Hydraulic Investigations
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PAP-517

Progress Report (Phase -II)

Sound and Vibration Measurements at Flatiron Power and Pumping Plant

Loveland, Colorado
Fall 1986 - Summer 1987

by

M. M. Skinner

for

U. S. Bureau of Reclamation
Division of Research and Laboratory Services
Denver, Colorado

September 30, 1987

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INTRODUCTION

For a six (6) month period between October 20, 1986 and August 31, 1987 an IPA Mobility Assignment Agreement for Dr. Morris M. Skinner was initiated between the Bureau of Reclamation, Division of Research and Laboratory Services and Colorado State University, Civil Engineering Department. The Mobility Assignment was for the purpose of developing data acquisition procedures for evaluating critical operating conditions at hydropower plants. A three phase study was planned to extend over approximately three calendar years:

- Phase I - Summer 1986, develop procedures.
- Phase II - Fall 1986 - Summer 1987, develop base-line spectra and expand measurements to a variety of different units.
- Phase III - Fall 1987 - Summer 1988, Training of hydropower personnel.

The detection of damaging flow conditions in a turbine at various operating points and the use of sound and vibration spectra for monitoring the condition of a turbine were of prime interest. Efforts were directed towards the goal of developing practical procedures for minimizing maintenance costs and downtime.

Four (4) specific tasks were defined:

A. Develop and implement a data acquisition plan to collect vibration, pressure, sound, and other data at the Bureau of Reclamation's Flatiron Powerplant in Loveland, Colorado, and at other Bureau of Reclamation Power Plants. The Hewlett-Packard 3561A Dynamic Signal Analyzer would be the primary piece of equipment used. The type of analysis would include run-up and coast-down (waterfall display) of sound and vibration spectra, one-third octave analysis and measurement of pressure transients.

B. Work closely with the Bureau of Reclamation engineers to develop appropriate techniques (such as acoustic emissions) to differentiate between cavitation in the flow versus cavitation against a boundary and to develop methods to locate the source of a signal. The Bureau of Reclamation would supply supplemental instrumentation to investigate various methods.

C. Continue development of a hypothesis based on a background appraisal of cavitation in turbines and other information in the literature that accounts for the observed data within a theoretical framework and can be used as a basis for further investigation.

D. Report on the findings of the study.

PLANT DESCRIPTION

The Flatiron Power and Pumping Plant, part of the Colorado Big Thompson project, began initial operation in 1954 and is located approximately ten (10) miles southwest of Loveland, Colorado. Units #1 and #2 are 35 megawatt Francis type turbines turning at 514 RPM and used primarily as peaking plants. Difference in elevation between the Forebay Reservoir (Pinewood Lake) and the Tailrace (Flatiron Reservoir) is approximately 1100 feet. The two separate penstocks are 84-inch welded, plate steel, 5790 feet long with 84 inch butterfly valves at the power house. A flow rate of approximately 550 cubic feet per second can be delivered to each unit. A snorkel tube mounted in each draft tube provides outside air to the vortex over a set range on the wicket gates. Also a pump-turbine unit (Unit #3) operates at two (2) speeds; 300 RPM for delivering 370 cubic feet per second to Carter Lake against a head of 240 feet, and 257 RPM when producing 8.5 megawatts at a net effective head of 250 feet and 100% power factor. Unit #3 was one of the first pump-turbines installed in the U.S.

Upgrading of Units 1 and 2 from 35 megawatts to 43 megawatts was started in February 1987. Photographs of the draft tube and some galling damage on Unit 1 is shown in Appendix D, Figs. 5 and 6. The Ampco Bronze runners will be replaced with new stainless steel runners having 17 instead of 13 buckets. The units will continue to operate at 514 RPM. The increase in power output will result from larger wicket gate openings (increased flow rate) and improved efficiency. Unit 3, the pump-turbine unit, will have a new runner installed also. Followup sound and vibration measurements should provide interesting comparisons.

MEASUREMENTS

In Phase II two (2) basic sensors have been emphasized:

1.) Brüel and Kjaer Type 4370 Accelerometer with magnetic mount;

2.) Brüel and Kjaer Type 8104 Standard Measuring Hydrophone.

Both sensors use the Brüel and Kjaer Type 2635 Charge Amplifier.

Output was analyzed and displayed on a Hewlett Packard Model 3561A Dynamic Signal Analyzer with bubble memory. Hard copy records of narrow band and one-third octave analyses were produced with a Hewlett Packard Model 7470A Plotter. These devices provided a very easy to use, compact, and precise measurement system for accomplishing the major objectives of this study. Acoustic emissions instrumentation and pressure transducers on the penstock were not utilized in this phase; a magnetostriction oscillator test facility for looking at acoustic cavitation was constructed and operated in the hydraulics laboratory at the Denver Federal Center. Preliminary results of the acoustic cavitation study will be described later in this report. Selected references on acoustic cavitation are provided in Appendix A.

One of the Major improvements in the measuring process during this phase was the acquisition and use of calibrators for the accelerometer and hydrophone. A Brüel and Kjaer Type 4294 hand-held calibration exciter (S.N. 1310358) for the accelerometer and a Brüel and Kjaer Type 4223 Hydrophone Calibrator (S.N. 1270132) were obtained on December 3, 1986 and used routinely thereafter. The calibrators served to check out the individual sensors, but more importantly allowed for checkout of the assembled system, including the transmission lines. Adequate field calibration is an absolute necessity for acquiring reliable data on the units.

Both the hydrophone calibrator and the exciter for the accelerometer calibration were first used on December 4, 1986. The Bruel and Kjaer Type 4370 Accelerometer (S.N. 1111665) checked out well, but the Brüel and Kjaer Type 8103 Hydrophone (S.N. 812703) would not calibrate properly. Subsequently, the hydrophone was sent to Brüel and

Kjaer for checkout. After about a six (6) month wait, Brüel and Kjaer reported that the "8103" could not be repaired. Note that the "8103" was also used during the Phase I study (June 22, 1986 - August 22, 1986) and that some or all of that data may have been incorrect.

A tabulation of instrumentation and transducers used during Phase II is given below:

INSTRUMENTATION AND TRANSDUCERS

(Phase II)

Item	Manufacturer	Serial No.	Owner
1.) 3561A Dynamic Signal Analyzer w/bubble memory	Hewlett Packard	2338A01027	CSU
2.) Charge Amplifier Type 2635	Brüel and Kjaer	795728	USBR
3.) 7470A Plotter	Hewlett Packard	2308A36635	M.M. Skinner
4.) Optical Trigger	Monarch	189055	CSU
5.) TV Camera Model WV-1500	Panasonic	3YA09419	CSU
6.) Video Monitor Model TR-930	Panasonic	KD6220381	CSU
7.) SLR AutoFocus Camera	Polaroid	7G976373237	M.M. Skinner
8.) Hydrophone Type 8104	Brüel and Kjaer	1252029	M.M. Skinner
9.) Accelerometer Type 4370	Brüel and Kjaer	1111665	USBR
10.) Calibrator Type 4294	Brüel and Kjaer	1310358	USBR
11.) Calibrator Type 4223	Brüel and Kjaer	1270132	USBR
12.) Hydrophone Type 8103	Brüel and Kjaer	812703	USBR

Results

(Task A) A data acquisition plan involving an accelerometer, hydrophone, microphone, and a dynamic signal analyzer has been developed. Trial measurements have been obtained at Flatiron, Pole Hill, Big Thompson, Estes and Mary's Lake. Combination of narrow band and one-third octave analyses appear to be most promising as indicators of cavitation intensity. The broad-band frequency spectra of cavitation (along with other noise) breaks over the top of the strong tones, harmonics, and side bands associated with bucket and wicket gate passing frequencies in the narrow band analyses; and flattens out the one-third octave analyses display. In addition, overall RMS levels increase at the onset of cavitation. Just how much of the increase in the total noise output is due to cavitation is difficult to determine under the field operating conditions. The hydrophone measurements in the tailrace appear to be very sensitive to the changing noise levels and the frequency spectra are repeatable for given power settings and tailwater levels.

For machine condition, the accelerometer measurements may prove to be the most valuable. Dynamic imbalance of the rotating mass and mechanical looseness (for example in the wicket gate linkage) are supposedly represented in the fundamental and harmonics of the shaft speed. Each of the machines measured during this phase of the study had different shaped spectra and some displayed relatively large amplitude shaft speed and harmonic frequencies. The change in spectra shape or content over time correlated with the mechanical change may be the only way to develop spectral signatures. A table detailing "vibration analysis symptoms" is given in the latest edition of the

"Pump Handbook". Examples of selected narrow band and one-third octave analyses collected during the Phase II study are provided in Appendix B; a summary of all measurements made during Phase II is also included.

The basic components of the data acquisition plan are:

1.) Identify and record the conditions under which the measurements are made. (See example data/plot sheet in Appendix C).

2.) Insure that the flow conditions are as steady as possible and preferably no other units are operating at the site.

3.) Use adequate time for averaging measurements ($\geq$ 50 RMS values).

4.) Reject measurements if either overload indicators on the 3561A or 2635 appear during the data collection process.

5.) Obtain photographic records of accelerometer, microphone and hydrophone locations.

6.) Calibrate all sensors under operating conditions before and after measurement.

7.) Reduce the measurement results to the basic dimensions of acceleration, velocity, and sound pressure level and compare with past measurements before leaving the site.

8.) Conduct both a pre- and post-measurement conference with plant operator(s) and/or plant supervisor.

9.) Measurements should include using:

   a) Brüel and Kjaer Type 4370 accelerometer/magnet at the draft tube (see Appendix D, Figs. 3 and 4), scroll case (see Appendix D, Figs. 1 and 2), and on the wicket gate ring. Be sure the magnet is attached firmly to a flat, clean, unpainted surface.

b) Brüel and Kjaer Type 8103 Hydrophone (microphone) (suspended vertically with a soft cord 30-inches from centerline of mandoor) at the draft tube and

c) Brüel and Kjaer Type 8104 Hydrophone in tailrace in line with draft tube and 18-inches below water surface.

10.) <u>Accelerometer</u> measurements should include:

a) 0-50 hz narrow band/thd/shaft frequency.

b) 0-400 hz narrow band/thd/bucket passing frequency.

c) 0-400 hz top-bottom format/one(1) volt/division.

<u>Microphone</u> measurements should include:

a.) One-third octave, 0-20khz, RMS level

<u>Hydrophone measurements should include:</u>

a) one-third octave, 0-80khz, RMS level

b) 0-400 hz narrowband/thd/bucket passing frequency.

11.) Trending analyses measurement should be repeated at least every three months.

12.) A computerized data base should be developed for trending analyses and for rapid retrieval and review of selected individual records.

(Task B) A proposal has been prepared for the Department of Energy for funding (see Appendix E) to develop and test techniques such as acoustic emissions for cavitation detection using the 40.3 to 1 scale model of Grand Coulee Third. The Bureau of Reclamation and Colorado State University would each cost-share equally in the project.

A test tank for studying acoustic cavitation using a magnetostriction oscillator was constructed at the Hydraulics Laboratory, Denver Federal Center (see Appendix D, Figs. 19-22).

Buttons of five (5) different metals (aluminum, brass, copper, stainless, and steel) were machined for testing (see Appendix D, Fig. 23). The original hypothesis was that cavitation on a button would "sound" different depending on the material.

Some important verifications and discoveries related to the "acoustic cavitation tank study" were made:

1.) Subharmonics can be used to detect the onset of ultrasonic cavitation, see Appendix F.

2.) Localized "worm hole" cavitation damage can be developed at very low input power levels.

3.) Cavitation damage patterns developed with the acoustic tank look very similar to some of the cavitation patterns found on the old runner (made of Ampco Bronze) from Flatiron #1 (see Appendix D, Figs. 7-14). For comparison, some microscope photographs of the damage on Flatiron #1 and the aluminum button are shown in Appendix D, Figs. 24-28.

(Task C). A considerable amount of literature in the form of Journal Articles and Textbooks related to cavitation in turbines has been collected during Phase II. The development of a theoretical framework for explaining the observed measurements in the field and in the "sound tank" is continuing.

Recommendations

1.) Base line measurements in accordance with the data acquisition plan outlined under results (Task A) should be continued at Flatiron, Pole Hill, Big Thompson, Estes, and Mary's Lake. Regularly scheduled base line measurements should be started at Guernsey and Glendo.

2.) Sound tank studies at the Hydraulics Laboratory, Denver Federal Center, should continue in order to provide quantitative measurements for a Journal paper for publishing on "worm hole" cavitation.

3.) Model turbine (Grand Coulee Third) set-up should be completed during Fall 1987. Hopefully, an eighteen (18) month testing program can be started January 1988 under Department of Energy funding.

4.) Fabricate, install, and evaluate a viewing module for insertion in the three (3) inch transverse snorkel tube at the draft tube of Flatiron Unit-1. The "borescope system" recently purchased by the Bureau could be used to monitor and record cavitation activity near the bottom of the runner, see Appendix D, Fig. 18. (Phase III IPA funding).

5.) Some ongoing training sessions should be started at the Denver Federal Center by May, 1988. (Phase III IPA funding).

6.) Sound and vibration measurement programs should be initiated for selected additional Bureau Power Plants (Phase III IPA funding).

7.) Prepare final report and several journal articles for publication. (Phase III IPA funding).

