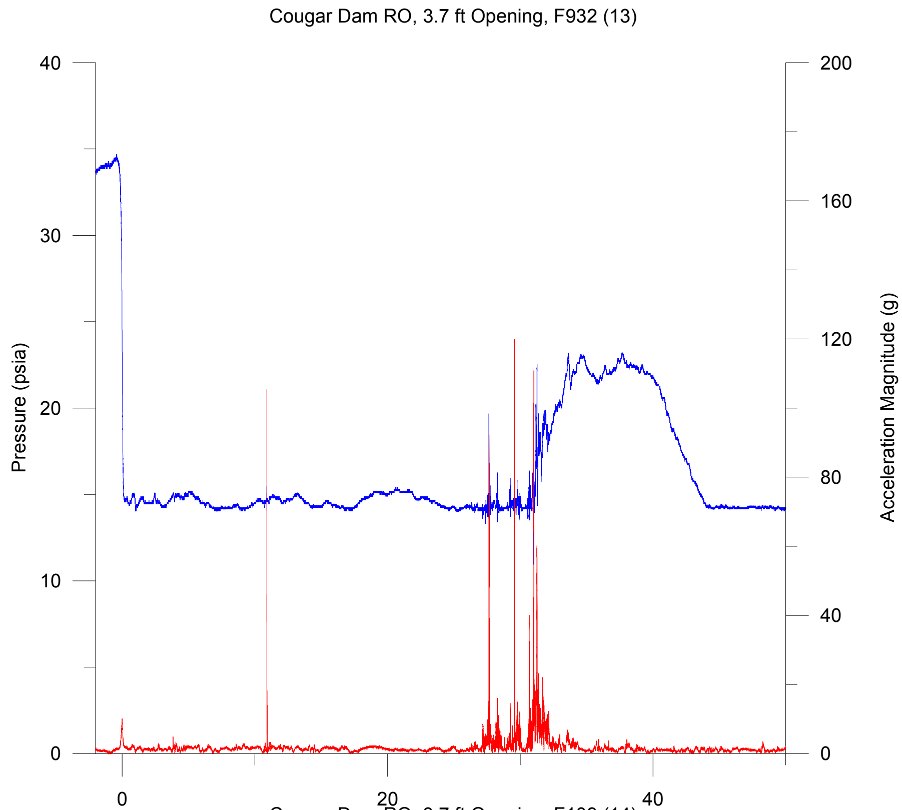

Cougar Dam RO, 3.7 ft Opening, F121 (10)
40
30
20
10
0
Pressure (psia)
200
160
120
80
40
0
Acceleration Magnitude (g)
0
20
40
Time (s)

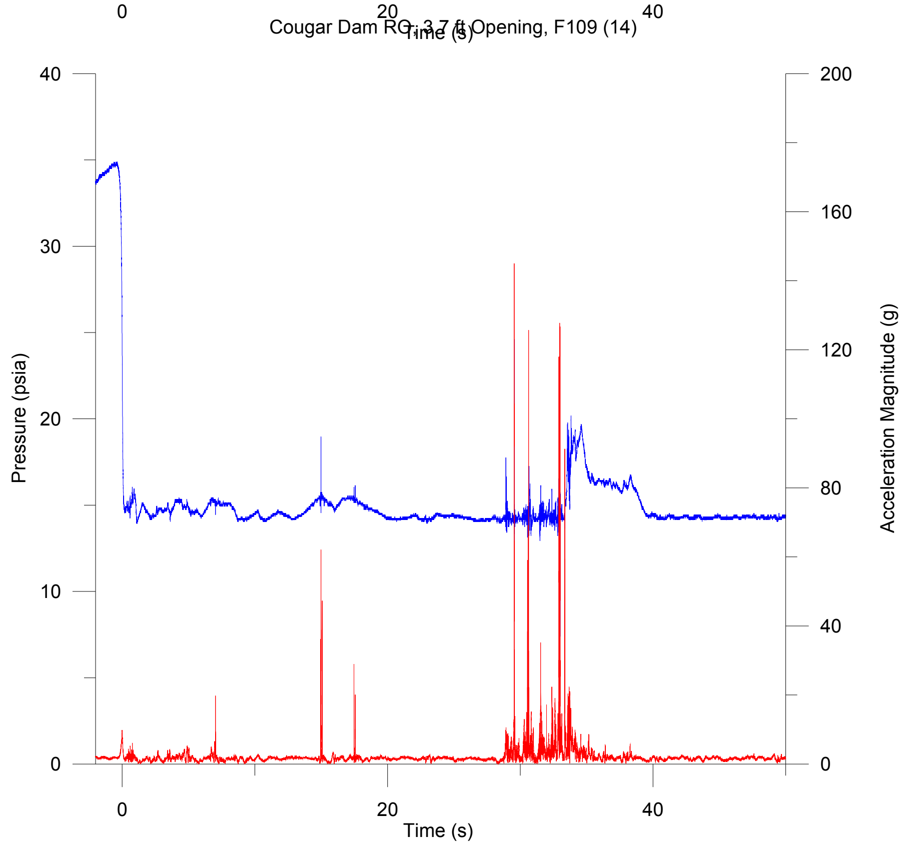


Cougar Dam RO, 3.7 ft Opening, F914 (11)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
40
30
20
10
0
200
160
120
80
40
0
0
20
40

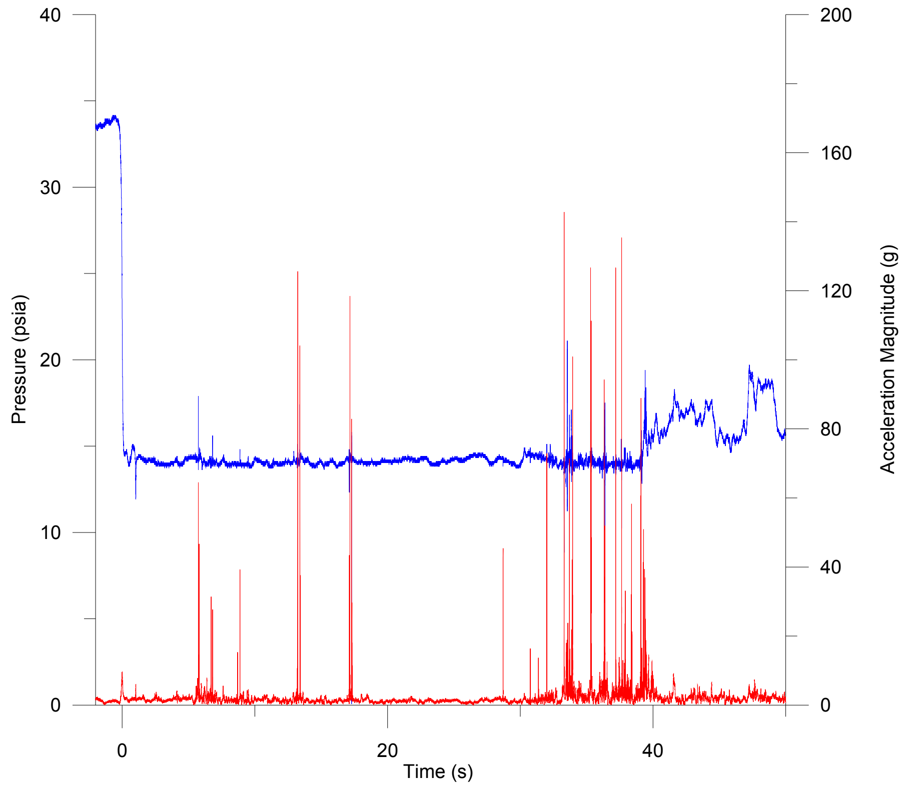


Cougar Dam RO, 3.7 ft Opening, F923 (12)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
40
30
20
10
0
200
160
120
80
40
0
0
20
40

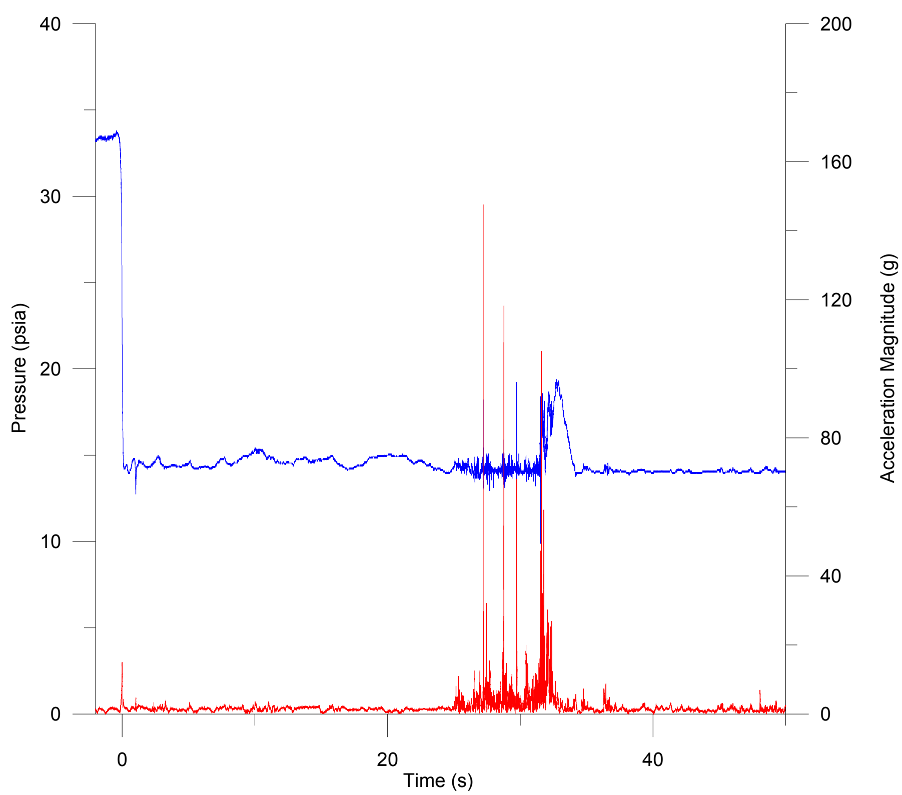

Cougar Dam RO, 3.7 ft Opening, F932 (13)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200


Cougar Dam RO, 3.7 ft Opening, F109 (14)
Pressure (psia)
Acceleration Magnitude (g)
Time (s)
0
10
20
30
40
0
40
80
120
160
200

Cougar Dam RO, 3.7 ft Opening, F929 (15)

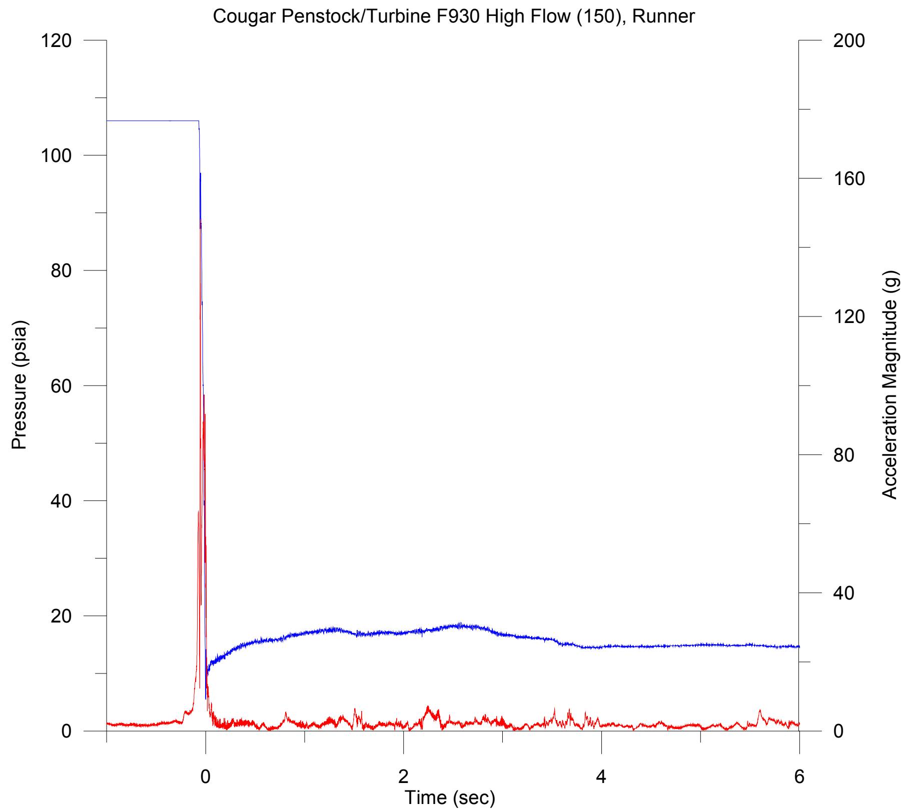


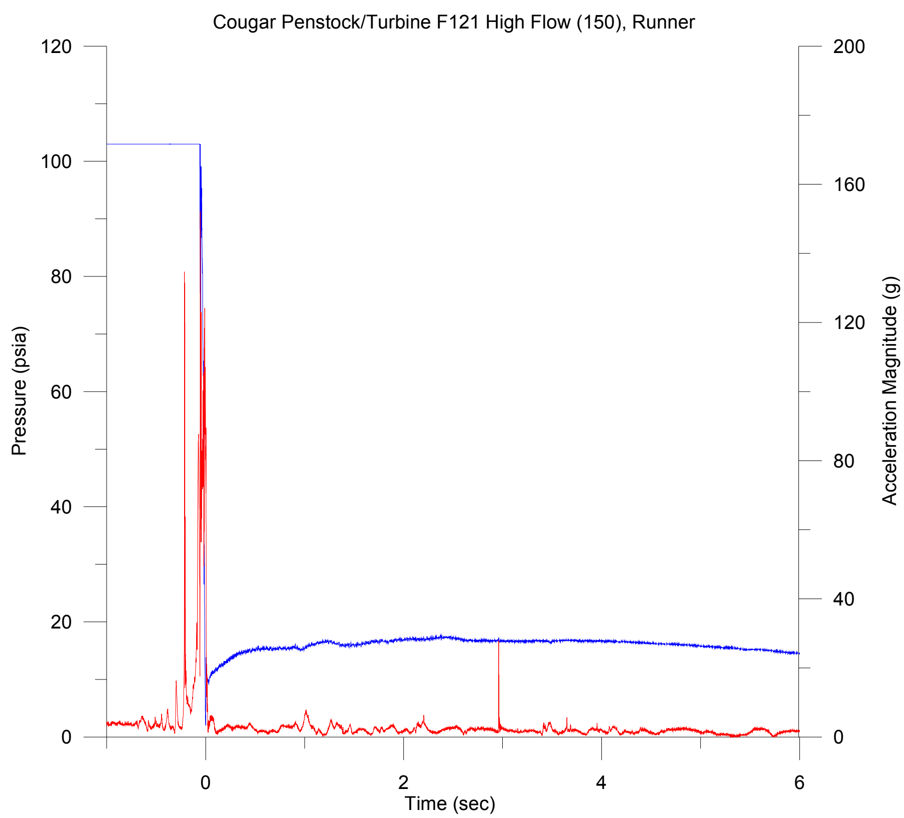
Cougar Dam RO, 3.7 ft Opening, F913 (16)

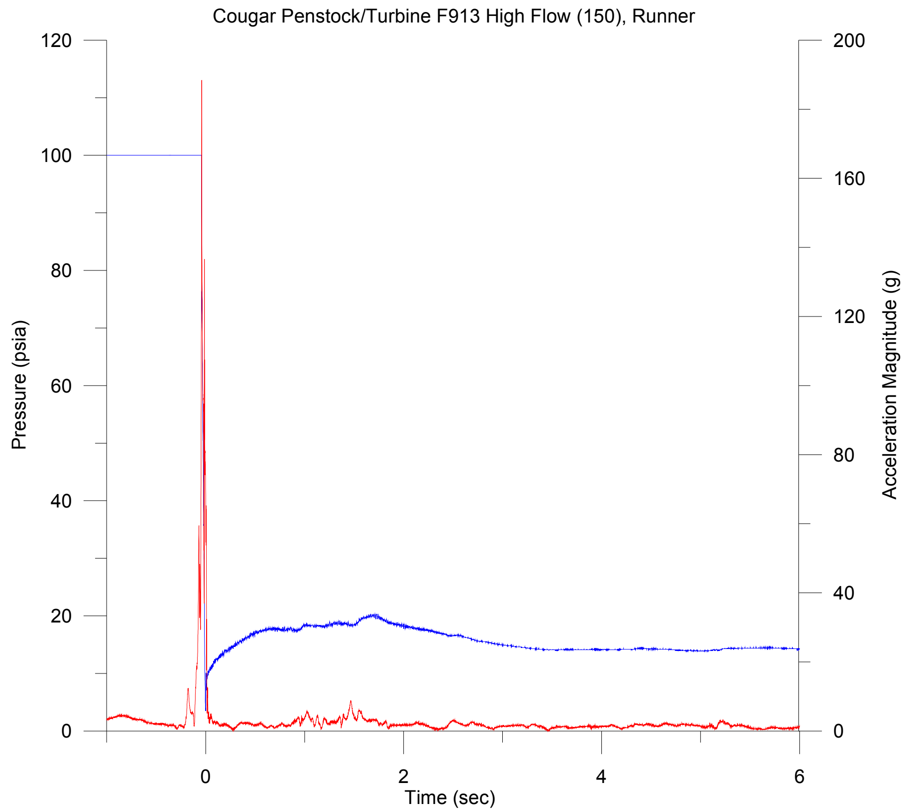


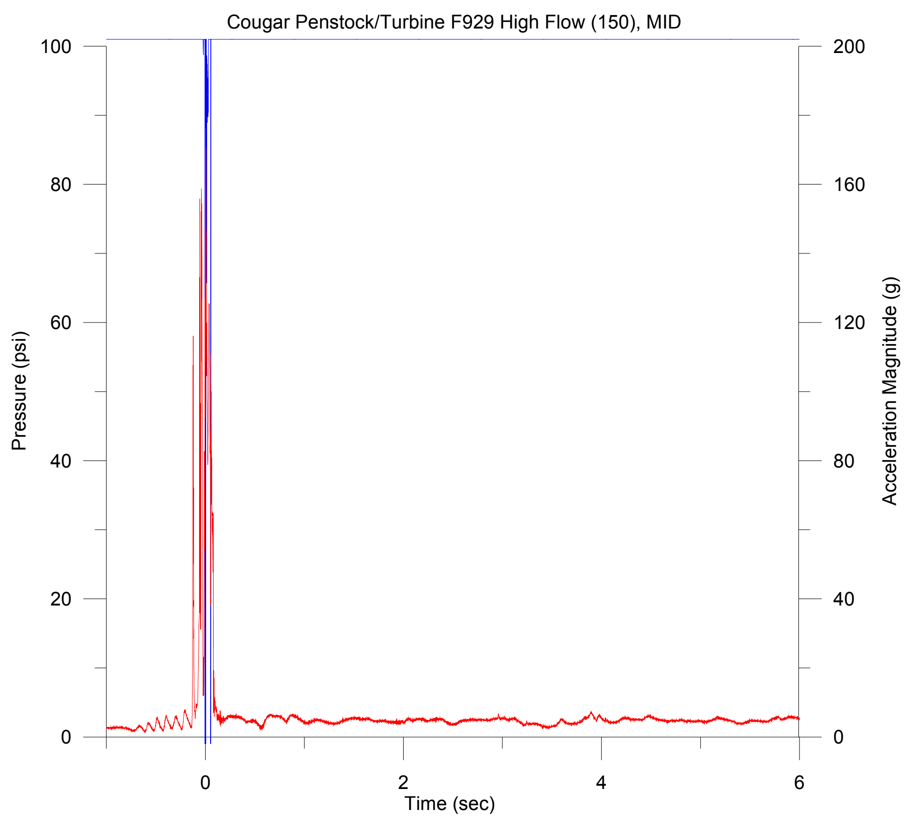
Cougar Dam Turbine Unit 2

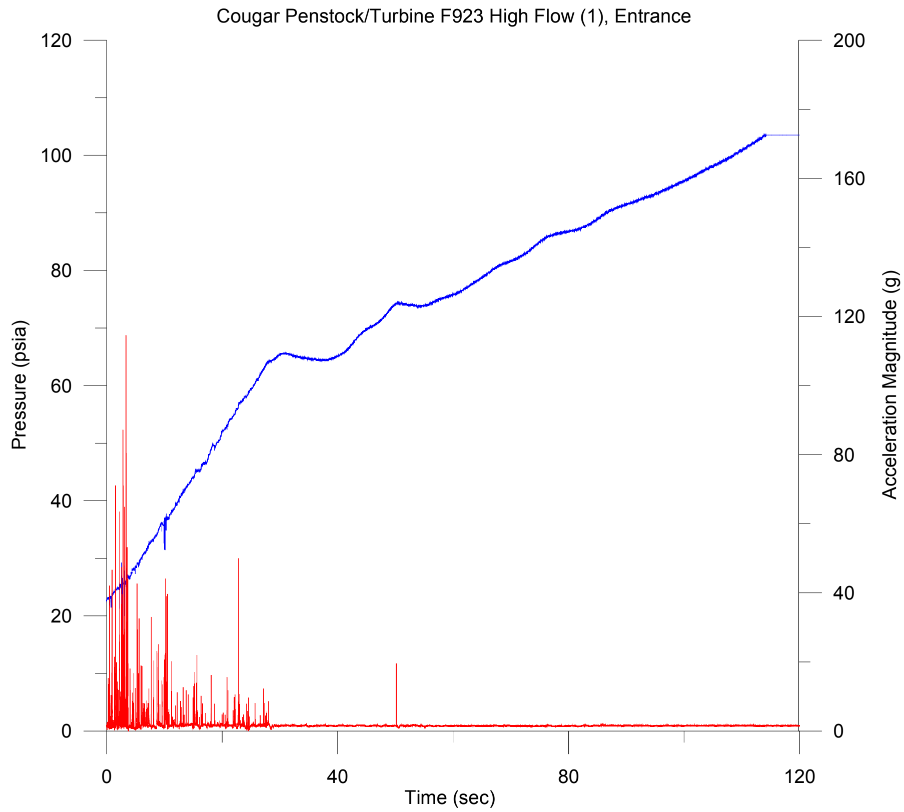
Maximum Wicket Gate Opening


Cougar Penstock/Turbine F930 High Flow (150), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
2
4
6

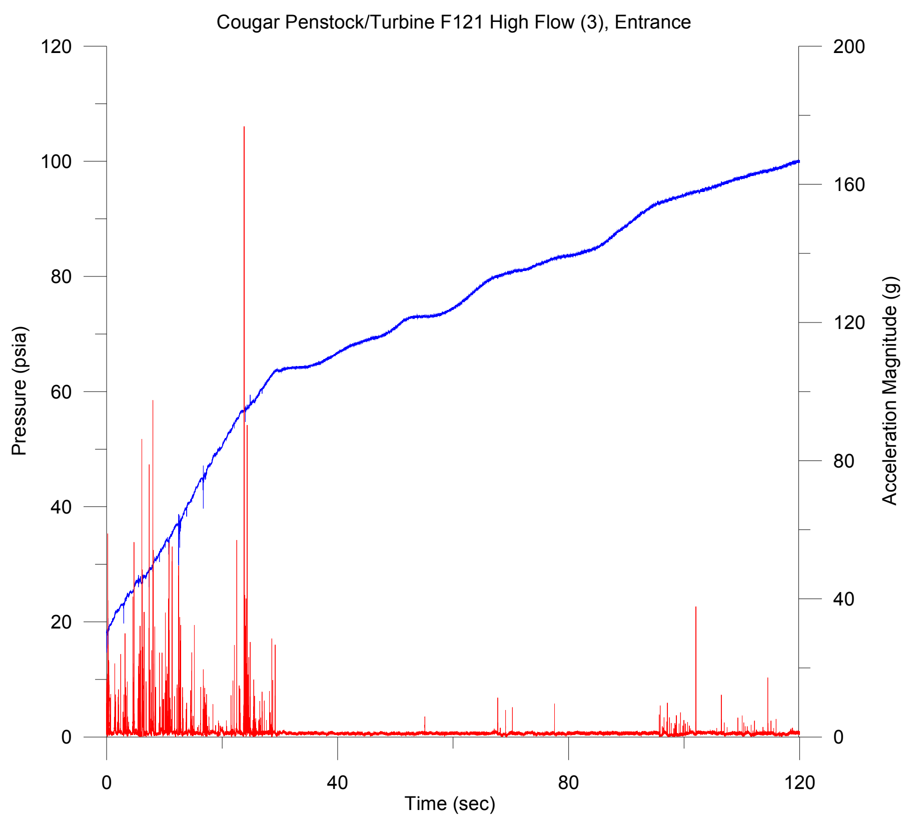

Cougar Penstock/Turbine F121 High Flow (150), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
2
4
6


Cougar Penstock/Turbine F913 High Flow (150), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
120
100
80
60
40
20
0
200
160
120
80
40
0
0
2
4
6

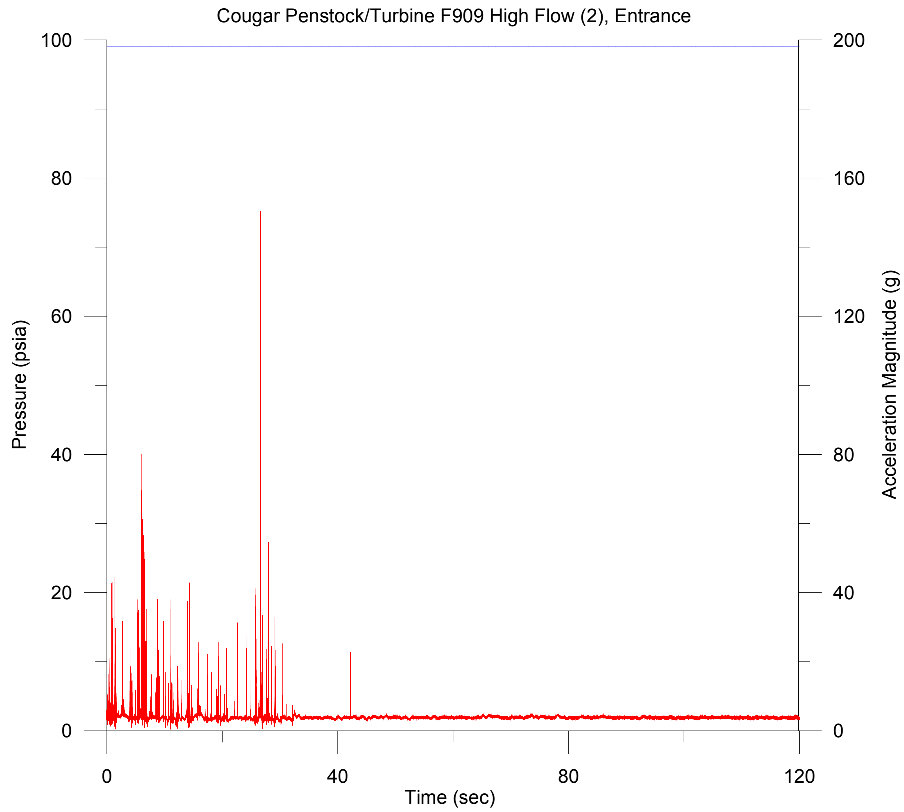

Cougar Penstock/Turbine F929 High Flow (150), MID
Pressure (psi)
Acceleration Magnitude (g)
Time (sec)
100
80
60
40
20
0
200
160
120
80
40
0
0
2
4
6



