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DEVELOPMENT of NONDESTRUCTIVE EVALUATION TECHNIQUES FOR DAM INSPECTION

Clifton Court Forebay

Prepared For

California Department of Water Resources

By

Albert E. Brown
Graham H. Thomas

University of California
Lawrence Livermore National Laboratory
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By
Albert E. Brown, and Graham H. Thomas
Nondestructive & Materials Evaluation Section
Manufacturing & Materials Engineering Division
Lawrence Livermore National Laboratory
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EXECUTIVE SUMMARY

The Clifton Court Forebay, ultrasonic inspection revealed that the tendons were not fractured and that the nominal lengths of the tendons are as published in the blueprints. The locations of the dual and single tendon anchors have been identified and are located at the proper nominally depths. The surrounding concrete is in intimate contact to the tendons leaving an ungrouted length of approximately 4 feet below the Howlett nut grip. The top of the tendons down to about 3 feet show corrosion, but the depth of corrosion is limited to approximately 1/16 inch. Pitting appears to be uniformly distributed with rounded bottoms. The most severe corrosion is located circumferentially at the level of Howlett nut cirque hole, and down the tendon to about 18 inches. The conduit around the tendon has a welded joint that approximates the depth of significant corrosion. Pier 3, Tendon 4; and Pier 4, Tendons 1,2 and 3, show acoustic waveforms that are significantly different when compared with the other tendons. The difference in waveforms suggests that the concrete piers 3 and 4 should be inspected for cracks. The broken and bent tendons supporting the failed gate 4 were inspected with magnetic particle, dye penetrant and high frequency ultrasound: No fractures were identified in these tendons. The corrosion damage on the exposed tendons appears to be typical to the damage that may be expected on all tendons.

The two tendons that were tested at the Oroville Dam had less coupling to concrete than was found at the Forebay. The tendon lengths to the anchors were located to the nominal depths indicated in the blueprints. The major corrosion damage is located around the tendon at the cirque hole in the Howlett nut. The depth of pitting is estimated 1/16 inch. The corrosion extends downward from the Howlett nut to approximately 18 inches. Tendon 17, produced an ultrasonic echo at 19 feet down from the top. Tendon 29, produced two echoes, one at 1.3 feet and the other at 4.3 feet down from the top of the tendon. Both tendons are located on the same trunnion.

Each tendon that was subjected to acoustic inspection was first faced with specially purchased tools using machining techniques that would minimize further damage to the tendons. A specially engineered and constructed ultrasonic system was designed especially for the inspection of long tendons at the Oroville Dam and Clifton Court Forebay sites.

Commercial products were identified for either inhibiting corrosion or preventing corrosion to steel tendons. Some commercial products for protecting surfaces from corrosion were found less than adequate for use on the tendons and some were found that would promote corrosion.

PIER	TENDON	HF_UT	LF_UT	MAG. PART.	DYE PENETRANT	CONDITION
1	1 Top	X	X			Pits to 0.062", dominantly at grout hole and on the circumference
1	2 Bottom	X	X			Same as above
2	1	X	X			Same as above
2	3	X	X			Same as above
2	2	X		X	X	Rust and pitting along the length to 18". Pits to 0.06"
2	4	X				Too short and non-flat surface for good examination
3	1	X		X	X	Heavily corroded with pits to 0.062" depth along top 18"
3	3	X		X	X	Same as above
3	2	X	X			Rust and pitting along the length to 18". Pits to 0.06"
3	4	X	X			Same as above
4	1	X	X			Corrosion pits detected at center length of Howlett nut and on circumference at grout hole, also down along tendon length to 18". Heavy tendon circumferential corrosion at conduit junction weld. Pits>0.060"
4	2	X	X			Same as above, but fewer pits and somewhat shallower depth
4	3	X	X			Clean except for back (180°) of grout hole area
4	4	X	X			Similar to #2 above, but deeper corrosion at back (180°) of grout hole area
5	1	X	X			Fair condition except for corrosion at and around from grout hole
5	2	X	X			Corrosion from 6" to 8" down and on circumference around grout hole. Corrosion depth greater than tendon 1 above to 0.06"
5	3	X	X			Best of 4 tendons. Some corrosion at and around from grout hole
5	4	X	X			Corrosion at 3" down and on circumference around grout hole
6	1 Top	X	X			Corrosion at 3" and 4" and around circumference from grout hole
6	2 Bottom	X	X			Corrosion inside Howlett nut, deepest at circumference through grout hole

Table 1: Clifton Court Forebay Data

ABSTRACT

The Lawrence Livermore National Laboratory has concluded a two and a half year study on the development of an ultrasonic inspection system to inspect post stressed steel tendons on dams and flood gates. The inspection systems were part of a program for the California Department of Water Resources. The effort included the identification of the location and amount of corrosion damage to the tendons, identification of the cause of corrosion, and the technology for inhibiting corrosion. Several NDE methods for inspecting and quantifying damage to steel reinforced concrete water pipes were investigated and presented to the DWR for their consideration. The additional methods included:

- Ground Penetrating RADAR,
- Electro-Potential Measurements,
- Infrared Technology,
- Pipe Inspection Crawlers, designed to travel inside pipelines and simultaneously report on the pipe condition as viewed by ultrasonic methods and video cameras from within the pipeline.

Reference to consultants hired by LLNL for similar on-site corrosion inspections were given to the DWR. The LLNL research into industries that have products to prevent corrosion resulted in the identification of an Innsbruck, Austria, company. This company claims to have products to permanently protect post- or pre-stressed tendons. The caveat is that the tendon protection system must be installed when the tendons are installed because no retrofit is available. Corrosion mitigation on the steel reinforcements surrounding the concrete was addressed through active and passive cathodic protection schemes. The combination of corrosion and erosion were addressed during consideration for the inspection of water-pump impeller-blades that are used in the three stage, million horsepower, pumping stations at Edmunston.

INTRODUCTION

Ultrasonic instrumentation was developed for the inspection of the California Department of Water Resources. The instrumentation consists of:

- High energy (1 mJ) ultrasonic transducer with the capability for producing pulsed compressional waves over a round trip distance of greater than 80 feet within steel rods with various diameters,
- Waveform Digitizer,
- Laptop computer for controlling the data archiving and data reduction. The software is all commercially available and operates in a Microsoft Windows 95 environment,
- And a commercially made, ultrasonic pulser-receiver.

The transducer is driven by a factory modified pulser-receiver. The pulser-receiver was modified to operate with an increased energy output, reduced pulse repetition rate, and an expanded low frequency range. The ultrasonic echoes are viewed on the computer to identify the location of anchors at the far end of the tendons. The temporal histories are stored on a laptop computer where the waveforms may be examined and transformed into a corresponding spectral domain. With an external printer connected to the computer, hard copies of the waveforms are available. The computer may be connected to a local area network for transferring data. The computer is complemented with an IOmega JAZZ drive, PCMCIA ports, and a CD ROM drive.

The ultrasonic instrumentation was developed to enable the inspection of steel tendons at the Oroville Dam, where there had been some tendon failures caused by stress corrosion cracking. The failure of a trunnion at the Clifton Court Forebay immediately turned the focus of attention on the inspection of those tendons. The Forebay tendons are smaller in diameter and are about 3/4 the length of the Oroville Dam tendons. The reduction in tendon diameter results a reduction in the acoustic impedance compared with that of the Oroville Dam. The reduction in acoustic impedance was accompanied by a severe acoustic coupling into the surrounding concrete. This acoustic coupling resulted in reengineering the design criteria for the transducer and the development of special acousto-mechanical transformers. The reengineered transducer can be used on any tendon from 1 to 1 3/8 inches in diameter without causing significant changes in signal resolution. The transducer is less sensitive (approximately, -10 dB) to the artifact noise propagated into the tendon by wind and water slap against the concrete Forebay structure.

The contract between the DWR and LLNL specified that LLNL would perform proof of principle inspections on the tendons after LLNL developed a suitable transducer and ultrasonic acquisition-reduction system for the DWR. The effort by LLNL would be determined by the requirements established by the DWR in mutually agreed upon task orders. The scope of the work was flexible and allowed priorities to be assessed during the year. For example, a failure at the Forebay made necessary a change in the ultrasonic transducer configuration to match the smaller diameter tendon. There were also differences between the reality of construction and the information on the corresponding metallurgical reports and blueprints that influenced the direction of LLNL effort.

TASK ORDERS

The blanket contract with DWR established a procedure for writing task orders and setting priorities. LLNL would bring to bear on the DWR task, the unique expertise that had been developed through the years on DOE applications. The work on developing a low frequency ultrasonic transducer was an imperative to the inspection of the Oroville Dam, full length tendons and thus transducer design began immediately. The DWR had received reports from Russel Lund, and George Moller, Metallurgists, who had been contracted by DWR to inspect and report on the Oroville Dam tendon failures. The metallurgist's reports were forwarded to LLNL for review along with several blueprints for the Oroville Dam. DWR requested that LLNL develop technology for inspecting the full length of tendons and propose methods for the prevention of corrosion to those tendons. The earliest LLNL reference for providing ultrasonic inspections to DWR facilities is dated, January 25, 1995. Information gathering and the logistics involved with providing inspections to the Oroville Dam and other DWR facilities started coalescing in parallel with ongoing contract negotiations.

TASK 1: OROVILLE DAM TENDONS

In a task order dated, April 15, 1996, LLNL was requested to ultrasonically inspect the 1 3/8 inch nominal diameter by 40 feet long, post stressed tendons on the Oroville Dam. The inspections would include the full length of the tendons. The tendon inspections will require the invention and construction of an ultrasonic transducer. Higher resolution ultrasonics is required for the top 2 to 3 feet of the tendons than is required to resolve the anchors.

The Oroville Dam was visited by a group from LLNL and DWR, Sacramento. The facility at Oroville provided LLNL personnel the opportunity to determine the logistics involved in the ultrasonic inspection of tendons. Several photographs were taken of the work site for later review.

Blueprints of the Oroville Dam were requested of the DWR personnel that would show the construction of the gate system and tendon anchors and points of changing stress application during operation of the gates.

It was noted that certain tendons had indication of severe external corrosion, while many others showed little or no corrosion and this observation led to Task 2. There were obvious bird feces splattered around the tendons, trunnions and elsewhere.

ULTRASONIC TRANSDUCER

The design of the low frequency transducer required research into commercially available low frequency transducers and into the available literature on high power, pulsed transducers. Ultrasonics instrument manufacturers were questioned regarding the availability of pulser-receivers that could produce significant output energy to operate a low frequency transducer.

No suitable transducers were manufactured for the inspection of long rods. A unique, low frequency, transducer was engineered at LLNL. The transducer was designed to transmit a high energy pulse into, and receive echoes from the tendons and anchors. The specialized transducer required the development of transducer support instrumentation that would generate high energy output pulses and digitally process and archive returning ultrasonic echoes from each tendon. An example of the temporal history for the LLNL rod is shown in Figure 1.

The transducers are designed to produce an extensional wave with a 1 mJ output pulse at 30 kHz into a long tendon. The transducer impedance was matched to the tendon acoustic impedance with an acousto-mechanical matching transformer inserted between the transducer and the tendon. A specific transformer is required for each tendon diameter.