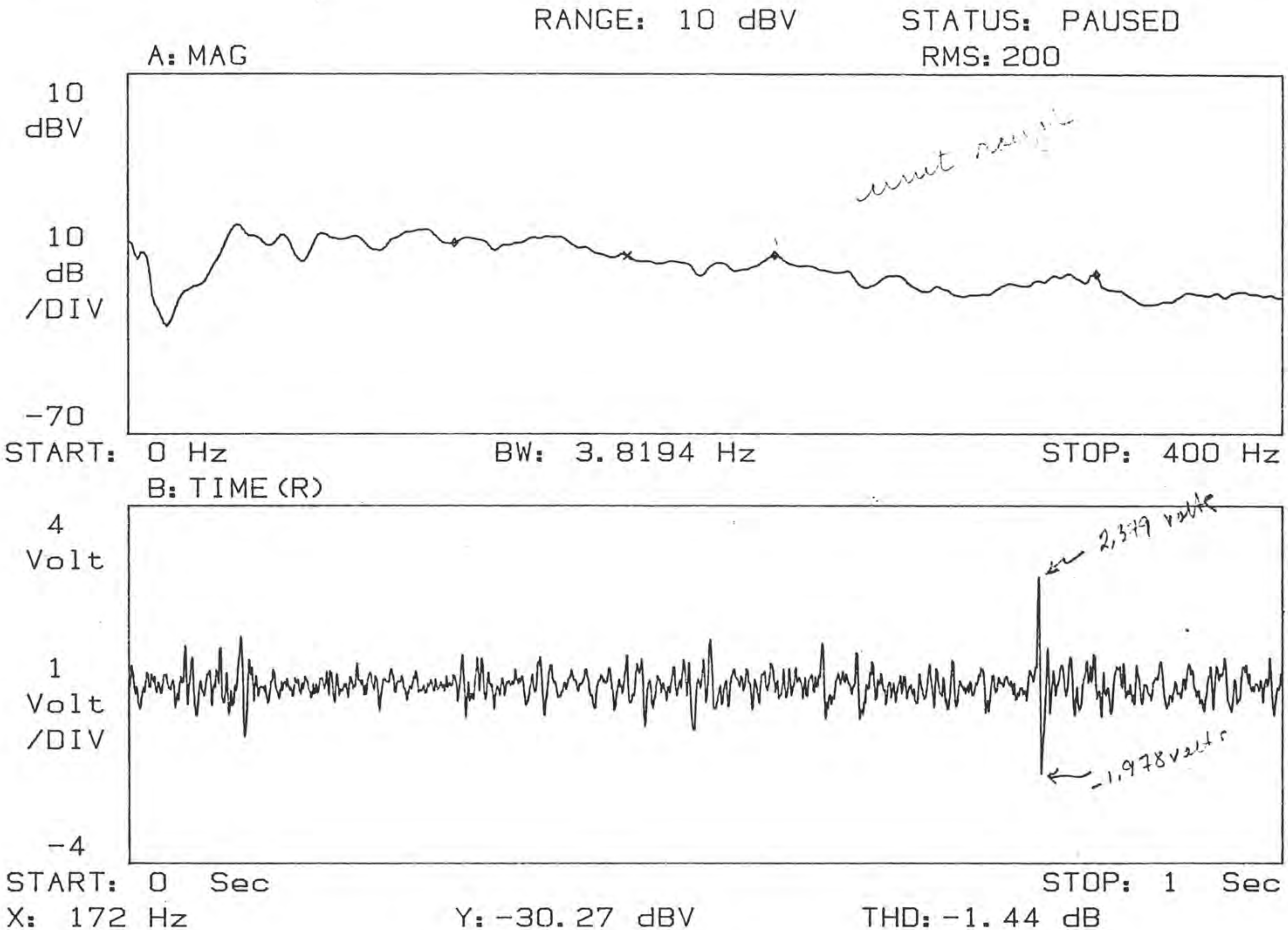
A Procedure for Identifying the Onset and Evaluating the Intensity of Vortex Collapse in the Region of the Draft Tube.

Collapse of vortices in the draft tube appear to produce discrete, relatively high intensity implosions that are readily discernible at the hydrophone location in the tailrace. Several waveforms of the pressure rise associated with individual collapses have been recorded at Flatiron #2; example plots are shown on the following two pages.

The rise time for the waveform seems to be about one to two milliseconds with characteristic pulsations before and after the main pulse. The commonly used one second time span associated with 400 hz frequency span on the HP 3561A can be used to monitor the onset of the bursts (see example plot). When the spikes (or bursts) begin to occur as the turbine operation moves into a rough range, the HP 3561A can be programmed to capture individual waveforms of preselected amplitude. These discrete waveforms can be immediately analyzed directly on the HP 3561A. The implosion waveforms seem to have similar shapes. Cavitation implosion waveforms may be similar in shape, but have been reported to have rise times on the order of a few microseconds.

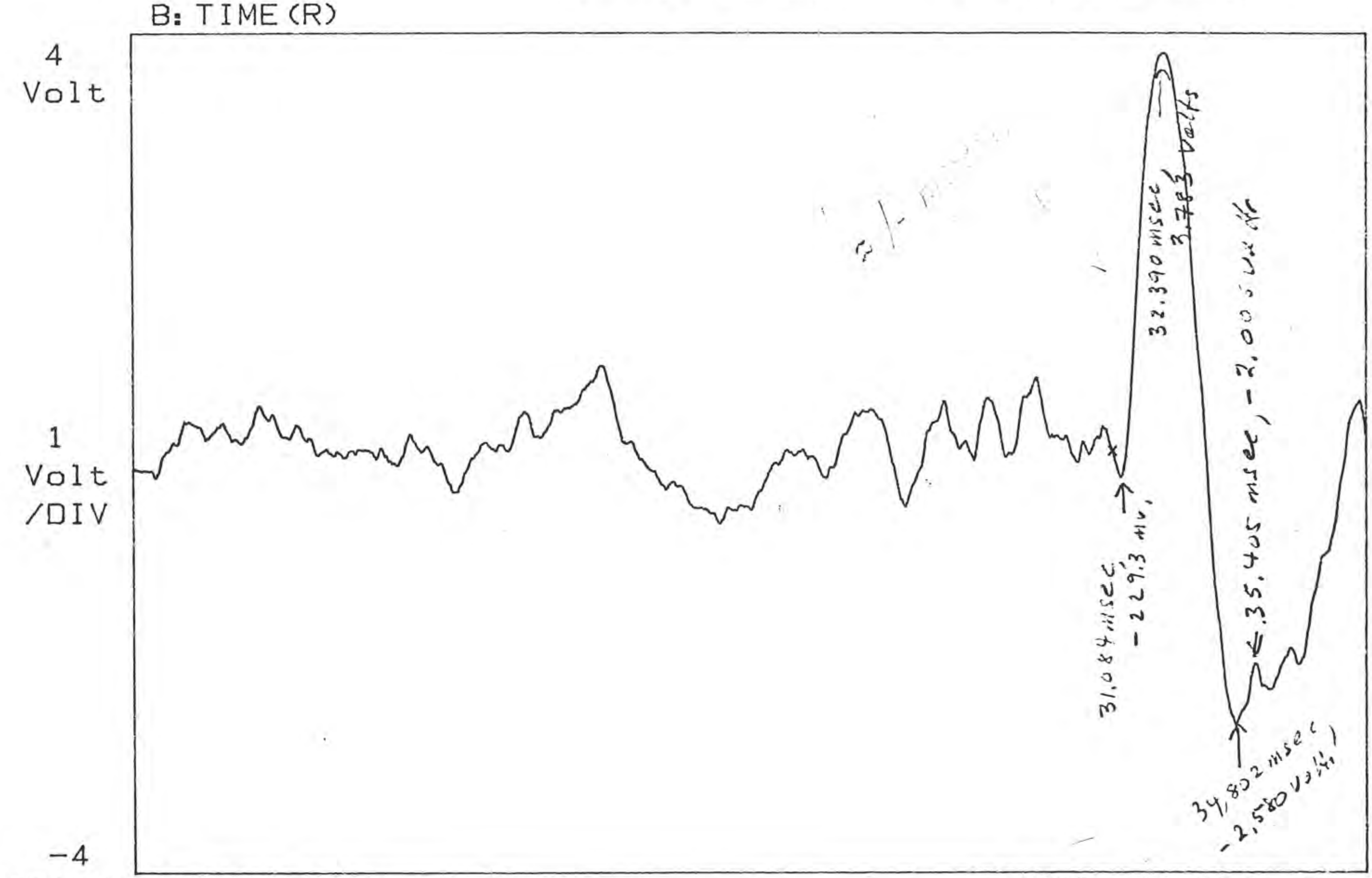
Pressure rises associated with vortex collapse certainly represents an important case of damaging flow condition in a turbine. The model turbine studies planned for Phase III of this study should afford an excellent opportunity to study waveforms associated with vortex collapse and cavitation implosions in greater detail.

ensor: s/n: Loc: Dial Setting: Tailrace: Temp: 63 F° Baro. 829



ensor: BK/8134 s/n: ______ Loc: ______ Dial Setting: 3/5-2-10 Tailrace: ______ Temp: 66 F° Baro. 828

RANGE: 10 dBV STATUS: PAUSED



START: -976.56 uSec STOP: 39.023 mSec

X: 30.883 mSec Y: 0 Volt

APPENDIX A

Selected References on

Acoustic Induced Cavitation

Selected References on Acoustic Induced Cavitation

1. P. DeSantis, D. Sette, and F. Wanderlingh, "Cavitation Detection: The Use of the Subharmonics", J. Acoustic Soc. Am., 1967, Vol. 42, No. 2, 514-516.

2. A. Eller and H. G. Flynn, "Generation of Subharmonics of Order One-Half by Bubbles in a Sound Field", J. Acoustic Soc. Am., 1969, Vol. 46, No. 3 (Part 2), 722-727.

3. G. Houghton, "Theory of Bubble Pulsation and Cavitation," J. Acoustic Soc. Am., 1963, Vol. 35, No. 9, 1387-1393.

4. H. G. Olson and F. G. Hammitt, "High Speed Photographic Studies of Ultrasonically Induced Cavitation", J. Acoustic Soc. Am., 1969, Vol. 46, No. 5 (Part 2), 1272-1283.

5. E. A. Neppiras, "Subharmonic and Other Low-Frequency Emission from Bubbles in Sound-Irridiated Liquids", J. Acoustic Soc. Am., 1969, Vol. 46, No. 3 (Part 2), 587-601.

6. H. G. Flynn, "Physics of Acoustic Cavitation in Liquids", Physical Acoustics (edited by Mason), Academic Press, Vol. 1, Part B, 1964, 57-172.

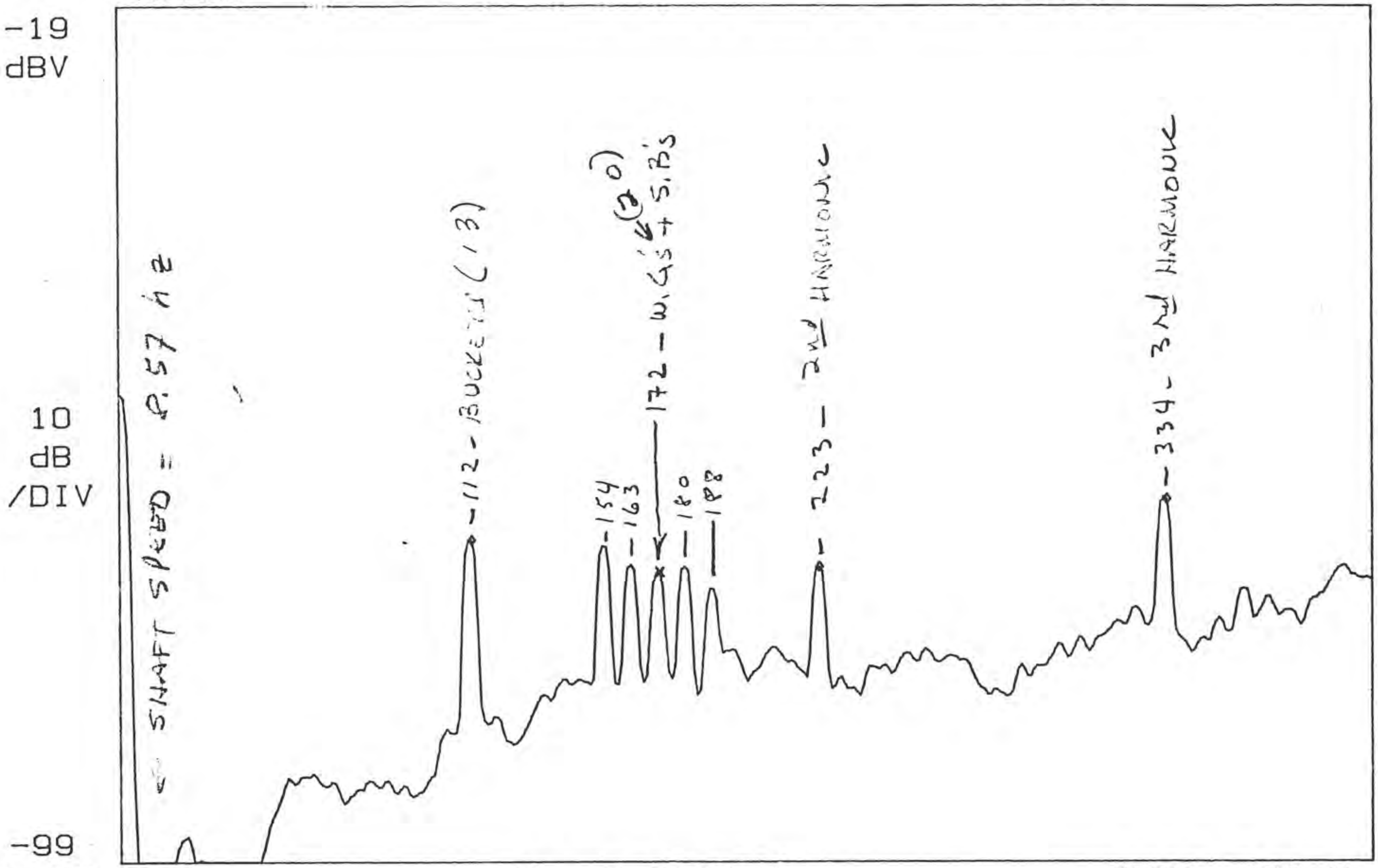
APPENDIX B

Examples of Narrow-Band
and One-Third Octave Analyses Plots
Collected during Phase-II

Sensor: B&K Acc s/n: 111165 Sensor Location: S.C. #1 Dial Settings: 10 / 2 / 30 Tailrace Level: 67.5 Water Temp: 36°F