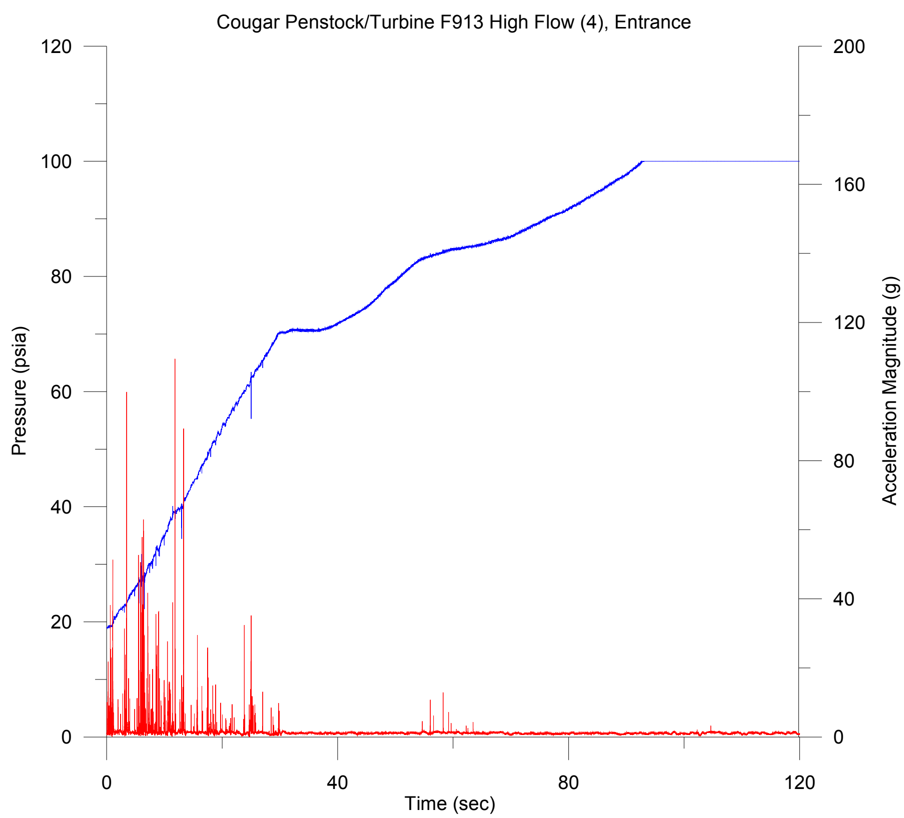
Cougar Penstock/Turbine F923 High Flow (1), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
40
80
120
0
20
40
60
80
100
120
0
40
80
120
160
200



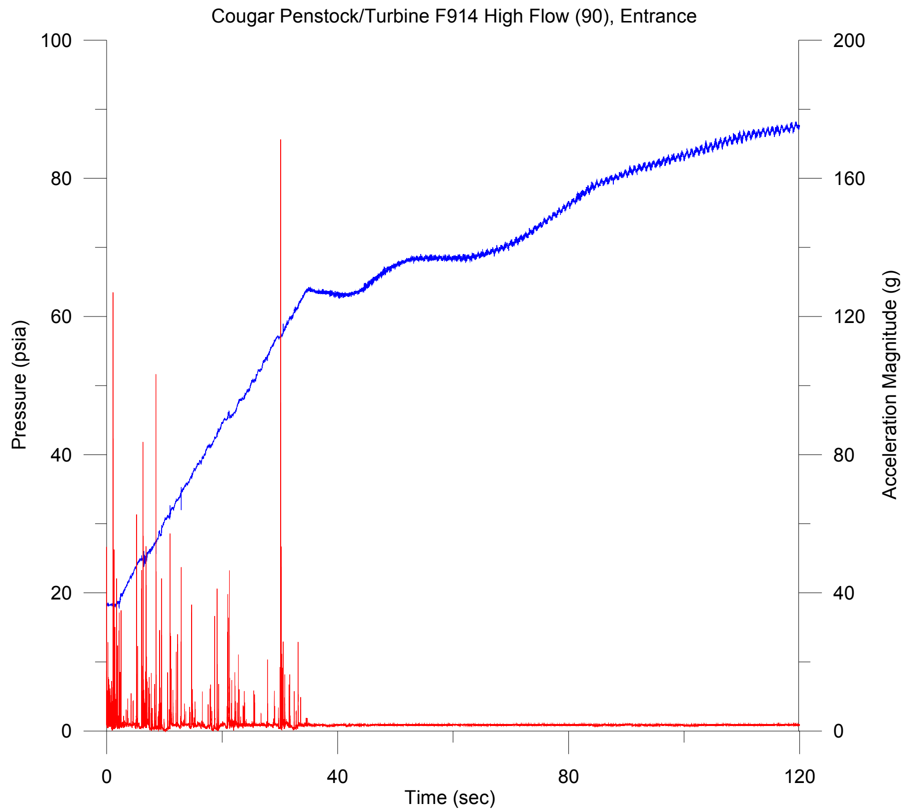
Cougar Penstock/Turbine F121 High Flow (3), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
40
80
120
0
20
40
60
80
100
120
0
40
80
120
160
200



Cougar Penstock/Turbine F909 High Flow (2), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
0
40
80
120
160
200
0
40
80
120



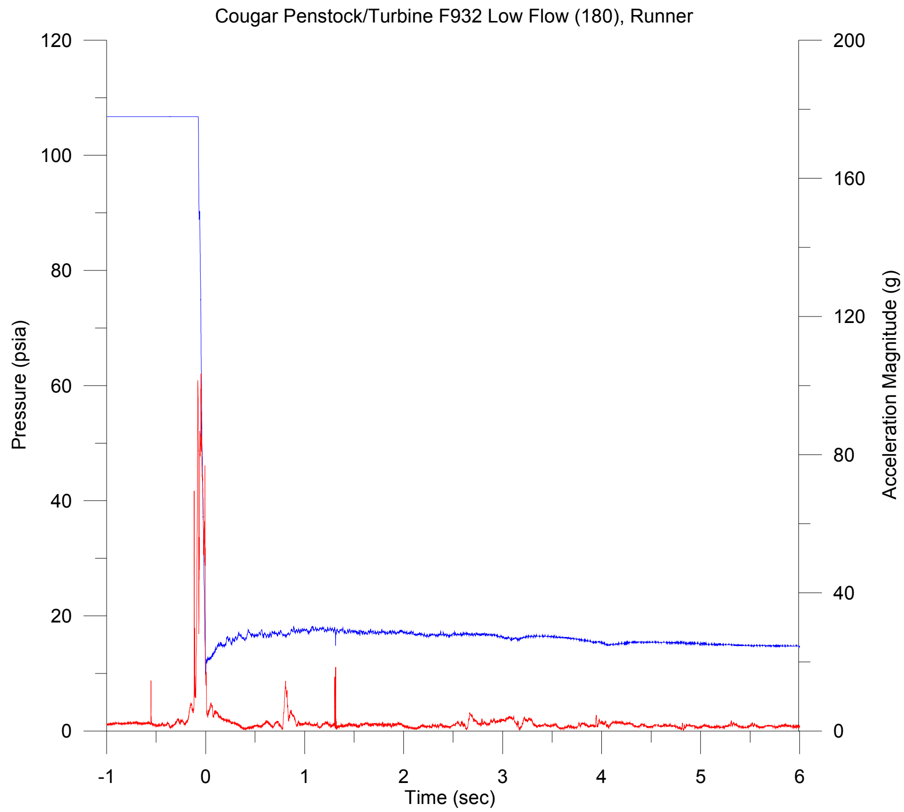
Cougar Penstock/Turbine F913 High Flow (4), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
40
80
120

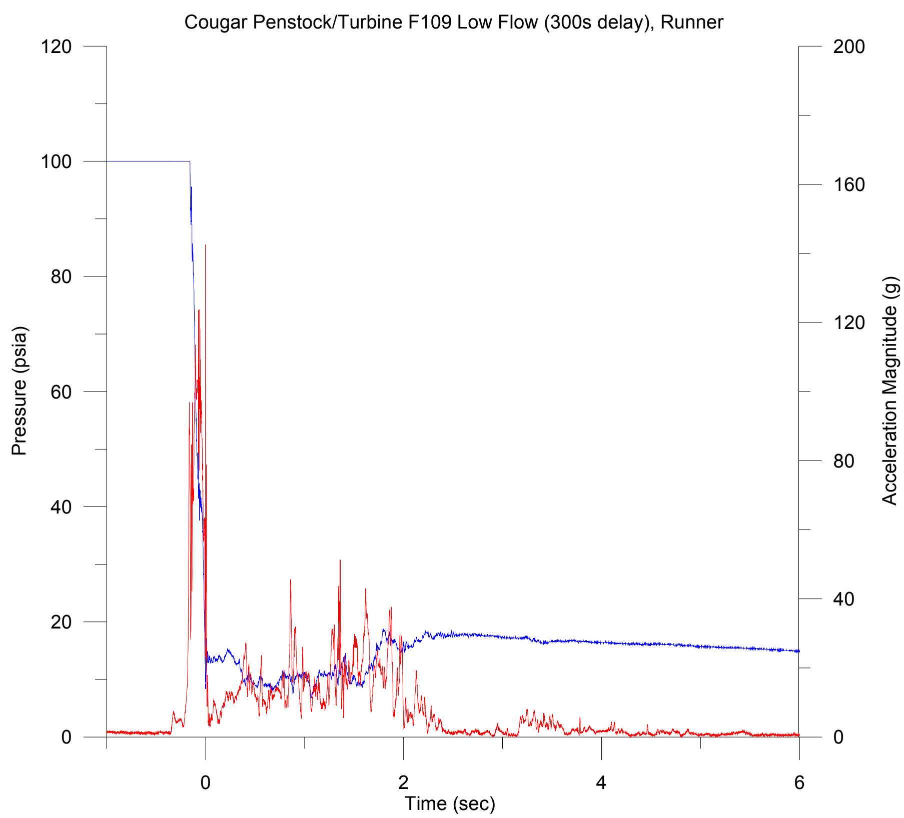


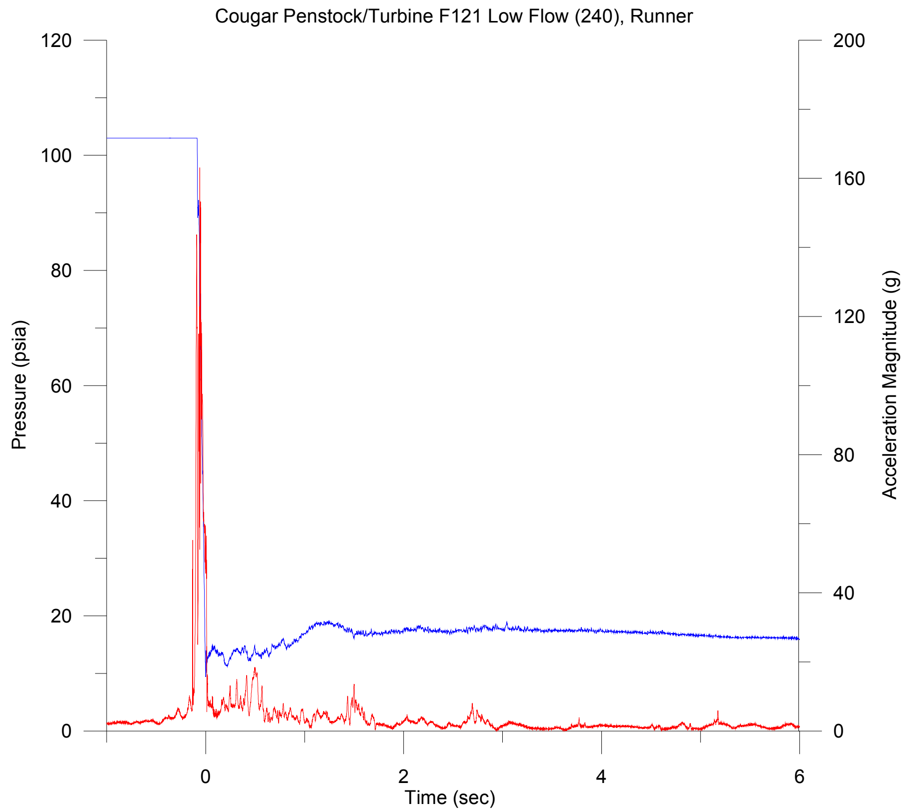
Cougar Penstock/Turbine F914 High Flow (90), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
0
40
80
120
160
200
0
40
80
120

Cougar Dam Turbine Unit 2

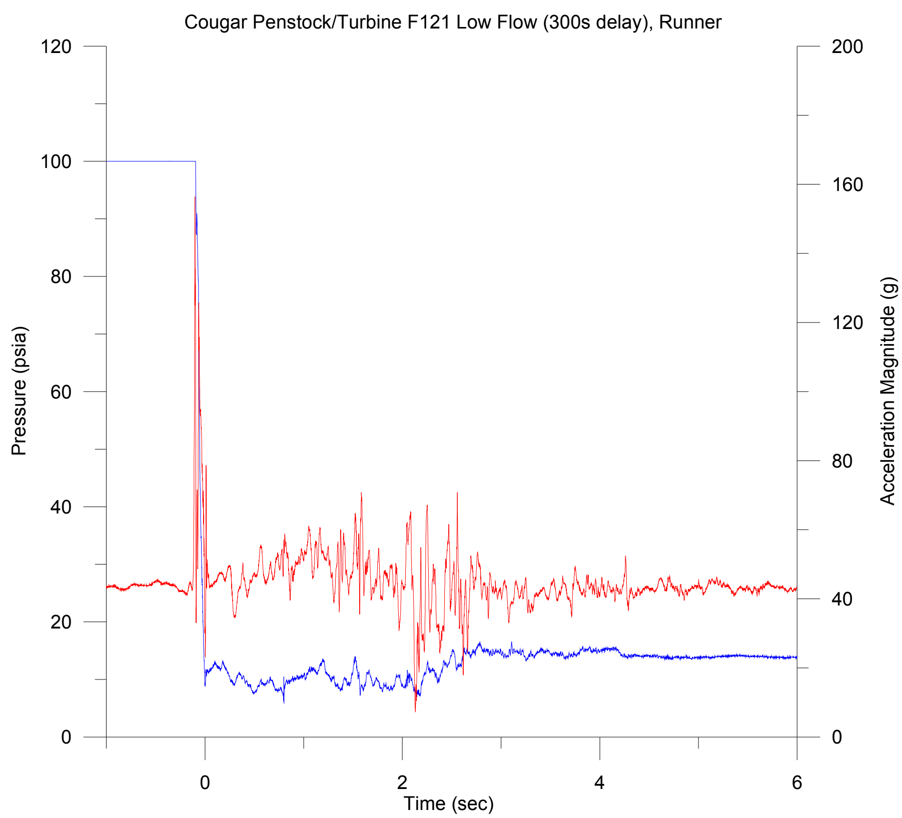
Minimum Wicket Gate Opening


Cougar Penstock/Turbine F932 Low Flow (180), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
120
100
80
60
40
20
0
200
160
120
80
40
0
-1
0
1
2
3
4
5
6

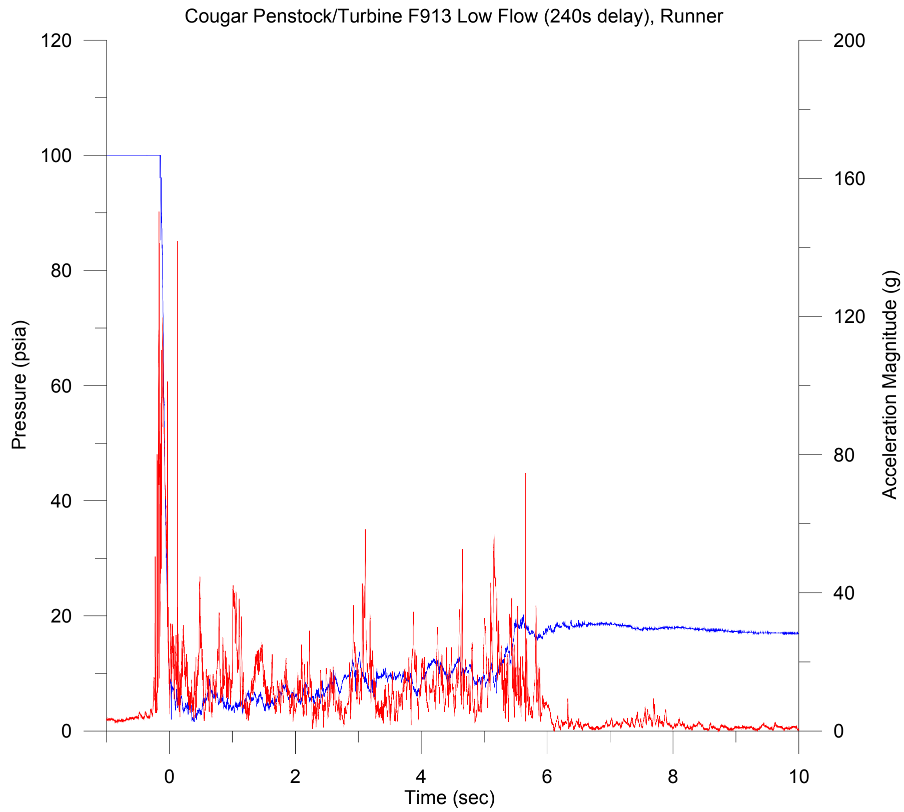

Cougar Penstock/Turbine F109 Low Flow (300s delay), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
120
100
80
60
40
20
0
200
160
120
80
40
0
0
2
4
6



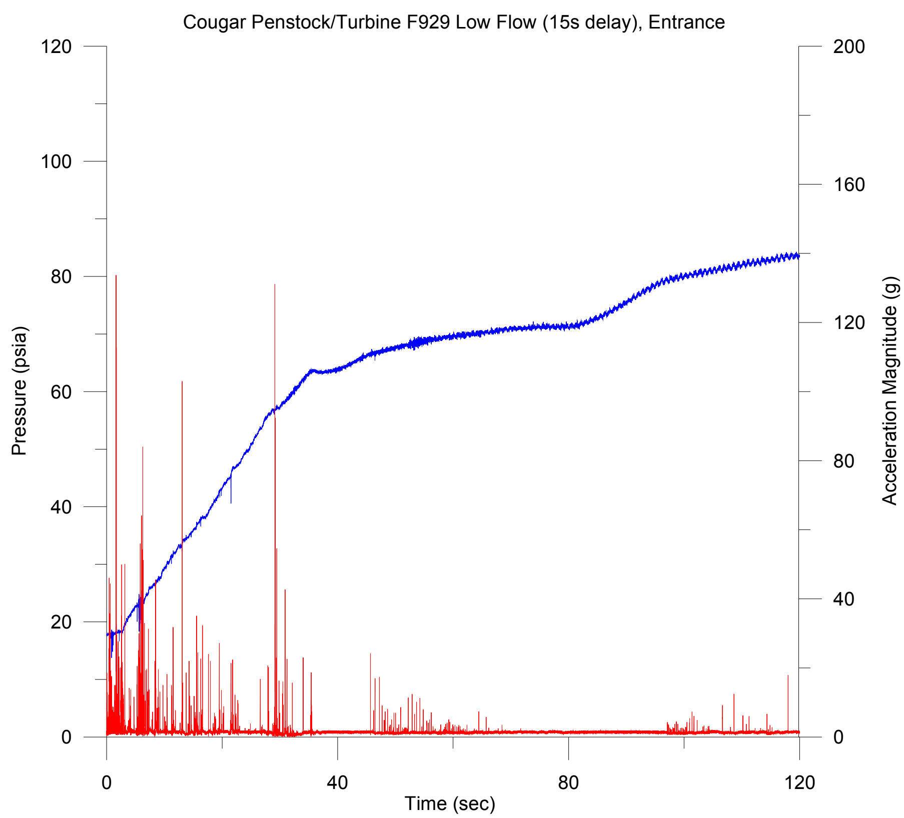
Cougar Penstock/Turbine F121 Low Flow (240), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
2
4
6



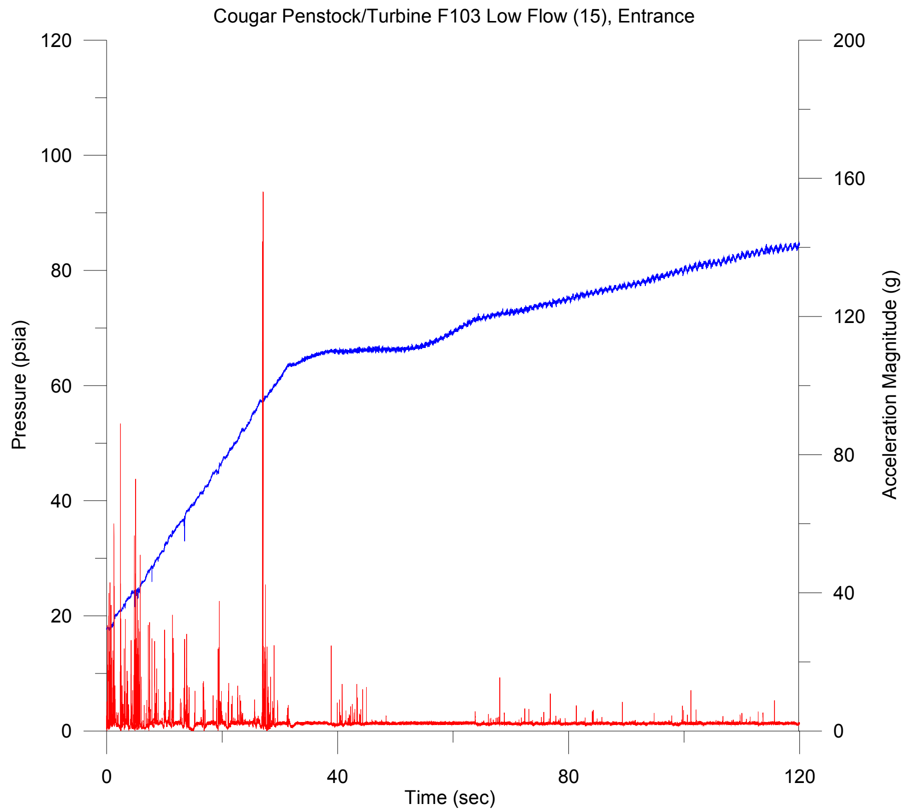
Cougar Penstock/Turbine F121 Low Flow (300s delay), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
2
4
6

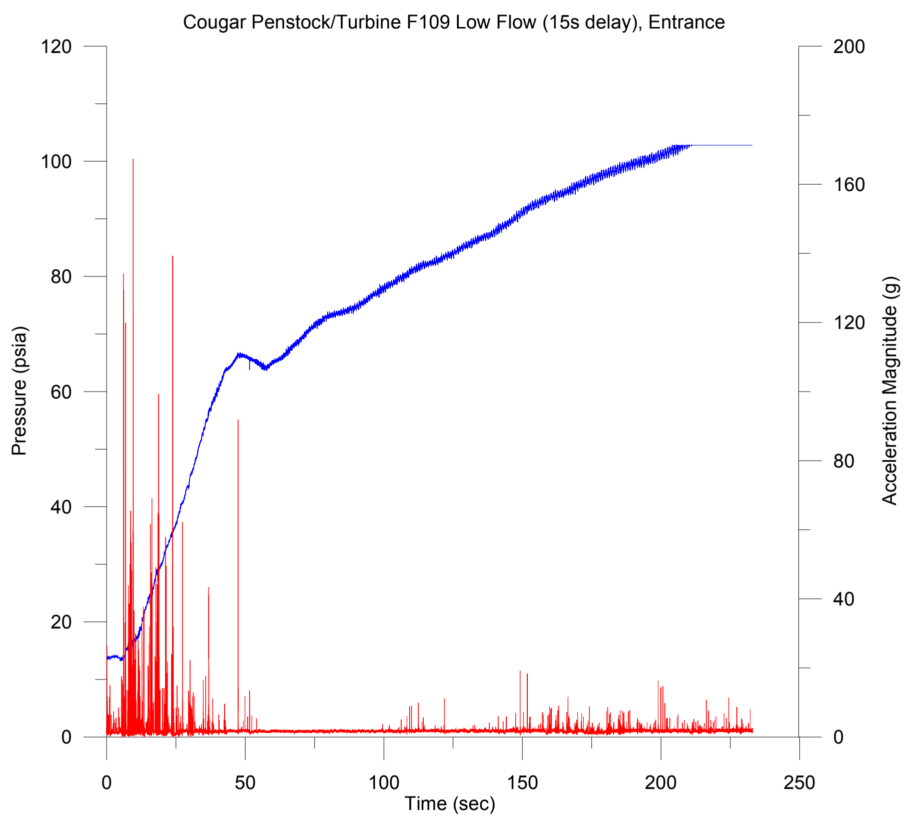


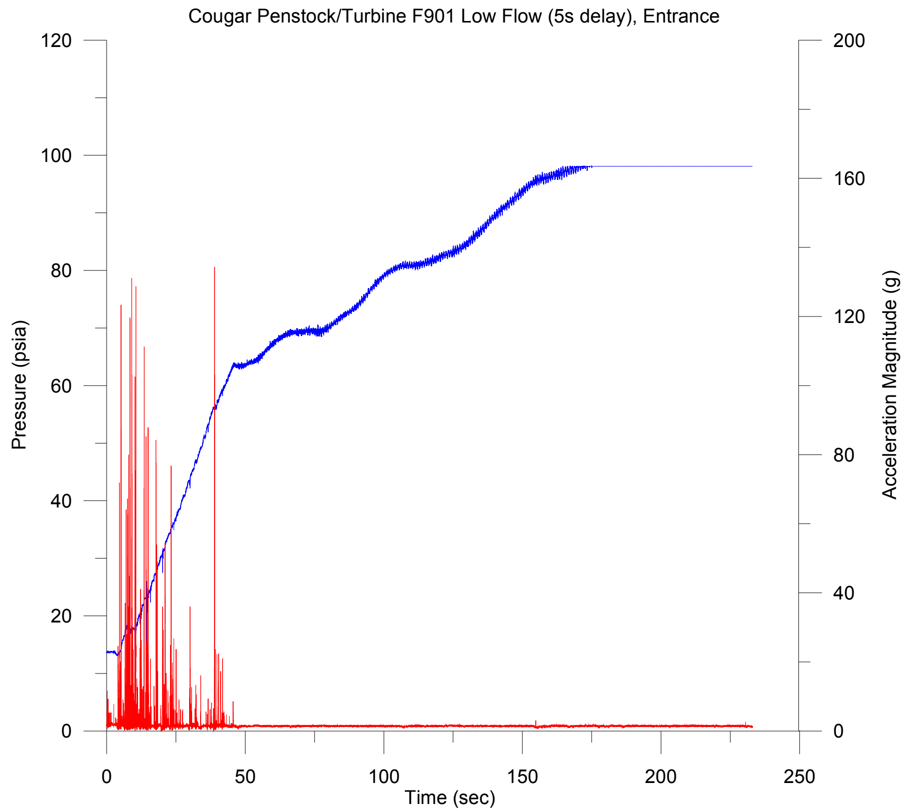
Cougar Penstock/Turbine F913 Low Flow (240s delay), Runner
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
2
4
6
8
10