TENDON PREPARATION

The DWR metallurgist's report stated that the hardness for tendons was HRC-33 and this number compared well with the specifications published by the tendon manufacturer. The free lengths of the tendons were reported to be 4 inches long.

Concurrent with the design of the low frequency transducer, LLNL determined methods for facing tendons to prepare them for ultrasonic testing. The rounded tops on each tendon precluded reliable ultrasonic inspections.

DWR sent a section of a broken tendon and grip nut to LLNL. Prepared samples of the broken tendons were ultrasonically examined to establish dynamic elastic properties. To prevent additional work hardening or deepening the hardness, specimen preparation was accomplished by hydraulically machining specimens to form flat, parallel surfaces that were also perpendicular to original long axis.

The mounting the low frequency transducer to the tendon was the subject of considerable research. The coupling had to be nearly as good as a coaxial, butt welded joint so that adequate acoustic energy would be transmitted into the tendon. The final concept for mounting the transducer had to take into consideration the vulnerability of the corroded tendons to external stresses. The LLNL machinists determined that the machining of the tops of the tendons must be done with a magnetic base drill press. A tendon grip fixture was designed to support the drill press concentrically above the tendon and prevent shear stresses along the tendon axis during machining.

TASK 2: CORROSION, TENDONS

LLNL was asked to investigate the corrosion problem found on the Oroville Dam tendons and recommend remedial action. The DWR metallurgist's report on failure and remedial recommendations, suggested the immediate use of a corrosion inhibitor. There had been a limited application of a Food Machinery grease (Chevron FM grease) to some selected tendons in an attempt to protect them from corrosion. DWR engineers questioned the advisability of using the grease or possibly injecting more grout into the Howlett nut.

In a memorandum, dated June 13, 1996, there was stated that grout could not fill the space inside the Howlett nut and is not required to be used. No hydrocarbon solvent would remove the FM grease that had been applied to the tendons. The memorandum further stated that the grease, "...will provide the best level of protection for the trunnion anchor rods...". The Chevron chemist said that the NLGI 2 was too viscous to be used for application on the tendons and that NLGI 0 should be the proper viscosity. The Chemist's reasoning was that a high viscosity will not cover as much of the enclosed volume and surfaces inside the Howlett nut assembly as would a low viscosity lubricant.

Two additional remarks made in the same memo are worth reviewing. The Chevron grease, "...does contain corrosion inhibiting properties...". A reading of the Chevron specifications revealed that this grease has excellent rust protection and is water resistant. The only mention to corrosion is to protection of exposed steel to food spillage and cleanup procedures. The main advantage to the FM grease is that it is edible and non-toxic. There is considerable side stepping in the specifications by omitting reference to corrosion inhibiting values, particularly for other than food processing applications. Adding the Chevron chemist's report to the bridging found in the specifications leads one to suspect that the Chevron FM, NLGI 2, grease is not appropriate for structural applications. This is not to say that the grease either will or will not promote corrosion; or, that the grease might interfere with the application of a different specific corrosion inhibitor gel or wax: The question of mixed chemistry is another topic for examination.

In telephone conversations with maintenance machinists working for the DelMonte and Heinz cannery, the maintenance machinists said that FM grease is always used on all the food machinery, but they have frequent machine failures from corroded and seized bearings. "The FM grease does not protect enclosed surfaces such as found in bearings."

The second comment in the memo was to the effect that the grease was, "...injected into blind voids and that it is likely that there remains voids between the grout and grease...". The statement may be interpreted that the viscosity and wettability of the grease are inappropriate for the intended purpose as was said earlier by the Chevron chemist. The memo included a request to use a sealant around the gripper nuts and anchor plates. In consultation with the DWR engineers, Chevron chemist, food processing specialists, we determined that a better sealant would be a polysulfide or polyurethane (with preference given to the former) to prevent the formation of moisture and biological intrusion along the interfaces.

OROVILLE PLANS PRESENTED

On May 14, 1996, an LLNL proposal was sent to DWR outlining a plan of action that LLNL believed appropriate for examining the Oroville Dam tendons. A nominal, 1 3/8 inch diameter by 40 feet long rod, with the same composition as the Oroville Dam tendons, was purchased. Pieces of the rod were cut off to be used for ultrasonic examination and hardness comparison to the Oroville Dam tendons. Additional pieces were cut off for metallurgical examination and for later use by the Electrochemists to determine susceptibility to stress corrosion. Additional pieces of this rod were used in the construction of the low frequency transducer. The remaining length of rod was machined to have grooves cut into each end of the rod in preparation for using the rod as an ultrasonic standard.

The broken section of DWR tendon, load bearing plate and parted sections of the Howlett nut assembly were received at LLNL and examined with ultrasound to determine the dynamic elastic properties. Results from the dynamic elastic properties of the DWR tendon were compared with the corresponding properties of the LLNL rod. The elastic constants govern the velocity of sound within a material. Internal dislocations, grain size, flaws, residual strain, etc., govern the attenuation and propagation of sound. The results from the acoustic inspections were used in the design of the ultrasonic transducer. The results were also used for assuring that the acoustic velocities and acoustic attenuation are essentially the same in the various tendons: In this way, it is often possible to develop an acoustic flaw standard for comparison with the material that will be subjected to inspection.

The LLNL metallurgists were presented with the available data on the tendons from Oroville. The data included the corrosion inhibiting efforts that had either been tried or proposed to be used on tendons in the near future by DWR.

The LLNL metallurgists and corrosion engineers produced a report, on June 6, 1996, to the DWR, addressing a DWR request for additional help in the mitigation of corrosion. The report concluded that the use of greases would serve to trap water and promote corrosion on the tendons: This sentiment was also expressed by Carl Ward, Chemist, Chevron Corporation. Carl said that the FM greases were never intended for use as a corrosion inhibitor, but as a replaceable coating to protect machinery from spillage. The recommendation by the LLNL metallurgists was to remove all water and water vapor from contact with the tendons and prevent further water contact with the tendons.

Research into the current science in protecting steel from corrosion in a marine environment started with inquiries to the National Association of Corrosion Engineers (NACE). The inquiries were focused on military and civilian ship protection against corrosion. The U.S. Navy, and maritime service had evaluated corrosion inhibitors of a variety of types, over many years. The consensus appeared to be that bees wax, as a base, had a short life span. The consensus preferred base for mitigating corrosion was anhydrous lanolin. One company, located in California, is a manufacturer of corrosion inhibiting gels using the anhydrous lanolin base. The corrosion inhibitor products could be purchased in bulk quantities and in a variety of viscosity. Additionally, there were U.S. Navy specifications written around this product. All the foregoing information was forwarded to DWR, in a report, dated July 9, 1996.

DWR asked LLNL to gather relevant information on the John Day Locks. Several contacts on the internet and telephone were required before contact with the correct individual was found at the Portland District Office of the U.S. Corps of Engineers. Dennis Hopman, Chief of Operations, sent a report to LLNL regarding the maintenance to the John Day

Lock. The report and supporting information for this investigation was sent to DWR along with the monthly report on August 2, 1996.

The LLNL Electrochemists were asked to test samples of corrosion inhibiting gels[1] against other techniques for inhibiting corrosion on the steel rods. The Electrochemists were asked to identify the cause and rate of corrosion to the DWR tendons as a means to identify the life expectancy of the tendons. The chemists asked for and received 10 gallons of Lake Oroville water for analysis. The water was to be used for its ionic properties and dissolved salts with the test tendons. Samples of the LLNL tendon were taken for tensile testing and for corrosion rate studies. Following a meeting between LLNL and DWR engineers, the DWR said that this phase of the program should be continued, but should be independently funded through a separate contract. The cost of this program appeared to be more than could be supported by the DWR contract and was postponed.

TASK 3: CLIFTON COURT FOREBAY

The Clifton Court Forebay took precedence over all other work when a trunnion tendon failed. LLNL was asked to immediately inspect the Clifton Court Forebay flood gate tendons after an unexpected failure of a tendon resulted in the closure of one of five gates. The tendons that were members of the failed tendons were visibly stretched and bent. The gate, trunnion, and the surrounding conduit were removed from the tendons. All the tendons appeared highly corroded with approximately 1/16 inch deep pits. Below the Howlett nut and down to a depth of about 3 to 4 feet there was no grout. The conduit that surrounded the tendon was designed as overlapping pipes that had been welded together at about 18 inches below the top of the tendon. Around the tendon and at the approximate center line of the weld, a piece of absorbent paper had been wrapped around the tendons and stuffed into the conduit. The paper had been slightly burned from the heat caused by cutting the top off the tendon during the final stage of tensioning.

Sections of the broken Forebay tendon and Howlett nut were sent to LLNL for inspection. Samples of the tendon were hydraulically cut to preserve the as received hardness properties. The prepared samples were tested for the dynamic elastic properties with ultrasound and then sent out for density measurements. The samples were then sent to the materials test laboratory for hardness measurements. A series of hardness measurements was taken along perpendicular diameters on both faces on each of the samples. The hardness ranged from HRC-36 from the lower end of the tendon to HRC-52+ at the upper end of the tendon. There were spots of hardness that ran axially downward for about 1/2 inch along the tendon that were in the HRC-52 range. In an attempt to determine how one might obtain an incorrect tendon hardness, we tried to measure the hardness along the unprepared cylindrical surface. There was some corrosion and pitting along the tendon surface. Hardness measurements ranged from HRC-22 to HRC-33. In close observation, it was obvious that the hardness indenter was sliding into rust contaminated pits, and the rod had a tendency to roll very slightly during the measurements. Measurements for hardness taken along the axis are not going to give correct hardness readings.

Inspections of the Forebay gate system revealed the tendons were smaller in diameter than the Oroville Dam tendons. The same process had been used at both facilities for installing the tendons, according to the DWR records. The Forebay tendons were case hardened more deeply than those at the Oroville site, but quantitative measurements of the ultrasonic, dynamic material properties and the hardness were verified to be similar to the Oroville

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[1] Eureka Chemical Company sent two different viscosity samples of corrosion inhibiting gels to LLNL for evaluation.

tendons. The DWR metallurgist had reported that the Forebay tendon had failed brittlely and not by the stress corrosion cracking that he found at the Oroville Dam.

The tendon above the Howlett nut measured 1 3/4 to 2 inches and 1 1/8 inches, nominal diameter, precluding the use of the tendon grip that had been designed to grip the larger diameter tendon. All tendons had as flame cut, rounded tops. A new grip was constructed that would grip to the Howlett nut and provide a mounting surface for the magnetic base drill press. The use of carbide machine tools was dismissed because they are too brittle, so cobalt drills and facing tools were ordered. The cobalt tools are used for their inherent toughness and hardness when machining case hardened steel. It was found that the case hardening penetrated downward along the tendon length like dendrites to a depth exceeding 0.5 inches. The machining of a tendon face was estimated to take under an hour per tendon. Once the tendon was faced, the high frequency ultrasonic transducer could inspect down to about 3 feet by scanning around the edge of the drilled hole. The drilled and tapped hole in the top of the tendon was the location for attaching the low frequency transducer that could evaluate the length of the tendon.