RANGE: -19 dBV STATUS: PAUSED

A: MAG RMS: 50

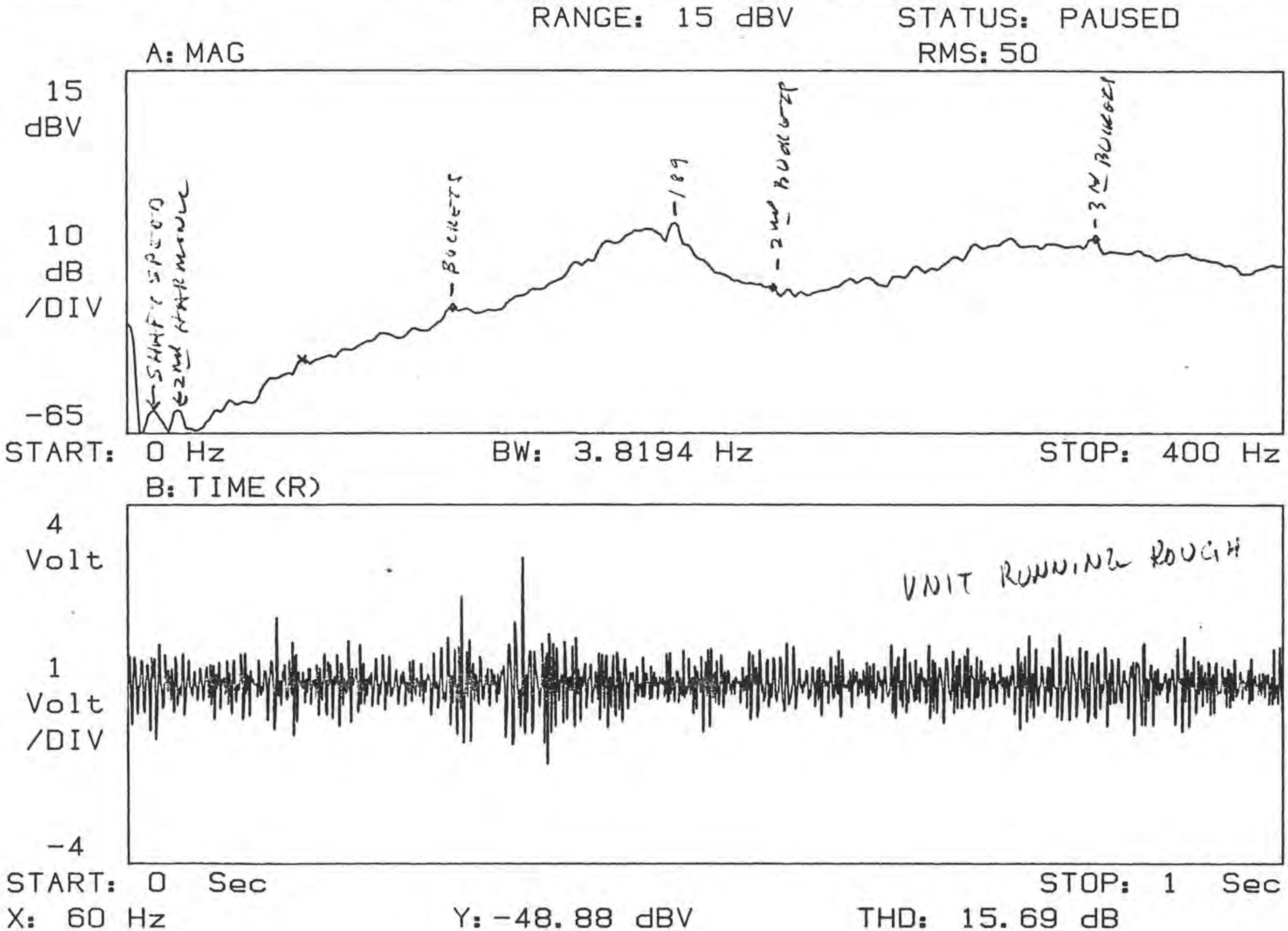


START: 0 Hz BW: 3.8194 Hz STOP: 400 Hz

X: 172 Hz Y: -71.90 dBV THD: 4.80 dB

Site Location: [illegible]

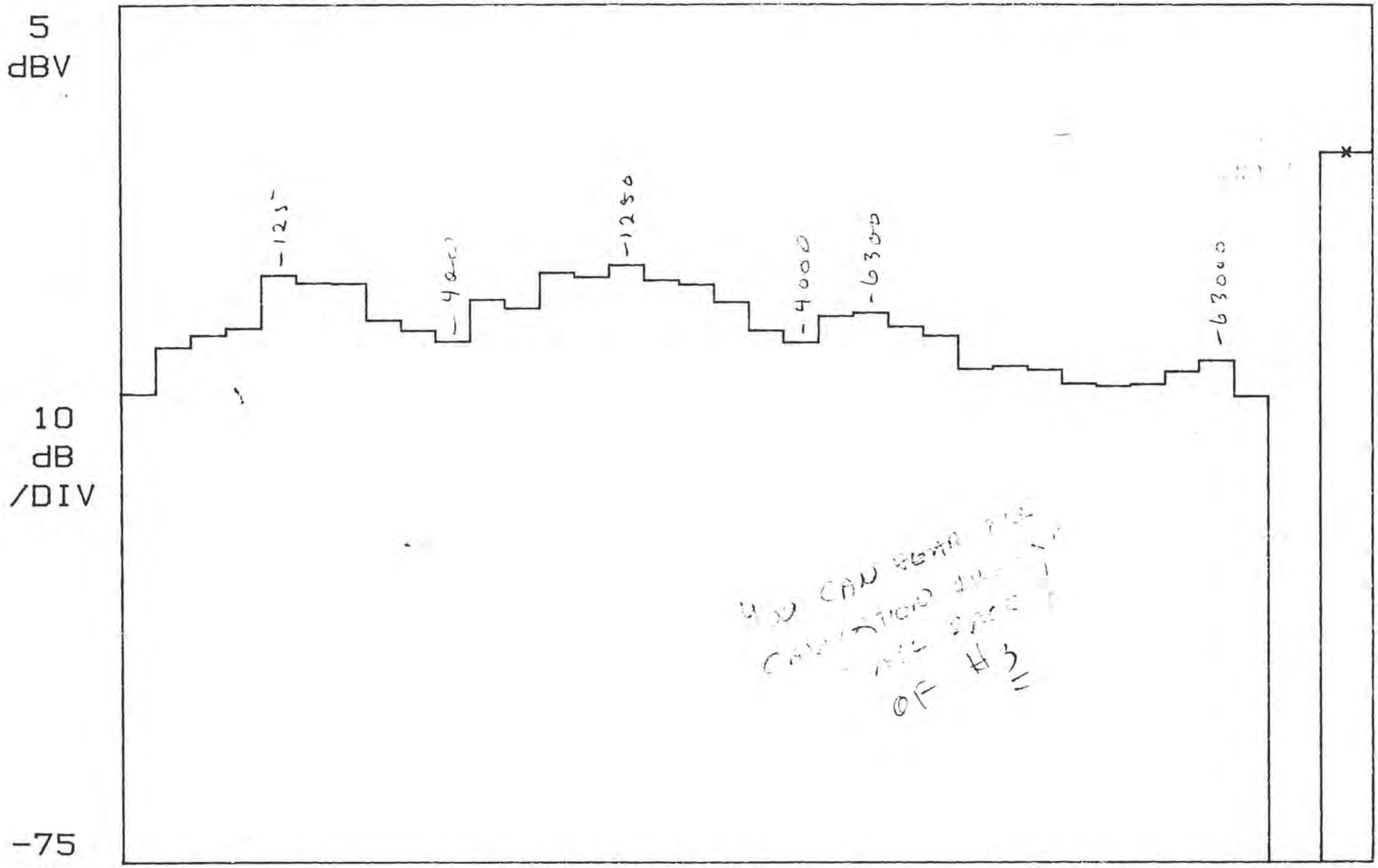
Sensor: B&K/Acc s/n: ______ Sensor Location: #2 - DT. Dial Settings: 100-2-1 Tailrace Level: 66.0 Water Temp: 37°



Sensor: B&K-HYDRO 8103 s/n: ________ Sensor Location: #3 - T.R. Dial Settings: ________ Level: ________ Temp: ________

RANGE: 5 dBV STATUS: PAUSED

A: 1/3 OCT RMS: 50

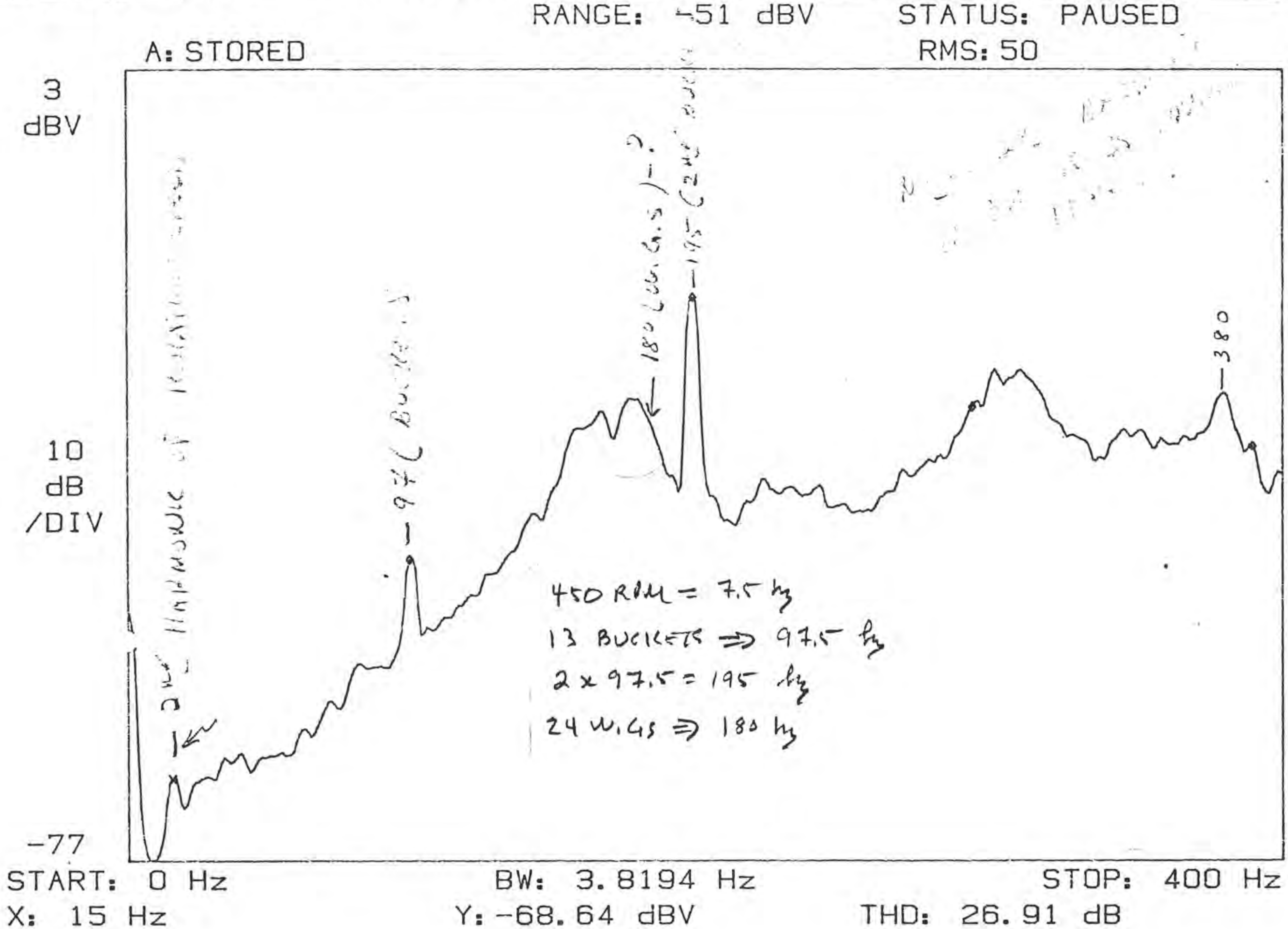


START: 50 Hz BANDS 17-49 STOP: 80 000 Hz

X: RMS LEVEL Y: -8.53 dBV

Site Location: TULE HILL Time: ______ Date: ______ Plot No.: ______ WG/Power Setting: ______