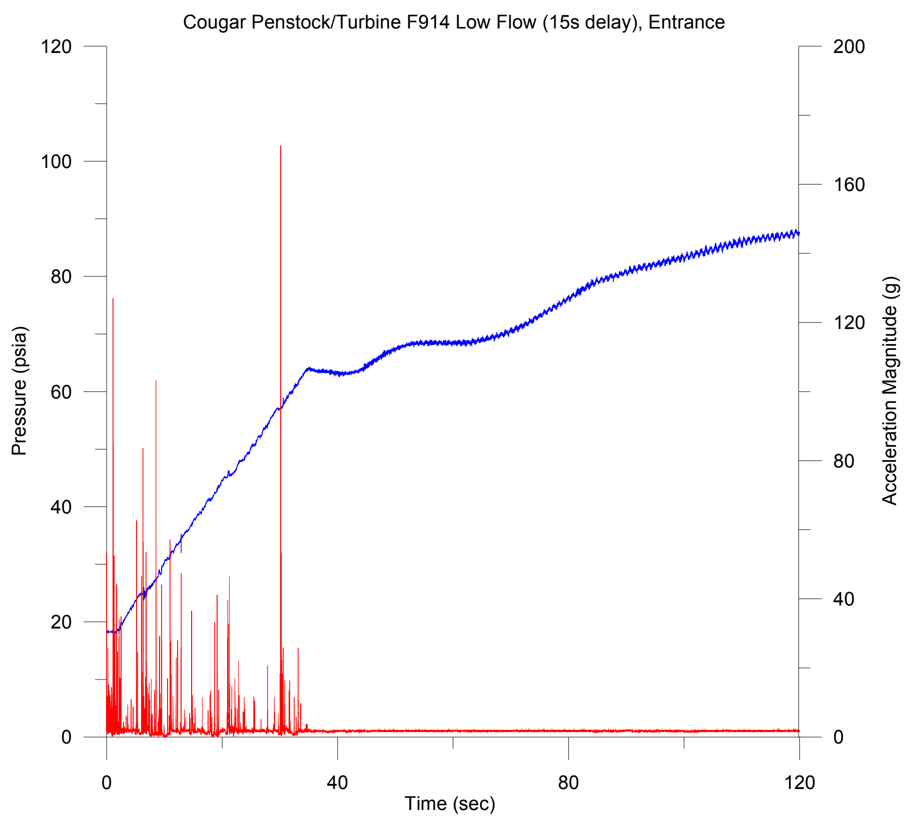


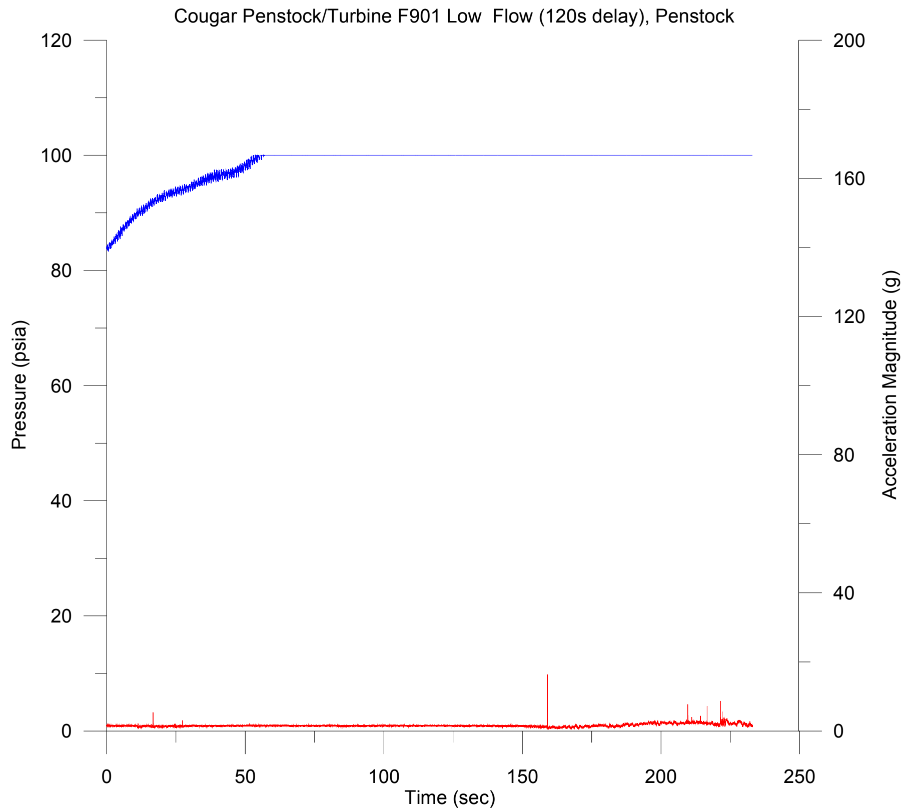
Cougar Penstock/Turbine F929 Low Flow (15s delay), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
40
80
120

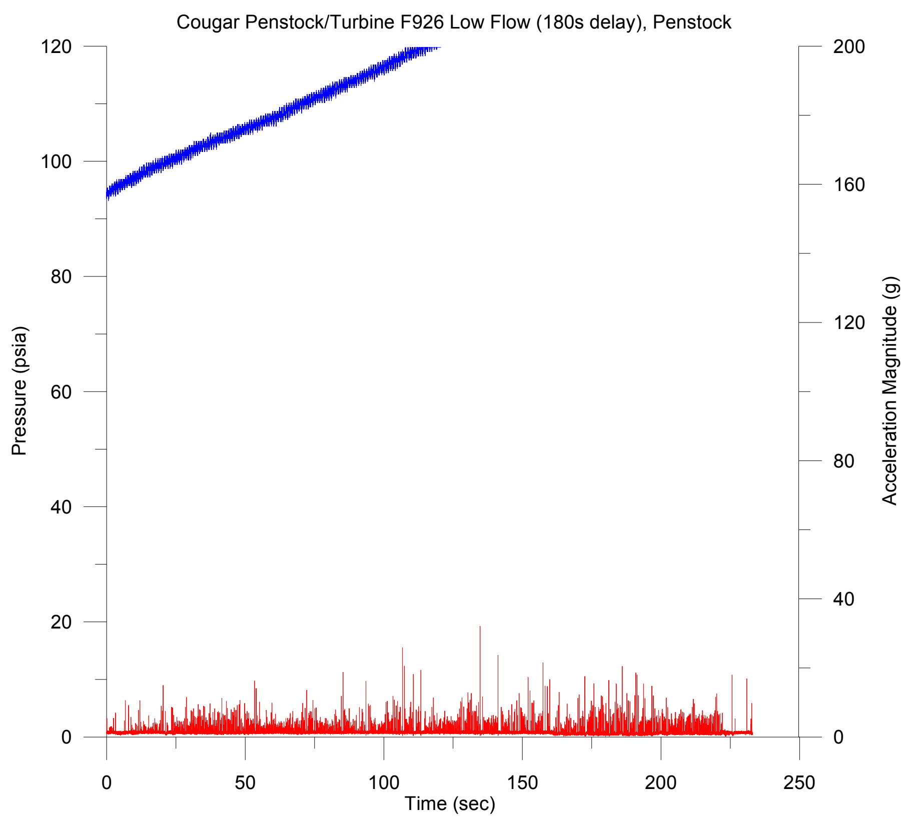

Cougar Penstock/Turbine F103 Low Flow (15), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
40
80
120


Cougar Penstock/Turbine F109 Low Flow (15s delay), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
50
100
150
200
250


Cougar Penstock/Turbine F901 Low Flow (5s delay), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
50
100
150
200
250


Cougar Penstock/Turbine F914 Low Flow (15s delay), Entrance
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
40
80
120

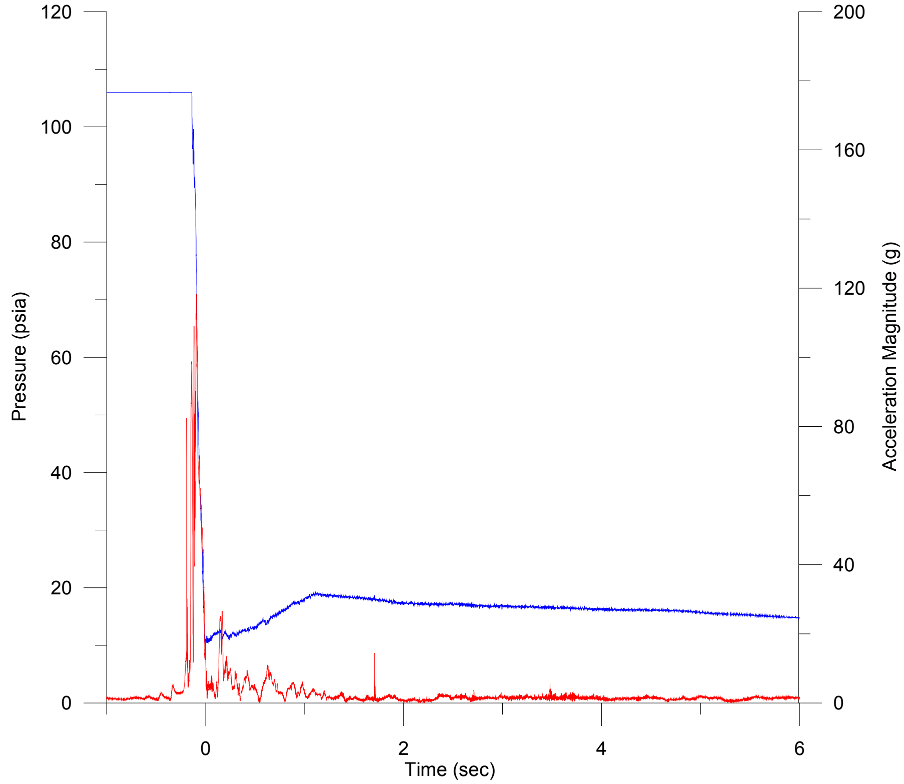

Cougar Penstock/Turbine F901 Low Flow (120s delay), Penstock
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
50
100
150
200
250


Cougar Penstock/Turbine F926 Low Flow (180s delay), Penstock
Pressure (psia)
Acceleration Magnitude (g)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
160
200
0
50
100
150
200
250

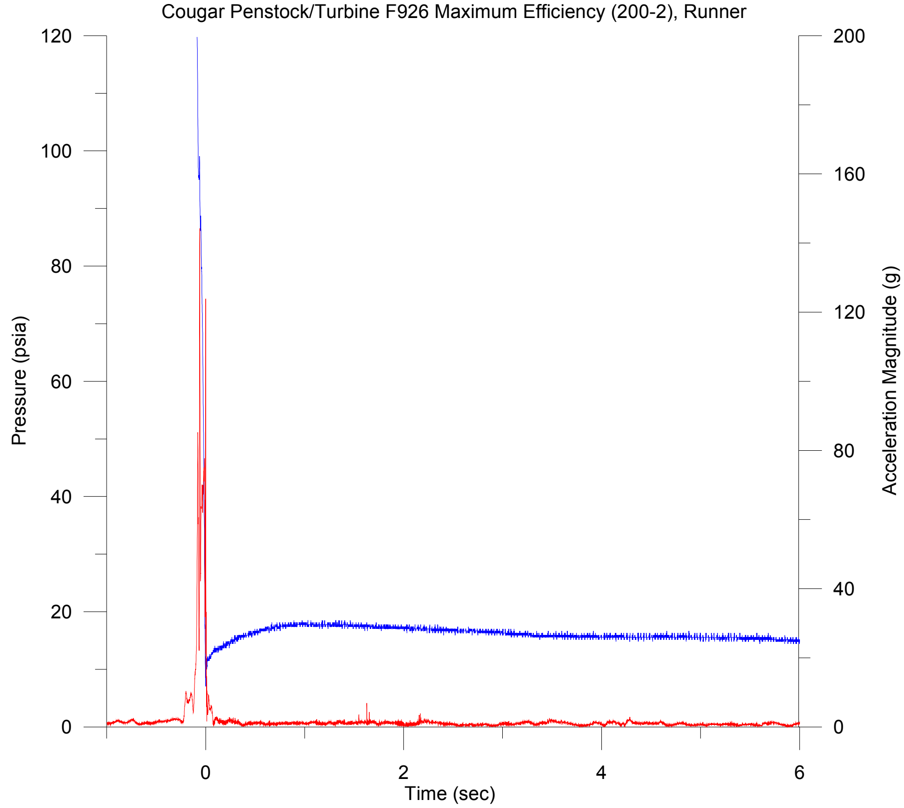
Cougar Dam Turbine Unit 2

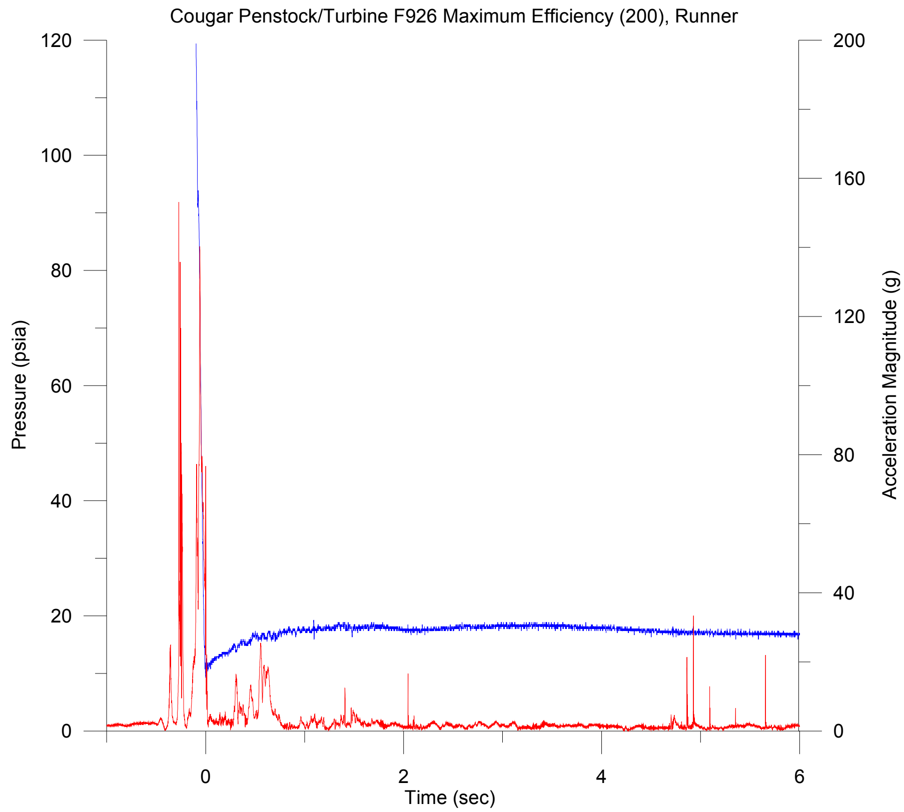
Peak Efficiency Wicket Gate Opening

Cougar Penstock/Turbine F930 Maximum Efficiency (200), Runner

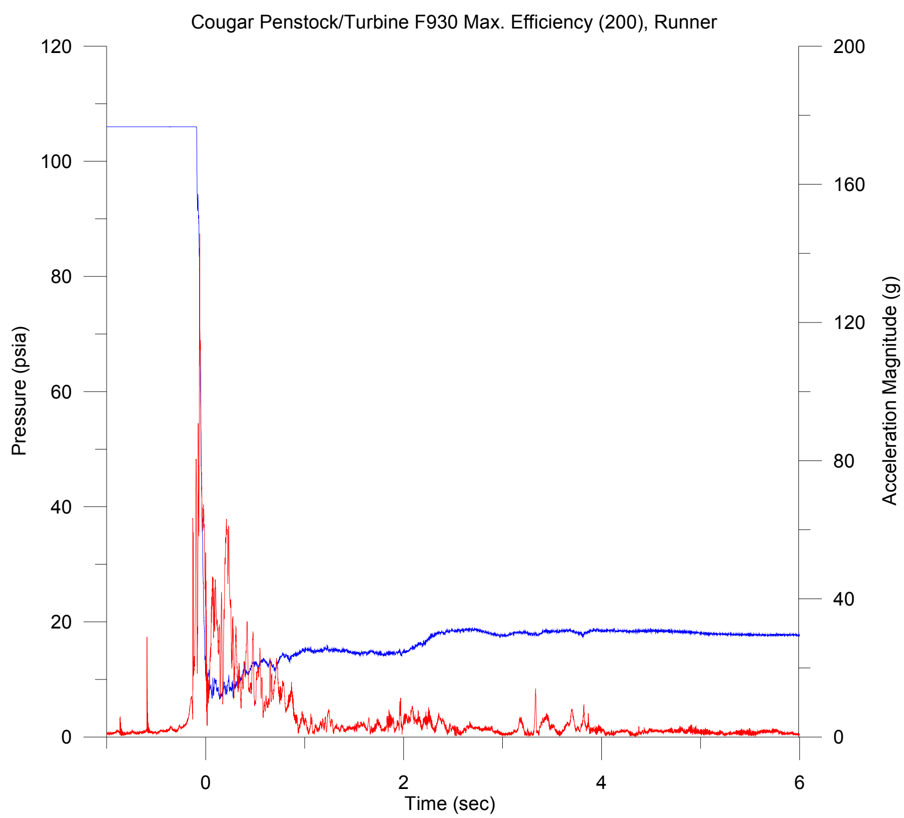


Cougar Penstock/Turbine F926 Maximum Efficiency (200-2), Runner





Cougar Penstock/Turbine F926 Maximum Efficiency (200), Runner
120
100
80
60
40
20
0
Pressure (psia)
200
160
120
80
40
0
Acceleration Magnitude (g)
0
2
4
6
Time (sec)



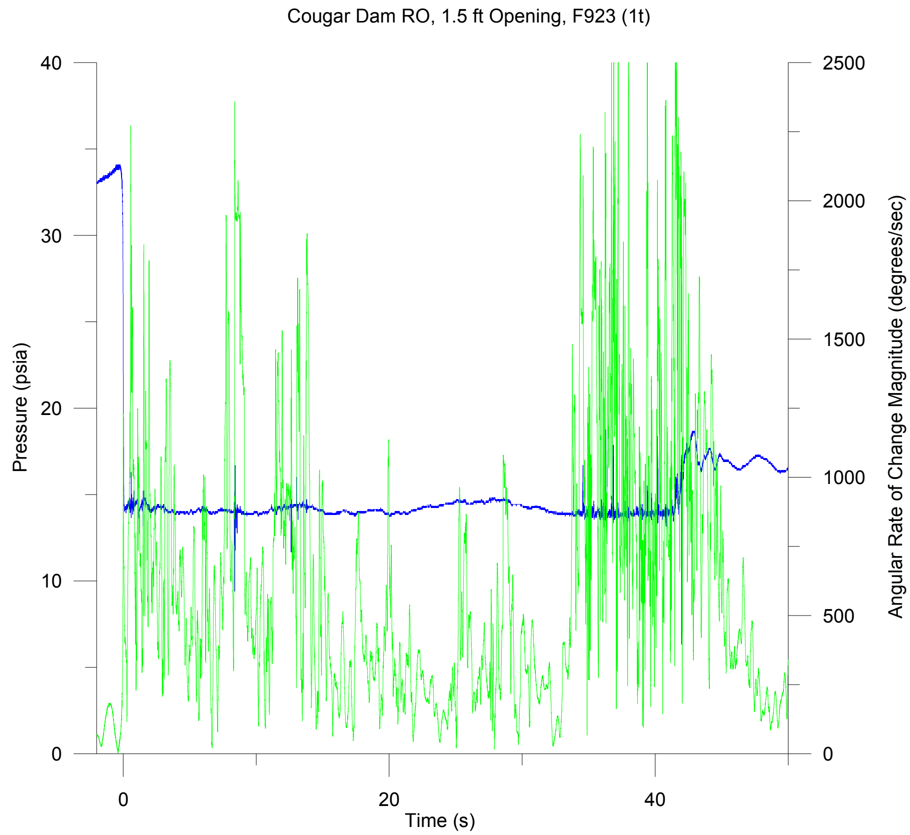
Cougar Penstock/Turbine F930 Max. Efficiency (200), Runner
120
100
80
60
40
20
0
Pressure (psia)
200
160
120
80
40
0
Acceleration Magnitude (g)
0
2
4
6
Time (sec)

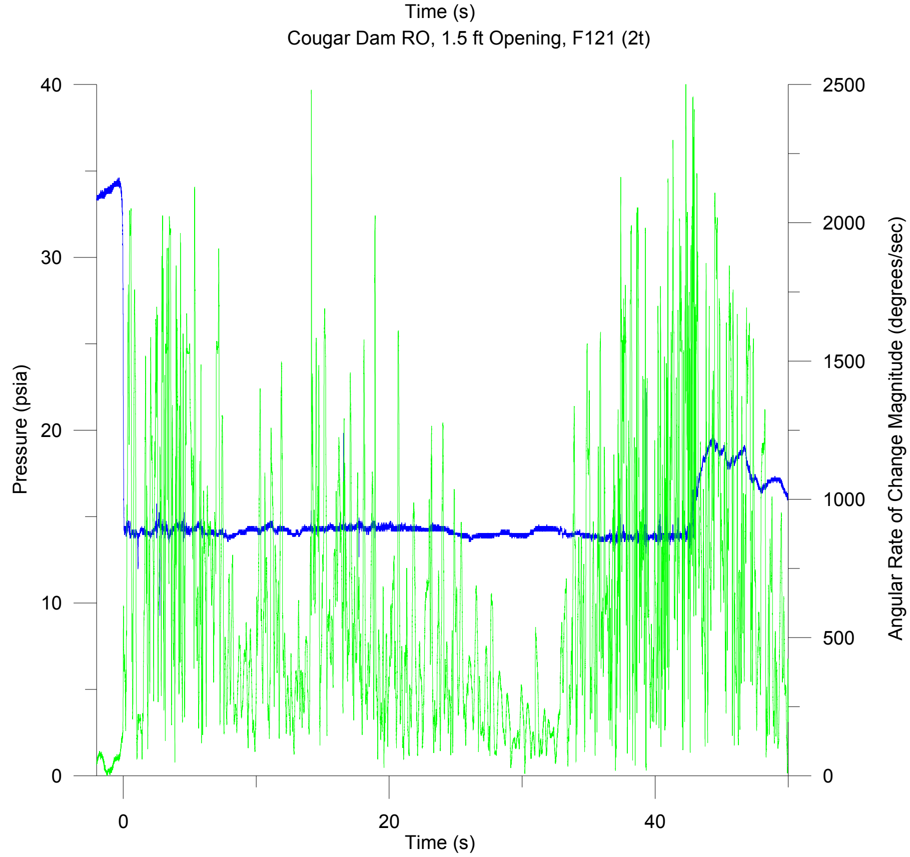
Appendix D

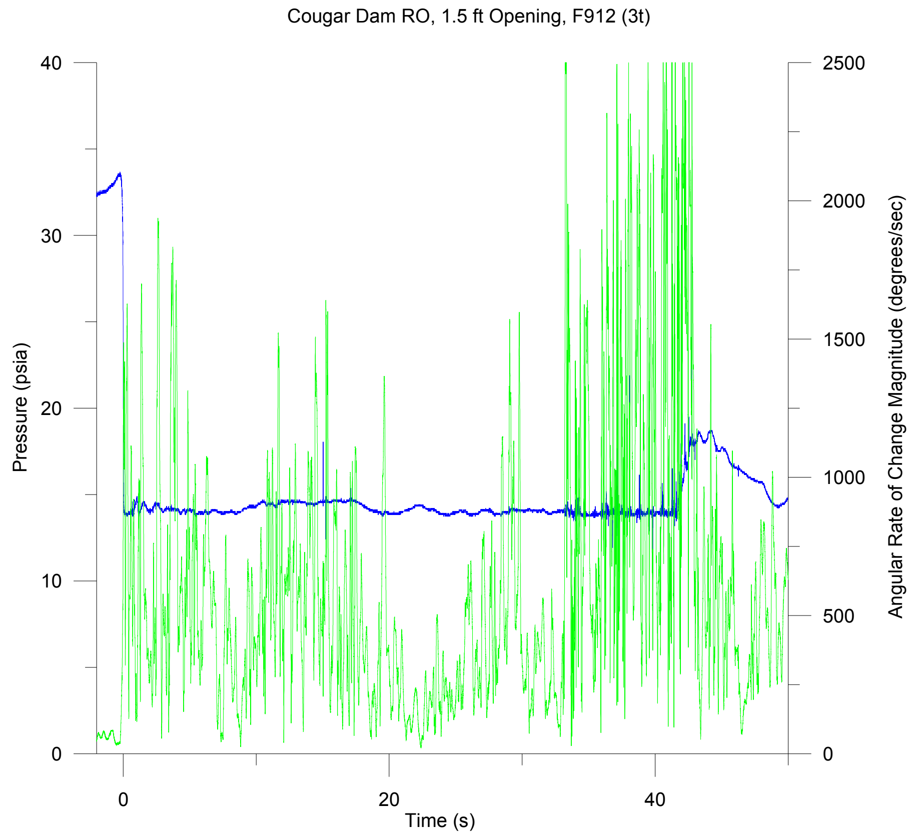
Angular Rate of Change Magnitude Time Histories of Each Sensor Fish Release

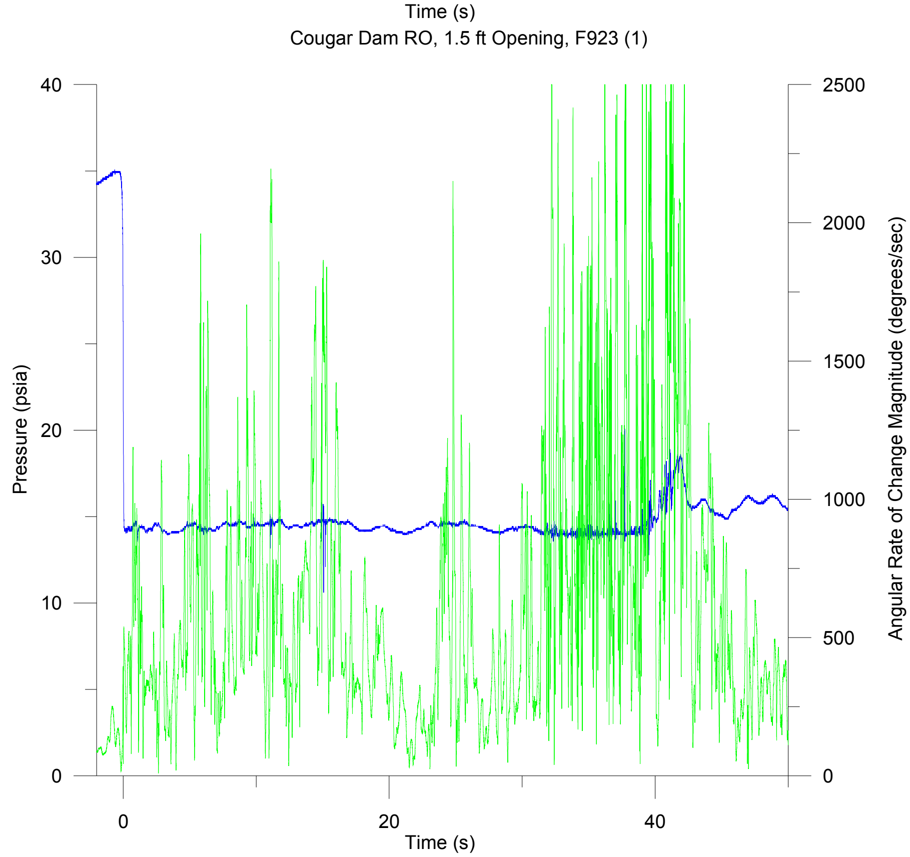
Cougar Dam Regulating Outlet

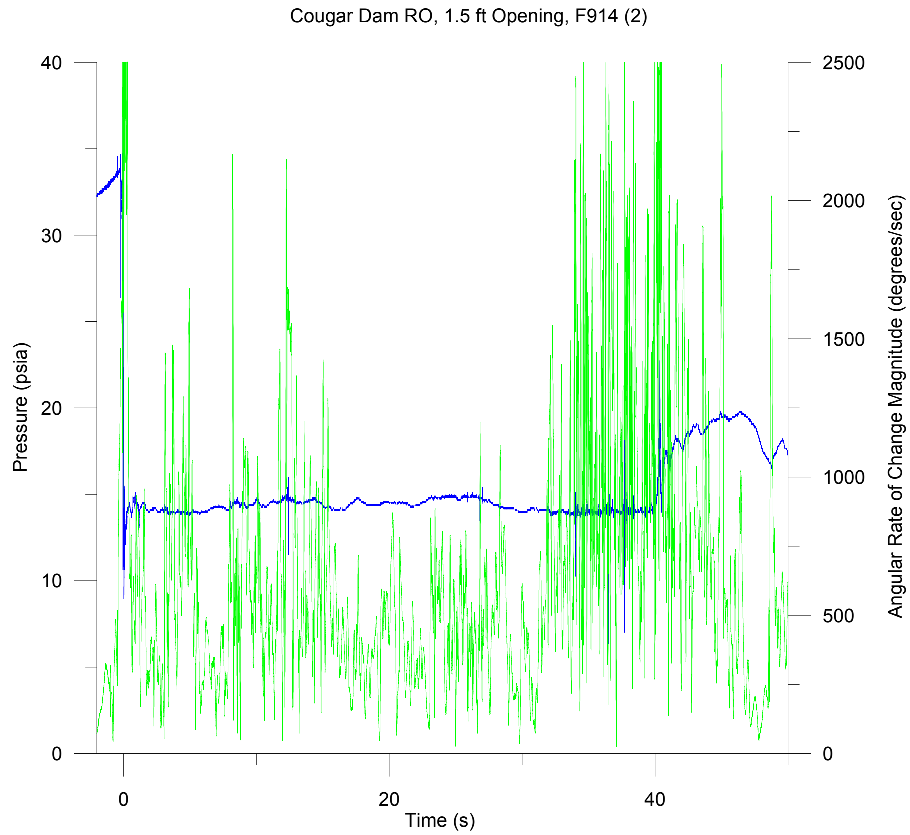
1.5-ft Gate Opening

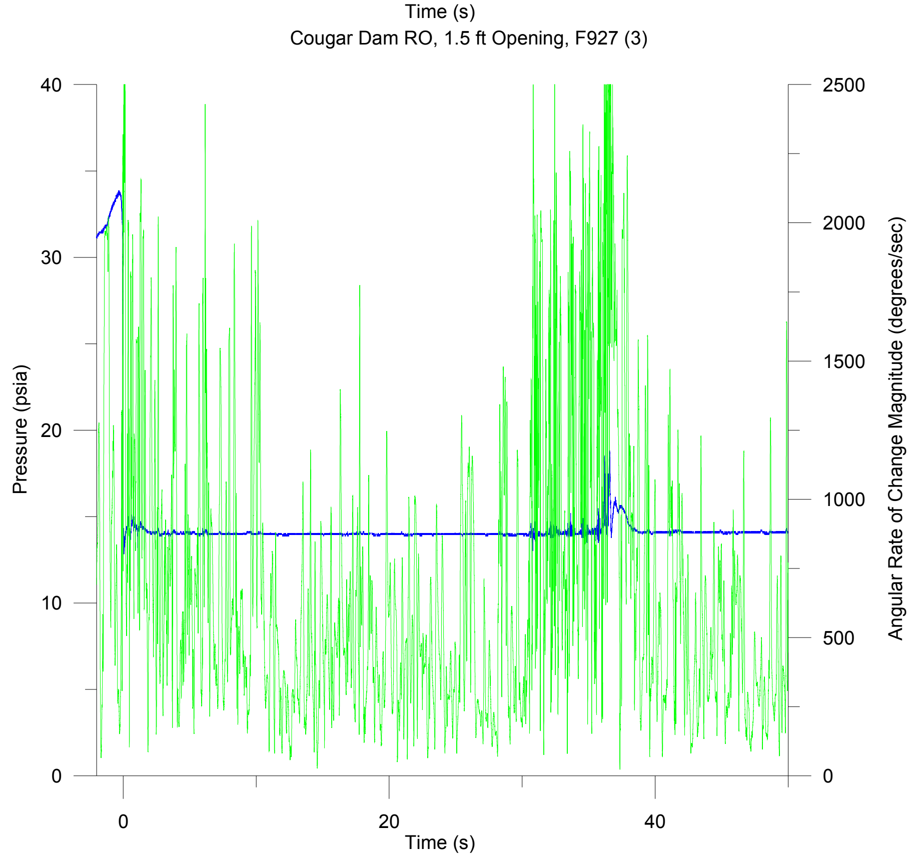

Cougar Dam RO, 1.5 ft Opening, F923 (1t)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500