The proximity of the Forebay to LLNL made an excellent proving ground on which we were able to test our concepts for inspecting the tendons. As it turned out, the Forebay was more challenging than the Oroville site. The unexpected challenges at the Forebay included the tight, acoustic coupled, concrete to the tendons; the double anchors at the bottom of the tendons, and the magnitude of, mechanically coupled, artifact noise sources.

RETURN TO OROVILLE

Meanwhile, DWR had preceded to construct weatherproof covers for the Oroville tendons according to the recommendation by LLNL metallurgists. Planning was prepared for LLNL to return to Oroville with the low frequency transducer, oscilloscope and a standard laboratory pulser-receiver.

By the October 3, 1996, monthly report, LLNL had gone to Oroville with the tendon grip and magnetic base drill press. The electronics that had been on order had been delayed due to the modifications that LLNL had specified. The tendons were measured to be less than 2.0 inches long above the Howlett nut. The indication that we had received said that the tendon lengths were over 4 inches long. This measurement had to include the height of the Howlett nut. The tendon grip fixture had to be modified at Oroville to grip to the Howlett nut. The machine tools were all high speed cutting tools in anticipation that the hardness was, HRC-33. This harness information was found to be incorrect because the high speed cutters were dulled immediately and had to be resharpened several times. It became obvious that there had been an incorrect method used to measure the hardness of tendons and that the true hardness was around HRC-52+ (this hardness was later confirmed at LLNL). The tendons at the Oroville Dam had been flame cut after installation and tensioning. The flame cutting caused the tendons to be case hardened in the same way as at the Forebay.

Two tendons (17 and 29) were faced and tested on one pier at Oroville. The Oroville machinist was extremely helpful in modifying the fixture to grip the short tendons and in his help in machining the tendon tops while we were at the site. The result of that test was reported to DWR in the October 3, 1996, monthly report. The Oroville tendons may be more easily inspected than were the Forebay tendons. The Oroville tendons appear acoustically similar to the LLNL purchased tendon. The corrosion extends downward from the Howlett nut to approximately 18 inches. Tendon 17, produced an ultrasonic echo from 19 feet down from the top of the tendon. The 19 feet is the approximate mid-length of the tendon and may be a reflection from the first overtone, flexural node. Tendon 29, produced two ultrasonic echoes, one at 1.3 feet and the other at 4.3 feet down from the top of the tendon. Both tendons are located on the same trunnion. It is essential that several more tendons be inspected with ultrasound before making judgment on these two tendons. The absence of a standard "good" and a standard "bad" rod, both imbedded into concrete, leaves the inspection to a statistical inference of "good" and "bad". Severity of the ultrasonic indication is often a function of amplitude of reflection relative to the distance from the source. Non-relevant ultrasonic indications may be duplicated on several seemingly unrelated tendons.

No additional tendons have been prepared for ultrasonic inspections at the Oroville site. The two tendons that have been inspected should be reinspected with the data archived on the computer systems.

RETURN TO THE FOREBAY

The Forebay tendons had been machined by the DWR machinists using the techniques developed by the LLNL machinists and the tools purchased for DWR by LLNL. Plastic end caps were purchased for the DWR to slip over the machined tendon ends to protect the metal from corrosion and dirt. The Clifton Court Forebay machinists kept the magnetic base drill press, all the cobalt tools including drills and centered spotfacers, and the fixturing to hold the drill press in alignment with the tendon. LLNL expected that the machine tools would be sent to Oroville after the Forebay tendons had been dressed. The tops of the Oroville tendons had to be machined before ultrasonic inspections at that site could begin. LLNL ordered two boxes of plastic caps, for the protection of the tendons, and the boxes were shipped to Oroville and to the Forebay.

The computer, digitizer, and pulser-receiver arrived in early October 1996, and the control programs were installed onto the DWR computer. Following some program debugging, the computer system and low frequency transducer was transported to the Forebay for inspecting the full length of the tendons. The initial tests confirmed that there was much work left to be done if we were going to be able to resolve the ultrasonic echoes from the Forebay tendons. The artifact noise was identified as water induced noise into the concrete piers and then into the tendons. Besides the water borne noise there was noise generated by the strong winds and the operation of the gates during the ultrasonics tests. All of these noises obscured the ultrasonic echoes. Several tests were conducted with the full electronic system on the LLNL tendon to establish a method for reducing the effect of the noise. The low frequency ultrasonic transducer was reconstructed to have a much reduced bandwidth. The reduced bandwidth had the effect of reducing some of the echo resolution and greatly reducing the sensitivity to artifact noise. Special acousto-mechanical transformers were machined to interface between the tendon and transducer to provide an acoustic impedance match between the two: The closer the impedance is matched between any two materials, the more acoustic energy that may be transmitted through that interface and into the second material.

On March 25, 1997, a report was sent to DWR regarding the straightening of bent tendons at the Forebay. The LLNL engineer's report included several caveats along with copies of papers written by a variety of authors and professors on the straightening of steel members. The monthly report gave the result from the ultrasonic high frequency ultrasonic transducer inspection of all tendons associated with the trunnion collapse. The bent tendons at the Clifton Court Forebay were inspected with dye penetrant, magnetic particle and high frequency ultrasound, but not with the low frequency ultrasonic system. The tendon residual strain and lack of a flattened face distort the propagation of ultrasonic signals. If the tendons are cut below the strained area and then faced for the coupling of ultrasonic transducers, then these remaining tendons will become inspectable.

On July 24, 1997, the monthly report was sent out to DWR to describe the low frequency ultrasonic inspection of each of the faced and intact tendons at the Forebay. An example of the low frequency ultrasonic temporal history from a Forebay tendon is shown in Figure 2. The high amplitude, long duration signal at the left of the figure suggests that there are acoustic reverberations within the Howlett nut assembly and the free standing length of tendon above the concrete. There is evidence of anchors at 22 feet and at 27 feet with the tendon length extending to 29 feet. There are also indications suggesting flexural nodes for the 22 and for the 27 foot anchored lengths of tendon. The waveform polarity below the zero signal crossing is indicative of acoustic coupling into a higher acoustic impedance than the impedance of the tendon (analogous to the signal seeing an open circuit termination). A higher impedance termination is consistent with acoustic coupling to large steel anchors or concrete. Waveform polarity above the zero signal crossing, is indicative of a signal passing into a lower acoustic impedance at the boundary of two materials and is consistent with acoustic coupling from the tendon to air or water (analogous to a short circuit termination). The monthly report also outlined the remaining work that needs to be completed on the ultrasonic wave analysis. The flexural modes for variously held bars and rods are illustrated in Figure 3, and 4. The rod support condition of major interest is the gripped-gripped mode showing the first four tones of excitation. Figure 5, is a sketch that shows the quarter wavelength relationship between the force and displacement in a rod subjected to flexure. The vibration node for the second tone, or first overtone, is located at the center of the rod. The displacement leads the force, or acoustic pressure, by 90 degrees, while the particle velocity is in phase with the force during the resonant excitation of the rod. It is believed that the high stress level at the node is responsible for generating an ultrasonic echo.

TASKS 4a and 4b: CONCRETE PIPE INSPECTION

In September 1996, LLNL received an email from DWR that inquired into our Ground Penetrating Radar as a possible technique for inspecting the condition of steel reinforced concrete pipe. The email was forwarded to the GPR group for their response. The LLNL response to the question on the application of GPR was sent to DWR before the end of September. LLNL was asked to investigate predictive NDE methods for corrosion to the steel reinforcement surrounding large diameter, concrete water pipes. Propose NDE methods for detecting the corrosion and possibly mitigating corrosion on pipe that may run below ground on school, residential and commercial property.

Another company[2], consisting of a consortium of three North American companies, built and demonstrated a pipe inspection system that consisted of crawlers that could travel inside pipelines and perform a number of NDE measurements. The crawlers can travel horizontally and vertically through pipes consisting of a wide variety of diameters. The system was built for PG&E gas and water pipelines. The brochures, names and addresses of this company and its products were sent to DWR.

TASK 5: EDMUNSTON PUMPS

LLNL was asked to investigate and propose methods for NDE of impeller blades that have been showing corrosion and erosion damage at the Edmunston pumping Facility. Propose NDE methods for detecting active erosion and determine logistics for providing radiography to turbine blades. Determine whether acoustic sensors could be mounted to detect the onset of erosion and relate those phenomena to other events occurring within the facility.

[2] International Submarine Engineering Ltd., Hal Hirtz, Project Manager, Port Coquitlam, B.C. Canada, (604) 942-5223

LLNL suggested a visit to the Edmunston site to determine whether it would be most feasible to transport the Varian Linatron to the Edmunston site or to ship the impeller blades to LLNL for radiography.

LLNL proposed to inspect the impeller blades with Infrared at the Edmunston site.

DWR determined that the radiography and acoustics at Edmunston could be postponed to a later date. The tendons should receive priority attention.

DISCUSSION

LLNL has engineered and constructed an ultrasonic inspection system for the DWR. The ultrasonic system has the capability of inspecting concrete-imbedded, post-stressed, steel rods. The rods may have a range of 1 to 1.5 inches in diameter and lengths to over 40 feet. Such geometry and physical restrictions as found with these steel tendons have never before been inspected with ultrasound. The closest inspection technique that has been done on long rods is a modal analysis that is limited to establishing a length without identifying surface conditions.

A second generation ultrasonic transducer has shown great improvement in the reduction of artifact noise over the original transducer design. The low frequency transducer has successfully identified concrete adhesion according to length of tendon, identified location of anchors, and possibly identified the location of corrosion damage along the length of the tendon. More work is required to integrate the physical properties of the tendons with the ultrasonic temporal histories from the tendons. This effort to integrate the known parameters of time, materials and space will require signal processing. This programming could be performed on a commercial software package, such as "ProMatLab". Preliminary investigations in filtering the temporal data from the tendons would indicate that it may be possible to resolve tendon damage apart from the echoes from flexural nodes and anchors reflected from within the tendons.

The ability of the DWR to have their machinists perform the facing of tendons has had the effect of reducing the cost for developing a tendon inspection system. The techniques that the LLNL machinists developed to face the tendons without introducing additional damage to the tendons are considered a valuable contribution to the inspection procedures. No reliable ultrasonic coupling or inspections could have been achieved on the as-cut tendons.

In response to a DWR inquiry regarding Ground Penetrating RADAR, the LLNL engineers in the Electromagnetic group suggested that GPR could identify the location of pipeline under certain favorable conditions. However, the amount of ground water would substantially influence the ability to locate the pipes. If there were significant water leakage from the damaged pipe into otherwise relatively drier soil, the GPR could locate the leak based upon the soil moisture. The same response was given by the Infrared engineers and for the same reasons given by the RADAR engineers. The relative corrosion to the steel reinforcements surrounding the concrete pipes could be identified with infrared even though the metal may be covered with concrete. However, without actually testing the pipe with infrared, it would be difficult to predict the ability to quantify the damage.

The Department of Water Resources, asked LLNL to review work done by other organizations on problems similar to those in the DWR. LLNL identified the organizations and their status for preventive maintenance as a compared with the DWR:

- those organizations that have similar problems with dams and other water control systems,

- the level of maintenance that others are reporting on similar systems,
- the methods that are currently accepted by the military and industry for mitigating corrosion in the marine and utilities industries,
- organizations that provide inspection tools and consultants to industry for measurement and control of corrosion.