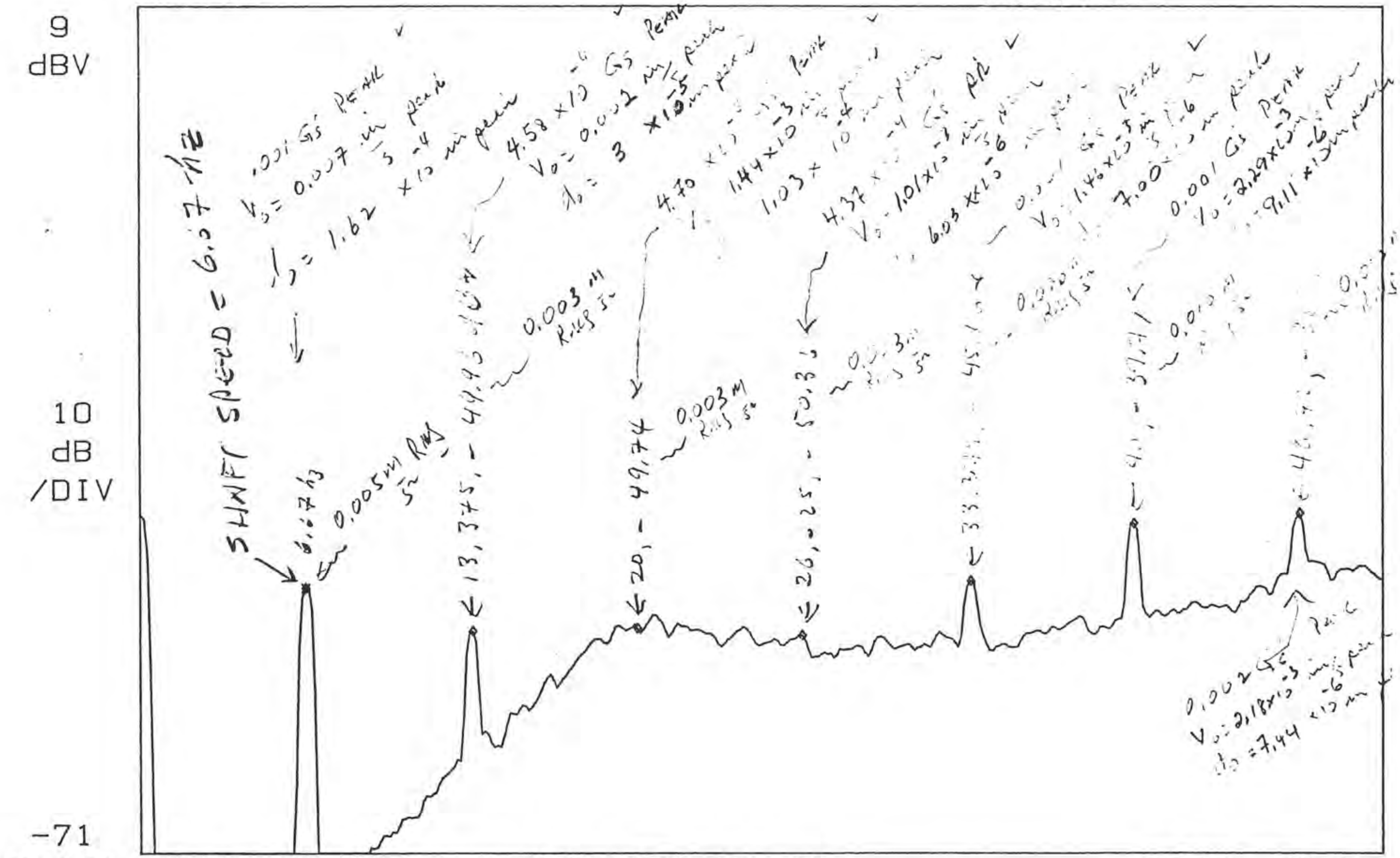
Sensor: B&K/Acc s/n: ______ Sensor Location: DT, Dial Settings: 100-2-1 Tailrace Level: ______ Water Temp: ______



ensor: BAK/Acc s/n: ______ Loc: W. G. Dial Setting: 1000. 2.0 / Forebay: SCP-45 Tailrace: ______ Water Temp: 69 F° Baro. ______

RANGE: 9 dBV STATUS: PAUSED

A: MAG RMS: 50



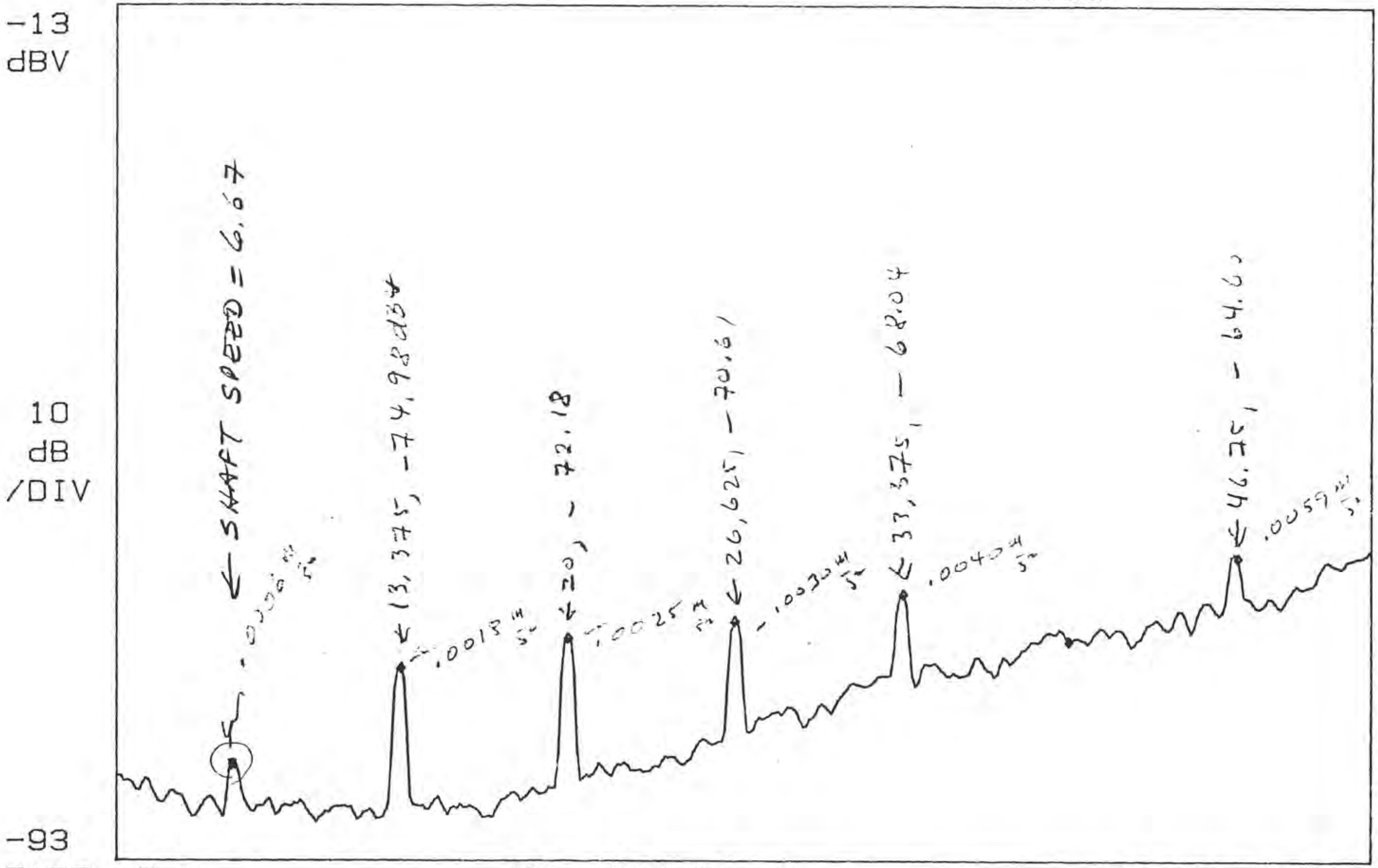
START: 0 Hz BW: 477.42 mHz STOP: 50 Hz

X: 6.625 Hz Y: -45.84 dBV THD: 10.62 dB

ensor: s/n: Loc: #1-DT Dial Setting: Forebay: Tailrace: Water Temp: 20°C F° Baro.

RANGE: -51 dBV STATUS: PAUSED

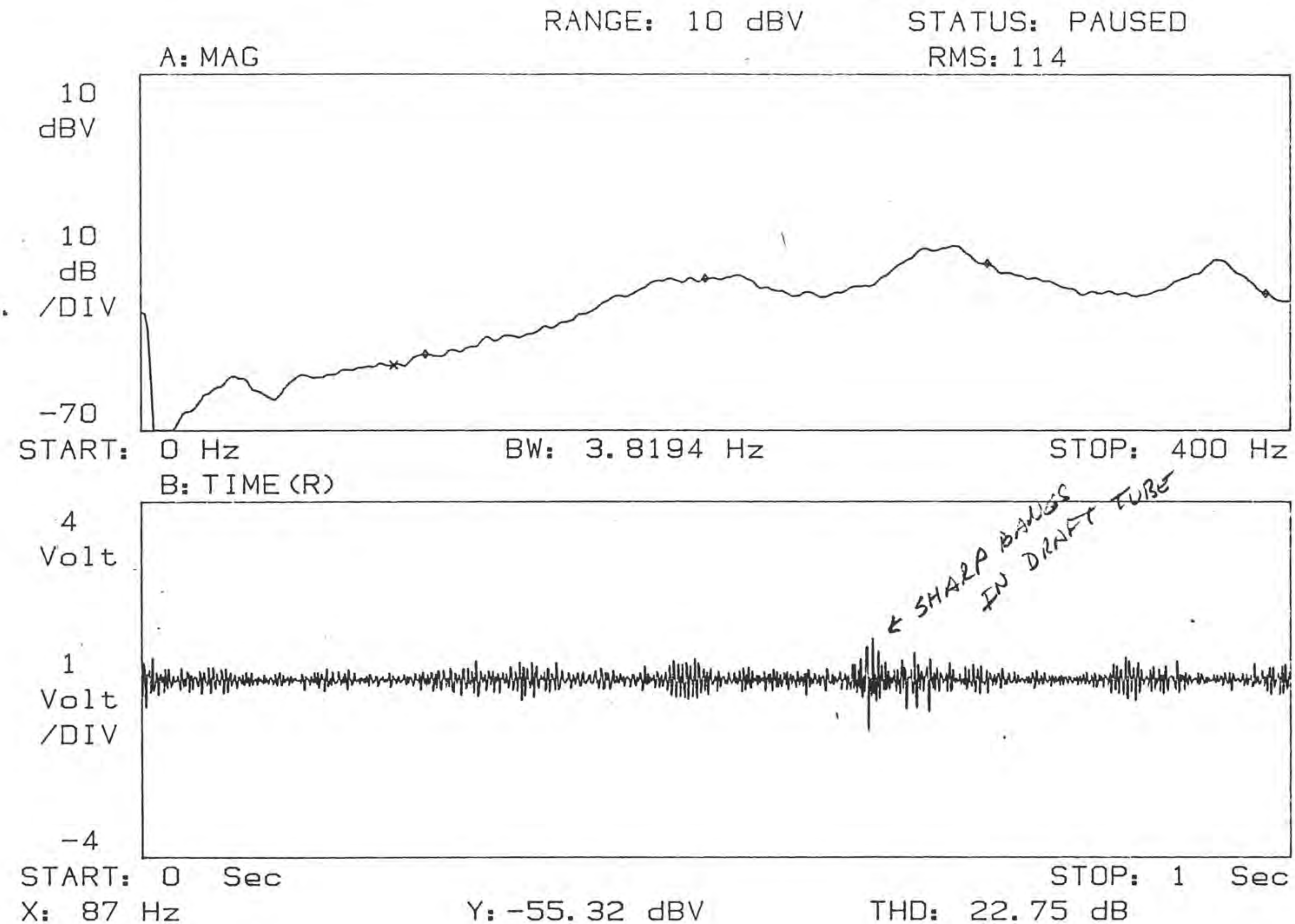
A: STORED RMS: 53



START: 2 Hz BW: 477.42 mHz STOP: 52 Hz

X: 6.625 Hz Y: -84.04 dBV THD: 22.74 dB

8034.24


RANGE: 10 dBV
STATUS: PAUSED
A: MAG
RMS: 114
10 dBV
10 dB /DIV
-70
START: 0 Hz
BW: 3.8194 Hz
STOP: 400 Hz
B: TIME (R)
4 Volt
1 Volt /DIV
-4
← SHARP BANGS IN DRAFT TUBE
START: 0 Sec
STOP: 1 Sec
X: 87 Hz
Y: -55.32 dBV
THD: 22.75 dB

Summary of Measurements
Made During Phase II

Location	Transducer	Type of Measurement (See key below)	Power Range (Megawatts)	Number of Measurements
		Flatiron #1		
Head Cover	B & K 8103	M-400	15-24	5
Wicket Gate	B & K 4370	A-100	13-18	3
Wicket Gate	B & K 4370	A-400	10-20	11
Scroll Case	B & K 4370	A-400	15-30	10
Scroll Case	B & K 4370	A-50	20-22	2
Scroll Case	B & K 4370	A-100	15	1
Scroll Case	B & K 4370	A-400	14-35	16
Scroll Case	B & K 4370	Misc	13-29	5
Draft Tube	B & K 4370	A-400TB	13-28	18
Draft Tube	B & K 4370	A-20	19	1
Draft Tube	B & K 4370	A-50	28	2
Draft Tube	B & K 8103	M-400	0-26	6
Draft Tube	B & K 8103	M-5000	0-20	2
Draft Tube	B & K 8103	M-20000-$\frac{1}{3}$	10-26	4
Draft Tube	B & K 4370	A-400	22	1
Draft Tube	B & K 4370	A-400T	18-23	4
Tailrace	I/O Hydro	H-400TB	20	1
Tailrace	I/O Hydro	H-400	0-32	19
Tailrace	I/O Hydro	H-625	22	2
Tailrace	I/O Hydro	H-5000	0	1
Tailrace	I/O Hydro	H-10000	18	1
Tailrace	B & K 8104	H-400	14-29	10
Tailrace	B & K 8101	H-420	18-31	10
Tailrace	B & K 8104	H-80000-$\frac{1}{3}$	20-28	5
Tailrace	B & K 8104	H-40	20	1
			Subtotal	141

Key:
M-400: microphone, 0-400hz
A-100: accelerometer, 0-100hz
H-5000: hydrophone, 0-5000hz

Location	Transducer	Type of Measurement	Power Range (Megawatts)	Number of Measurements
		Flatiron #2		
Head Cover	B & K 8103	M-400	12-17	2
Wicket Gate	B & K 4370	A-50	19-36	5
Wicket Gate	B & K 4370	A-400	18-36	5
Scroll Case	B & K 4370	A-400TB	15-35	10
Scroll Case	B & K 4370	A-50	18-36	13
Scroll Case	B & K 4370	A-100	16	1
Scroll Case	B & K 4370	A-400	12-36	17
Scroll Case	Endevco	A-5000	36	1
Scroll Case	B & K 4370	Misc	13-30	2
Draft Tube	B & K 4370	A-50	18	1
Draft Tube	B & K 4370	A-400TB	14-35	15
Draft Tube	B & K 4370	A-20	18	1
Draft Tube	B & K 4370	A-50	18-36	5
Draft Tube	Columbia	A-200	25	1
Draft Tube	B & K 4370	A-400	33-36	3
Draft Tube	B & K 8103	M-400	0-24	9
Draft Tube	B & K 8103	M-5000	0	1
Draft Tube	B & K 8103	M-20000-$\frac{1}{3}$	14-24	3
Draft Tube	B & K 4370	A-400TB	15-32	7
Draft Tube	B & K 4370	Misc	19-20	2
Tailrace	B & K 8103	H-10	23	1
Tailrace	B & K 8103	H-400	21	1
Tailrace	I/O Hydro	H-5000	13-15	2
Tailrace	I/O Hydro	H-10000	20	1
Tailrace	B & K 8103	H-80000-$\frac{1}{3}$	15-30	4
Tailrace	B & K 8104	H-80000-$\frac{1}{3}$	15-36	26
Tailrace	B & K 8104	H-400TB	18-36	2
Tailrace	B & K 8104	H-400	29-36	22
Tailrace	B & K 8103	H-400	16-30	5
Tailrace	I/O Hydro	H-400	0-25	10
Tailrace	B & K 8104	H-50	33	1
Tailrace	B & K 8104	H-100	36	1
Tailrace	B & K 8104	H-160	36	1
Tailrace	B & K 8104	H-800	36	1
Tailrace	I/O Hydro	H-200	15	2
Tailrace	I/O Hydro	H-625	25-28	2
Tailrace	I/O Hydro	H-5000	0	1
Tailrace	I/O Hydro	H-10000	15	1
			Subtotal	188