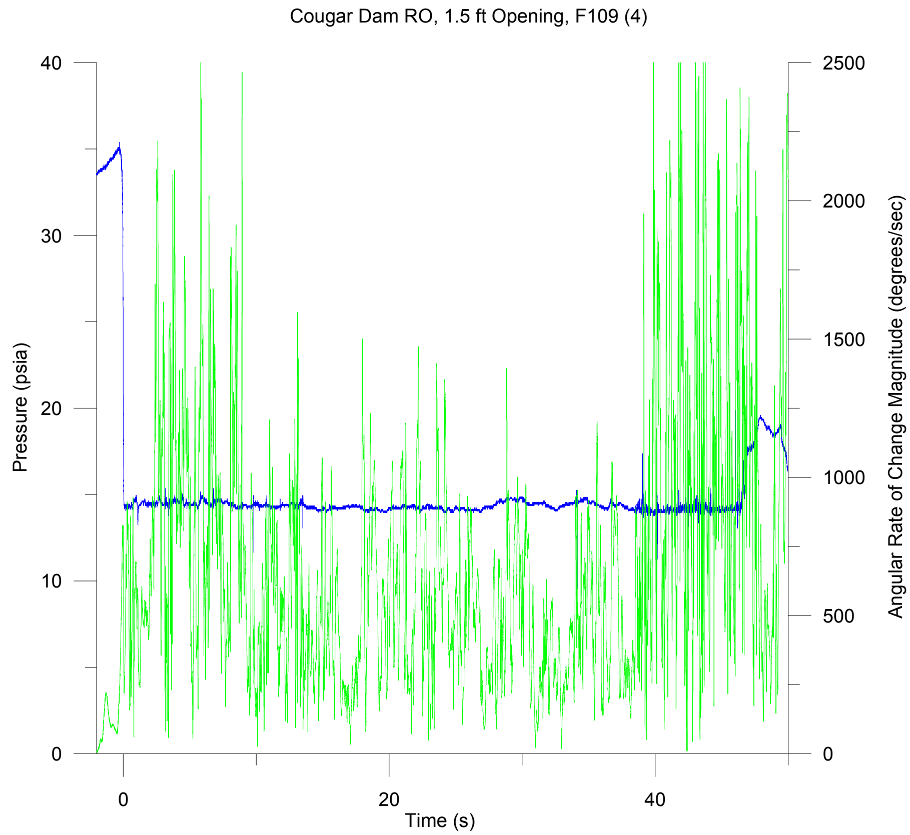

Cougar Dam RO, 1.5 ft Opening, F121 (2t)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500


Cougar Dam RO, 1.5 ft Opening, F912 (3t)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

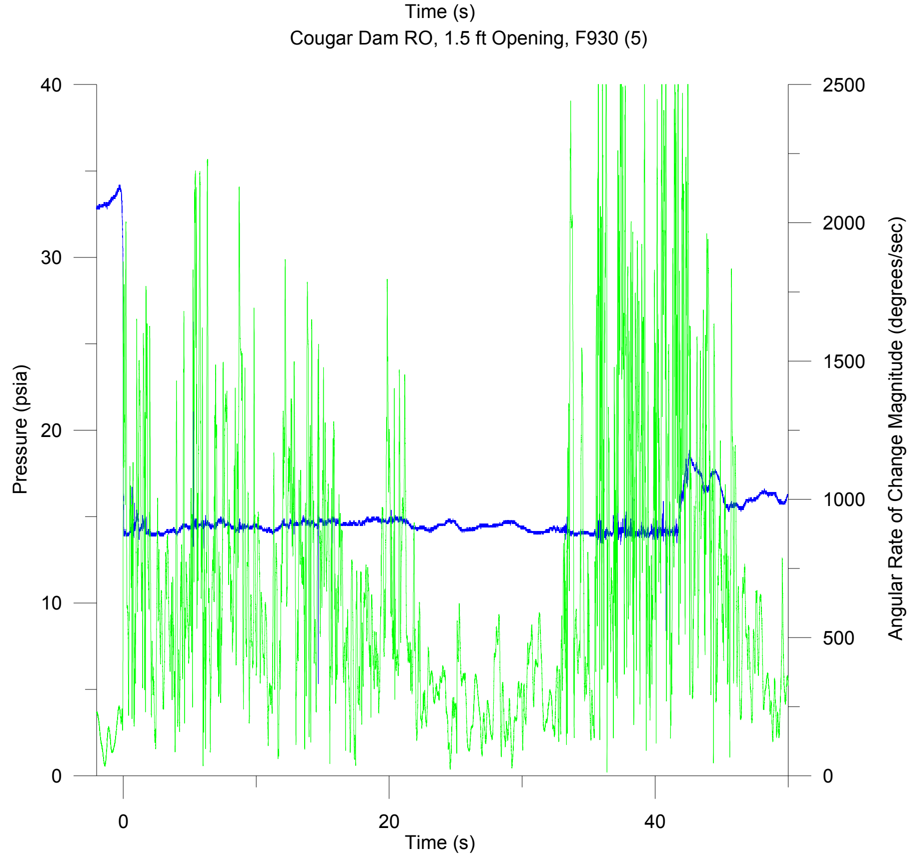

Cougar Dam RO, 1.5 ft Opening, F923 (1)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40


Cougar Dam RO, 1.5 ft Opening, F914 (2)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

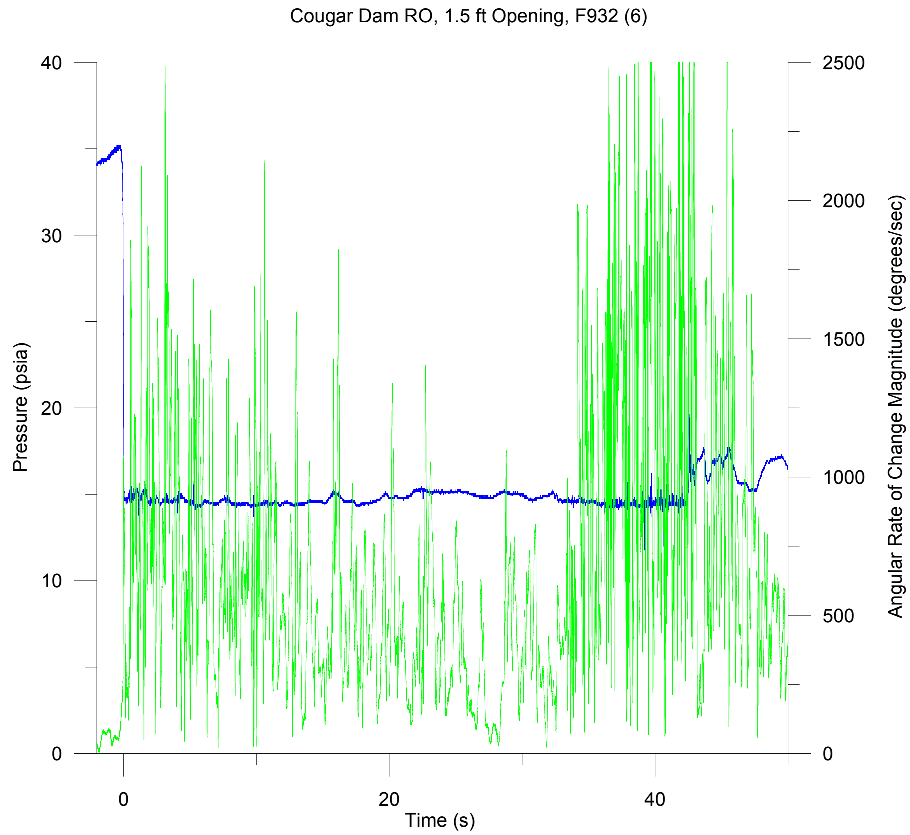

Cougar Dam RO, 1.5 ft Opening, F927 (3)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

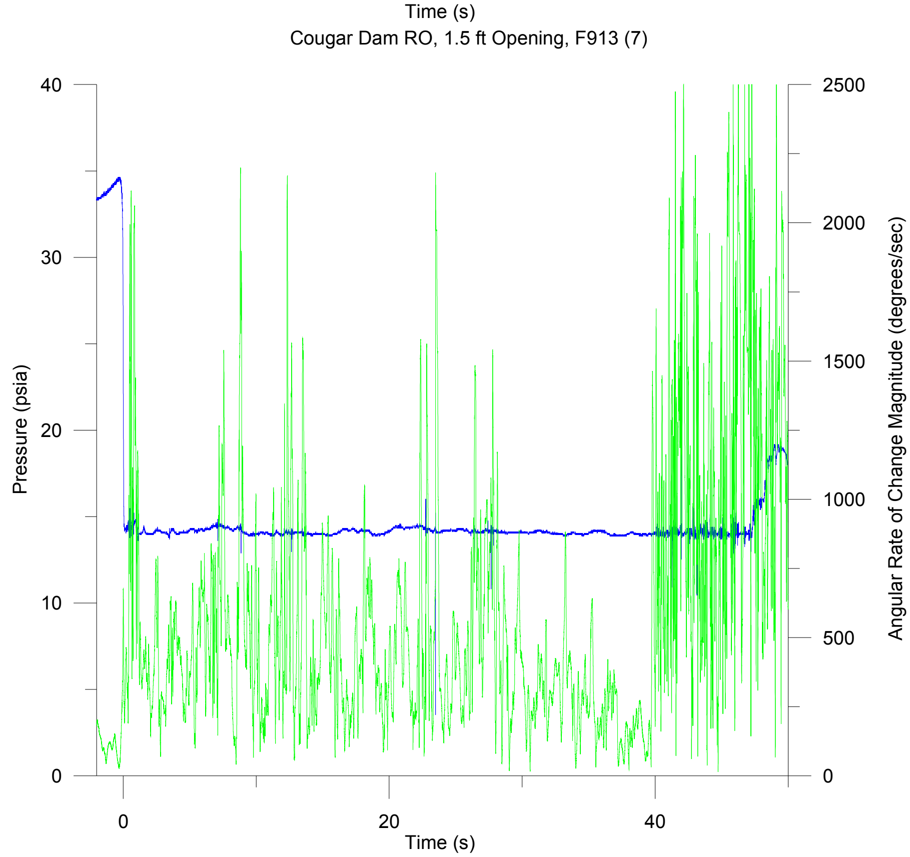


Cougar Dam RO, 1.5 ft Opening, F109 (4)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

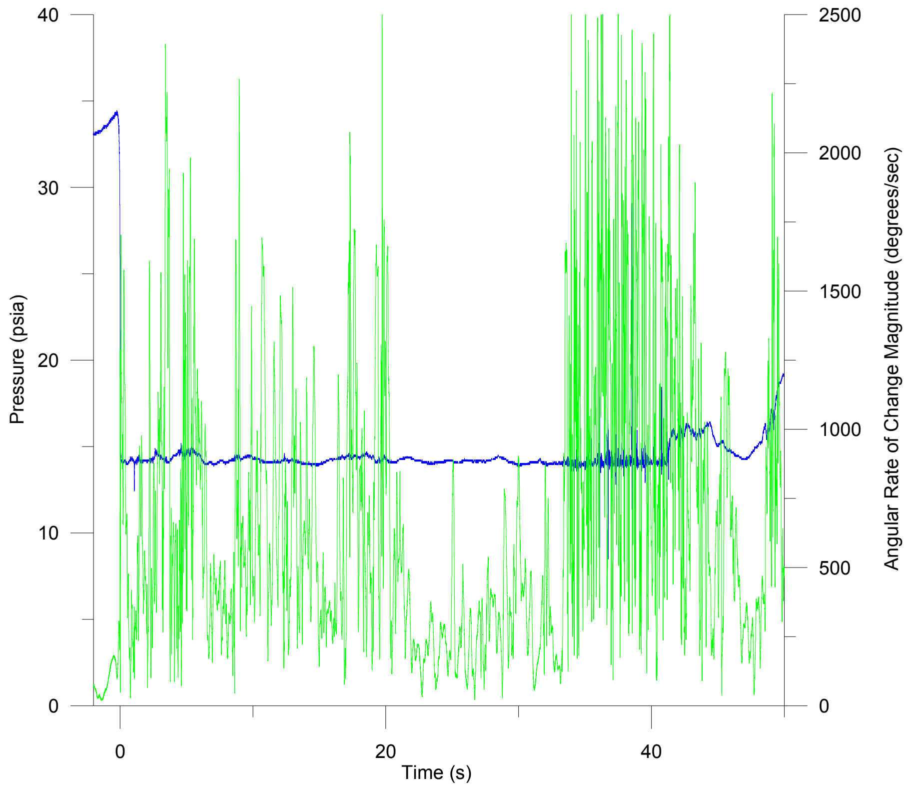


Cougar Dam RO, 1.5 ft Opening, F930 (5)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

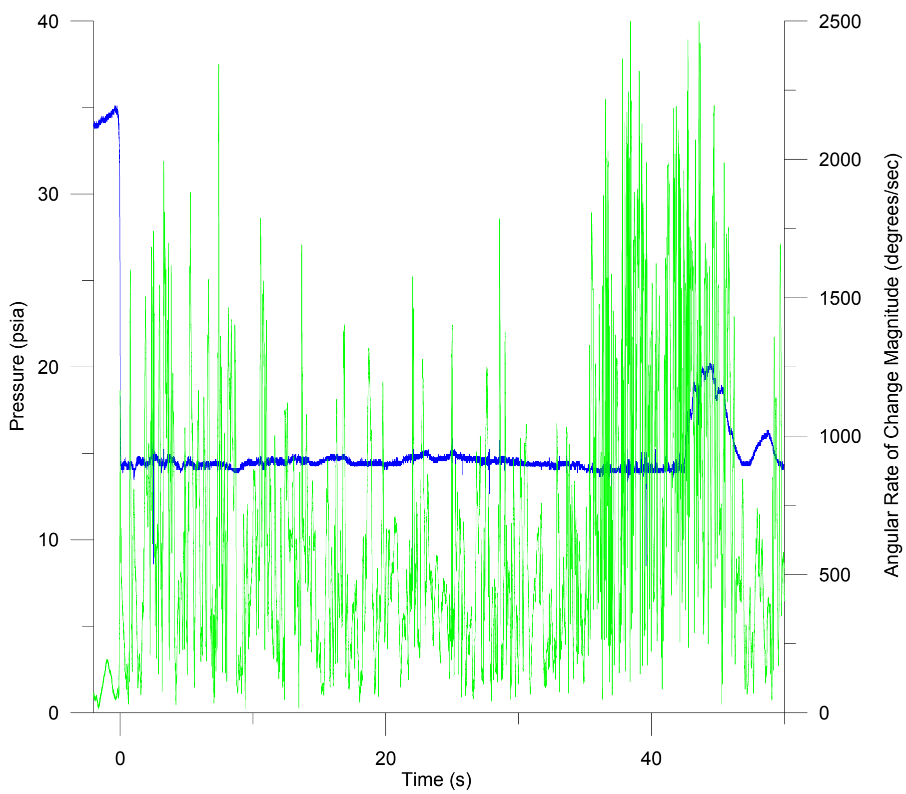

Cougar Dam RO, 1.5 ft Opening, F932 (6)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500

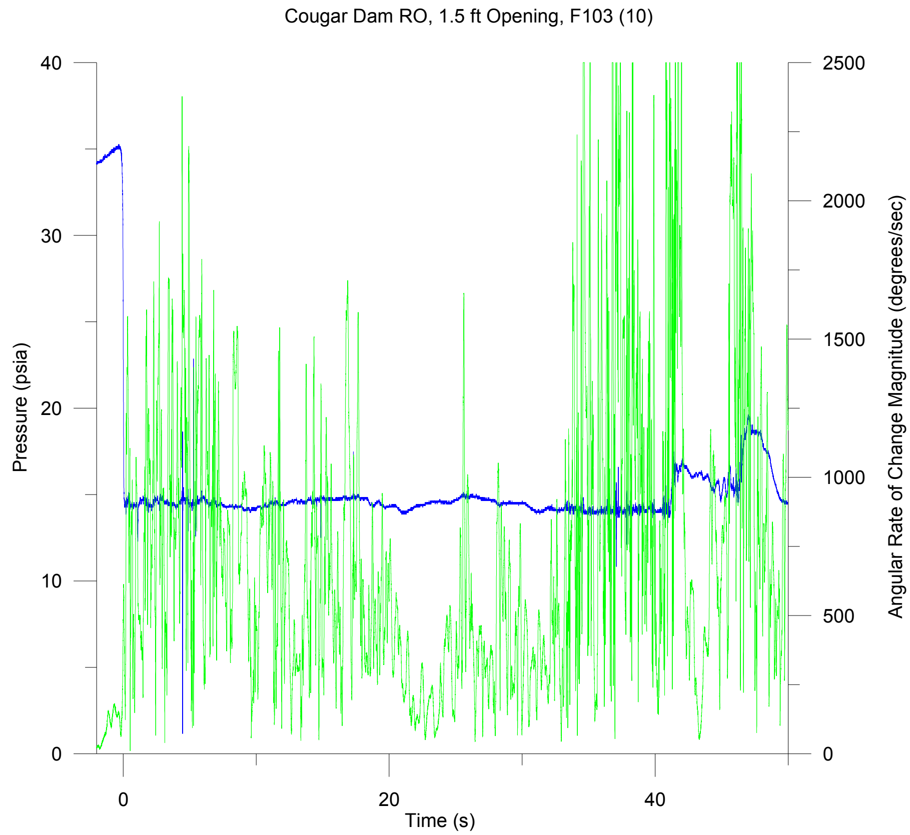

Cougar Dam RO, 1.5 ft Opening, F913 (7)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500

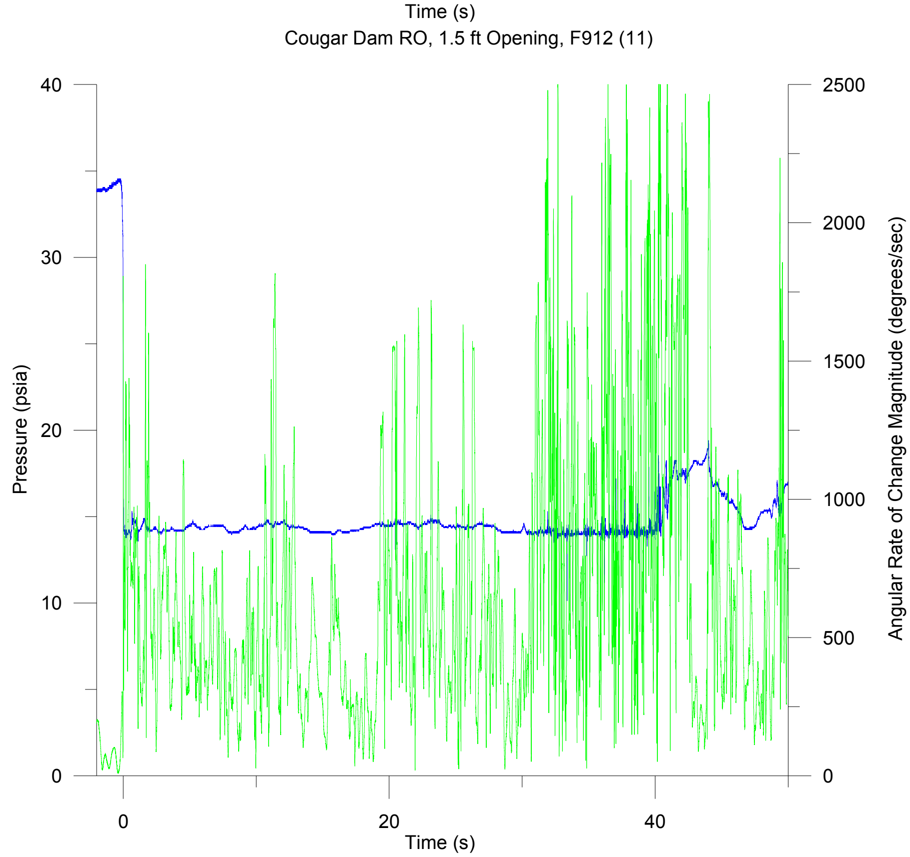
Cougar Dam RO, 1.5 ft Opening, F912 (8)



Cougar Dam RO, 1.5 ft Opening, F121 (9)




Cougar Dam RO, 1.5 ft Opening, F103 (10)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500