The determination of life expectancy of existing tendons was started by the LLNL Electrochemistry Department. A program for determining the remaining life expectancy based upon the amount of detected corrosion is a valuable adjunct to the tendon inspections.

An Innsbruck, Austria, company known as VETEK published a number of papers on corrosion prevention. The VETEK Systems Corporation, with local offices in Elkton, MD, has a product that the company claims will give permanent protection to tendons that are used for either pre- or post-stressed concrete. The protection system must be installed when the tendons are installed. The advertising brochures for this company were passed on to the DWR, O&M office in, July 1996. DWR may wish to investigate this method for tendon installation on any future construction involving post-stressed tendons[3].

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

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[3] Work performed under auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

GLOSSARY, PARTIAL, WAVEFORM ANALYSIS

ACOUSTIC IMPEDANCE	is analogous to an electrical impedance. The impedance is the product of the sound velocity in the material and the density of that material ($Z = \rho C$ where $D \geq 5\lambda$). The acoustic impedance of a material with a reduced cross sectional area, subjected to a low frequency compressional wave, is modified by the further multiplication by the cross sectional area ($Z = \rho CA$, where $D \leq 0.2\lambda$). Where D is the diameter of the sample material.
ADAPTIVE FILTER	is a self-adjusting filter capable of adaptively estimating the bulk delays (arrivals) from noisy data.
AUTO-CORRELATION	estimates the "self-similarity" of a signal
CEPSTRAL ANALYSIS	estimates the arrival times of reflected and attenuated signals (log of power spectrum)
COMPRESSIONAL WAVE SPEED	is the velocity of a normal compressional wave within a material. Wavelength of the sound compared with the cross sectional area of the material will influence the measured velocity.
CROSS-CORRELATION	measures the similarity of two different signals (actually) if one of the signals is a replica of the excitation into the tendon, it provides the optimal "matched-filter" detector for arrival or reflection in uncorrelated noise
DE-NOISE FILTER	is an optimal mean-squared error, least-squares or Wiener filter designed to estimate the arrivals from both inputs (replica) and measured tendon ultrasonic data.
DIFFRACTION	is the scattering of radiation at an object smaller than one wavelength and the subsequent interference of the scattered wavefronts.
DISPERSION	is a wave propagating in a material, where the frequency of the wave is interdependent upon the wave velocity.
ERGODIC	signifies that the time average of any sample is that of all samples.
FLEXURAL NODES	one or more discrete demarcations within a vibrating material or structure at which there is no displacement. The displacement on either side of a node will be vibratory and in opposite directions. The point of maximum particle velocity and maximum acoustic pressure or force.
FLEXURAL WAVE	is the lowest velocity for any induced acoustic wave and is largely responsible for fatigue damage in a material by causing the material to distort through bending moments. The flexural wave is highly dispersive.
FLEXURE	is the dynamic bending of a material in response to an external excitation.
INTENSITY	is a measure of power density.
MODE	is a description of the shape of a structure that is in resonance with its

excitation.

NODE	in a resonant system is the point of zero vibration or displacement on a vibrating material. Because the displacement leads the force by a quarter wavelength, the node is also the point of maximum force or acoustic pressure and maximum particle velocity.
RANDOM VIBRATION	is one containing no periodicity.
REFLECTION	is the angular return of a wave from the interface composed of two different acoustic impedances.
REFRACTION	Is the bending of a wave as it passes obliquely from one density or velocity medium into another.
SPIKING FILTER	is an optimal deconvolution filter for both arrival time and pulse shapes. It can be thought of as an inverse filter converting the measured tendon data to a train of "spikes" or impulses corresponding to the correct arrival times
STATIONARY WAVES	involves the probability that the structure is independent of a time shift. Also, stationary wave is a descriptor used to identify a simple standing wave system consisting of two equal plane waves traveling in opposite directions.
STOCHASTIC WAVES	is a wave involving the probability of a random finite time series.
TIME-DELAY FILTERS	are sets of filters designed to optimally estimate or extract time delays from input/output (replica/tendon measurement) data.
WAVELENGTH	λ is the ratio of the speed of sound to the fundamental frequency in that sound