Location	Transducer	Type of Measurement	Power Range (Megawatts)	Number of Measurements
		Flatiron #3		
Head Cover	B & K 4370	A-400	9	4
Scroll Case	B & K 4370	A-20	8	2
Scroll Case	B & K 4370	A-50	8	4
Scroll Case	B & K 4370	A-100	8	2
Scroll Case	B & K 4370	A-400TB	8-9	17
Scroll Case	B & K 4370	Misc	9	5
Draft Tube	B & K 4370	A-20	8	1
Draft Tube	B & K 4370	A-50	8	1
Draft Tube	B & K 4370	A-400TB	8-9	17
Draft Tube	B & K 4370	A-5000	9	1
Draft Tube	B & K 8103	A-400	9	2
Draft Tube	B & K 4370	Misc	9	2
Draft Tube	B & K 8103	M-20000	9	3
Tailrace	B & K 8103	H-400	9	4
Tailrace	B & K 8103	H-80000-$\frac{1}{3}$	9	4
Tailrace	B & K 8103	H-10	9	1
			Subtotal	70

Location	Transducer	Type of Measurement	Power Range (Megawatts)	Number of Measurements
		Pole Hill		
Wicket Gate	B & K 4370	A-50	21-30	4
Wicket Gate	B & K 4370	A-400	21-30	4
Draft Tube	B & K 4370	A-50	21-30	3
Draft Tube	B & K 4370	A-400	21-30	3
Draft Tube	B & K 4370	Misc	23	3
		Big Thompson		
Wicket Gate	B & K 4370	A-50	4.1	1
Wicket Gate	B & K 4370	A-400	4.1	1
Scroll Case	B & K 4370	A-50	4.1	1
Scroll Case	B & K 4370	A-400	4.1	1
Draft Tube	B & K 4370	A-50	4.1	1
Draft Tube	B & K 4370	A-400	4.1	1
		Estes #1		
Wicket Gate	B & K 4370	A-50	17.5	1
Draft Tube	B & K 4370	A-50	17.5	3
Draft Tube	B & K 4370	A-400	17.5	2
Draft Tube	B & K 4370	A-400TB	17.5	1
		Estes #2		
Wicket Gate	B & K 4370	A-50	6.5	1
Draft Tube	B & K 4370	A-50	4-16.5	2
Draft Tube	B & K 4370	A-400	4-16.5	2
Draft Tube	B & K 4370	A-400TB	16.5	1
		Estes #3		
Draft Tube	B & K 4370	A-50	12.5	1
Draft Tube	B & K 4370	A-400	12.5	3
Draft Tube	B & K 4370	A-400	12.5	2
		Mary's Lake		
Draft Tube	B & K 4370	A-50	7.9	2
Draft Tube	B & K 4370	A-400	7.9	2
Draft Tube	B & K 4370	A-400	7.9	1
Draft Tube	B & K 4370	A-400TB	6.3	1
			Subtotal	48

APPENDIX C

Example Data Sheet/Plots

Comments

1.) WG/Power Setting - Wicket gate opening in percent/power setting in megawatts. A TV camera is useful for this measurement (See Appendix D - Figure. 17).

2.) Air - Indicate if air is visible in tailrace and identify unit. For example... Yes #2. (See Appendix D, Figs. 15 and 16).

3.) Dial Setting - Record all three (3) basic dial settings from Brüel and Kjaer charge amplifier type 2635...for example...10-2-100.

4.) Forebay/Tailrace - Elevations (in feet) above mean sea level (or a known local reference).

5.) Baro - Barometric Press (mbar); use barometer supplied with the Brüel and Kjaer type 4223 hydrophone calibrator.

APPENDIX D

Selected Photographs

Fig-1. Accelerometer location on Mandoor of Scroll case of
Flatiron Units 1 and 2

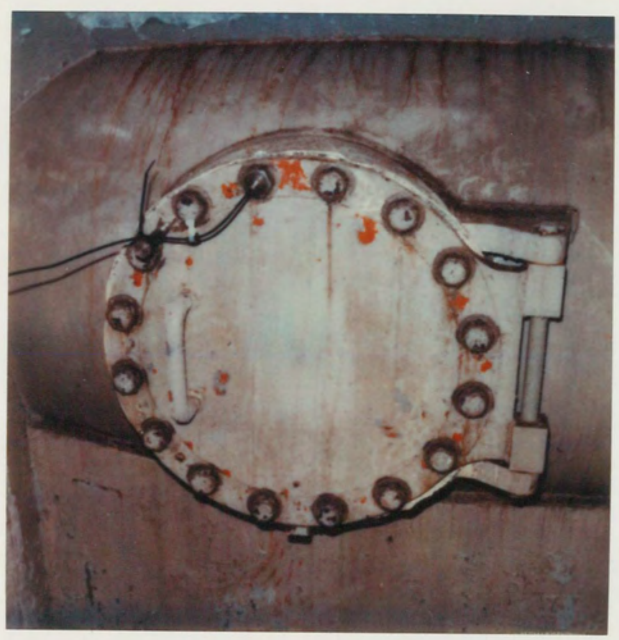


Fig-2. Accelerometer location on Mandoor of Scroll case of Flatiron Unit 3

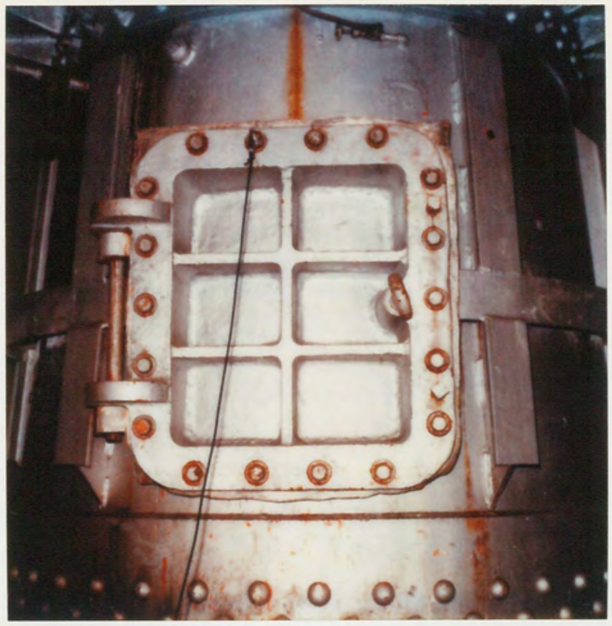


Fig-3. Accelerometer location on Mandoor of Draft Tubes of Flatiron Units 1 and 2