Cougar Dam RO, 1.5 ft Opening, F912 (11)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
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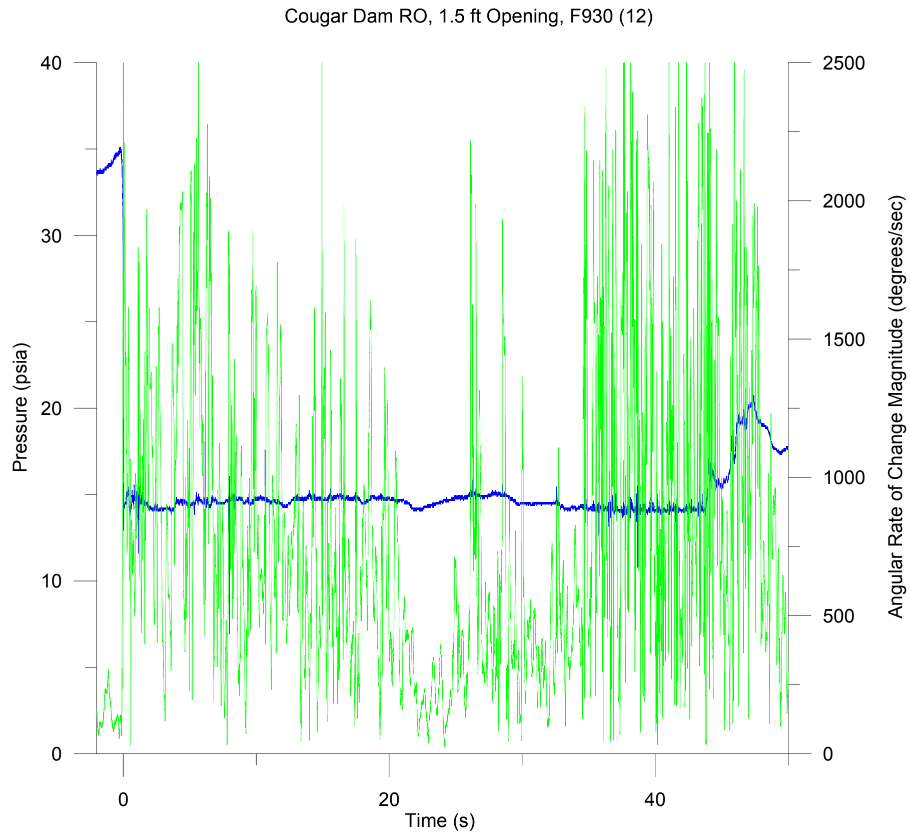
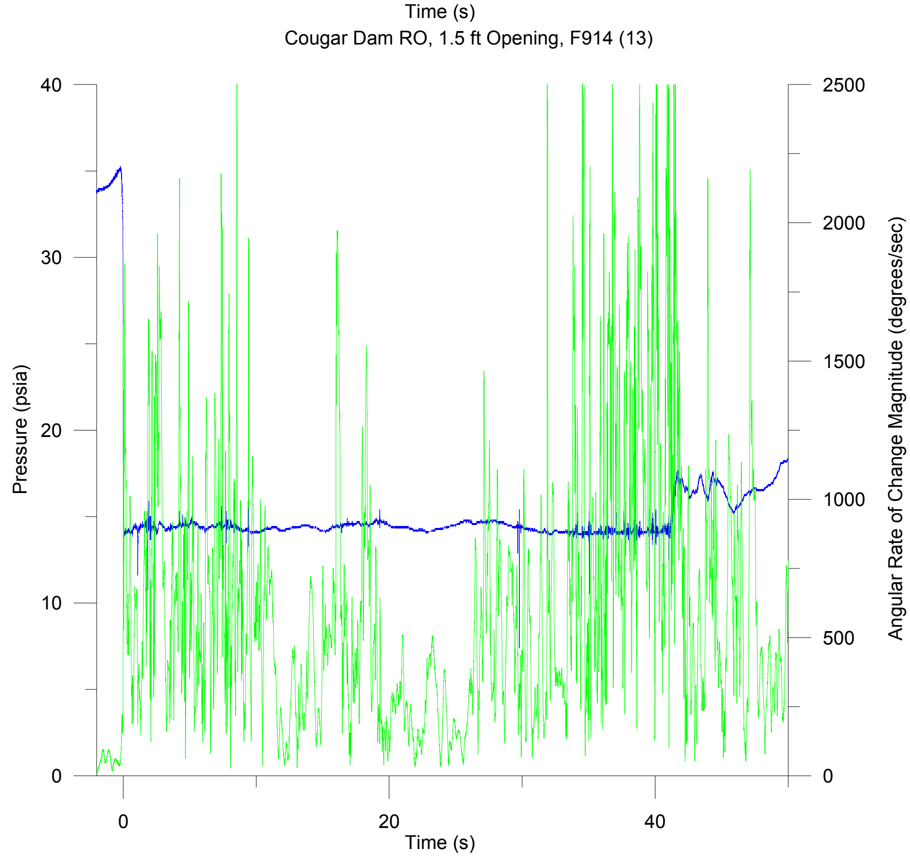
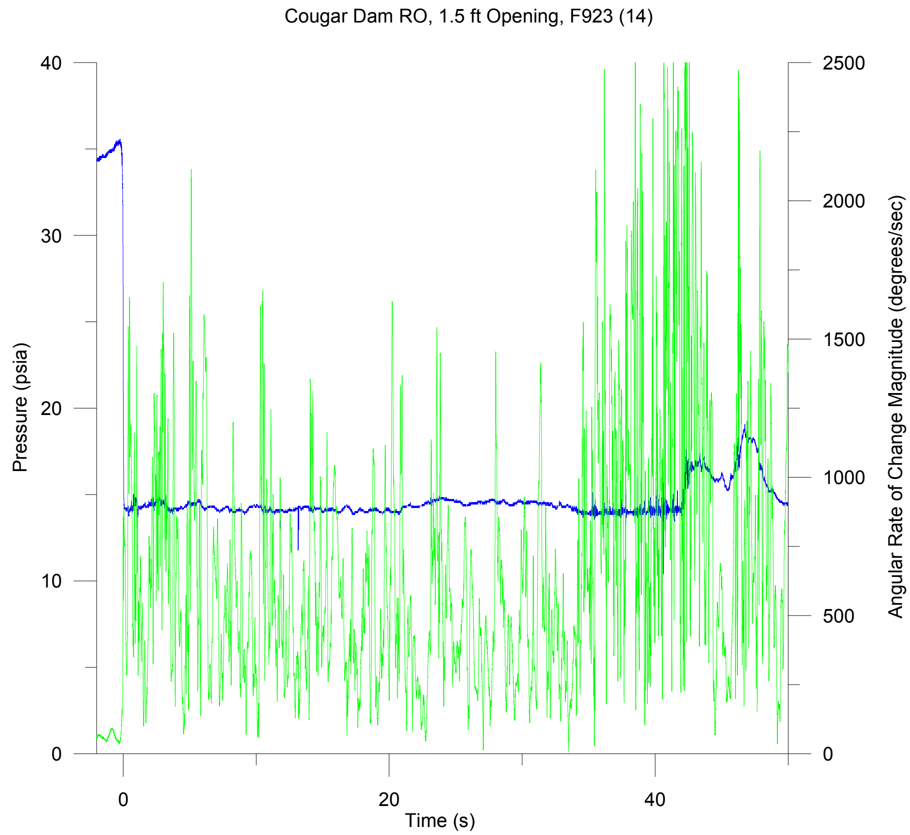
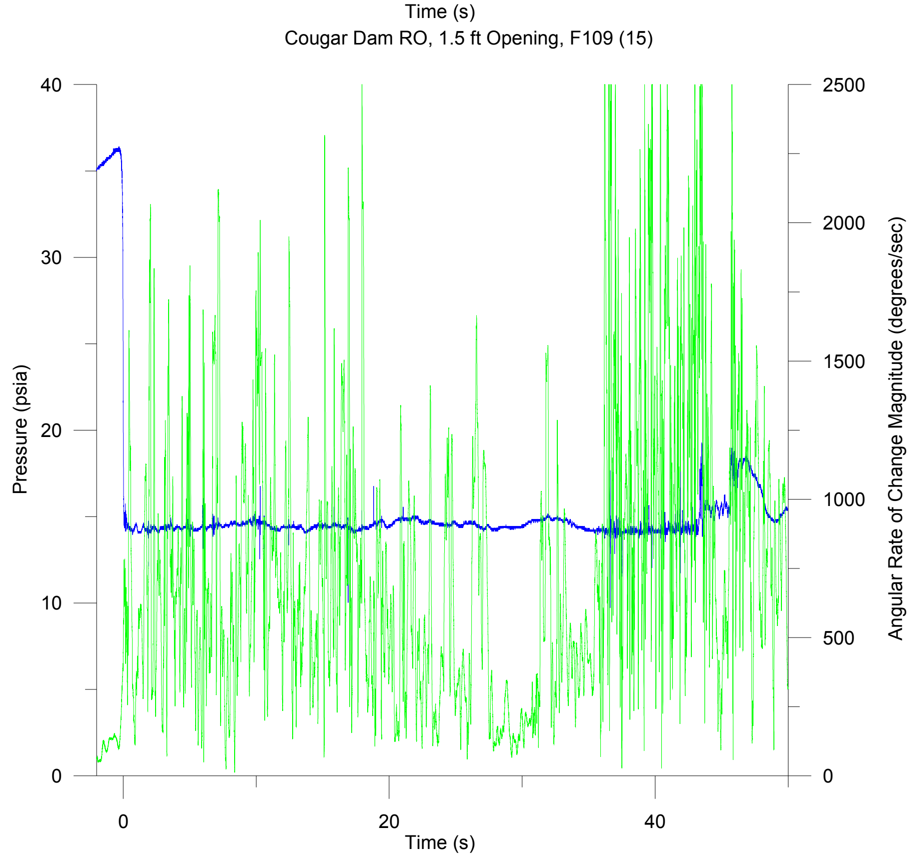
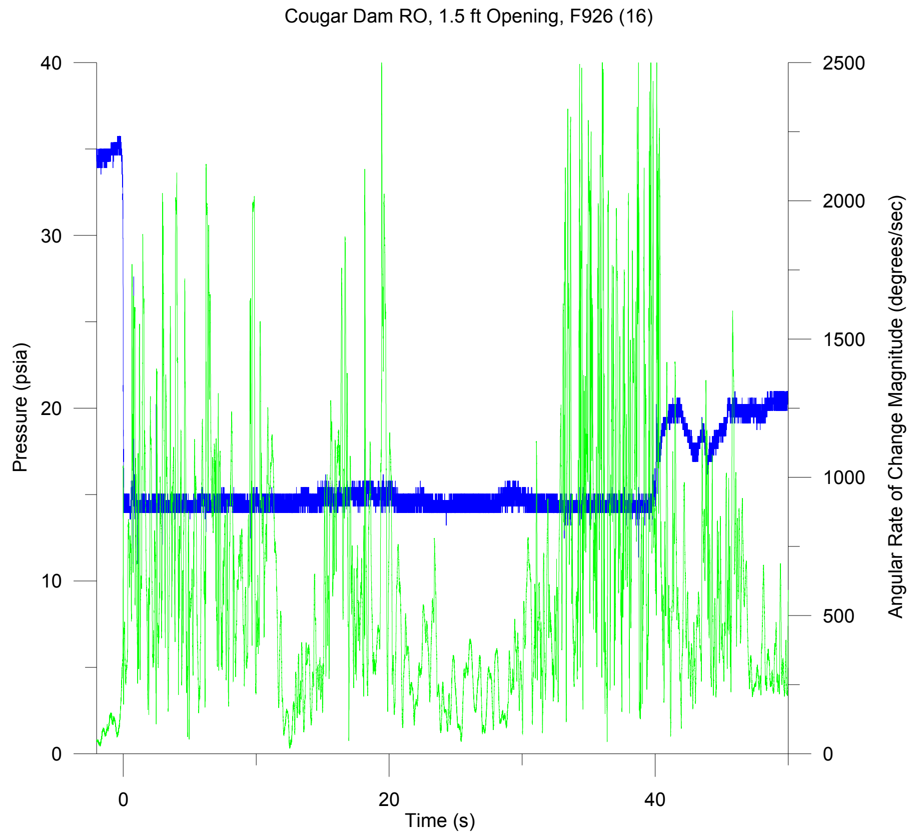
500
1000
1500
2000
2500


Cougar Dam RO, 1.5 ft Opening, F930 (12)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
20
40
0
500
1000
1500
2000
2500


Cougar Dam RO, 1.5 ft Opening, F914 (13)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
20
40
0
500
1000
1500
2000
2500


Cougar Dam RO, 1.5 ft Opening, F923 (14)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40


Cougar Dam RO, 1.5 ft Opening, F109 (15)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

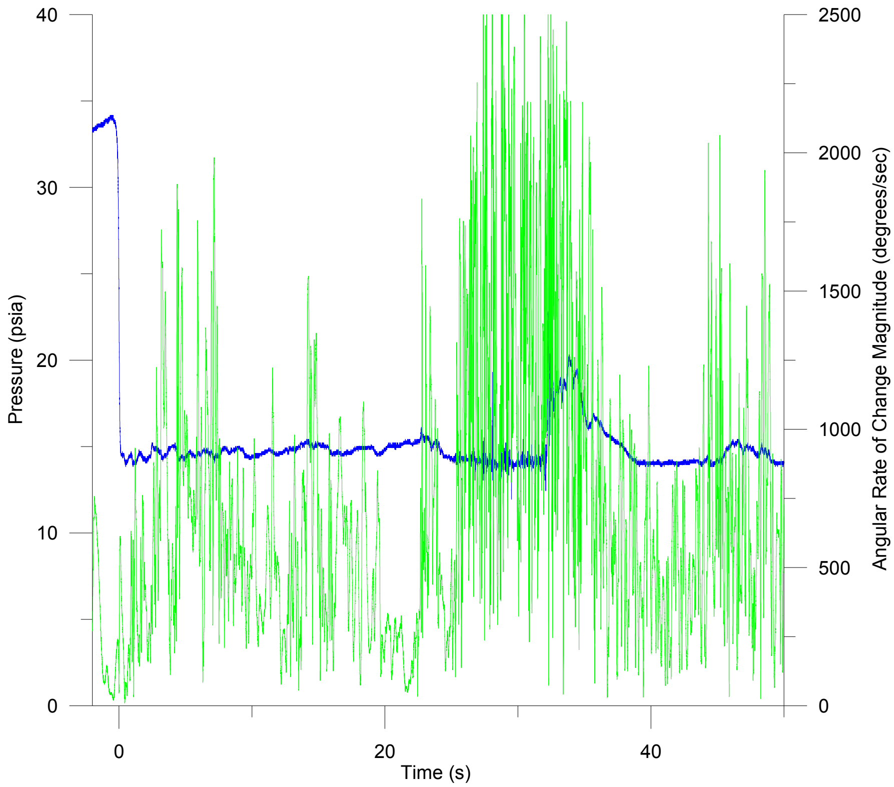


Cougar Dam RO, 1.5 ft Opening, F926 (16)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

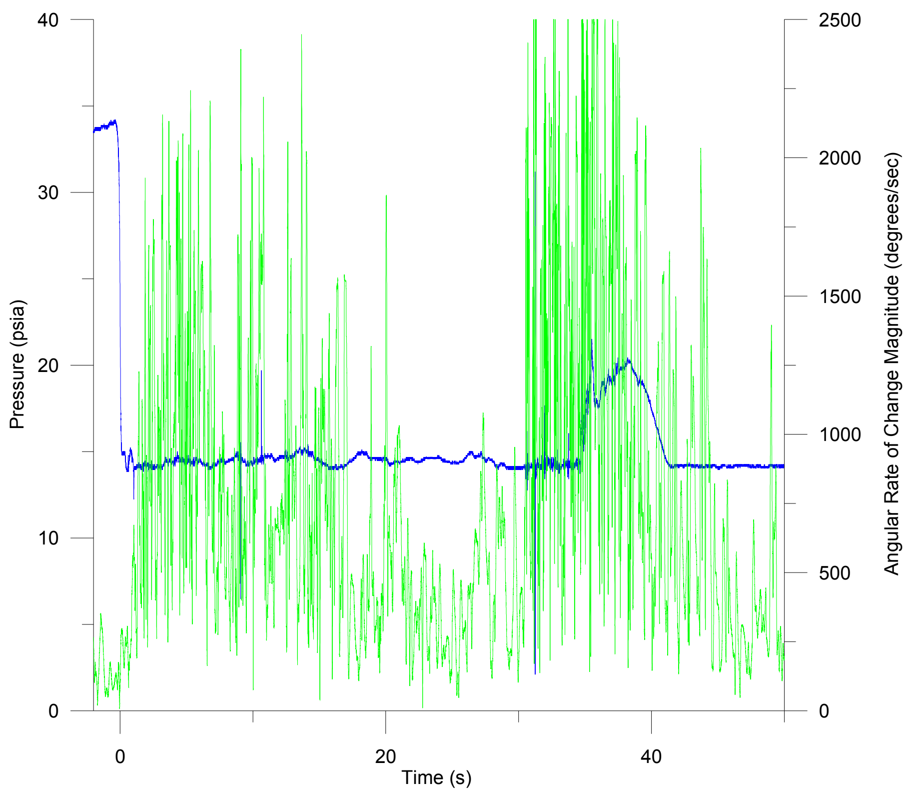
Cougar Dam Regulating Outlet

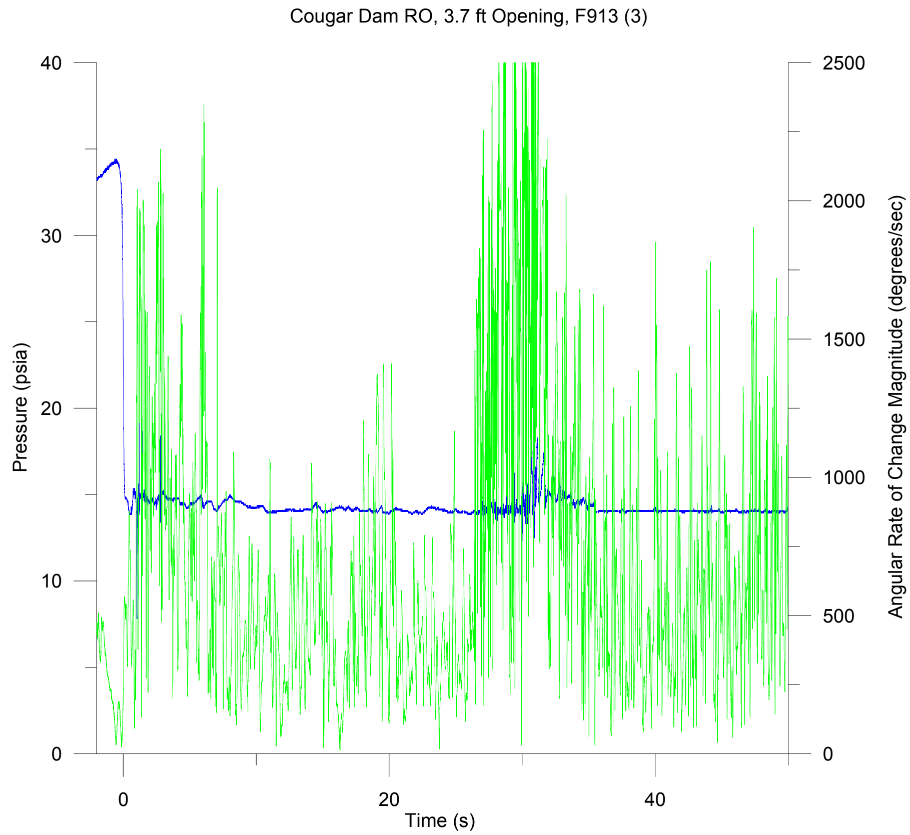
3.7-ft Gate Opening

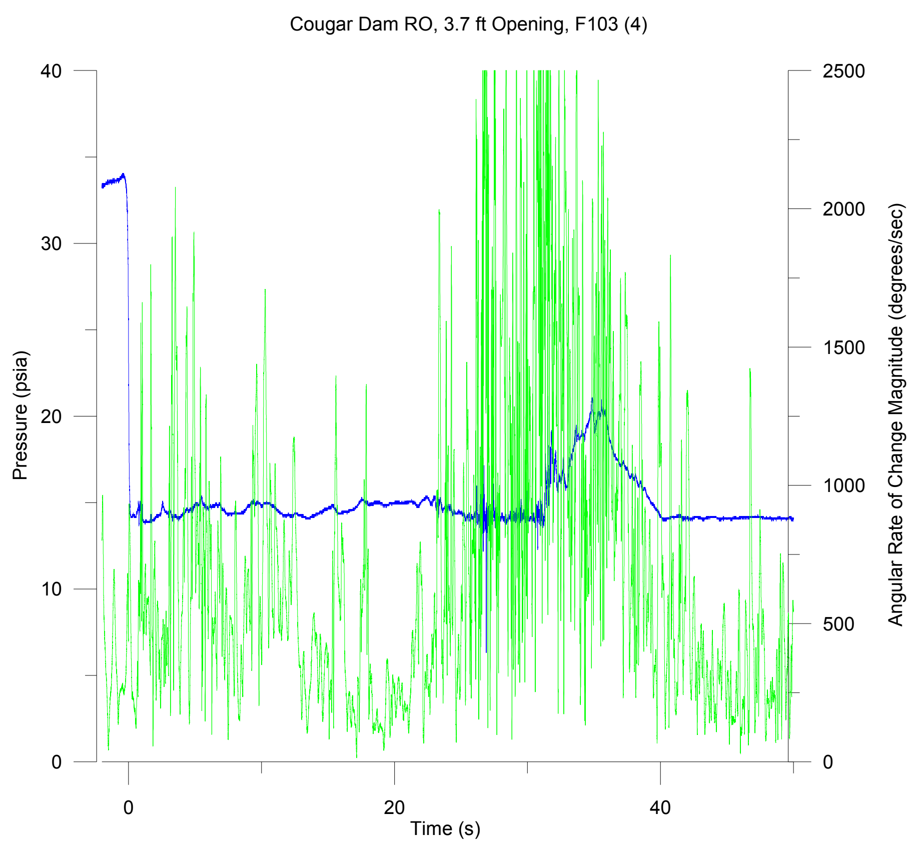
Cougar Dam RO, 3.7 ft Opening, F929 (1)

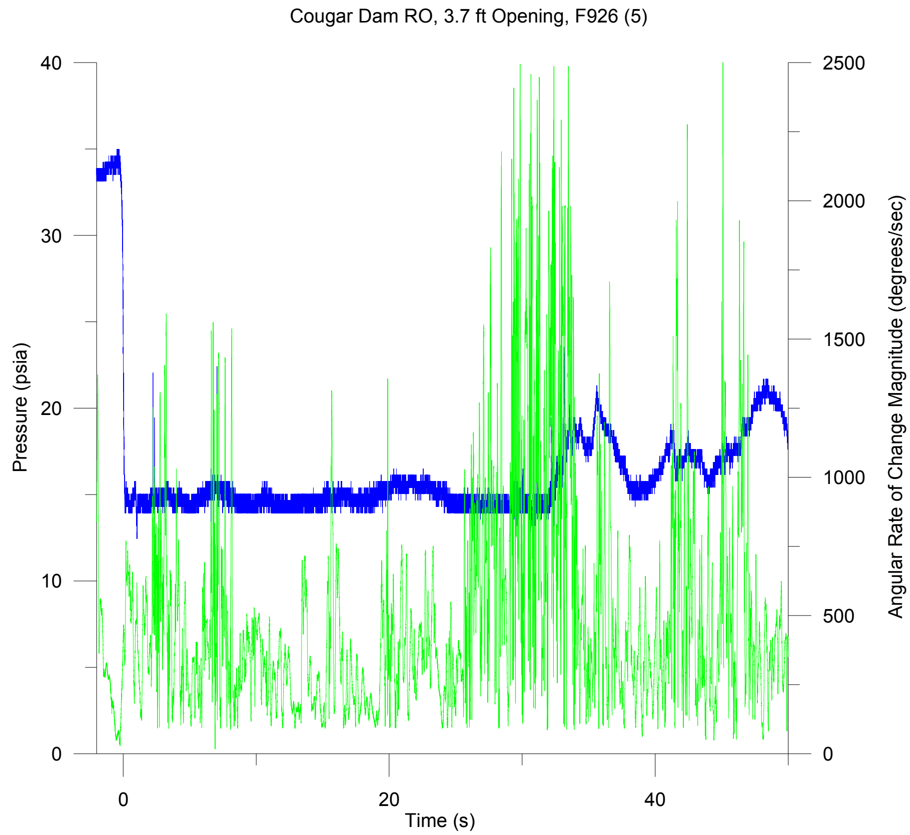


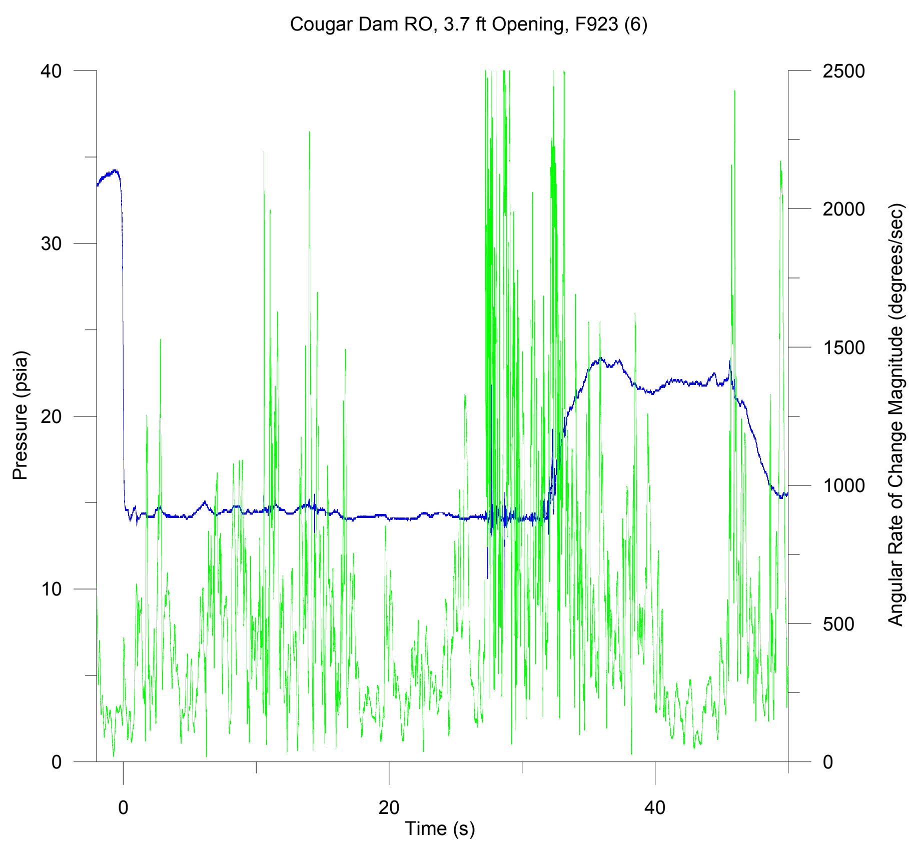
Cougar Dam RO, 3.7 ft Opening, F932 (2)

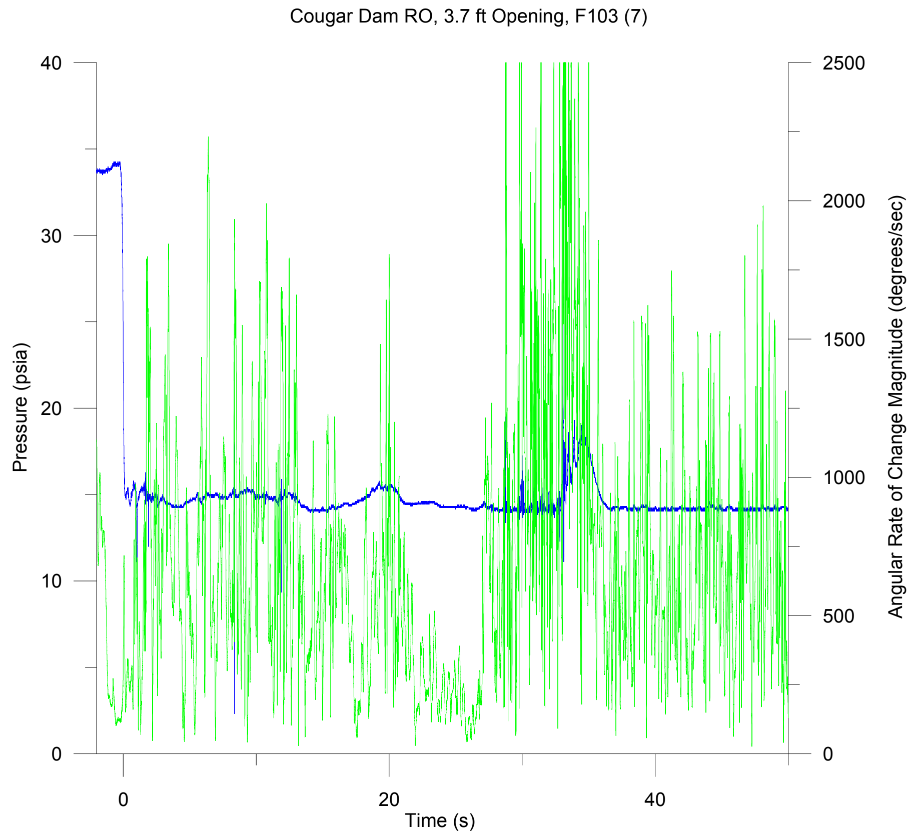


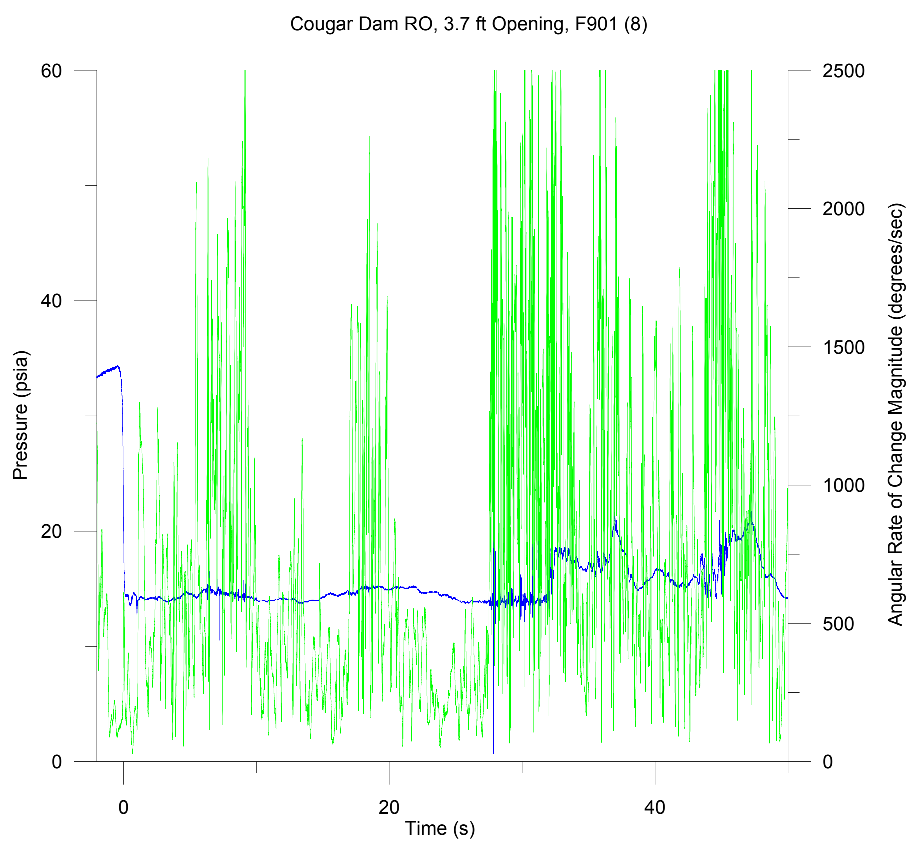

Cougar Dam RO, 3.7 ft Opening, F913 (3)
40
30
20
10
0
Pressure (psia)
2500
2000
1500
1000
500
0
Angular Rate of Change Magnitude (degrees/sec)
0
20
40
Time (s)