FIGURES

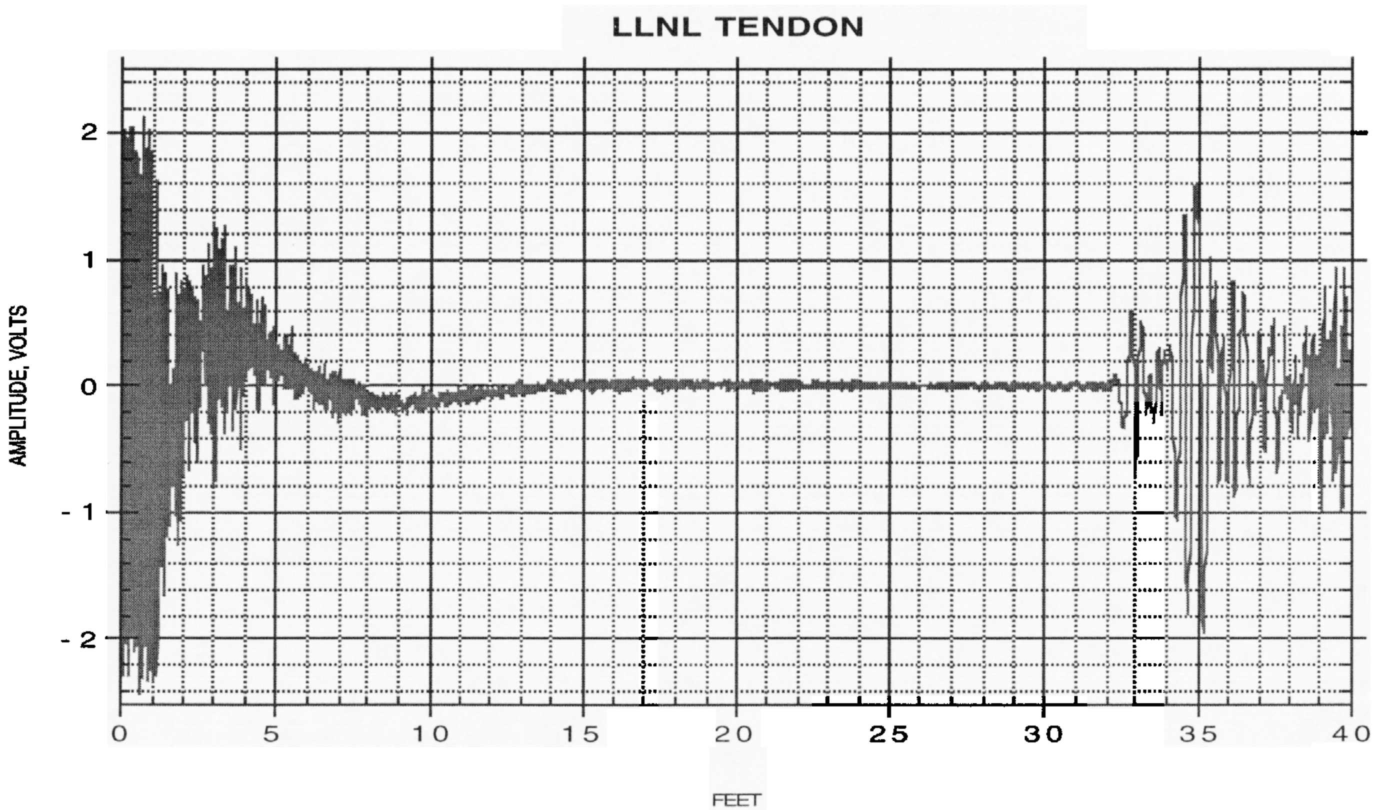


Figure 1: Showing notch at 18 inches from end of tendon

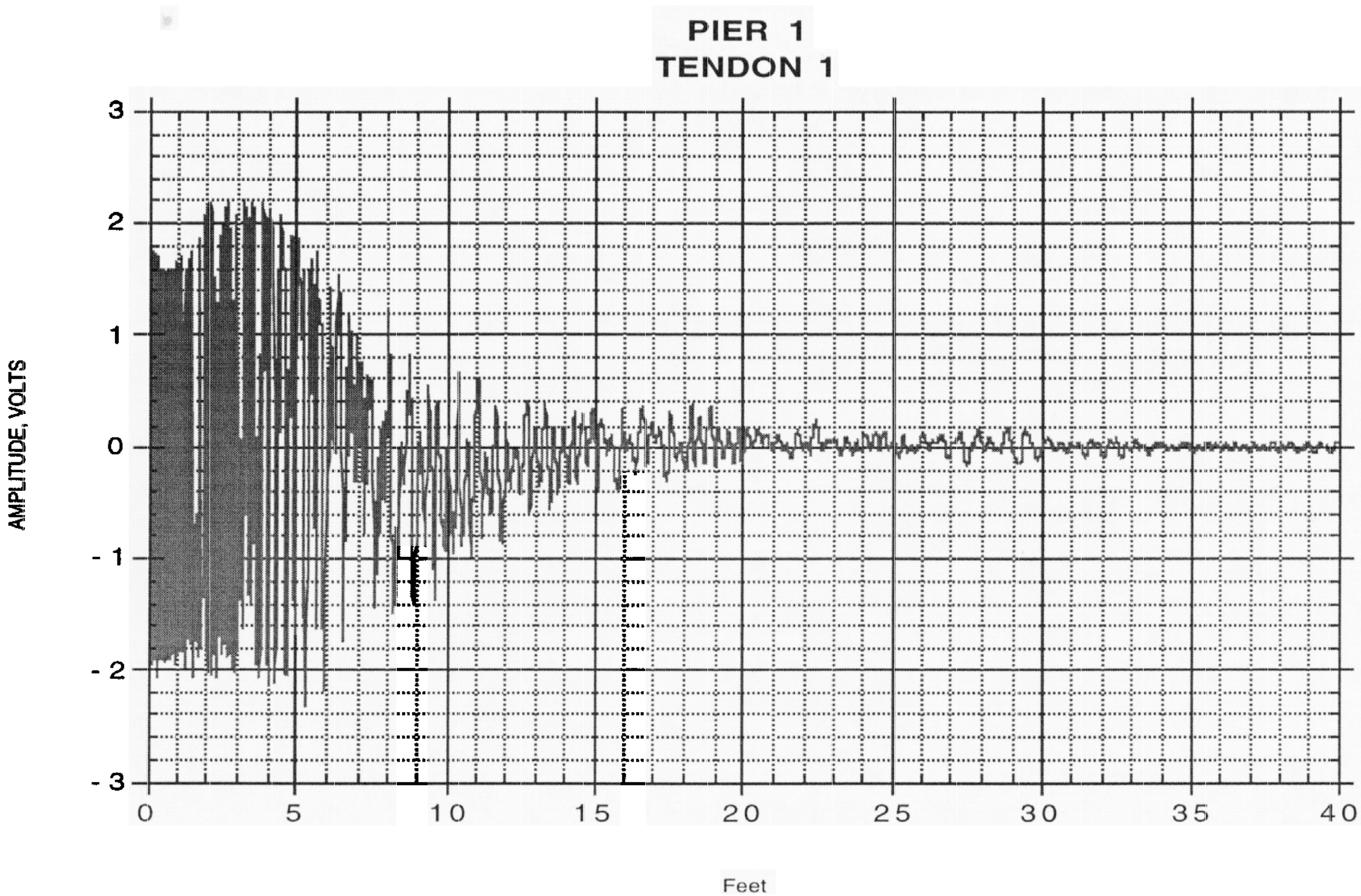


Figure 2: Example of Forebay Tendon

Figure 3: Flexure Modes in Bars

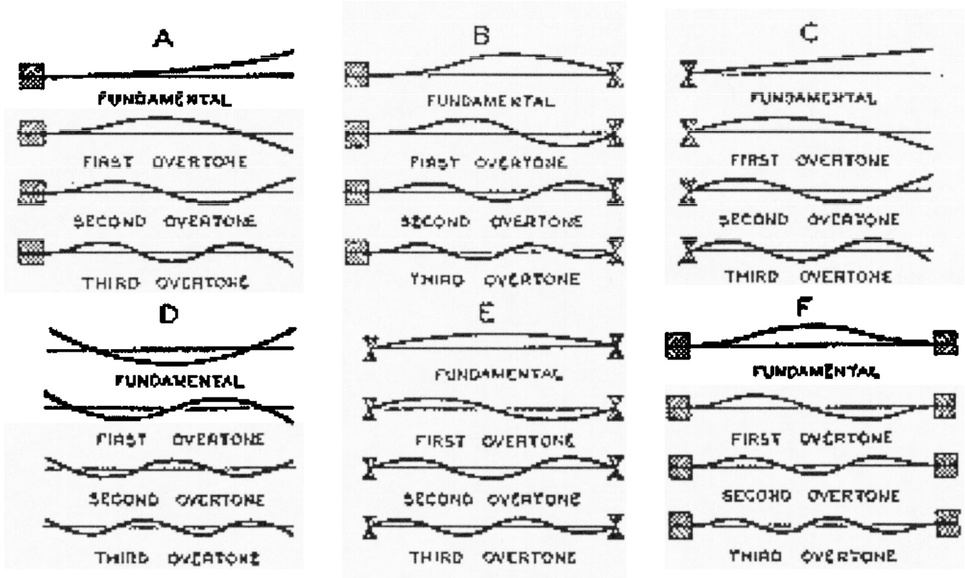


FIG. 3.2. Modes of transverse vibrations of bars. A. A bar clamped at one end and free at the other. B. A bar clamped at one end and supported at the other. C. A bar supported at one end and free at the other. D. A bar free at both ends. E. A bar supported at both ends. F. A bar clamped at both ends.

Figure 4: Flexure in Bars

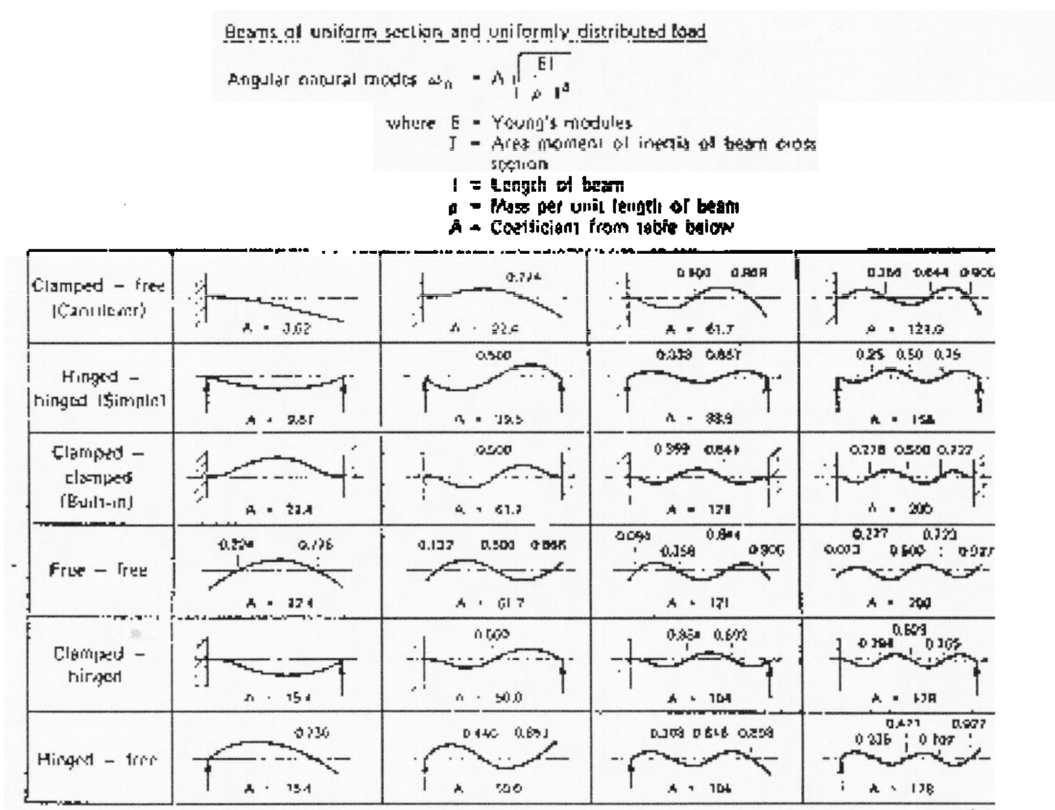
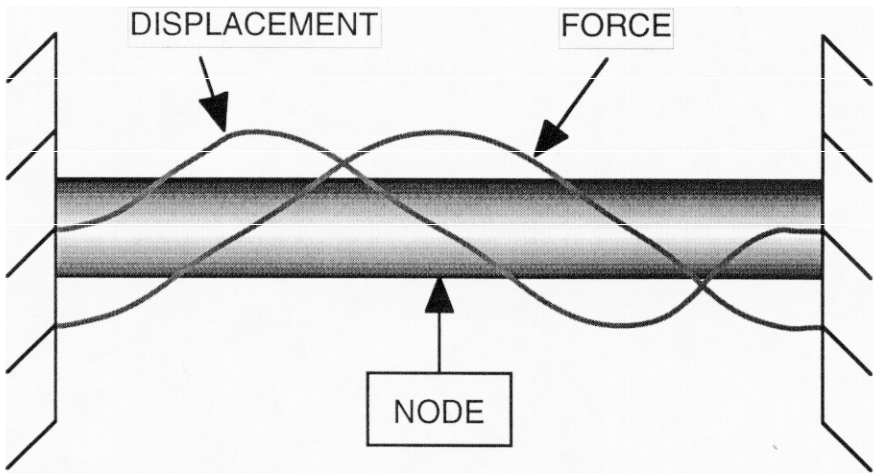


Fig. 3.19. Examples of boundary conditions and mode-shapes for various single uniform beam configurations

Figure 5: Second Tone Excitation



BEAM WITH ANCHOR AT EACH END

ULTRASONIC INSPECTION of DWR TENDONS

A TUTORIAL

OVERVIEW

The tendons must be machined to provide a flat face that is perpendicular to the long axis before any attempt is made to inspect the tendon with ultrasound. The tendons have a distorted face caused by the flame cutting after the installation and tensioning was finished. The distortion on the face prevents any attempt to ultrasonically resolve defects along the tendon length. The tendon facing procedure is shown in Appendix A. Following the tendon facing, the 2.25 to 5.0 MHz, high frequency ultrasonic inspection system is used to inspect the top 3 to 4 feet of the tendon length. The low frequency ultrasonic system is used to inspect and archive the ultrasonic echoes from the full length of the tendon (up to 160 feet of round trip length). The low frequency transducer is coupled the tendon face with a, 1/2 - 20 UNF, threaded stud, to the center of the tendon face. An ultrasonic coupling agent should be used at the interface between the transducer and the tendon, regardless of whether the high, or low frequency transducers are used. Only qualified, ASNT[1], Level 2 or Level 3, ultrasonic inspectors should use the ultrasonic instrumentation or attempt interpretation of the ultrasonic echoes.

The computer program that controls the tendon inspection routines is LabVIEW. The program is titled as either, DWR1.vi, or DWR2.vi, and both versions are given status with a "shortcut" on the computer desk-top. The DWR2 program permits the use of averaging over several round trip echoes from the tendons and is useful in reducing the amplitude of artifact random noise. Activating either vi[2] sends the computer to a folder that stores the LabVIEW programs called, Lv_w31, residing on C:\ drive. A block diagram of the system is shown in Figure 1. Data reduction may be done using another program, KaleidaGraph, also on this computer as a shortcut. The data may be manipulated in KaleidaGraph to show the FFT and other mathematical reconstruction of the waveform. Networked printers may be used to print hard copy of any waveform displayed by KaleidaGraph. At present, the, IOTech, Wavebook (digitizer) Driver is available in 16-bit only. Within about 120 days, there should be a 32-bit driver available and this driver should then be installed on the computer.

Appendix B includes two tables of items purchased with DWR funding. The first table includes the items that have been turned over to the, Clifton Court Forebay, Machinists. The second table includes the items that were purchased with DWR funding, but are held at LLNL, pending a determination from DWR, on the disposition of these items.

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[1] American Society for Nondestructive Testing
[2] The extension, vi, signifies, "Virtual Instrument".

CONNECTIONS

Connect the Iotech Wavebook to the uninteruptable power supply (UPS) with the short cable that is terminated with DIN, 5 pin connectors. The cable will connect between the Wavebook "Power In" and the "Power Output to Wavebook" on the UPS. Connect the large, finned power supply to the UPS "Power In" using the DIN connector, and connect the AC plug to a surge protected power distribution source. A multipin connector is connector is fastened to the Wavebook "To Computer" connector and the smaller connector marked, Iotech, is connected to the PCMCIA card plugged into the top left side of the computer. The bottom PCMCIA card slot is the input for the connection of the PCMCIA, "Buss Toaster", SCSI II adapter, to which the 1 GByte, JAZ Drive is connected[3]. The JAZ Drive may be used to store and archive all the tendon waveforms developed by the special low frequency transducer, thereby reducing the amount of hard disk storage. A small power supply, identified as a "DELL, TSA 8", is connected to the computer power input located next to the PCMCIA card holders. The AC plug is connected to the surge protected power distribution source. The computer has an internal battery supply that is good for some time in the advent of a power outage. The configuration just described will remain active without the loss of data should there be a power interruption. The Panmetrics PR 5058, "RF OUTPUT" is connected to the Wavebook through an adapter to the left BNC and "Analog Common" connectors. The adapter interfaces the single ended output from the PR 5058 to the differential input on the Wavebook. A multipin connector on the right front of the Wavebook provides the trigger input to the Wavebook. The trigger signal is developed by the PR 5058, labeled "+SYNC OUT". There are two trigger inputs to the Wavebook: "1" and "TG 13". The TG 13 input is the analog trigger input that is connected to the PR 5058, "+SYNC OUT". The "1" trigger input is for a TTL input trigger and it is not used for this application.