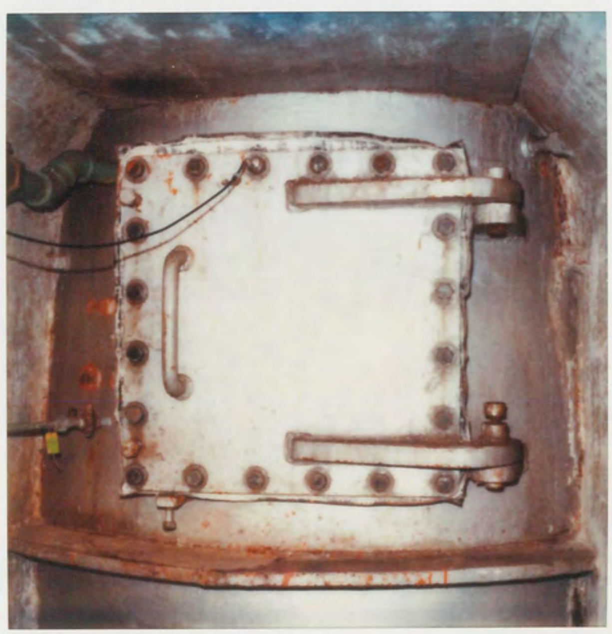


Fig-4. Accelerometer Location on Mandoor of Draft Tube of Flatiron Unit 3

Fig-5. Draft Tube of Flatiron Unit 1

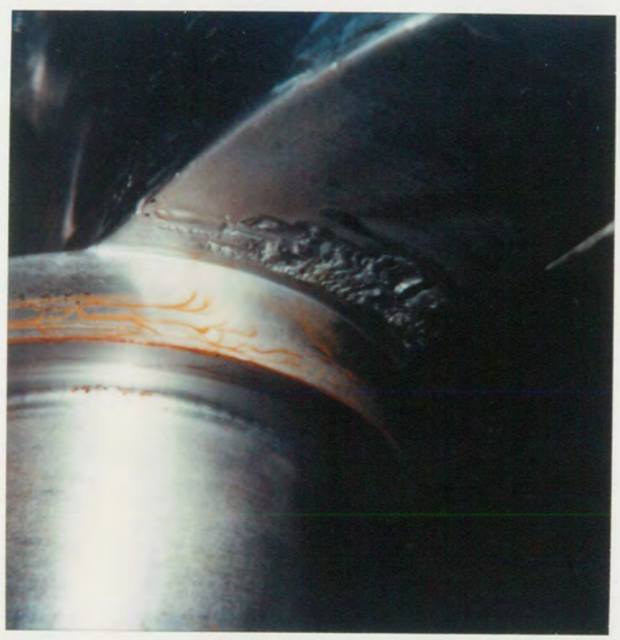


Fig-6. Galling Damage on Bottom of Wicket Gate #12 of Flatiron Unit 1

Fig-7. Old Runner from Flatiron Unit 1

Fig-8. Lower Part of Runner Bucket, Suction-Side, Flatiron Unit 1

Fig-9. Runner Bucket, Flatiron Unit 1

Fig-10. Close-up View of Runner Bucket Flatiron Unit 1

Fig. 11. Close-up View of Runner Bucket Flatiron Unit 1

Fig-12. Saw-cuts on Runner Bucket Flatiron Unit 1

Fig-13. Section of Runner Bucket, Suction Side, Flatiron Unit 1

Fig-14. Section of Runner Bucket, Pressure Side, Flatiron Unit 1

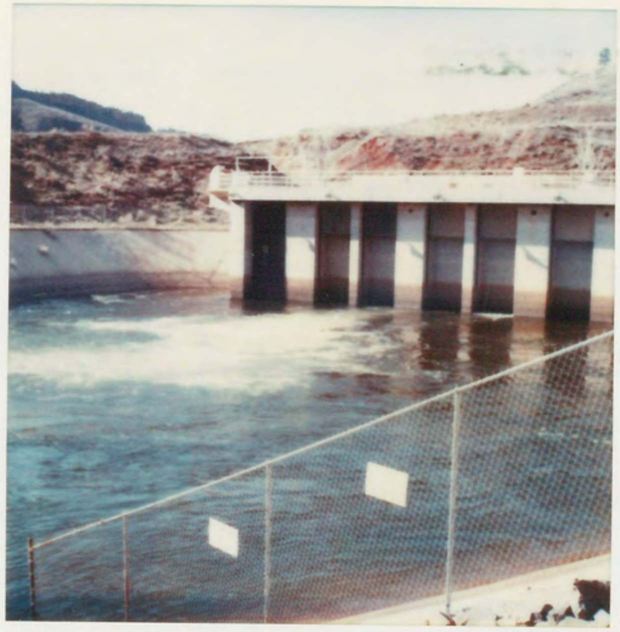


Fig-15. General View of Air Rising in Tailrace of Flatiron Unit 2

Fig-16. Close-up View of Air in Tailrace of Flatiron Unit 2

Fig-17. TV Camera for Monitoring Instrument Panel in Control Room

Fig-18. Plug on Left Provides Direct Access to Transverse Snorkel Pipe

Fig-19. Magnetostriction Oscillator Assembly

Fig-20. Access Port in Test Tank for Oscillator Assembly

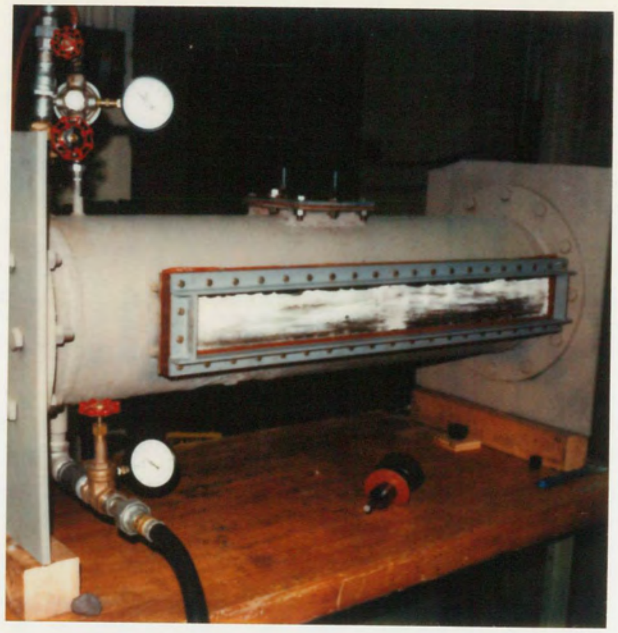


Fig-21. Overall View of Test Tank

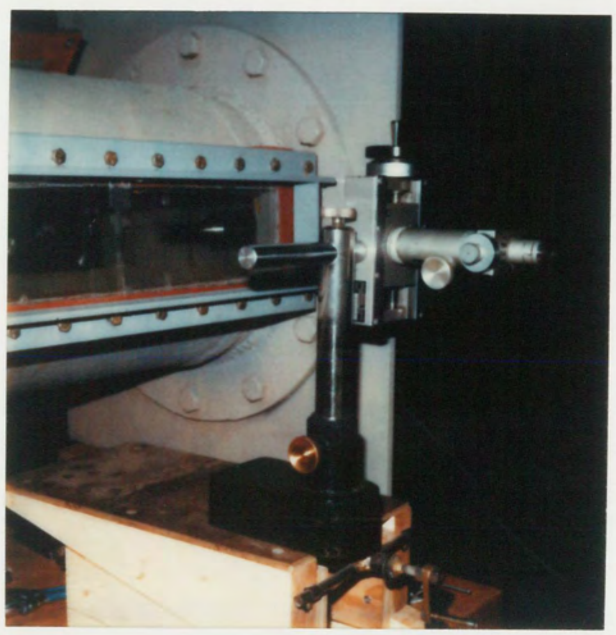


Fig-22. Filar Microscope Location for Observing Cavitation on the Button

Fig-23. Five (5) Sample Buttons

Fig-24. Cavitation Pattern on Aluminum Button

Fig-25. Microscope Photo of Cavitation Pattern on Aluminum Button

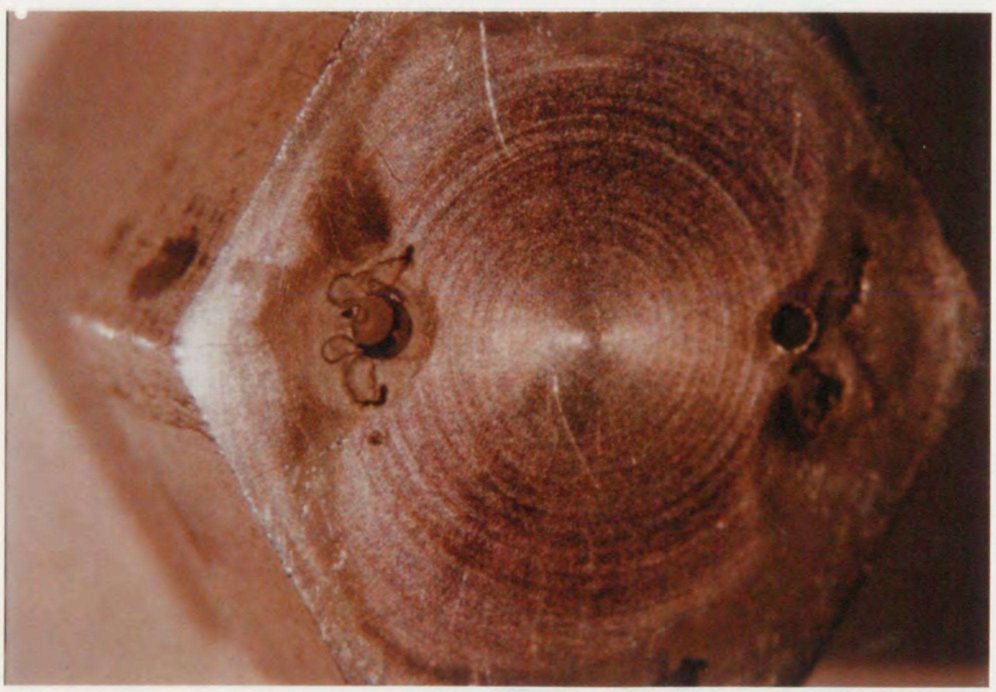


Fig-26. Microscope Photo of Cavitation Pattern on Aluminum Button

Fig-27. Microscope Photo of Cavitation Damage on Runner of Flatiron Unit 1.

Fig-28. Microscope Photo of Cavitation Damage on Runner of Flatiron Unit 1.

APPENDIX E

Department of Energy Proposal

PROPOSAL

Evaluation of Techniques for Detection of Cavitation on the Runner of a Model Turbine

by

M. M. Skinner

Civil Engineering Department

Colorado State University

B. W. Mefford

Hydraulics Branch

U. S. Bureau of Reclamation

W. H. Duncan

Power Branch

U. S. Bureau of Reclamation

June 1987

Evaluation of Techniques for Detection
of Cavitation on the Runner of a Model Turbine

M. M. Skinner, B. W. Mefford, and W. H. Duncan

INTRODUCTION

The Bureau of Reclamation as well as other entities, both public and private, are upgrading hydropower generation facilities. If the old runner can be utilized, then the upgrade cost is significantly reduced and the economic benefits appear to be favorable. With the advent of improved insulating materials, uprating of the generator can now be accomplished and more power output can be achieved by increasing the wicket gate opening (flow rate).

This means, however, that the turbine runner will be operating outside of the original design conditions--overloaded. Increased flow conditions can lead to severe cavitation which may result in increased vibration and sound levels, rapid damage rates to the runner as well as other components such as seal rings and wicket gate assemblies, and fluctuating torque on the turbine shaft. Improved techniques for cavitation detection on the runner are critically needed. Also, where the cavitation damage will occur on the runner under the new regime of flow conditions needs to be investigated.

The proposed study will evaluate several techniques for monitoring the onset and severity of cavitation on the runner of a model Francis-type turbine. The model is a 40.3 to 1 scale of Grand Coulee Third including the water passage system from the penstock inlet to the tailrace. The cavitation activity monitoring techniques will involve acoustic emissions and instrumentation (1)*, narrow band and third octave analyses of hydrophone and accelerometer output (2), magnetostrictive films plated on the turbine shaft for detecting dimensional changes associated with sound travel through the shaft (3), and shaft torque transducers (4). Each of the above listed techniques have demonstrated some potential for effective cavitation detection on prototype facilities. Controlled evaluation and development of procedures for these cavitation activity measures, however, can be most effectively accomplished with a scale model operating over a range of carefully controlled flow conditions in a laboratory environment. Subsequently, each of the four techniques described above should be scaleable to prototype size.

The Colorado State University Hydromachinery Laboratory, located on the Foothills Campus near Horsetooth Reservoir, affords a suitable site for the investigation. The laboratory is housed in a 70-foot by 192-foot prestressed concrete building with a 3-foot-thick concrete floor section designed specifically for cavitation and vibration testing of hydraulic machinery. The water supply is provided directly from Horsetooth Reservoir and appropriate discharge and head combinations are available for the proposed model tests. A budget of $90,000 is requested in order install, instrument, and test the model during a period of eighteen (18) months. Costs for moving, installing, and operating the test facility amount to an additional $60,000. Installation details, instrumentation requirements, testing and reporting schedule, and associated budget are outlined.

INSTALLATION

The 40.3 to 1 scale model is presently located at the Bureau of Reclamation's Estes Powerplant facility at Estes Park, Colorado (see Appendix A). The complete model will need to be dismantled, transported approximately forty (40) miles to Fort Collins, Colorado, and installed in the Hydromachinery Laboratory at Colorado State University (see Appendix B). The model will be located in the southeast corner of the laboratory as shown on the laboratory floor plan (see Appendix C). A support stand for the head tank and dynamometer will be fabricated and positioned prior to the arrival of the model from Estes park. All anchor bolts and attachments to the laboratory floor will be installed prior to final positioning of the assembled test facility. Upstream and downstream piping will be fitted after the model is in place. Complete description of the model components are given in Appendix D. Alignment and leveling checks will be made by Bureau of Reclamation engineers and technicians before any floor tests are started. Model operation, maintenance, and safety procedures will be carefully studied and observed by all personnel involved with the tests.

INSTRUMENTATION

A booth will be constructed adjacent to the model to protect delicate instrumentation, reduce noise level, and provide safe work space for personnel involved in the data collection. The basic instruments and devices for controlling the model, and for indicating the recording model operation and test data are furnished with the model. A high-speed, computerized data acquisition system is planned to be added to the facility in order to improve the efficiency in processing of certain information. The rental cost for this improvement is included in the budget. Additional sensors will be installed such as hydrophones, pressure transducers, accelerometers, and thermocouples. Costs for additional sensors are listed.

Specialized instrumentation related to the acoustic emission testing, narrow band and third octave analyses, magnetic field pickup devices, and torque measurements will be rented in order to reduce costs.

FUTURE STUDIES

This project will provide a modern test facility for future testing and evaluation of many critical operating parameters for Francis-type turbines. Better delineation of pressure and suction side cavitation, periodic and intermittent draft-tube surging, draft-tube throat cavitation, and cavitation at other critical locations in the machine needs to be identified and included on efficiency-hill curves.

The model turbine and associated equipment will be the property of and operated by Colorado State University. The U. S. Bureau of Reclamation and the Department of Energy will have priority access to the turbine test facility provided it does not conflict with either the teaching or research activities of the University. The Civil Engineering Department at Colorado State University intends to use the turbine test facility to greatly enhance both teaching and research capabilities.

TIME SCHEDULE

1.	Remove model system from Estes Powerplant and transport to Colorado State University (CSU), Fort Collins, Colorado. Simultaneously construct support structure and place foundation anchors in Laboratory at CSU	1-1/2 months
2.	Install, align, and balance model turbine.	1 month
3.	Run checkout tests, evaluate emergency procedures, and do trial runs. Simultaneously install sensors, connect computerized data acquisition system, and debug	1 month
4.	Install and test A. E. system	1 month
5.	Install and test hydrophones and accelerometers	1 month
6.	Install and test magnetostrictive film plating and readout equipment	1 month
7.	Install and test shaft torque transducers and readout device	1 month
8.	Prepare progress report and refine testing program	2 months
9.	Test combinations of sensors under selected flow conditions	2 months
10.	Special testing, progress report, demonstrations	2 months
11.	Conferences, formal review and final report	4 months
12.	System refinement for prototype trials	1/2 month
	TOTAL	18 months

BUDGET

Direct Costs:

1.	Salaries, 6 months, M. M. Skinner, CSU	$32,000
2.	Salary, 3 months, B. W. Mefford, USBR	16,000
3.	Equipment rental	12,000
4.	Sensors (hydrophones, accelerometers, and pressure transducers)	9,000
5.	Technician and graduate student	9,000
6.	Travel	2,000
7.	Report preparation	1,500
	TOTAL	$81,500
	10% contingency	8,500
		$90,000

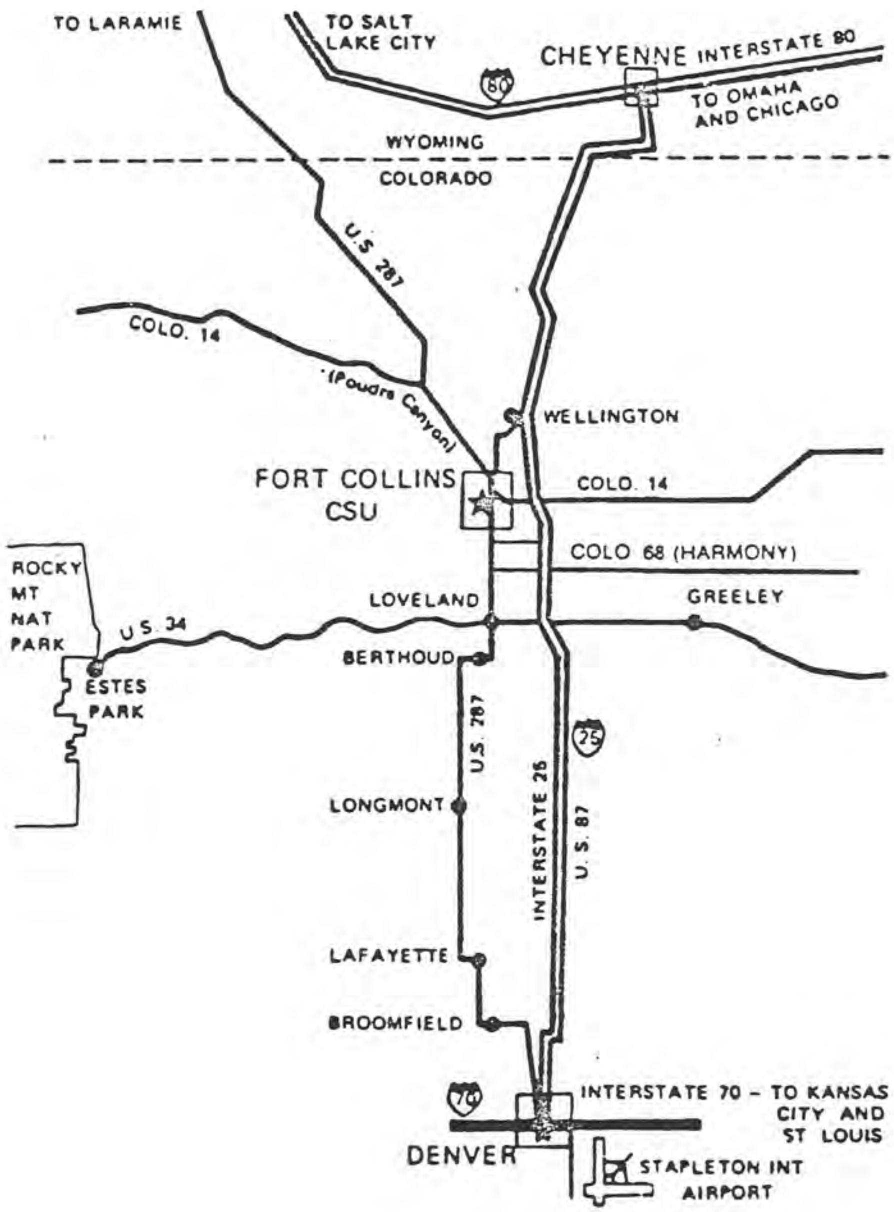
Contributions to Project:

1.	Cost of removing model, transportation, and supervising alignment and checkout		$30,000
2.	Rental on hydromachinery lab		
	$50/day - 240 days in 18-month period	12,000	
	Electric power	1,000	
	Maintenance on facility and instruments	3,000	
	Water costs @ $25/acre-foot	4,000	
			20,000
3.	Fabrication of stand for head tank and dynamometer control room, CSU		10,000
	TOTAL		$60,000