Cougar Dam RO, 3.7 ft Opening, F103 (4)
40
30
20
10
0
Pressure (psia)
2500
2000
1500
1000
500
0
Angular Rate of Change Magnitude (degrees/sec)
0
20
40
Time (s)

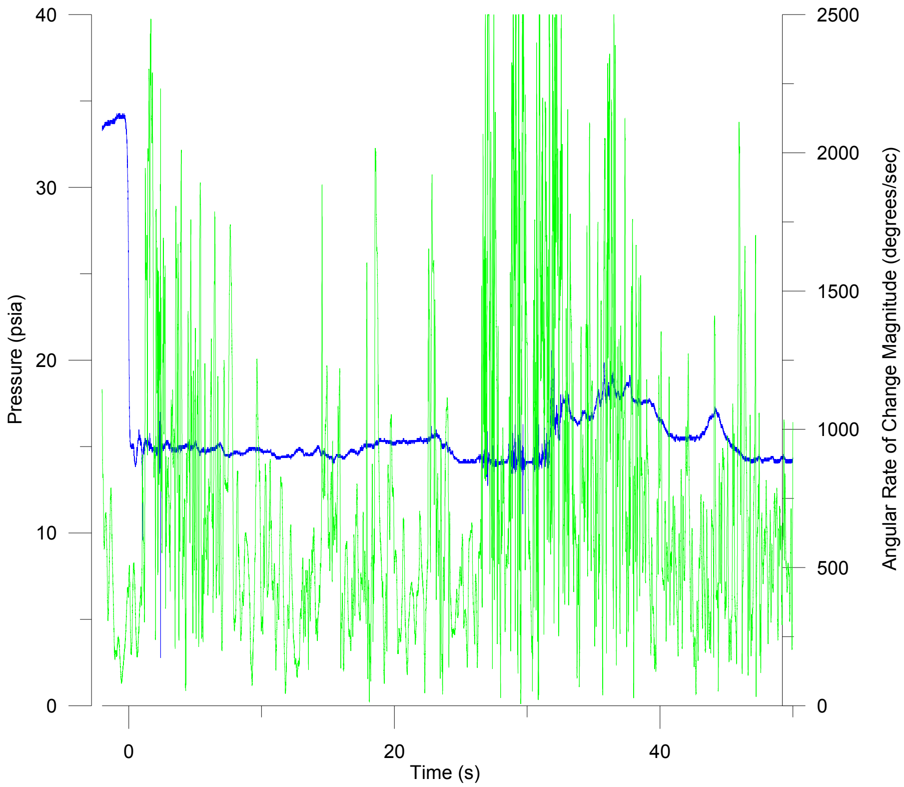

Cougar Dam RO, 3.7 ft Opening, F926 (5)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40


Cougar Dam RO, 3.7 ft Opening, F923 (6)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

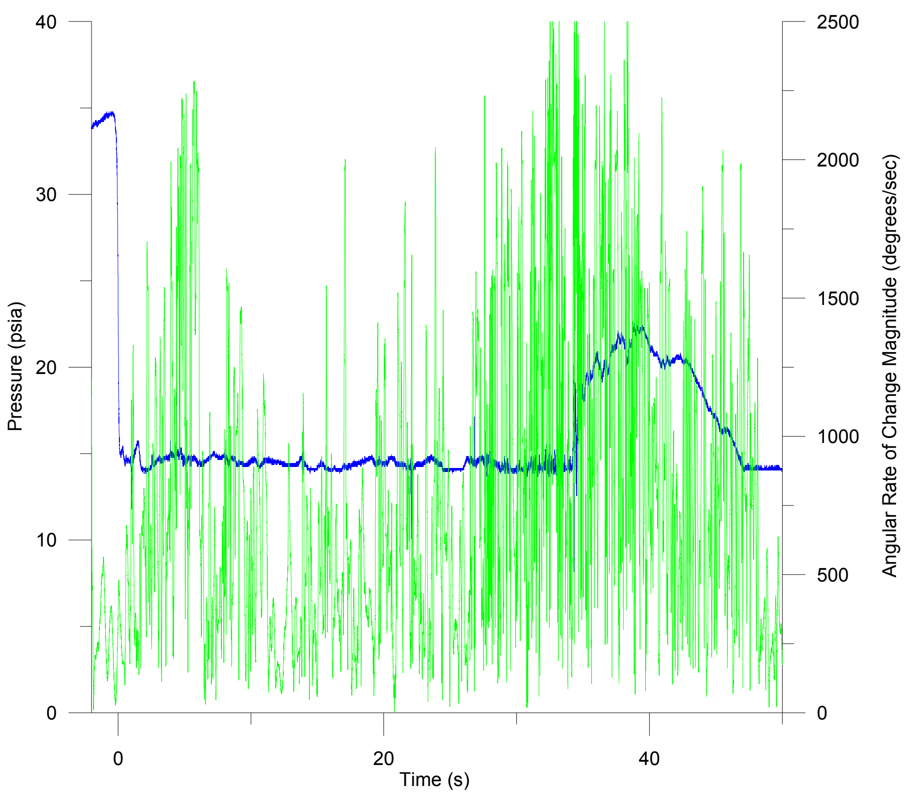

Cougar Dam RO, 3.7 ft Opening, F103 (7)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
0
500
1000
1500
2000
2500
0
20
40

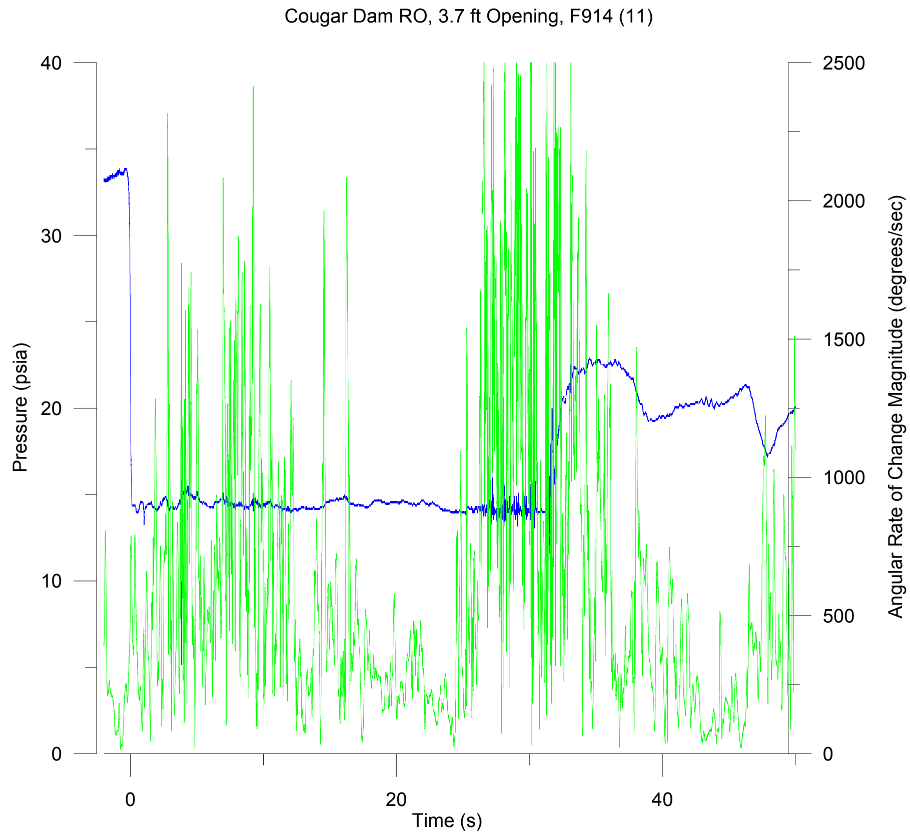

Cougar Dam RO, 3.7 ft Opening, F901 (8)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
20
40
60
0
500
1000
1500
2000
2500
0
20
40

Cougar Dam RO, 3.7 ft Opening, F930 (9)

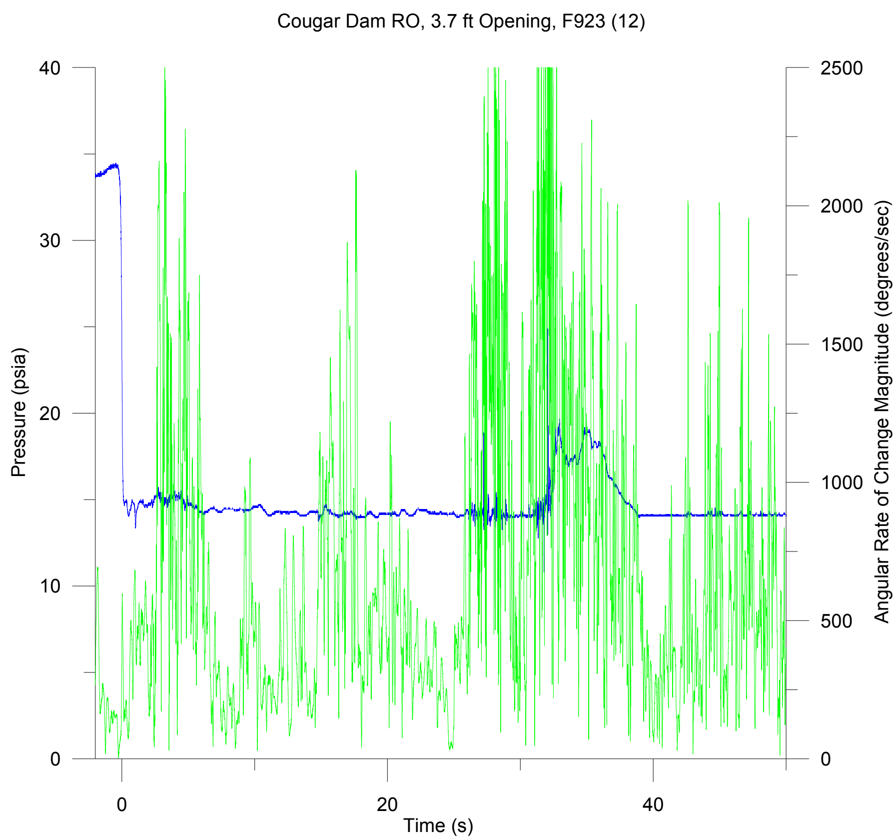


Cougar Dam RO, 3.7 ft Opening, F121 (10)

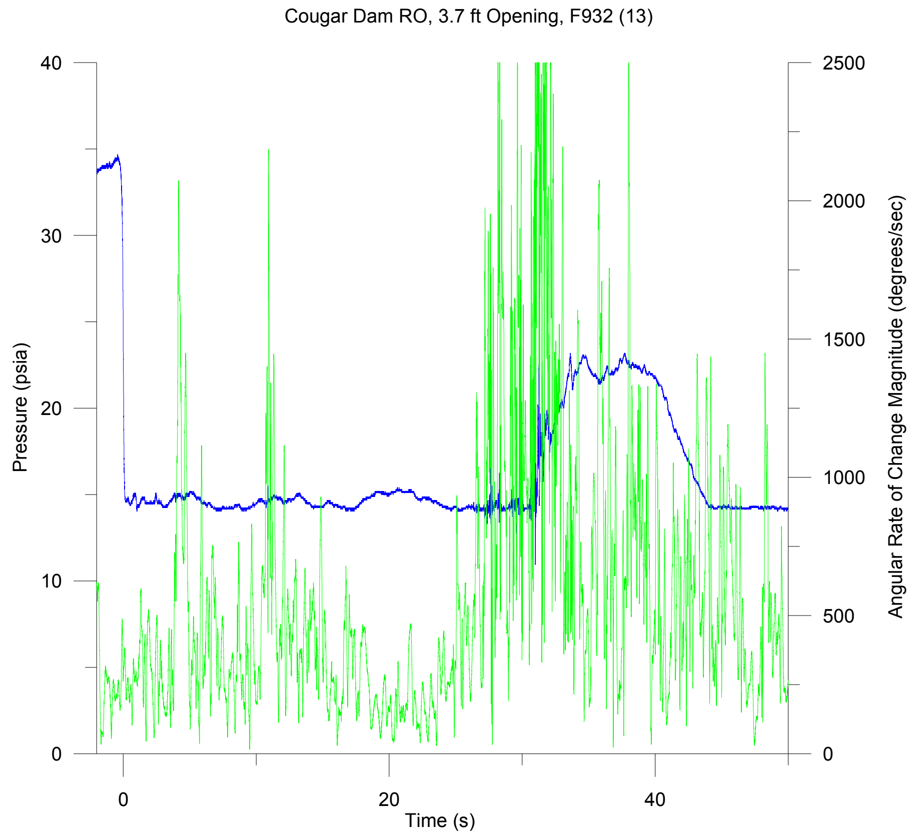


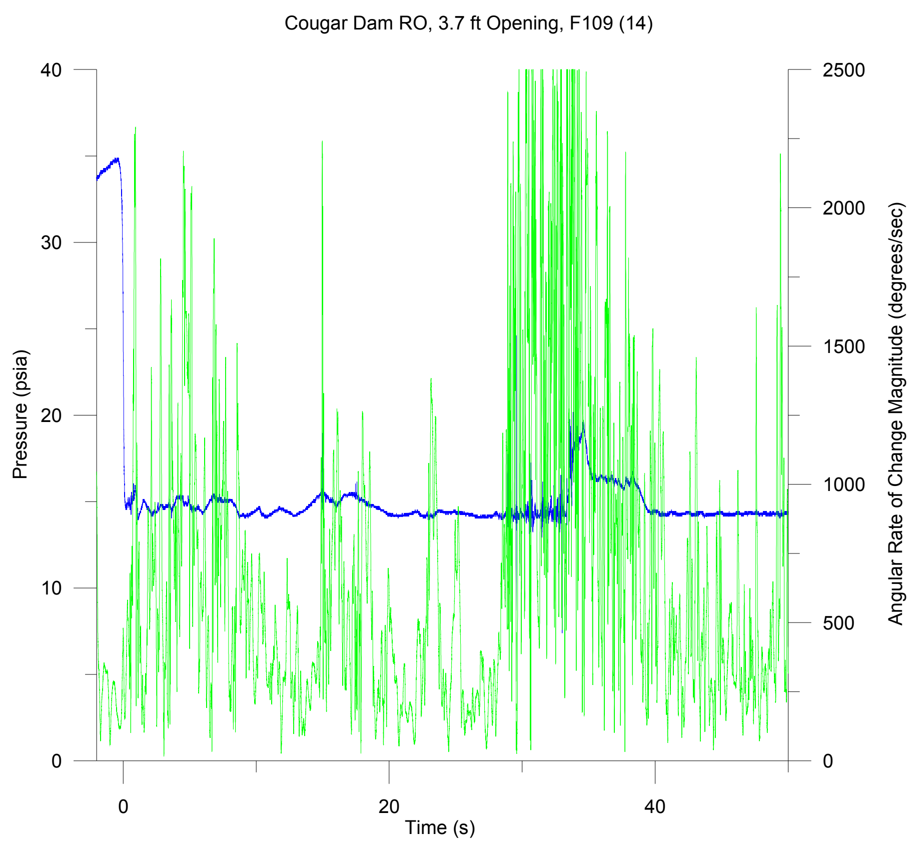


Cougar Dam RO, 3.7 ft Opening, F914 (11)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500

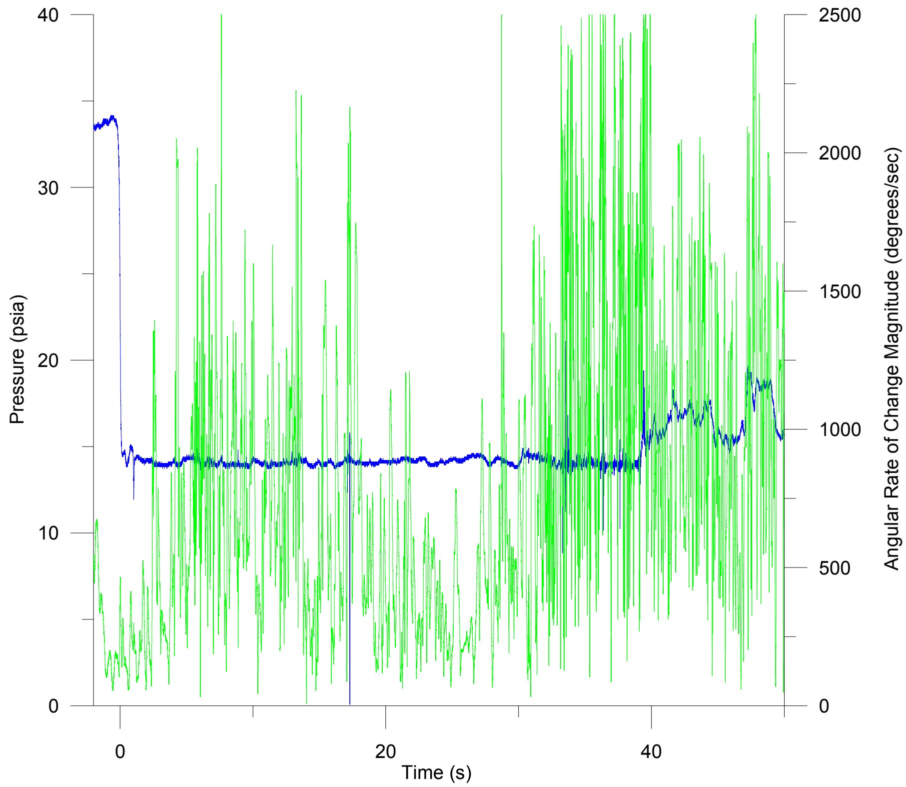


Cougar Dam RO, 3.7 ft Opening, F923 (12)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500

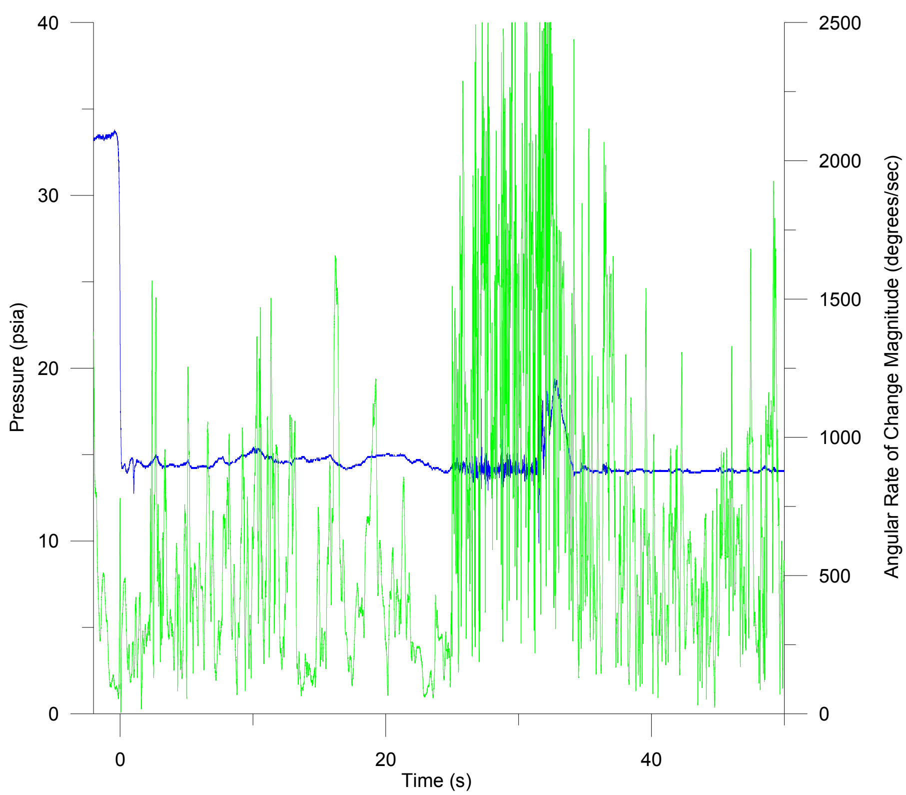

Cougar Dam RO, 3.7 ft Opening, F932 (13)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500


Cougar Dam RO, 3.7 ft Opening, F109 (14)
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (s)
0
10
20
30
40
500
1000
1500
2000
2500

Cougar Dam RO, 3.7 ft Opening, F929 (15)

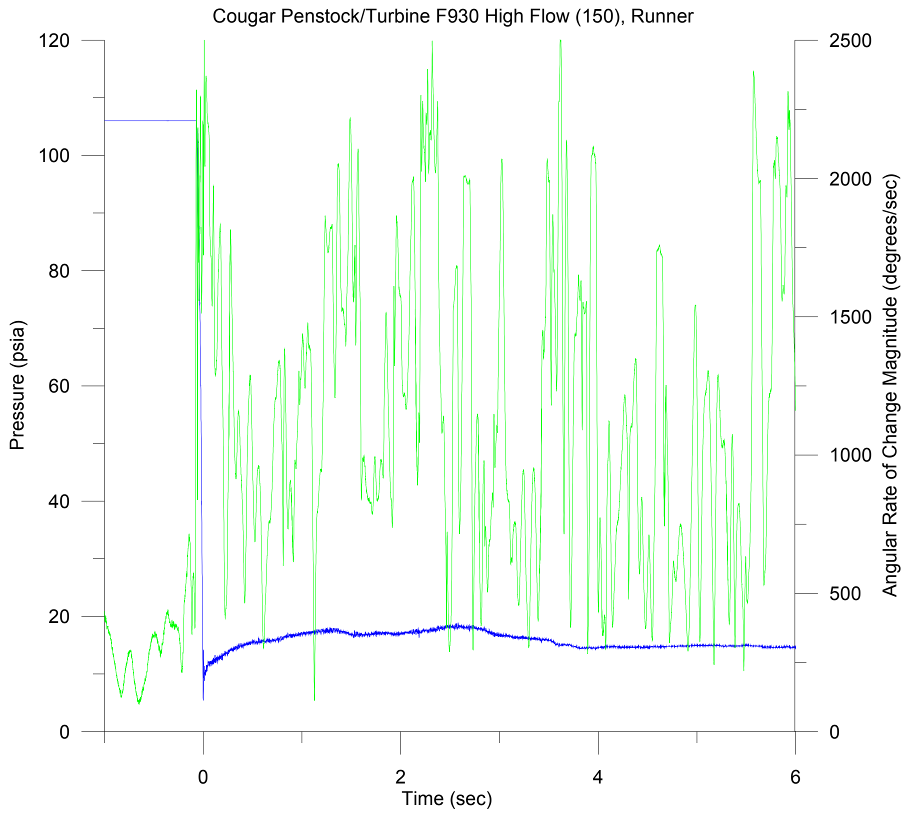


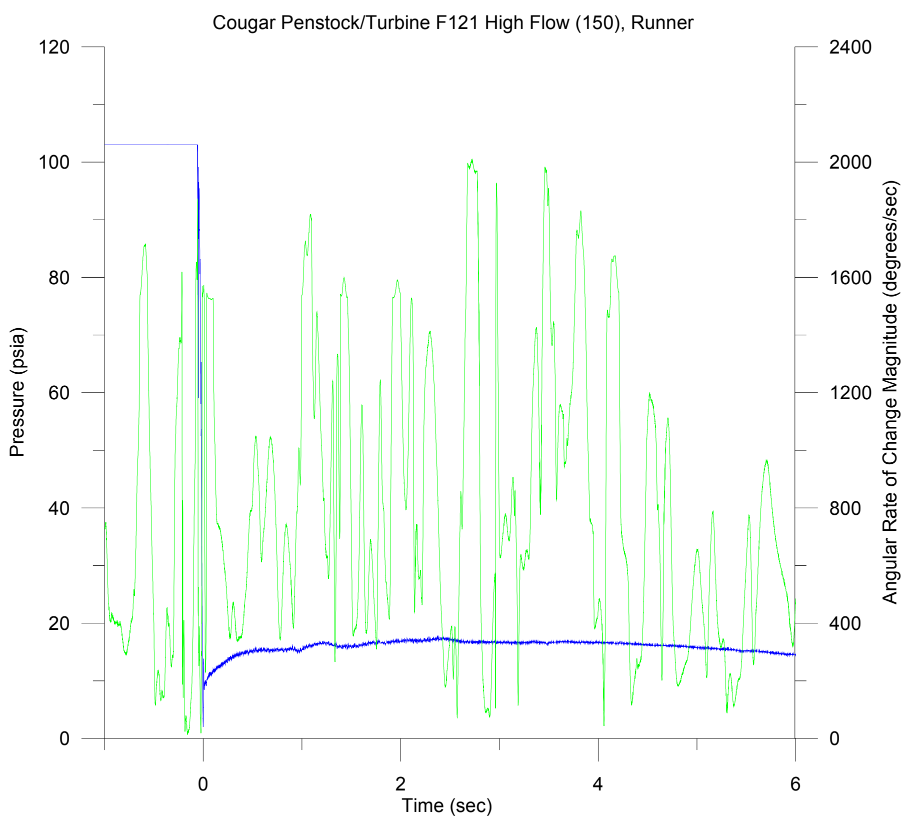
Cougar Dam RO, 3.7 ft Opening, F913 (16)

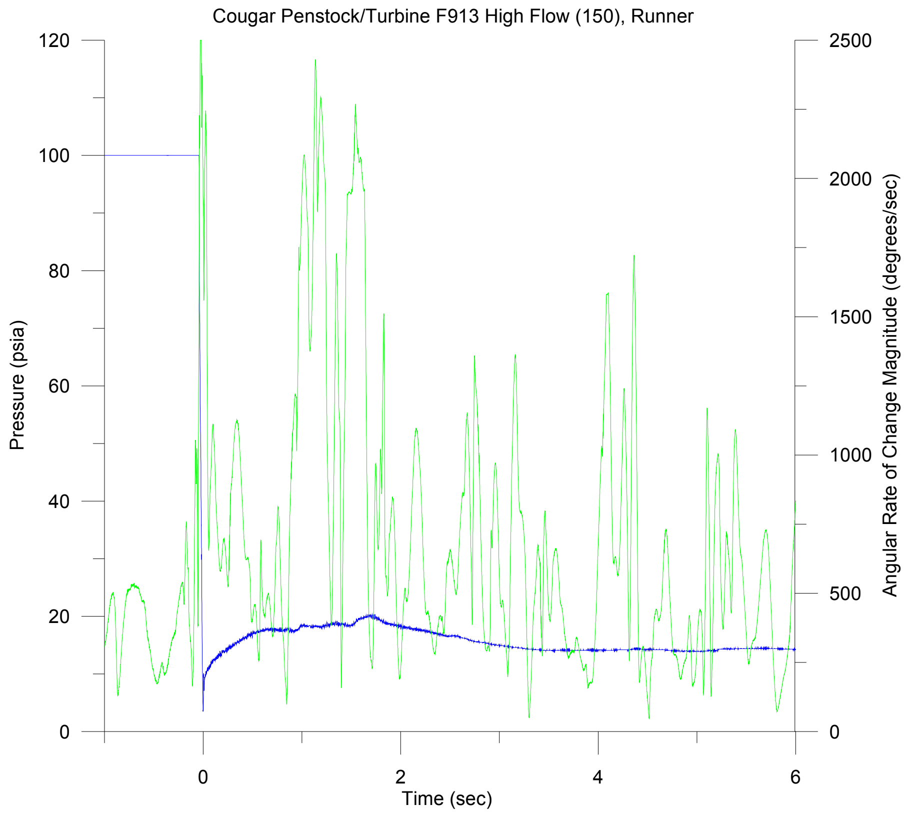


Cougar Dam Turbine Unit 2

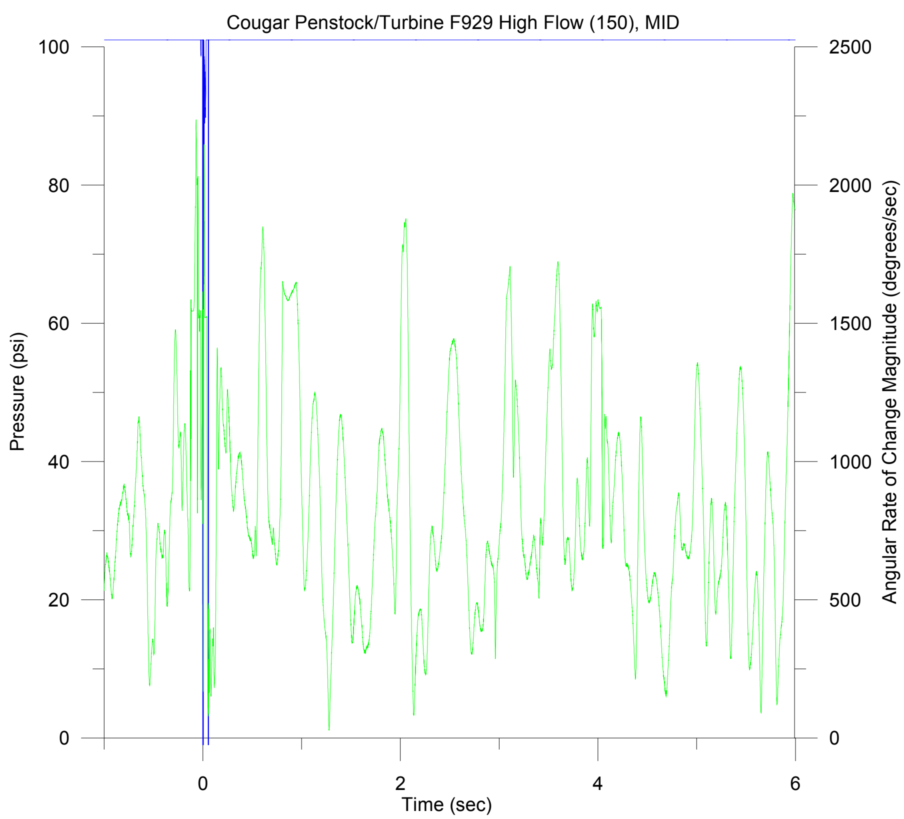
Maximum Wicket Gate Opening


Cougar Penstock/Turbine F930 High Flow (150), Runner
Pressure (psia)
0
20
40
60
80
100
120
Angular Rate of Change Magnitude (degrees/sec)
0
500
1000
1500
2000
2500
Time (sec)
0
2
4
6