OPERATION

Refer to Figure 1. The PR 5058 pulser-receiver should be set as follows: "(1) Rep Rate" 20 Hz; "(2) Damping" 100 ohms; "(3) Pulse Height" 100; "(4,5) Attenuation" 0 / 3 dB; "(6,7) Filter" Out / 0.5 Mhz; "Mode" switch up; "Vernier" pushed in; "Gain" 40 dB; "Phase" normal. The low frequency ultrasonic transducer should be connected to the BNC terminal "(11) T" on the front panel. The "(10) +SYNC" is connected to the Wavebook digitizer "TG13". The "(15) RF Out" is connected to the blue coupling box and then to the Wavebook digitizer. The coupling box converts the single ended output from the PR 5058 to the differential input on the digitizer. Turn the power switch on the Wavebook digitizer to the on position. Bring up the computer program, "DWR2.vi", after the instrumentation is turned on and is in an operating mode. The maximum unclipped amplitude displayed on the program oscilloscope trace is ± 2 volts. The initial pulse at time 0 seconds may be clipped without causing a problem, but the ultrasonic

[3] This input is also used to connect the MODEM, PCMCIA card.

echoes should not be clipped. Adjustment of the Damping, Pulse Height, or the Attenuation may be required to bring the ultrasonic echoes to within ± 2 volts.

The additional BNC connectors on the PR 5058 are normally not used in conjunction with the low frequency transducer. The PR 5058 may be used as a pulser-receiver with a single transducer, or separate transducers may be used in a pitch-catch mode of operation. The additional connectors are identified as, "(12) R" , "(13) Output", "(14) Input". The (13,14) connectors provide additional preamplification of the received ultrasonic signal, when needed in conjunction with "(12) R", the received ultrasonic signal: The use for these connectors is justified when a separate transmitter and receiver transducer is used. The power switch is identified as (9) on the diagram. The power switch should be turned off when there is no transducer attached to connector (11).

PROGRAM

Double click on the DWR2.vi, icon to activate the LabVIEW programs. Once the system connections are correctly, the correct settings on the instruments are made, and the program is running, click on the right facing arrow located below the FILE menu. The digitizer will start to accumulate the waveform data and present that waveform to the computer screen oscilloscope. Each new trigger pulse will result in a new waveform on the screen allowing the operator to make adjustments of the PR 5058 settings while watching the screen for the result of those changes. Clicking on the Stop Sign will terminate the acquisition immediately, leaving the program and Wavebook digitizer stopped in the middle of the signal processing routine.

NOTE: If the LabVIEW program is exited (FILE, QUIT) after the Stop Sign button is clicked, the LabVIEW program will not be able to reset or initialize the digitizer. The next time the program is restarted, there will be an error message from the digitizer. To reset the digitizer, restart the computer, then restart the program.

A BETTER WAY: Exiting the program requires a mouse click on the software, "End Program" button: At this point, the data acquisition will terminate, and the program will remain resident. Then go to the FILE menu and select QUIT to close out the program.

To start the data "save" routine, click on the "Acq Data" software button. The program will present the operator with a choice of where to save the data and in what form (text, EXCEL, MatLab) to save the data. "Text" save is usable for most programs, and text may be imported into KaleidaGraph for waveform post analysis. When it is desired to save the data to disk, the operator should follow the instructions on the screen that will follow the selection of write options. The options will not repeat on subsequent data saves after the first option selection is made, and all subsequent data will be stored the same as the first set of selected options.

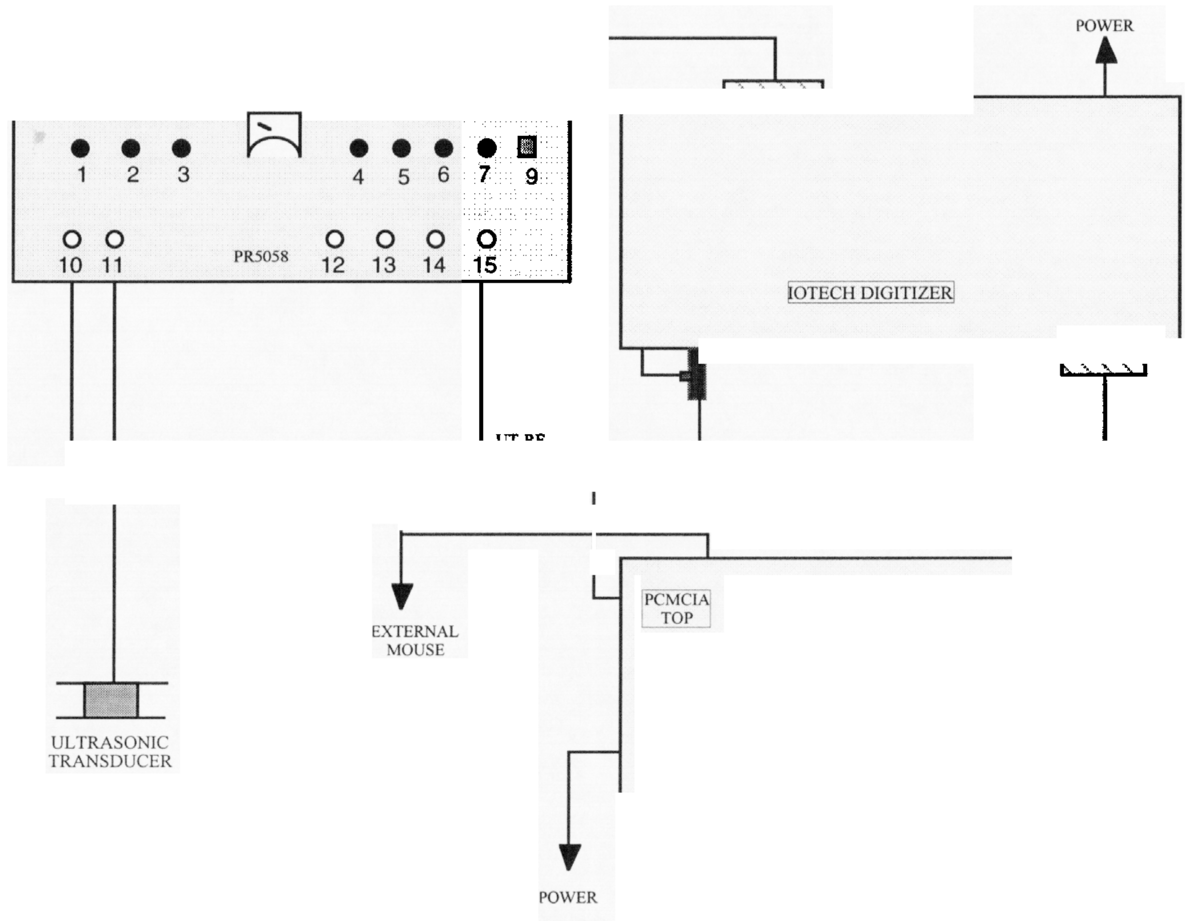

Figure 1: Data Acquisition System

APPENDIX A

Spotfacing & Tapping Procedures

Floodgate Tendons

1. Remove the scale from outside diameter of tendon approximately 5/16 of an inch down from the top. The tool used was a Dumore handheld die grinder with a 0.750 inch diameter 1 inch long aluminum oxide stone.

2. Saw about 0.250 inch off end of tendon. A portable band saw was used and the blades were 24 teeth per inch. The cut should be as a square to the outside diameter as possible by hand. The length of tendon left exposed above the nut must be 1.56 inches or more to allow for spotfacing above the magnetic drill fixture.

3. Use a center head and centerpunch to mark the center of the tendon on the saw cut face. (A center punch fixture may be a good idea here.)

4. Mount the magnetic base drill fixture on the outside of the tendon, place it down as close to the nut as possible.

5. Use a straight shanked center in the magnetic base drill to line up on the center punch mark before actuating the magnet. Tap the magnetic base with a soft blow hammer to adjust the lineup if it moves a little when the magnet pulls down.

6. Center drill (I used a #4 center drill, the drill motor at high R.P.M, and Westlube cutting fluid), using a 0.3125 cobalt stub drill to a depth of 0.750 inches, tap drill to the same depth using a 29/64 stub drill - slow the motor to as slow as possible.

7. Clean hole and check for clearance on the counterbore pilot. Fill hole with a good cutting oil. Using a spotfacer, machine the end of the tendon to minimum cleanup. Go slowly, frequently back off the tool and relubricate to avoid galling.

8. Chamfer with a 0.625 dia. Countersink and tap 0.500 dia. - 20 tpi for a fullthread depth of at least 0.250 inches.

9. Remove magnetic base drill, fixture and deburr outside edge of tendon.

Arthur M. Adams
Oct. 9, 1996

APPENDIX B

INVENTORY

Table 1:Items Delivered to DWR

ITEM	COMMENTS
Hougen Rotabroach magnetic drill press	5/8" Jacobs Chuck and adapter
Carrying Case	For Drill Press and Accessories
Cobalt drills	0.3125" and 29/64"
Cobalt Centering Endmills	Reground for zero taper
High Speed Drills	0.3125" and 29/64"
High Speed Centering Endmills	Reground for zero taper
Plastic Protection Caps for Tendons	Forebay and Oroville Dam
Tendon Grips	Support for Drill Press

Table 2:Items On Hand

ITEM	COMMENTS
Dell Computer, Latitude	Laptop, Battery backup
CD Drive	Removable, Swap with Floppy Drive
JAZZ Drive	Backup Memory, PCMCIA
IOTech Wavebook	Digitizer
IOTech UPS	Power Backup for Wavebook
Panametrics PR 5058	Factory Modified, Pulser-Receiver
Ultrasonic Transducers	2.25 and 5.0 Mhz
Ultrasonic Transducer	30 kHz, with Acoustic Transformers
Windows 95 Software	with DOS Operating System
LabVIEW Software	Data Acquisition
KaleidaGraph Software	Data Reduction
Microsoft Office	MSWord, EXCEL, etc.
ClarisDraw	Drawings, sketches

APPENDIX C

EQUIVALENT ANALOGS

OCTOBER 27, 1989

Albert E. Brown

There is often need to examine the analog equivalents for various engineering properties. The following list shows some of the relationships that tie one engineering discipline to another.

VOLTAGE	**FORCE**	**ACOUSTIC PRESSURE (N/m^2)**
CURRENT	**VELOCITY**	**VOLUME CURRENT (m^3/s)**
CHARGE	**DISPLACEMENT**	**DISPLACEMENT ($u/2\pi f$)**
CAPACITANCE	**COMPLIANCE**	**ACOUSTIC CAPACITANCE**
INDUCTANCE	**MASS**	**INERTANCE (kg/m^4)**
IMPEDANCE	**MECHANICAL IMPEDANCE**	**ACOUSTIC IMPEDANCE (rayles, ($kg/(m^2s)$), (kg/s))**
POWER	**POWER**	**POWER (N-m/s)**
RESISTANCE	**FRICTION**	**ACOUSTIC RESISTANCE**

ATTENUATION PROPERTIES OF MATERIALS

1. The imaginary part of the acoustic impedance represents the absorption per wave length $\alpha\lambda$ in the medium.

2. Liquids exhibit a viscoelastic relaxation of the type called non-Newtonian.

3. Most petroleum products exhibit Newtonian behavior, but not colloids, emulsions, polymer suspensions or biological materials.

4. Losses in high polymer materials (plastics, rubbers) are mainly viscous in nature. Within a relaxation region (wide frequency range) the loss per cycle is constant α/ω = constant. Below and above the relaxation region α increases in proportion to ω^2 and $\omega^{1/2}$, respectively.