APPENDIX A

Location Map

Denver - Estes Park - Fort Collins



APPENDIX A

Location Map

Denver - Estes Park - Fort Collins

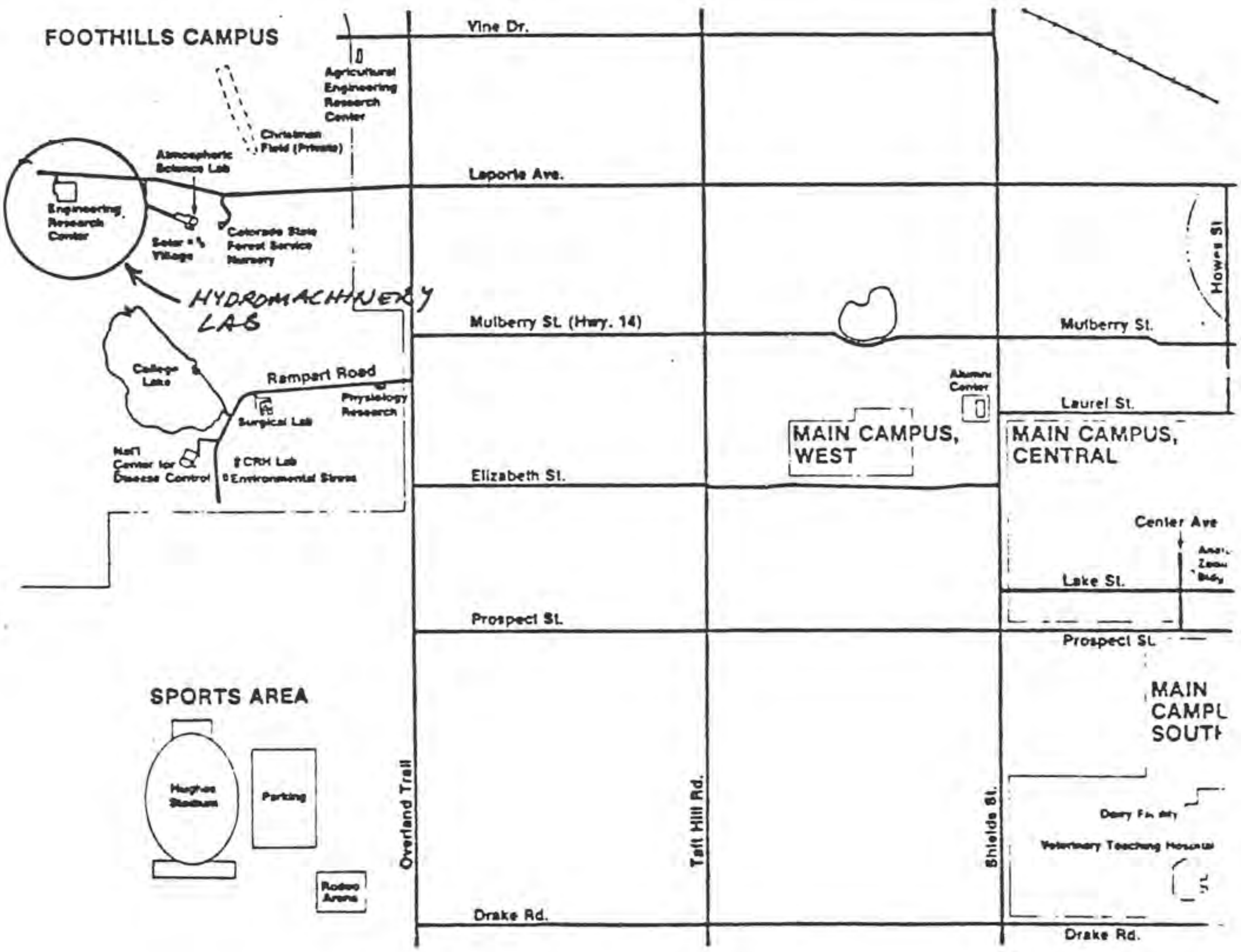
APPENDIX B

Location Map

Hydromachinery Laboratory

Colorado State University Foothills Campus

Horsetooth Reservoir



APPENDIX B

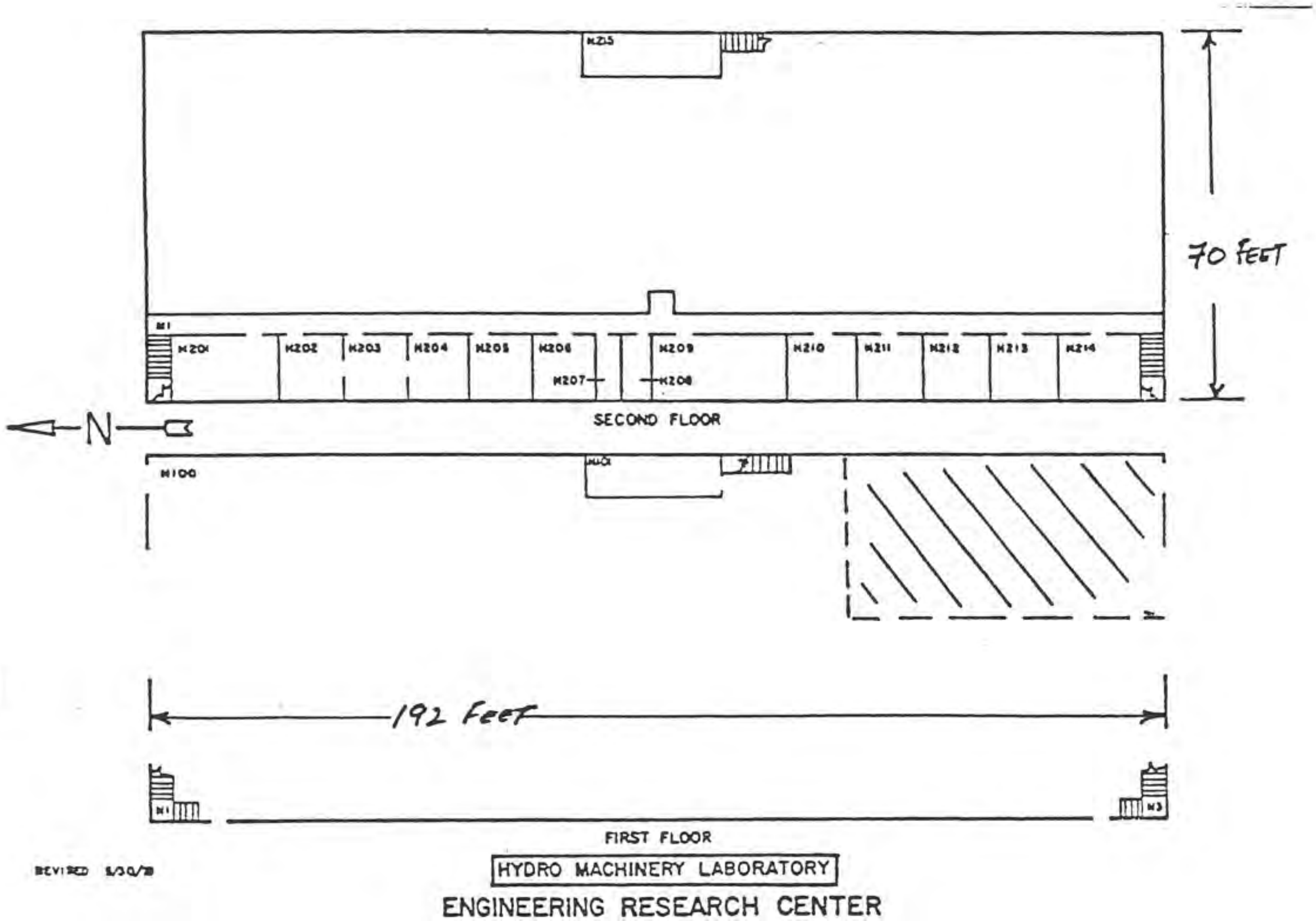
Location Map

Hydromachinery Laboratory

APPENDIX C

Floor Plan - Hydromachinery Laboratory

Foothills Campus - Colorado State University



APPENDIX C

Floor Plan - Hydromachinery Laboratory

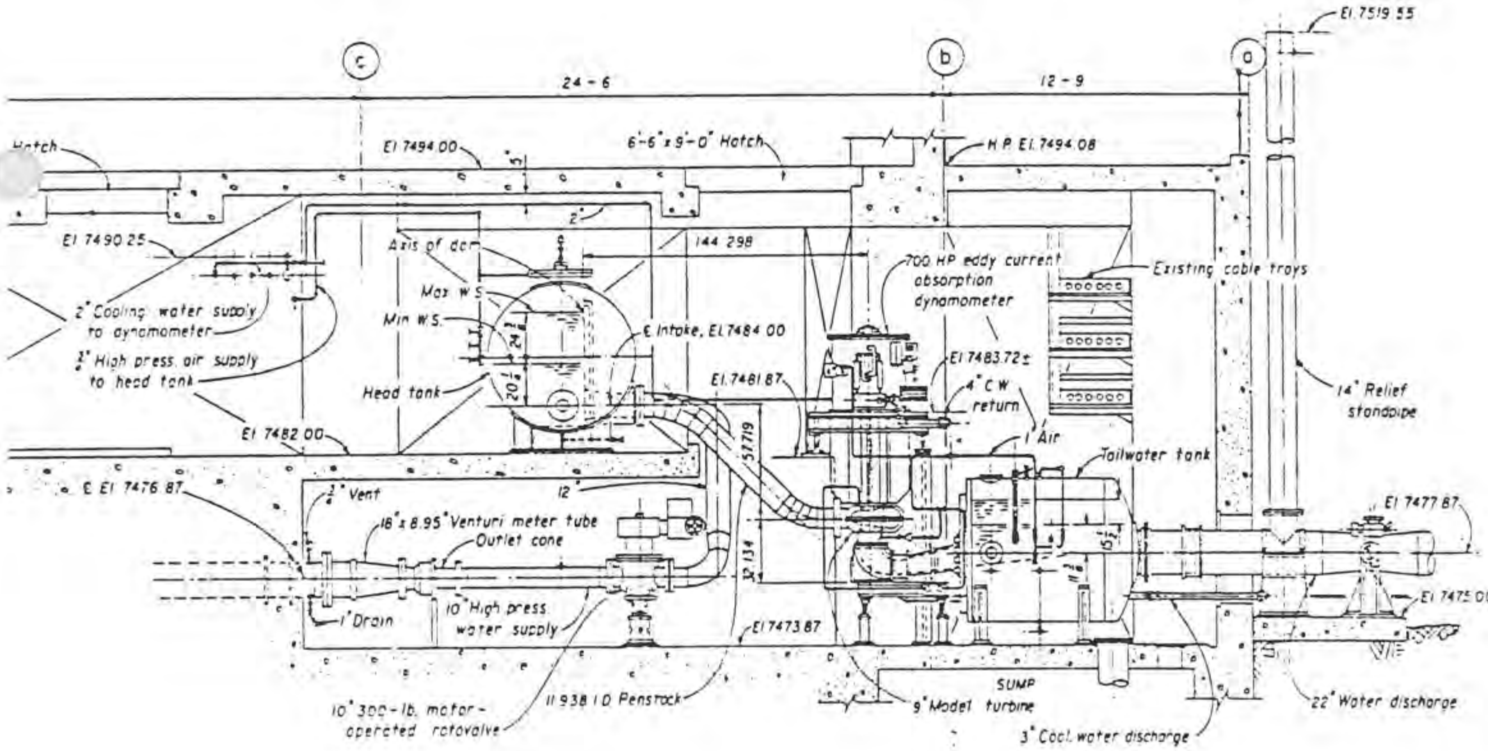
Foothills Campus - Colorado State University

APPENDIX D

General Description of

40.3 to 1 Scale Model of

Grand Coulee Third



APPENDIX D

General Description of 40.3 to 1 Scale Model

of Grand Coulee Third

Model Turbine

The 9-inch model turbine, with a size ratio of 40.3333 to 1, is homologous to the Grand Coulee Third, and has the following full-gate rating:

	Head ft	Turbine discharge ft^3/s	Turbine output hp
Maximum	355	21.3	748
Minimum	220	16.3	361

The model turbine has the following features:

(1) Spiral case. - Fabricated pressure box in two halves made of standard pipe and filed in with epoxy resin to hydraulic contour.

(2) Runner. - Thirteen individually cast stainless steel buckets assembled with separately machined stainless steel band and crown.

(3) Wicket gates. - Thirty-two, all stainless steel.

(4) Stay rings. - Thirty-one stay vanes. Machined rings and vanes welded together and protected with epoxy paint.

(5) Throat ring. - Molded transparent plexiglas, machined all over.

(6) Draft tube. - Water flows from the turbine through an elbow-type draft tube with two intermediate piers. The hydraulic contour of the draft tube is formed in plastic with welded steel encasement. It is homologous to the prototype. The connection between the turbine and the draft tube is fitted with an inflatable seal. The connection to the tailwater tank is sealed with a rubber O-ring gasket.

(7) Bearings. - Axial support for the upper end of the model turbine shaft is provided by a single-row, deep-groove, SKF 6212, unshielded, radial ball bearing. Axial support for the lower end of the turbine shaft and vertical thrust support for the rotating parts of the model turbine, including the intermediate floating shaft, are provided by a pair of single-row, angular-contact, face-to-face, duplex mounted, SKF 7214BG ball bearings. The bearings are purposely unshielded to allow passage of oil mist lubrications.

Dynamometer

The dynamometer is a vertical shaft, eddy-current, absorption type, rated 700 horsepower at 2,904 rpm. The model turbine drives the dynamometer through a direct-connected vertical shaft.

The dynamometer is basically an eddy-current brake cradled on trunnion bearings. It consists of a rotor, a stator, a toroidal field coil, a torque measuring system, control equipment, and a cooling system.

Control System

Control of operations at the facility is exercised by adjusting various valves to achieve desired head and water level conditions and by adjusting the electrical excitation of the dynamometer to achieve desired load and speed conditions. Automatically actuated electrical devices are provided, in some cases, to maintain desired test conditions and, in other cases, to prevent failures and damage due to overpressures or overspeeds. Indicating instruments are installed to provide means for monitoring operation and test conditions.