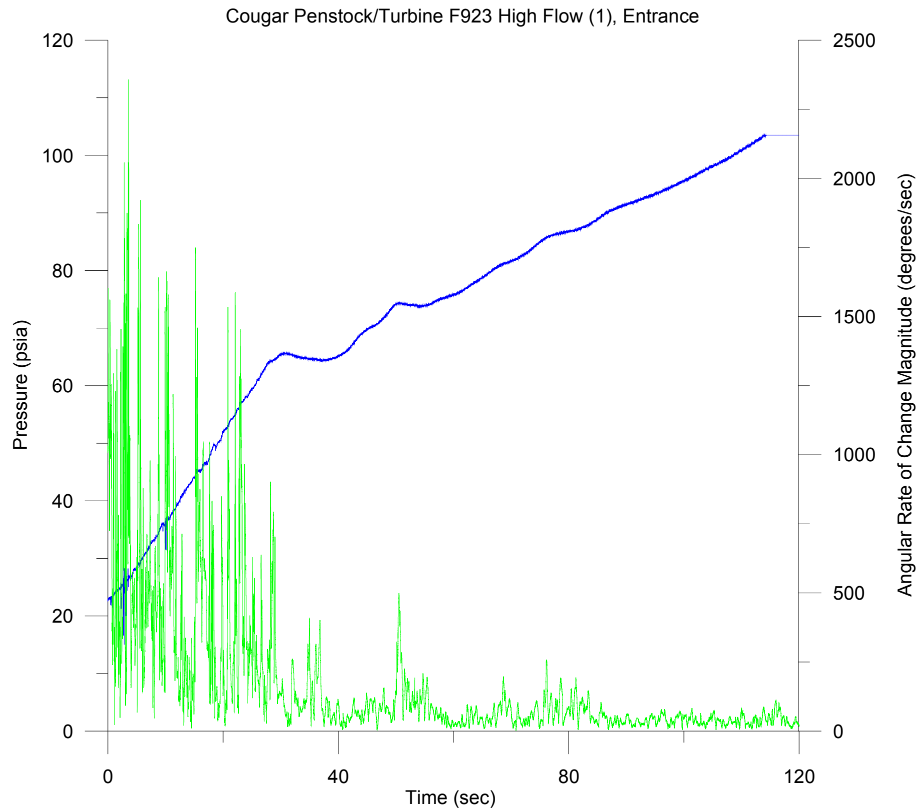

Cougar Penstock/Turbine F121 High Flow (150), Runner
Pressure (psia)
0
20
40
60
80
100
120
Angular Rate of Change Magnitude (degrees/sec)
0
400
800
1200
1600
2000
2400
Time (sec)
0
2
4
6



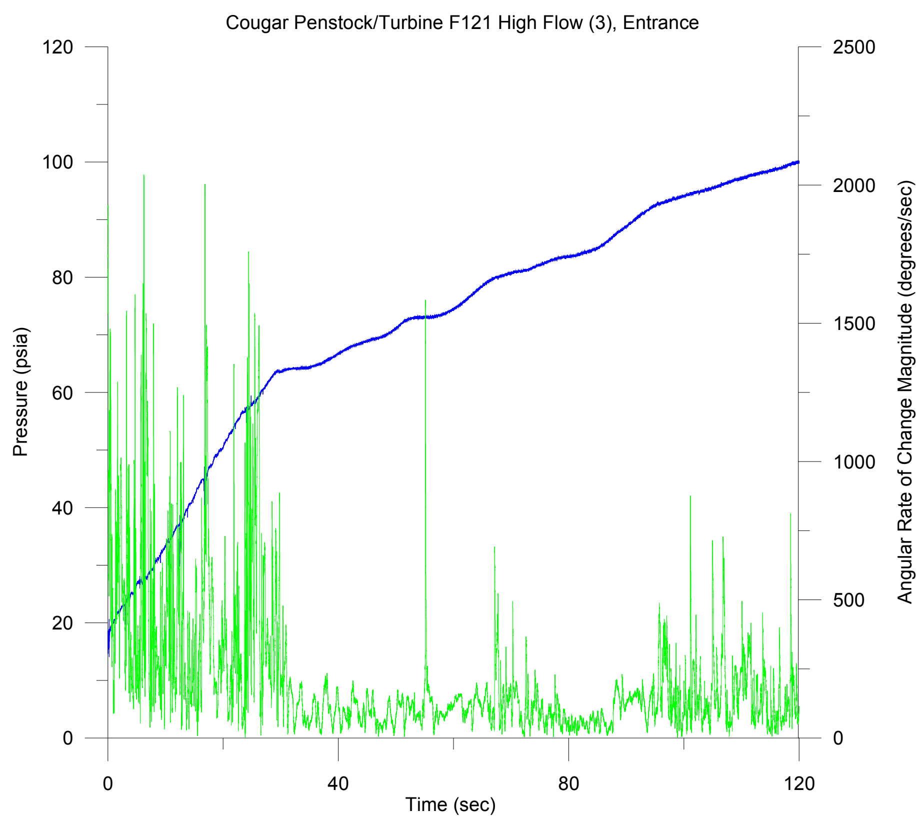
Cougar Penstock/Turbine F913 High Flow (150), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
120
100
80
60
40
20
0
2500
2000
1500
1000
500
0
0
2
4
6



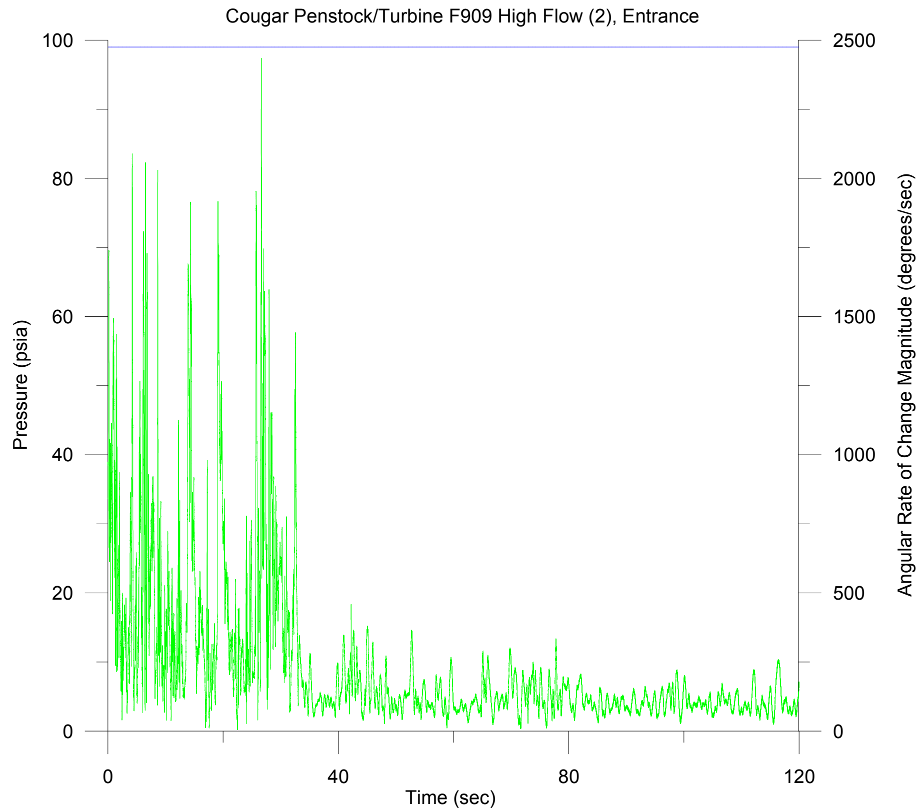
Cougar Penstock/Turbine F929 High Flow (150), MID
Pressure (psi)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
100
80
60
40
20
0
2500
2000
1500
1000
500
0
0
2
4
6



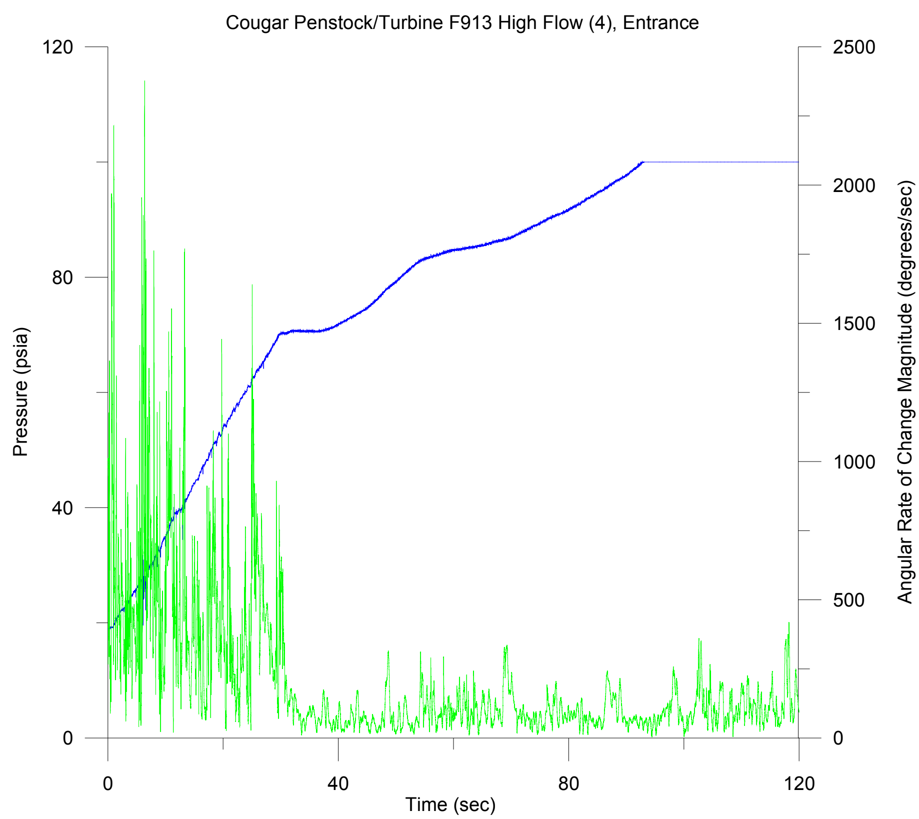
Cougar Penstock/Turbine F923 High Flow (1), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
0
500
1000
1500
2000
2500



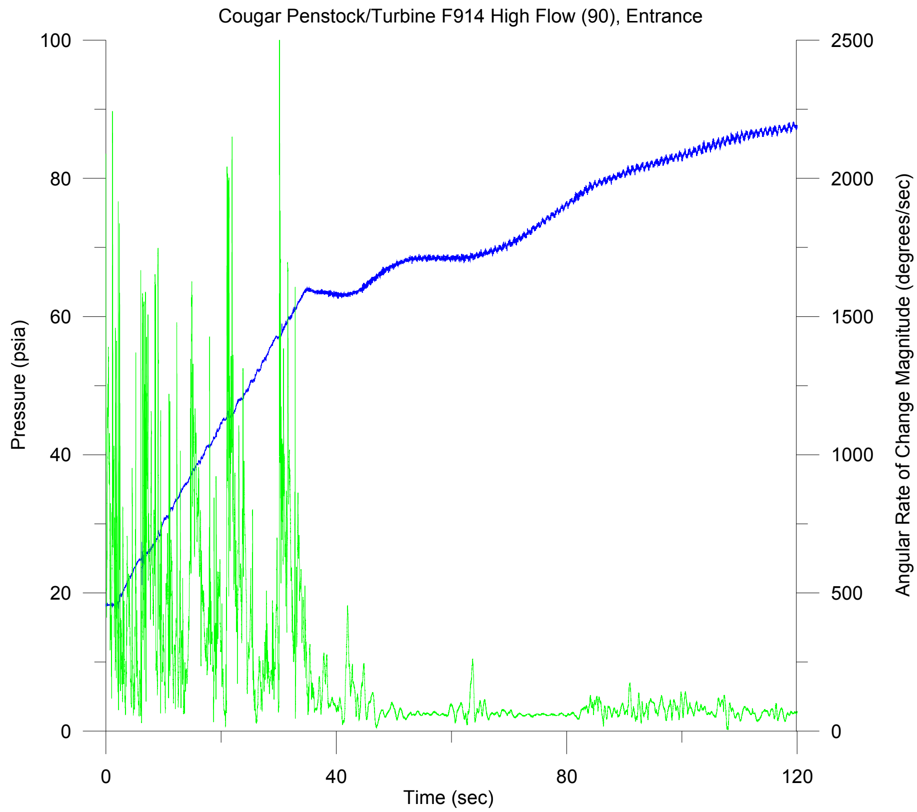
Cougar Penstock/Turbine F121 High Flow (3), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
0
40
80
120
0
500
1000
1500
2000
2500



Cougar Penstock/Turbine F909 High Flow (2), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
0
500
1000
1500
2000
2500
0
40
80
120

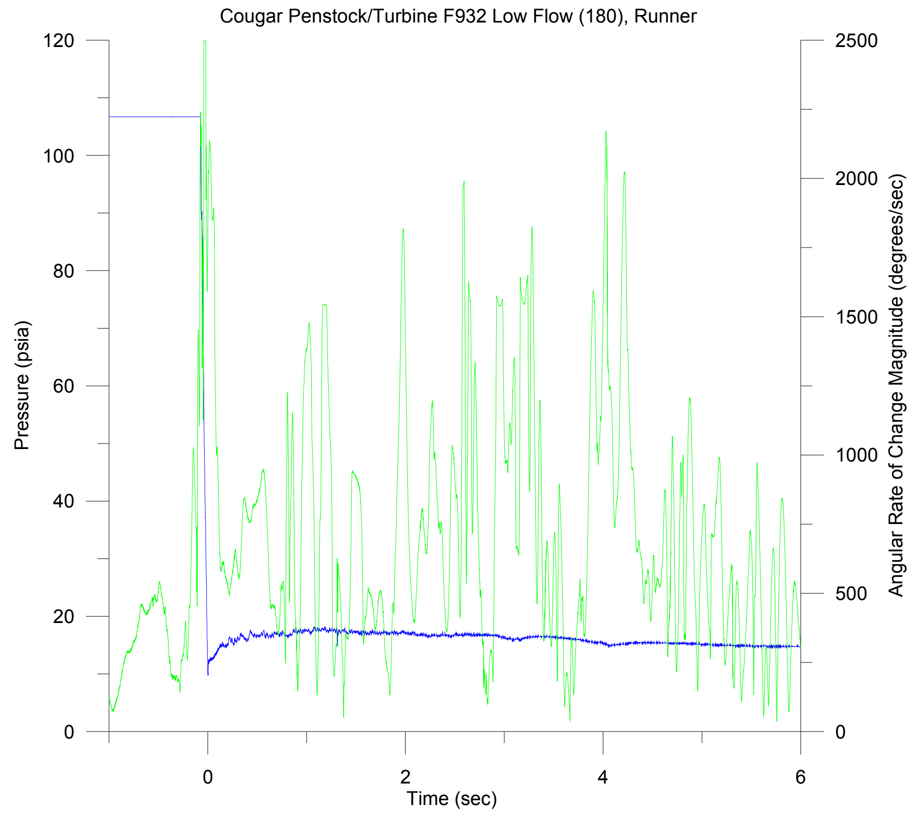


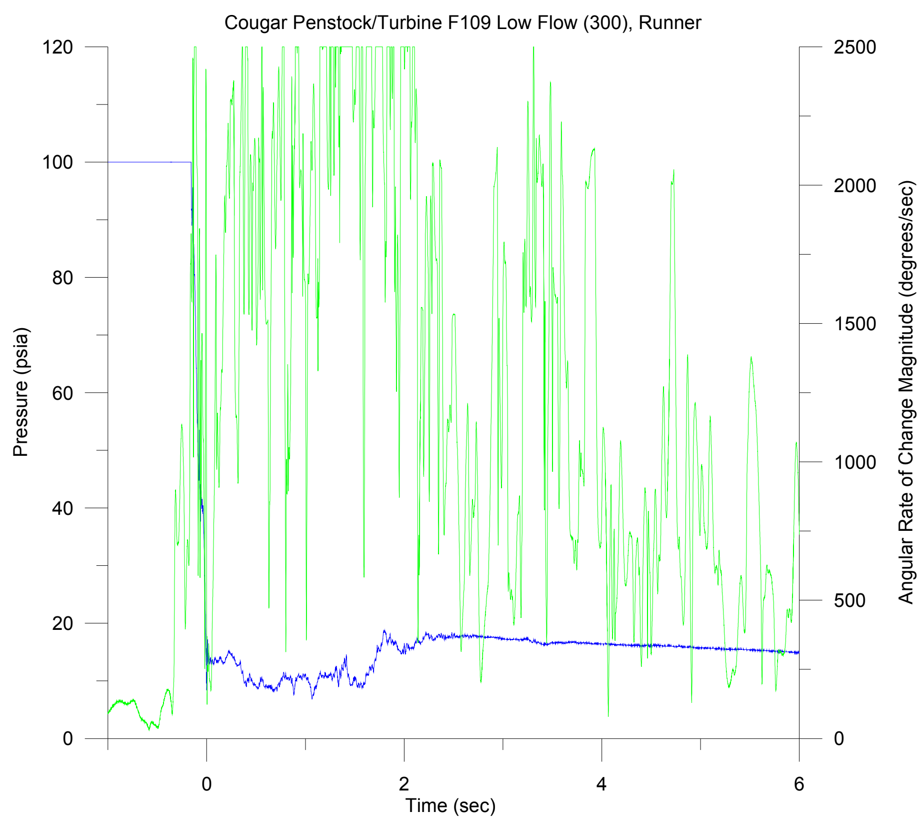
Cougar Penstock/Turbine F913 High Flow (4), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
40
80
120
0
500
1000
1500
2000
2500
0
40
80
120

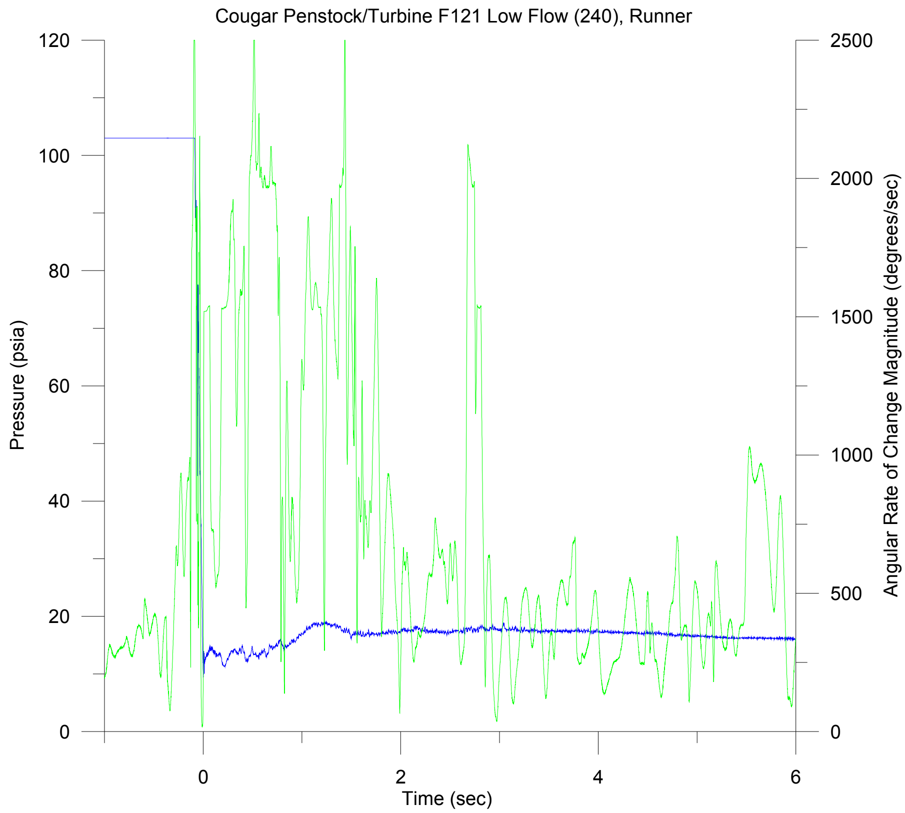

Cougar Penstock/Turbine F914 High Flow (90), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
0
500
1000
1500
2000
2500
0
40
80
120

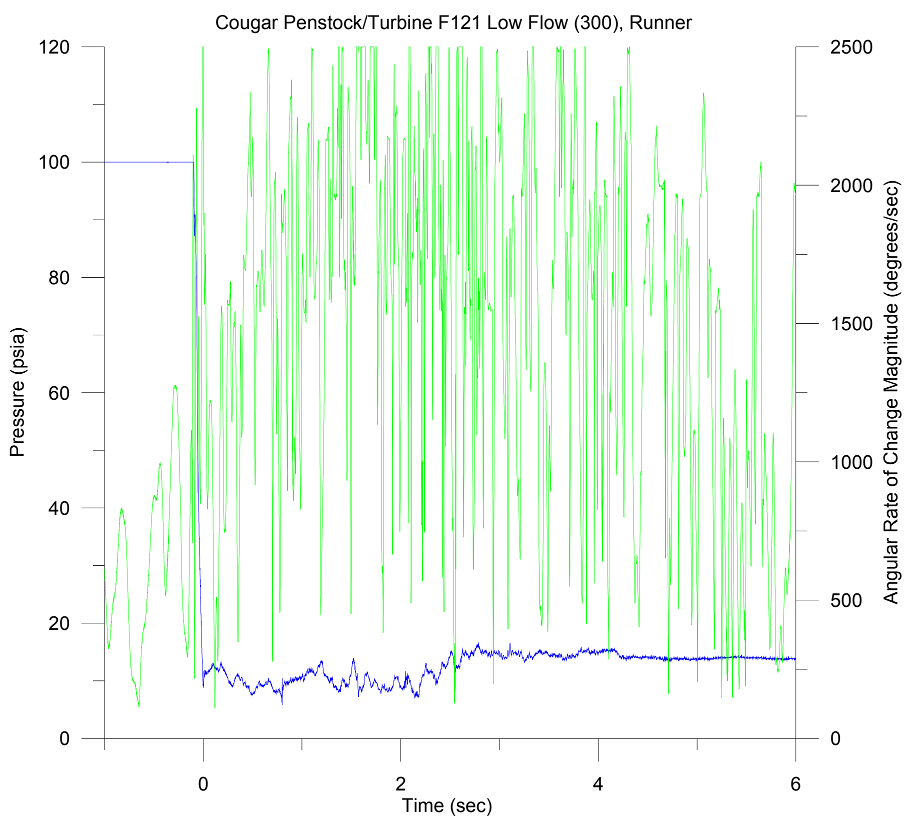
Cougar Dam Turbine Unit 2

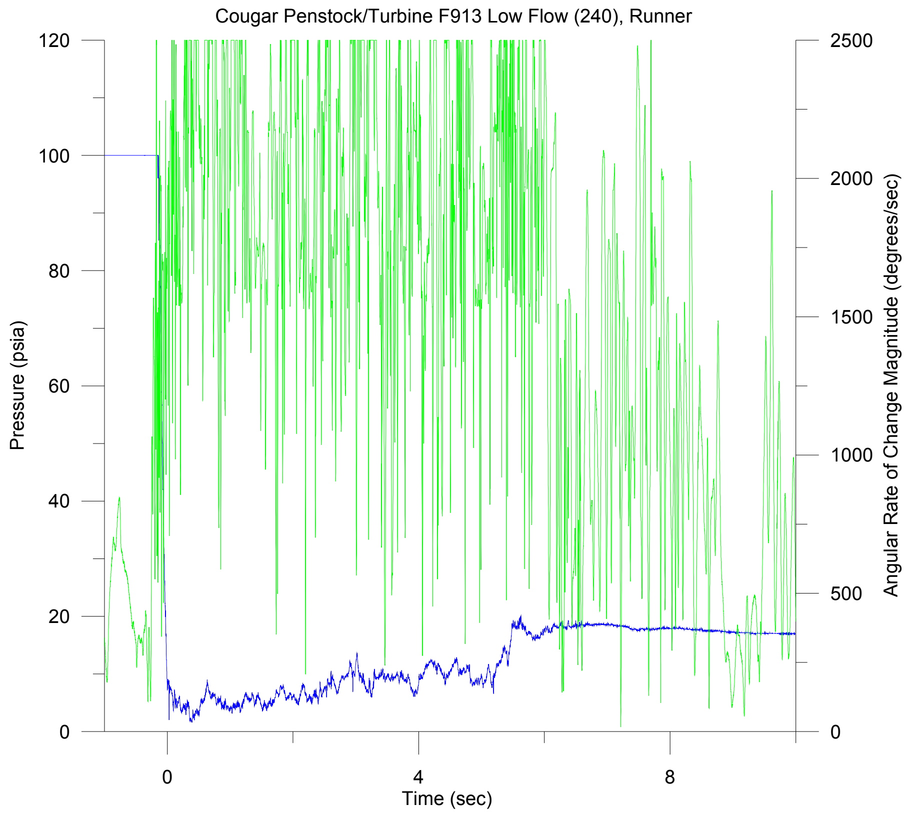
Minimum Wicket Gate Opening

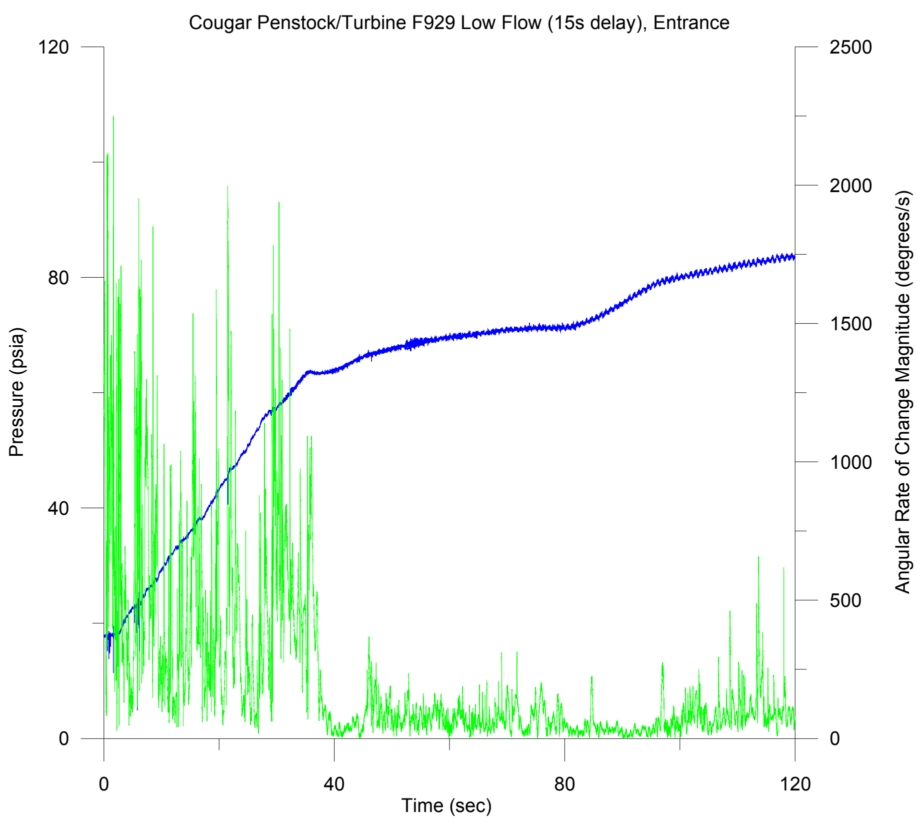

Cougar Penstock/Turbine F932 Low Flow (180), Runner
Pressure (psia)
0
20
40
60
80
100
120
Angular Rate of Change Magnitude (degrees/sec)
0
500
1000
1500
2000
2500
Time (sec)
0
2
4
6