5. The lowest losses are found in single crystals. The smaller the grain size, the higher the losses in polycrystalline materials.

LIMITING VELOCITIES

1 $C_P = C_S\sqrt{2/(1-\gamma)}$ Plate velocity: Low frequency limiting velocity in the first longitudinal mode.

2. $C_B = C_S\sqrt{2(1+\gamma)}$ Bar or Extensional Velocity: Limiting phase and group velocity at low frequencies in first longitudinal mode.

3. $C_L' = C_S\sqrt{2}$ Lamé velocity: Pure SV waves in plates

Near Resonance

- Velocity is about in phase with the applied force.
- Displacement leads the force by 90 degrees.
- Acceleration lags the force by 90 degrees.
- Resistive force dominates.
- The velocity maximum is usually accepted as the point of resonance.
- $V = F/R$

Below Resonance

- Stiffness Controlled.
- Force of spring dominates the inertia of mass and resistive force.
- Displacement is in phase with applied force.
- Acceleration leads force by 180 degrees.
- Velocity leads force by 90 degrees.
- $Y \approx F/k$ $k = N/m$ $V \approx f$ $a \approx f^2$

Above Resonance

- Mass controlled.
- Force accelerates mass.
- Acceleration is in phase with force.
- Displacement lags force by 180 degrees.
- Velocity lags force by 90 degrees
- At constant force, frequency is inversely proportional to displacement and velocity.
- $Y \approx 1/f^2$ $V \approx 1/f$ $a \rightarrow F/M$

APPENDIX D

SANDWICH ULTRASONIC TRANSDUCERS

By Albert E. Brown
24-April-97

ABSTRACT

A plate that is thinner than λ/4, has an impedance that becomes mass-like (inductive) and lowers the resonance frequency of the system.

A plate thickness between λ/4 and λ/2 becomes stiffness-like (capacitive) and raises the resonance frequency of the system. As shown in the vector diagrams of acoustic pressure and velocity in Figure 2 through 5, a plate that is λ/4 will invert its termination, and a plate that is λ/2 will repeat its termination.

A quarter wave plate transforms the resistive load impedance according to: $(\rho_P C_P)^2/\rho_O C_O$, where subscripts, P and O refer to the plate and load, respectively.

The electrical input impedance to the piezo-element is determined by the load acoustic impedance taken through the transformer-like action of 1:α equivalent turns ratio.

The front plate should be λ/4, $(Z_O^2 = Z_{IN} Z_{OUT})$, thickness, and the piezo-element and back plate follows the relationship: $\left(\tan\frac{2\pi d_m}{\lambda_m}\right)\left(\tan\frac{2\pi d_b}{\lambda_b}\right) = \frac{\rho_m C_m}{\rho_b C_b}$ **EQUATION A**

Where the subscripts, m and b refer to the piezo-element and back plate, respectively, and d is the thickness of the layer.

The electric impedance of the transducer is defined as, $R_e = Z_R/4\alpha^2$, where $\alpha = e_{ij}S/L$, and S is the piezo-element driving area. L is the piezo-element thickness. The piezo-stack is stiffness controlled with a motional impedance that has a large capacitive reactance. The value eij is a piezo-element constant: This capacitive component of the piezo-element must be canceled by the inductive back plate to form a low frequency resonance.

The front λ/4 plate transforms the low mechanical load impedance to a high impedance at [illegible]

At the opposite face of the piezo-element, there is a reactance: $\rho_m C_m \tan[k_m d_m + \pi/2]$. This reactance is canceled by the λ/8 back plate. The air interface on one side of the back plate results in an interface to the piezo-element of: $\rho_b C_b \tan[k_b d_b]$

For cancellation of reactances, the two expressions must be added and set to zero with the result shown in Equation A.

ENGINEERING DETAILS

The ultrasonic sandwich transducer was developed over 75 years ago by P. Langevin. This discovery allowed the design of a low frequency transducer using thin piezoelectric disks that would otherwise respond only to very much higher frequencies. The high frequency piezoelectric disk was centered between two solid masses. The piezo element, L_0, length is based upon a single thin element. When multiple elements are joined together, the elements are mechanically in series, but electrically in parallel. The total displacement caused by the pressure wave will be proportional to the sum of the number of elements. The solid ends could be either metal or plastic, depending upon the acoustic impedance matching required to the load, or device to be insonified. The back mass length is identified as L_1, and the front mass length as L_2. Each mass has an acoustic impedance defined by the product of its density, acoustic extensional velocity, and its cross sectional area. The length for each mass is determined by transmission line theory, originally developed for electrical circuits. The front mass, L_2, may approximate λ/4 long for the optimum power factor. However, for an end length < nλ/4, where "n" is an odd integer, the length becomes mass related, or inductive, and lowers the transducer frequency. If the end length > nλ/4, the length becomes stiffness related, or capacitive, and raises the resonant frequency of the transducer. In transmission line theory, the length of either L_1 or L_2 may be proportional to a 3λ/8 shorted section (capacitive, stiffness), or a λ/8 shorted section (inductive, mass). The shorted section is the result of the air to solid interface, wherein the air impedance is nearly a short circuit when compared with the impedance of the solid. The impedance of a shorted λ/8 section is $Z_S = jZ_C \mathrm{Tan}(\theta)$, and the impedance of a shorted 3λ/8 section is $Z_S = jZ_C \mathrm{Cot}(\theta)$. The relationship of acoustic pressure and velocity may be better understood by looking at the vector diagrams shown in, Figure 2 through Figure 5. The designations shown on the vector diagrams are as follows: V is the phase velocity; P is the acoustic pressure. The subscripts indicate, g=generator end, s=shorted end, r=reflected wave front, and in=the resulting input to the acoustic line. The front mass, L_2, is generally close to a λ/4, and the back mass, L_1, is generally close to λ/8, or 5λ/8. The interface between each piezoelectric element, shown in Figure 6, is a bronze fabric, 0.003 inch thick. A grease (Apiezon) is wiped into the fabric to provide good acoustic coupling between the elements and from the elements to the end pieces. The preferred input, or excitation pulse, is a "tail pulse" that will result in a compression rather than an expansion of the piezo elements. The end pieces should always be at ground potential. The bronze fabric tabs permit the soldering of wires to make contact to the element electrodes. The wires are then sorted and bundled to electrically wire the elements in parallel, while keeping the elements mechanically in series. The overall displacement of the piezoelectric stack is equal to the displacement of a single element multiplied by the number of elements. The thickness of the interspersed bronze fabric increases the length of the transducer and causes the transducer resonant frequency to be reduced. It is important that large excitation pulses cause the piezoelectric stack to compress rather than expand because the elements might otherwise fracture from the large displacements: Ceramics can withstand far more compression than tension. The loading bolt and nut are required to have a very high tensile strength and the bolt is usually torqued to load the transducer piezoelectric elements to about 3,000 pounds per square inch (20.7 MPa) of compressive loading. For example, a 0.25 inch by 20 threads per inch, class 8, lubricated bolt and nut should be torqued to about 132 to 138 pound inches.

When the front plate, L_2, is a λ/4 long, Langevin showed that the governing formula is:

$$Z = (\rho_P C_P)^2 / \rho_O C_O \qquad (1)$$

Where the subscripts "P" refers to the plate, and "O" refers to the load. The electrical impedance into the transducer is:

$$R_E = \frac{1.2}{4\alpha^2} Z_R \qquad (2)$$

Where α is the transformation factor. The impedance matching network is made from an additional λ/4 section of the front mass according to the formula:

$$Z_P = \sqrt{Z_E Z_L} \qquad (3)$$

Where "E" is the effective load impedance on the generator, "P" is the impedance of the transformer plate, and "L" is the impedance of the load.

The design formula for the transducer is a transcendental solution arrived at by the following equation:

$$\frac{\omega L_O}{V_O} + \tan^{-1}\left[\left(\frac{A_1\rho_1 V_1}{A_O\rho_O V_O}\right)\tan\frac{\omega L_1}{V_1}\right] + \tan^{-1}\left[\left(\frac{A_2\rho_2 V_2}{A_O\rho_O V_O}\right)\tan\frac{\omega L_2}{V_2}\right] = \pi \equiv 180^\circ \quad (4)$$

Where:

L_1, L_2, L_O	are the lengths of the back plate, front plate, and ceramic sections
V_1, V_2, V_O	are the sound velocities in the above lengths
ρ_1, ρ_2, ρ_O	are the densities for the above lengths
A_1, A_2, A_O	are the cross sectional areas for the above lengths

The output impedance of the transducer may need to be impedance matched to the load impedance. The load impedance is defined for a rod as: $Z_E = \rho C_E \pi D^2/4$. The $\lambda/4$, impedance matching Transformer must be the geometric mean of the Input (transducer) and Output (rod) terminations: $Z_T = \sqrt{Z_O Z_I}$. The output impedance of the transducer is the $\lambda/4$ inverted impedance of the transducer elements. The output impedance may be solved by using the formula for Z_T, if the element impedance is known: $Z_T^2/Z_I = Z_O$. The diameter of the $\lambda/4$ matching transformer is: $D = \sqrt{4Z/\rho C_E \pi}$.

IMPEDANCE MATCHING

Acoustic[1] echoes from the Howlett nut may be expected to continue for a long period following the input pulse from the transducer. The multiple echoes are caused by a large difference in the acoustic impedance between the grip-nut and the tendon. Conservation of energy suggests that if much of the energy is used to generate echoes within the nut, little energy will remain to propagate down the length of the tendon. The appropriate action would be to prevent the acoustic impedance mismatch at the top of the tendon.

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[1] See, "Nondestructive Testing Handbook, Ultrasonic Testing", Vol. 7, ASNT;
"Ultrasonic Testing of Materials", Krautkramer, J., Edition 4, Springer-Verlag, New York,etc.;
"Sonics", Heuter and Bolt.

The transducer output impedance must be matched the load impedance. A relatively simple method to produce impedance matching is through a quarter wavelength transformer[2]. However, the DWR tendons are not conducive to such simple impedance matching because the tendon assembly is composed of several complex impedances. That is, the tendon assembly consists of a short length of exposed tendon, followed by a fat, stubby jam nut, followed by the remaining length of tendon extending down to the bottom anchors, as shown in figure 1. Each element of the assembly may be described by a vector impedance: an impedance possessing both magnitude and direction. The top structure of the tendon assembly is capable of slight modification, such as extending the length of the exposed tendon by threading another rod to the end, or by adding a collar to the top face of the Howlett nut. Either modification will significantly change the impedance of the affected component. The design of a quarter wavelength transformer is restricted to matching pure resistive elements. The transformer cannot match conditions wherein there are (acoustic) mass and-or stiffness controlled elements[3] on either side of the transformer. A correction to the impedance of the tendon assembly is most easily accomplished by slightly changing the length of the grip nut. The technique for increasing the length of the grip nut may be accomplished by adding a collar that is acoustically coupled to the grip nut and the tendon end. The purpose behind the modification is to make the grip nut appear to be one-half wavelength in height. A one-half wavelength section will repeat its termination. If the nut is forced to appear as a half-wavelength element, the nut will acoustically disappear from the acoustic response. The long duration ringing at the beginning of the acoustic record is thereby temporally reduced.