APPENDIX E

Biodata for

M. M. Skinner

B. W. Mefford

MORRIS M. SKINNER, Ph.D., P.E.

Dr. Skinner received his doctorate degree in Civil Engineering from the University of Colorado at Boulder, and Masters and Bachelor of Science degrees in Civil Engineering from the University of Wyoming at Laramie. Graduate work involved hydraulics, water resources, and river mechanics.

Dr. Skinner is a member of the Hydraulics Program at Colorado State University and professor in charge of the Fluid Mechanics Laboratory on main campus. He has been in the Civil Engineering Department since 1958 and has background experience in a wide variety of teaching, research, and consulting activities. He is a registered professional engineer in Colorado, Wyoming, and Nebraska.

Dr. Skinner has twice been awarded the Chi Epsilon Outstanding Civil Engineering Professor Award. He is now actively involved in adapting "state-of-the-art" computer processing into the laboratory and classroom environment. High speed data acquisition, analyses, and display are vitally important new training aids for students, particularly in the study of transients in pipelines and open channels.

Dr. Skinner's research activities have included groundwater recharge; use of bentonite and soil-cement for reducing seepage losses in canals and ponds; river mechanics; scour and erosion studies around bridge piers; hydaulic modeling; stream improvement methods; cavitation studies on valves; acoustic methods for detecting cavitation in hydraulic machinery; and use of infrared imagery and photography for analyzing a wide variety of hydrologic and hydraulic processes. He pioneered much of the use of airborne data collection procedures (infrared imagery and photography) and interpretation techniques applied to river systems; many related short courses were presented in the U.S., one (1) in Venezuela and one (1) in Yugoslavia. He has over 50 publications dealing with his research.

He maintains close contact with local consulting firms, state, and federal agencies in an effort to keep course curriculum and research activities pertinent to current and expected professional needs. He has provided expert witness testimony in a variety of court cases related to hydraulics and water resources.

BRENT W. MEFFORD, P. E.

Mr. Mefford received his Masters and Bachelor of Science degrees in Civil Engineering and Watershed Science from Colorado State University. He concentrated on hydraulics in his postgraduate studies.

After his graduate work he was employed by the Bureau of Reclamation as a Hydraulic Engineer in the Hydraulics Branch of the Division of Research and Laboratory Services. For the past 9 years he has worked in the Hydraulic Equipment Section conducting research for the Bureau in the areas of hydraulic machinery and hydraulic structures. He is experienced in both model and prototype testing. He has conducted numerous studies on cavitation and cavitation detection techniques. Over 15 publications have resulted from his work at the Bureau of Reclamation.

APPENDIX F

Selected Bibliography

Selected Bibliography

1. Mefford, Brent W., "Experimental Investigations of Cavitation Using Acoustic Emission Transducers," 1986, Bureau of Reclamation, Hydraulics Branch, Denver, Colorado.

2. Skinner, Morris M., "Sound and Vibration Measurements at Flatiron Power Plant," 1986, Colorado State University, Civil Engineering Department, Fort Collins, Colorado.

3. Burke, Harry E., "Handbook of Magnetic Phenomena," 1986, Van Nostrand Reinhold.

4. Milano, B. and Duncan, W. H., "Startup Characteristics of Pump-Generator Unit at Flatiron Power Plant," 1984, Bureau of Reclamation, Power and Instrumentation Branch, Denver, Colorado.

APPENDIX F

Cavitation Detection by Observation of Subharmonics

a.) Summary Sheet

b.) Example Plots (Cavitating, Non-Cavitating)

SUMMARY SHEET

CAVITATION DETECTION BY OBSERVATION OF SUBHARMONICS

ACOUSTIC CAVITATION: A physical phenomenon in which the motions of bubbles generated by a sound field in a liquid bring about typical physical effects such as chemical reactions, emission of light, radiation of sound and erosion.

Acoustic cavitation is an effective mechanism for concentrating energy...it transforms the relatively low-energy density of a sound field into the high-energy density characteristics of the surroundings and interior of a collapsing bubble. Acoustic cavitation is a nonlinear phenomenon.

transient cavities...bubbles that collapse violently with an audible snap or click ("vaporous cavitation field")

stable cavities...bubbles that pulsate non-linearly about their equilibrium radius over relatively long intervals of time and may transform into transient cavities ("gaseous cavitation field").

RAYLEIGH CAVITY...a model used by LORD RAYLEIGH to look at the problem of high-speed propeller erosion (1917)...first theoretical study of cavitation dynamics.

A "gaseous transient cavity"...relative amounts of gas and vapor remain constant during the pulsation (no evaporation or condensation at the interface).

A "vaporous transient cavity"...relative amounts of gas and vapor may change during the pulsation.

A "shock wave"...a pressure jump which propagates with a speed greater than the sound speed.

GENERATION OF SUBHARMONICS IN A SOUND FIELD

w_o = linear resonance frequency of bubble

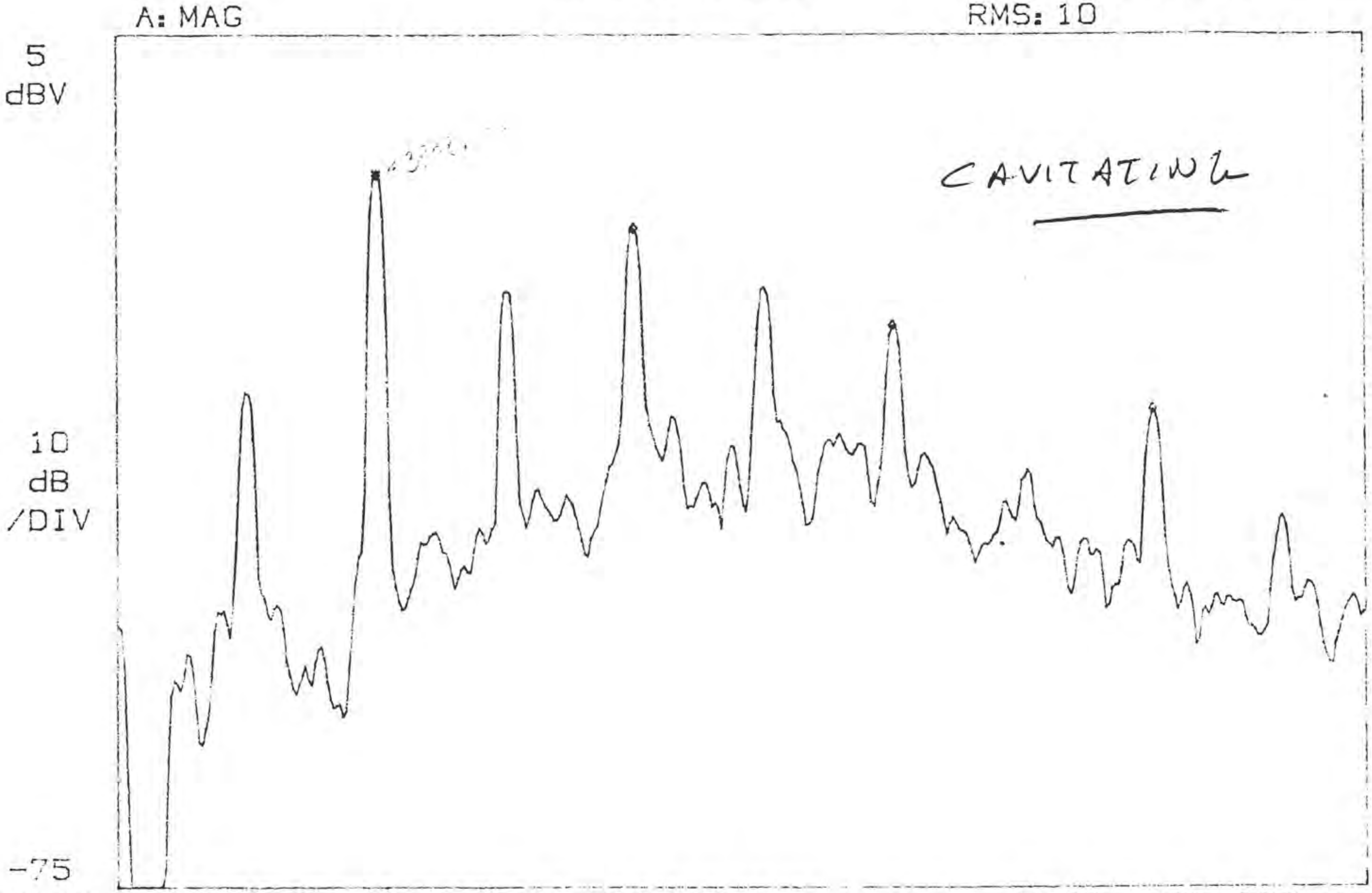
w = frequency of the sonar projector

$\frac{w}{w_o} = \frac{n}{m}$...is true if the motion is periodic

when n=2, and m=1 the free oscillation is a subharmonic and the forced oscillation is the 2nd harmonic of the free oscillation.

NOTE: The cavity (bubble) will have a subharmonic component only when the driving frequency is greater than the linear resonance frequency of the bubble. Also, the acoustic pressure amplitude must exceed a certain threshold value. The threshold value is a minimum when the driving frequency is approximately twice the linear resonance frequency of the bubble. Also, bubbles of any size may be shock excited to emit signals at their radial resonance frequencies. Any nuclei driven above its linear resonant frequency may be unstable (i.e., pulsate at its frequency of free oscillation until its radius becomes large and then collapse as a transient cavity) for pressure amplitudes much larger than the ambient, equilibrium pressure.

RANGE: 5 dBV STATUS: PAUSED



START: 0 Hz BW: 954.85 Hz STOP: 100 000 Hz

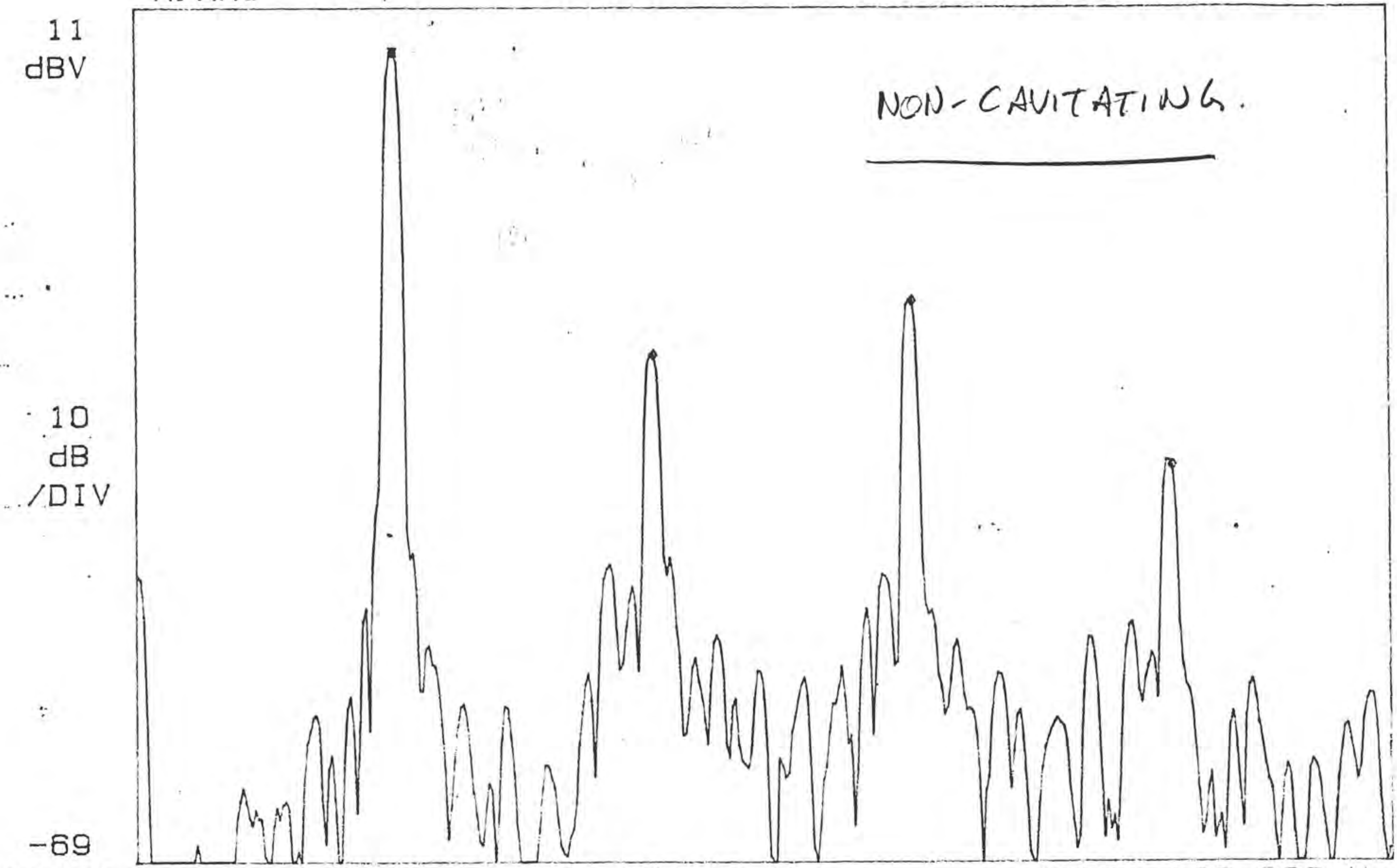
X: 20750 Hz Y: -8.16 dBV THD: -4.49 dB

Site Location: DFC-U4L Time: 11:05 AM Date 4-17-87 Plot No: 1 WG/Power Setting: (NO) CAV Air ______

Sensor: B&K/U4DPS 8104 s/n: ______ Sensor Location: ______ Dial Settings: 0.1-2-100 Tailrace Level: ______ Water Temp: ______

RANGE: 11 dBV STATUS: PAUSED

A: MAG RMS: 10



START: 0 Hz BW: 954.85 Hz STOP: 100 000 Hz

X: 20750 Hz Y: 6.84 dBV THD: -22.10 dB