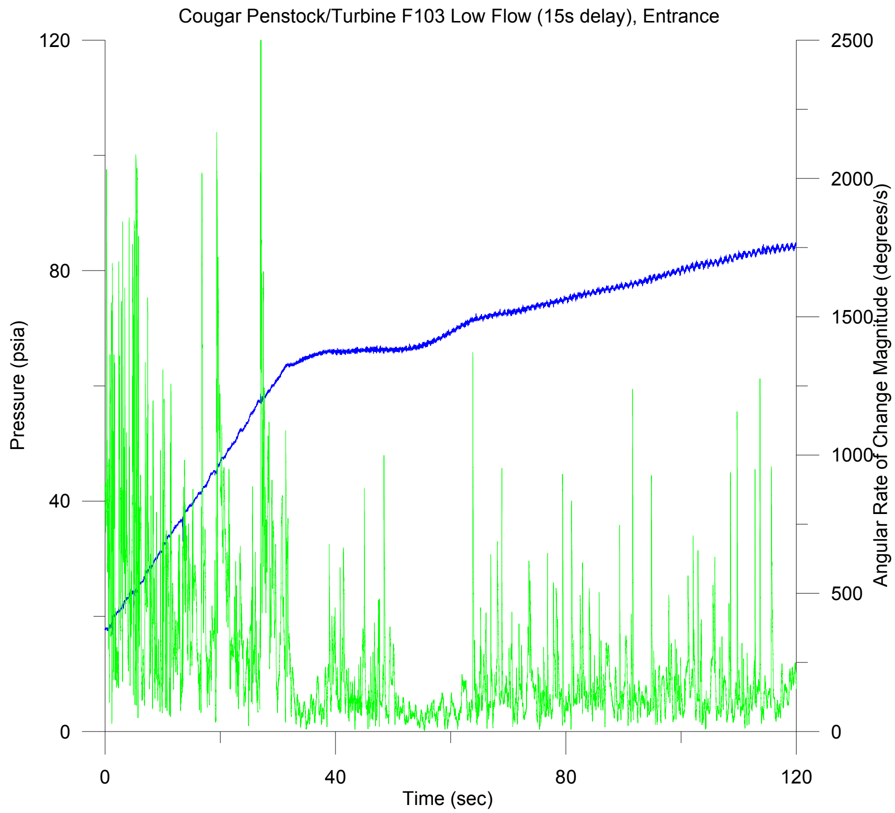

Cougar Penstock/Turbine F109 Low Flow (300), Runner
Pressure (psia)
0
20
40
60
80
100
120
Angular Rate of Change Magnitude (degrees/sec)
0
500
1000
1500
2000
2500
Time (sec)
0
2
4
6


Cougar Penstock/Turbine F121 Low Flow (240), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
0
2
4
6

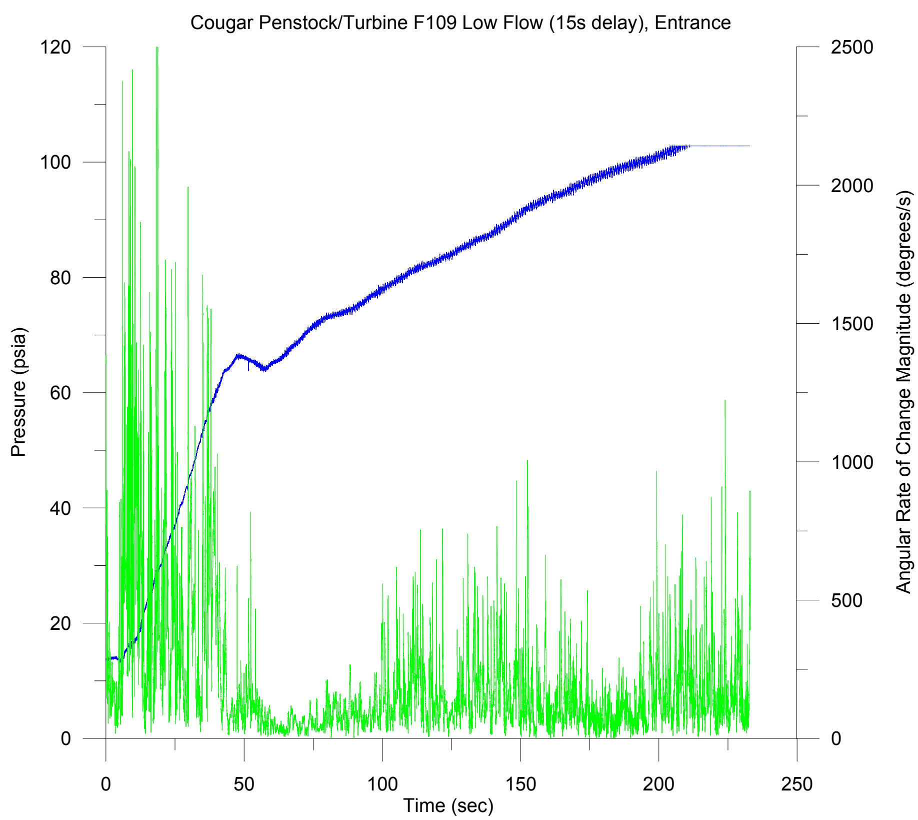

Cougar Penstock/Turbine F121 Low Flow (300), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
0
2
4
6


Cougar Penstock/Turbine F913 Low Flow (240), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
4
8
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500

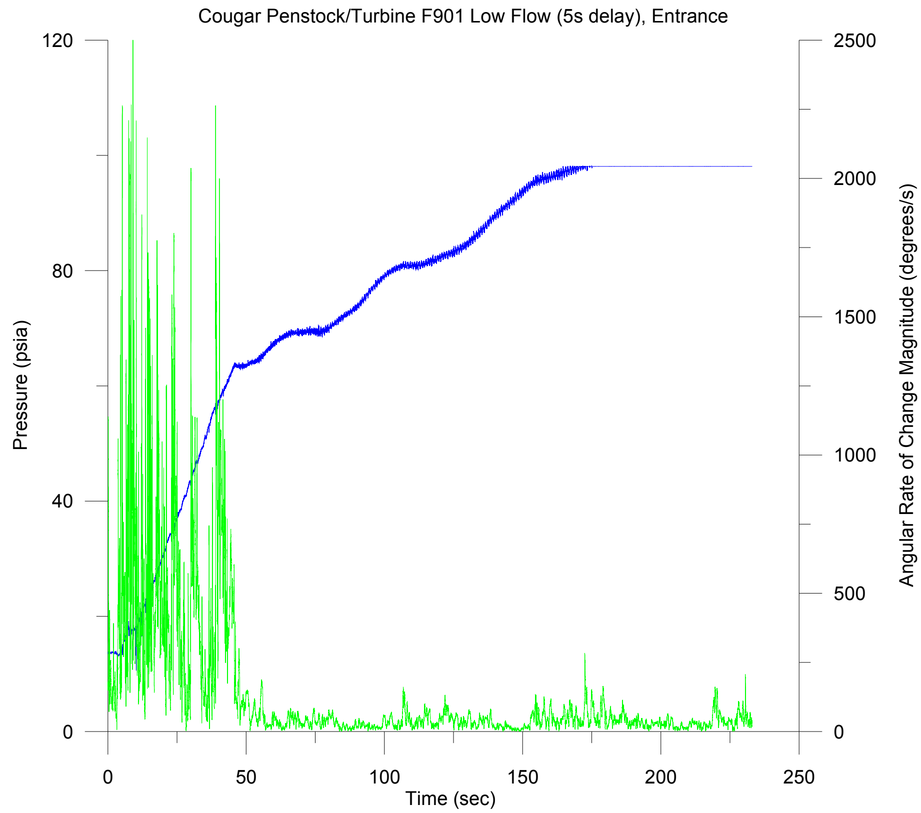

Cougar Penstock/Turbine F929 Low Flow (15s delay), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
40
80
120
0
40
80
120
0
500
1000
1500
2000
2500

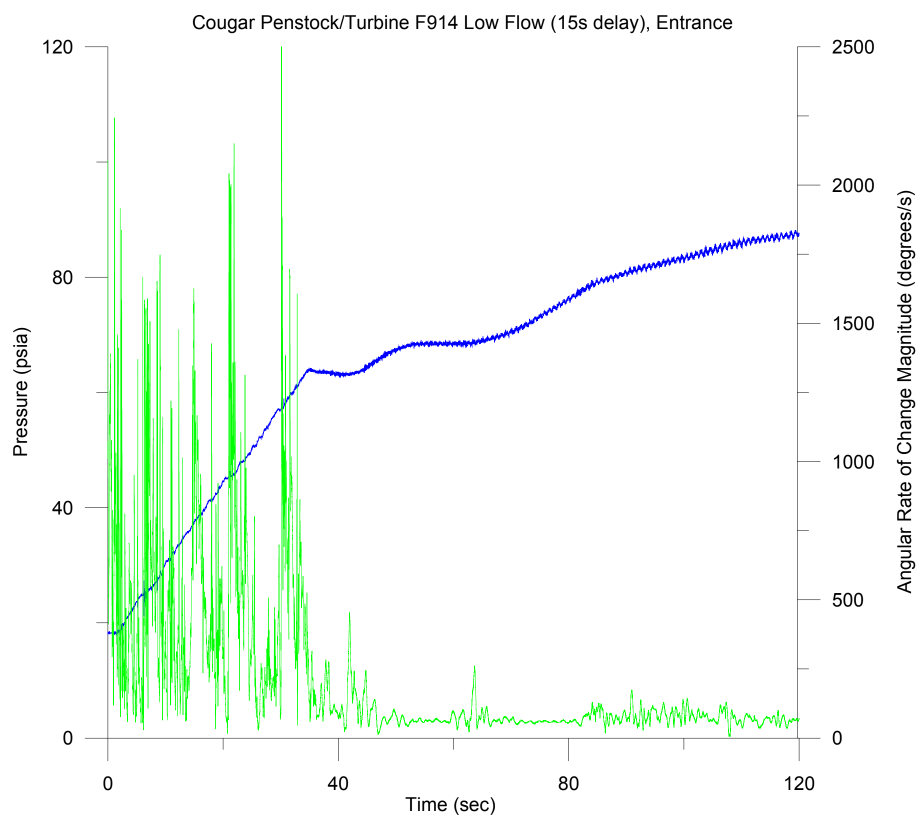


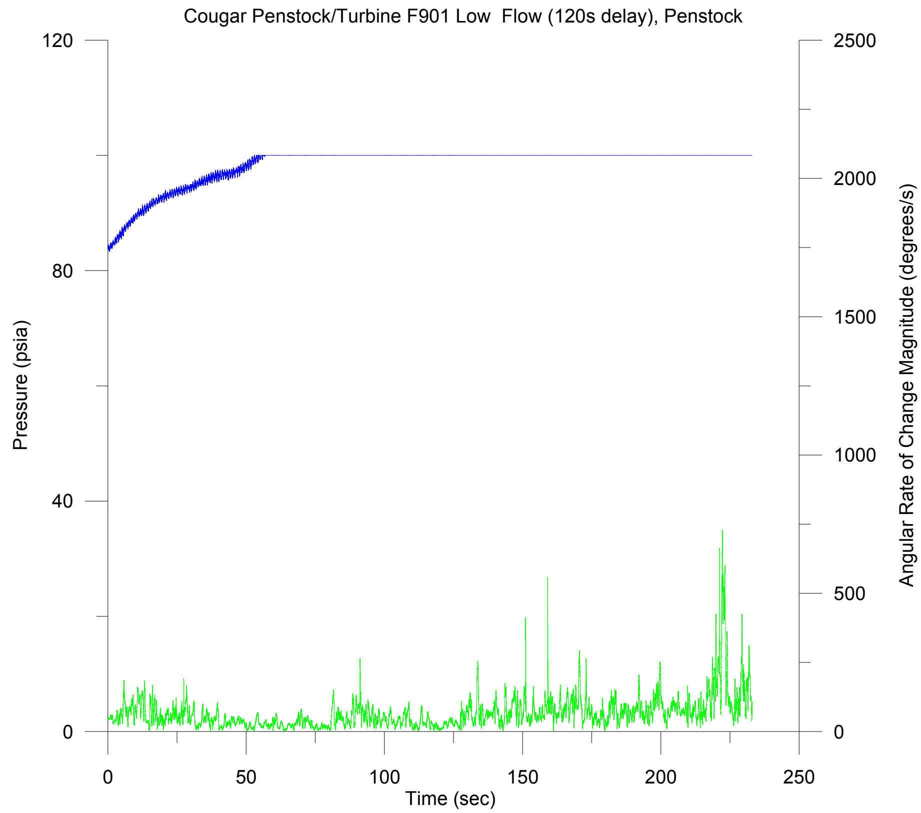
Cougar Penstock/Turbine F103 Low Flow (15s delay), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
40
80
120
0
500
1000
1500
2000
2500

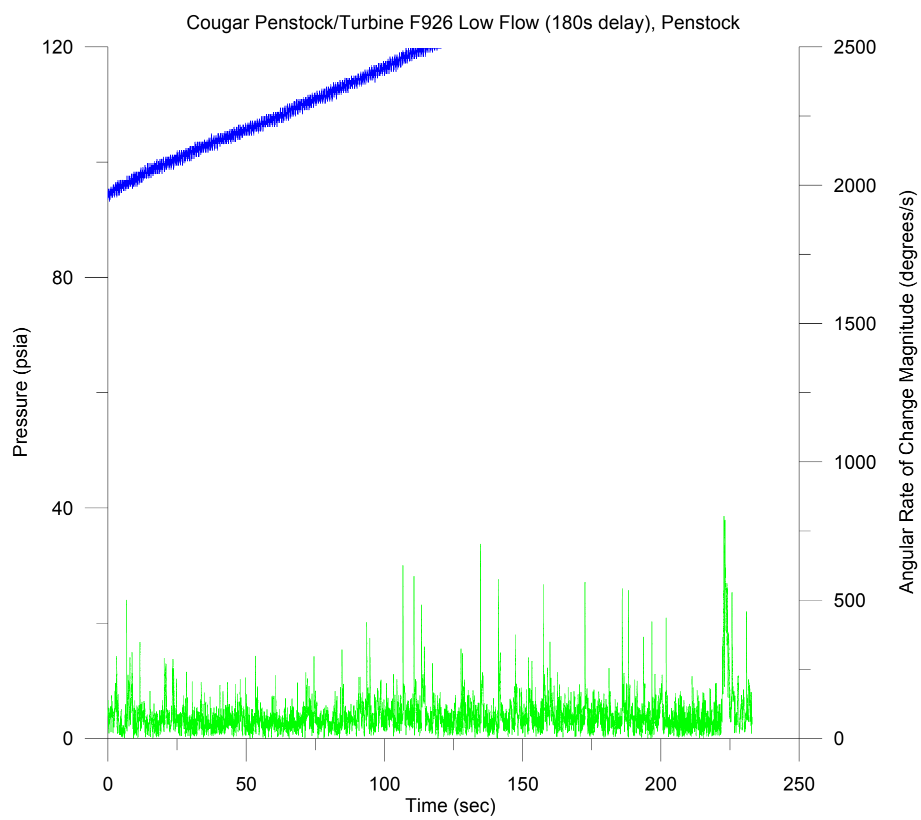


Cougar Penstock/Turbine F109 Low Flow (15s delay), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
20
40
60
80
100
120
0
50
100
150
200
250
0
500
1000
1500
2000
2500


Cougar Penstock/Turbine F901 Low Flow (5s delay), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
40
80
120
0
500
1000
1500
2000
2500
0
50
100
150
200
250

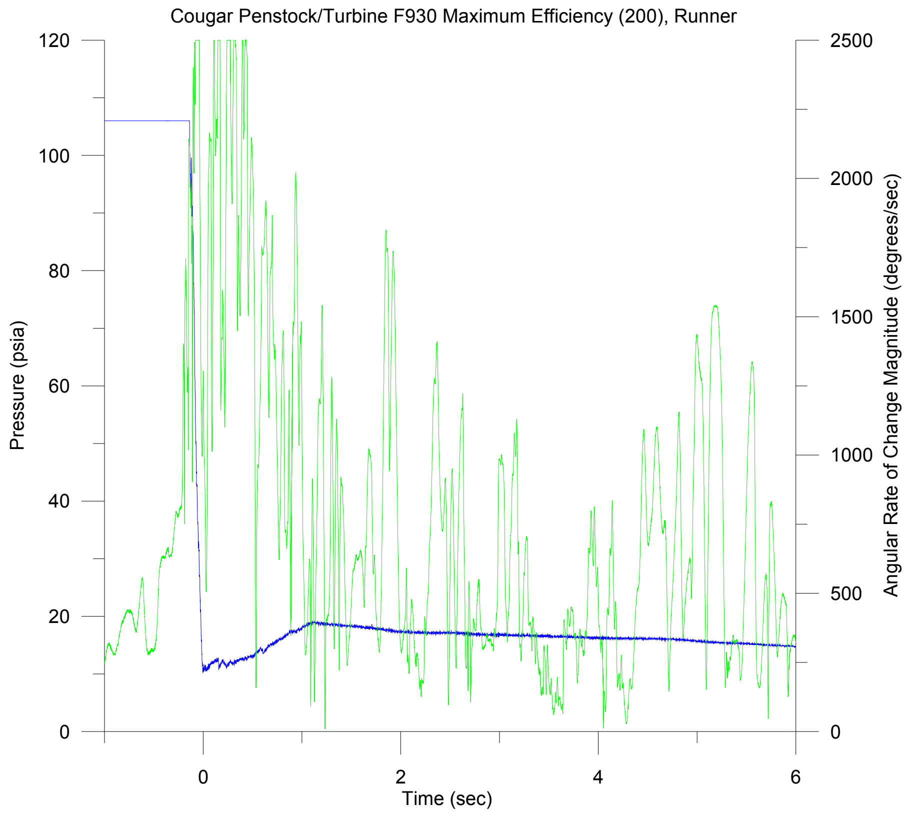

Cougar Penstock/Turbine F914 Low Flow (15s delay), Entrance
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
40
80
120
0
500
1000
1500
2000
2500
0
40
80
120

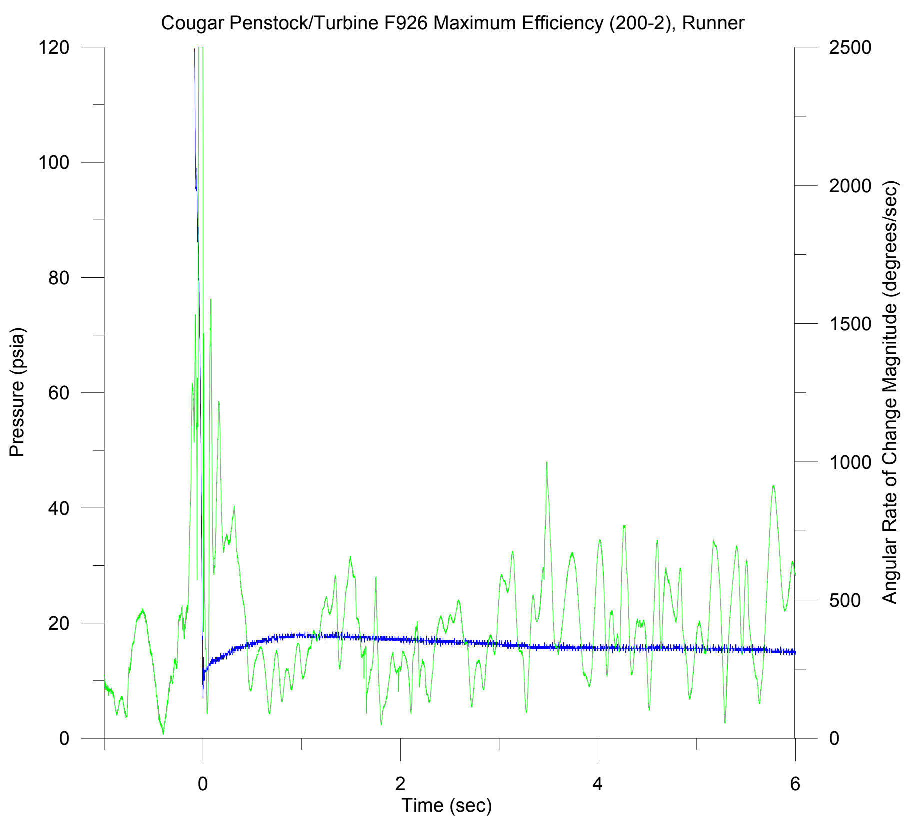

Cougar Penstock/Turbine F901 Low Flow (120s delay), Penstock
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
40
80
120
0
500
1000
1500
2000
2500
0
50
100
150
200
250

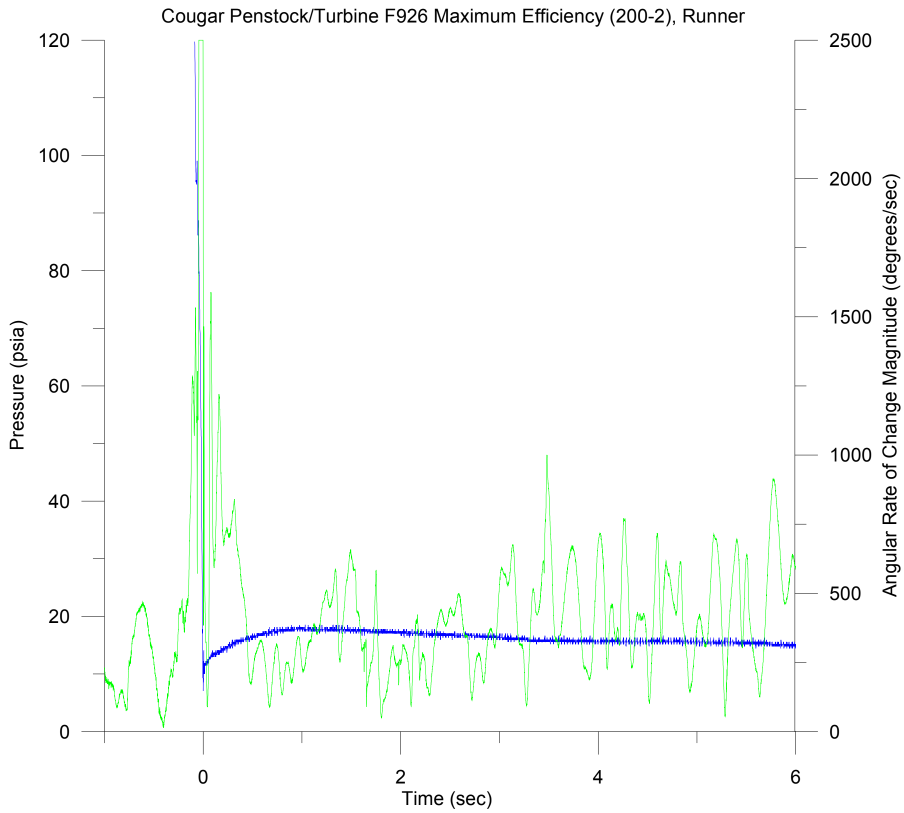

Cougar Penstock/Turbine F926 Low Flow (180s delay), Penstock
Pressure (psia)
Angular Rate of Change Magnitude (degrees/s)
Time (sec)
0
40
80
120
0
500
1000
1500
2000
2500
0
50
100
150
200
250

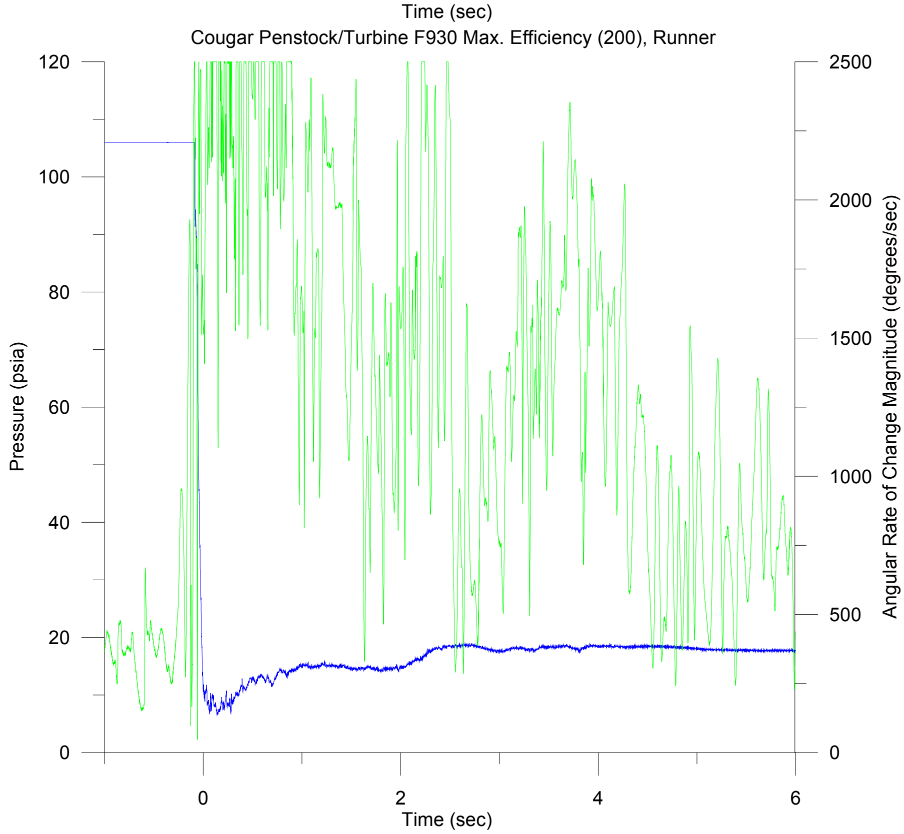
Cougar Dam Turbine Unit 2

Peak Efficiency Wicket Gate Opening


Cougar Penstock/Turbine F930 Maximum Efficiency (200), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
500
1000
1500
2000
2500
2
4
6


Cougar Penstock/Turbine F926 Maximum Efficiency (200-2), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
500
1000
1500
2000
2500
2
4
6


Cougar Penstock/Turbine F926 Maximum Efficiency (200-2), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
0
2
4
6


Cougar Penstock/Turbine F930 Max. Efficiency (200), Runner
Pressure (psia)
Angular Rate of Change Magnitude (degrees/sec)
Time (sec)
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
0
2
4
6

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