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[2] A quarter wavelength stub will invert it's ternmination, providing the termination is purely resistive.
[3] Mass and stiffness controlled elements are reactive and will cause a phase angle combined with an impedance magnitude.

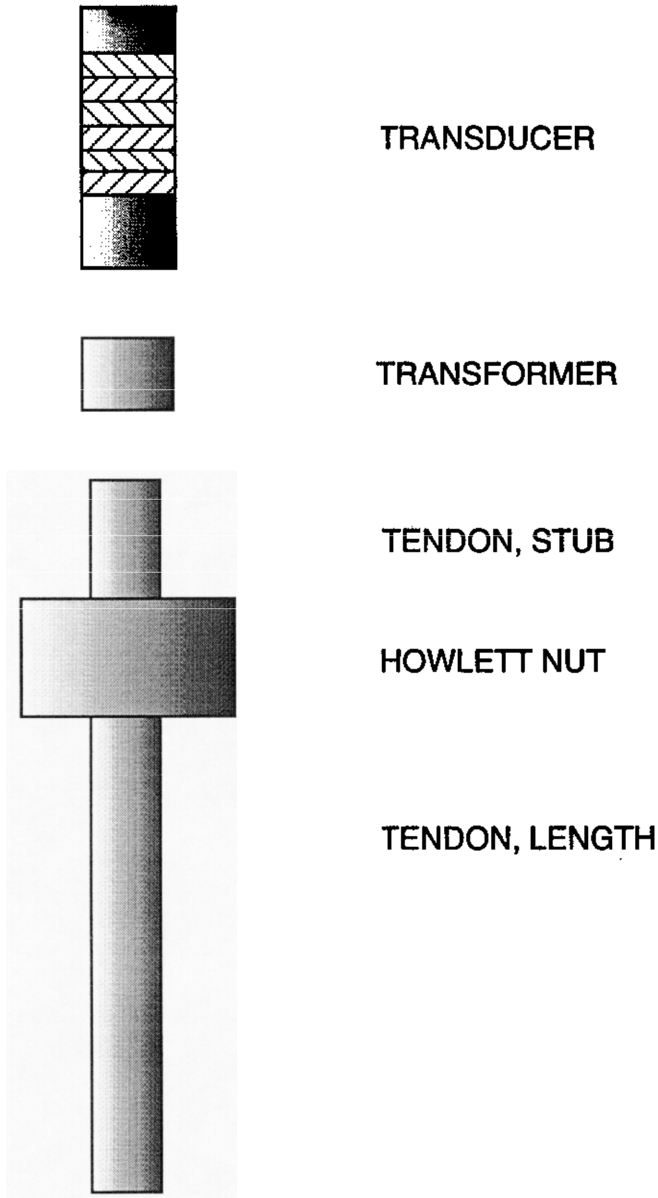


Figure 1: Sketch of Elements involved in the ultrasonics tests

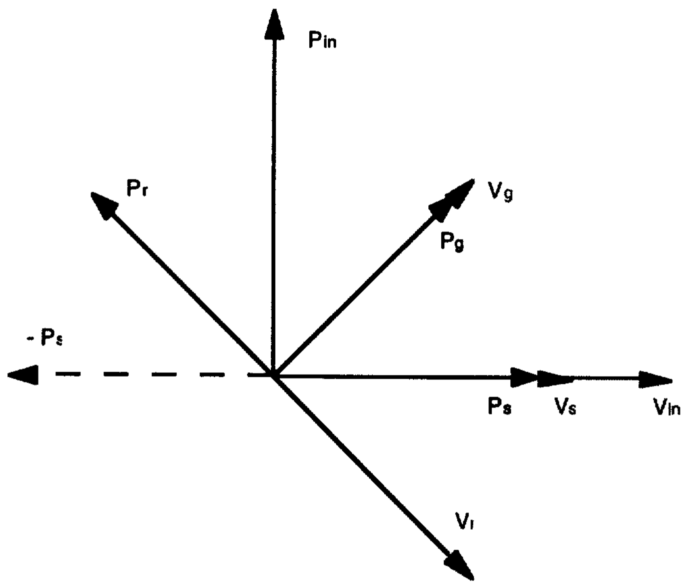


Figure 2: ONE EIGHTH WAVELENGTH SHORTED STUB

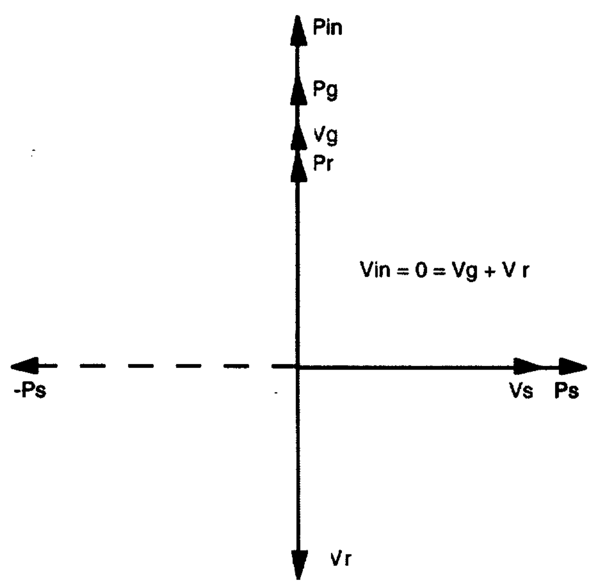


Figure 3: ONE QUARTER WAVELENGTH SHORTED STUB

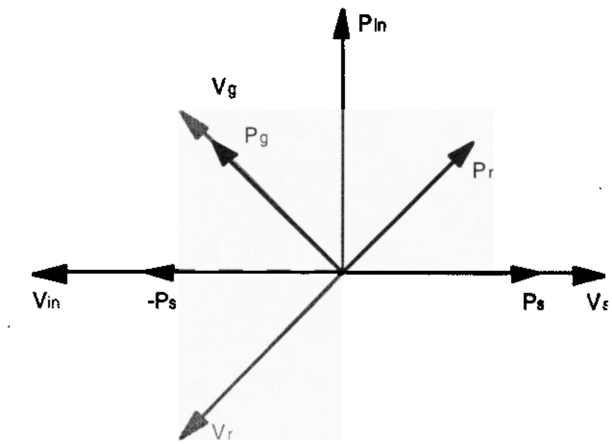


Figure 4: THREE EIGHTH WAVELENGTH SHORTED STUB

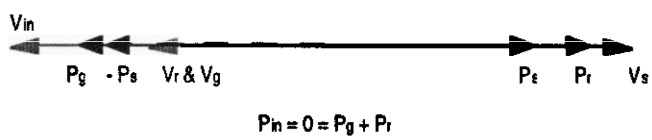


Figure 5: ONE HALF WAVELENGTH SHORTED STUB

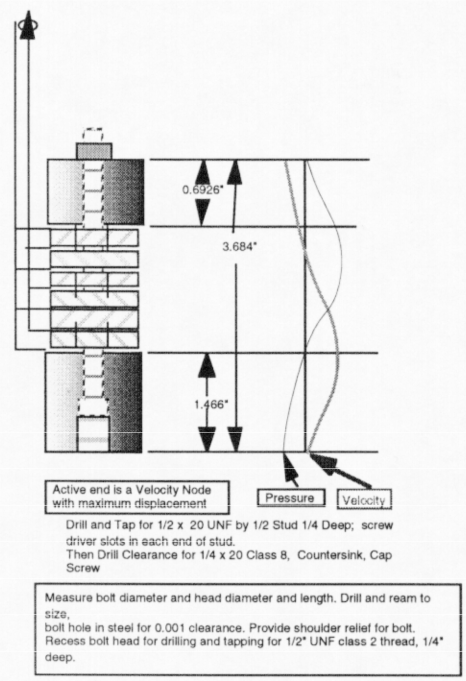


Figure 6: SANDWICH TRANSDUCER SKETCH

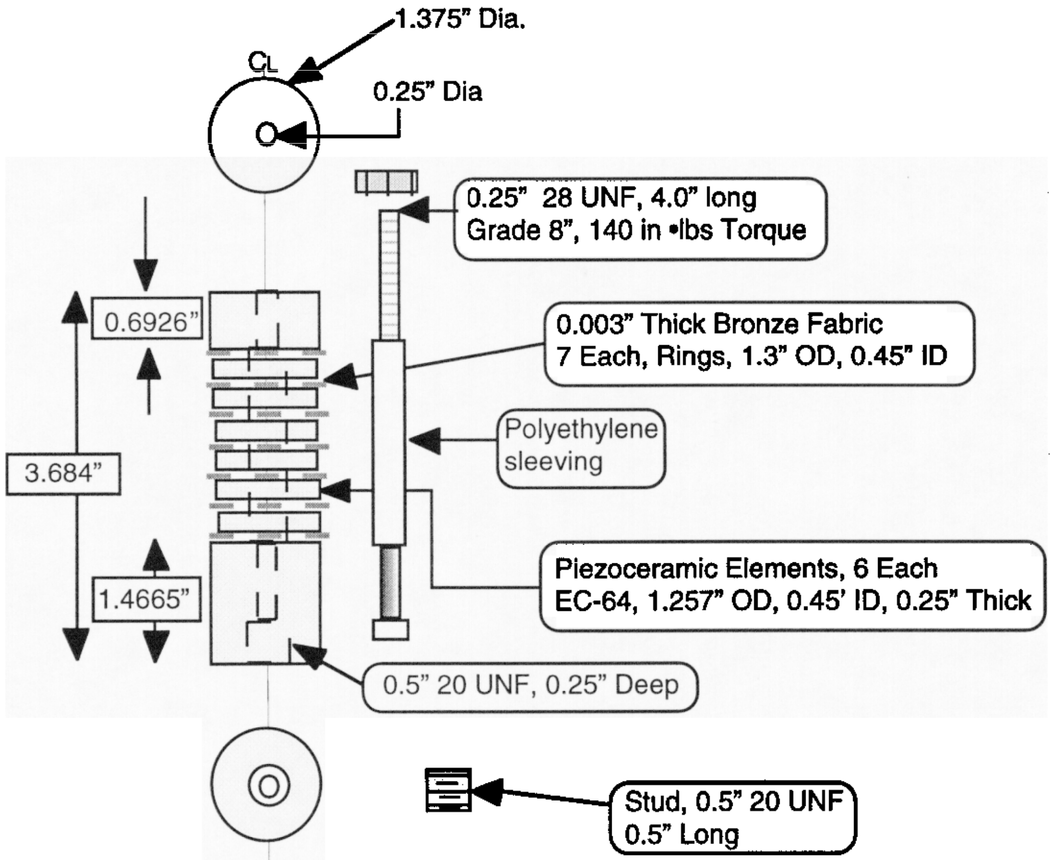


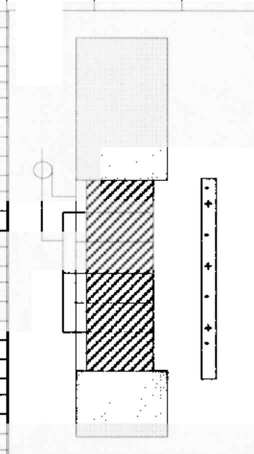
Figure 7: TRANSDUCER ASSEMBLY

	DWR Tendon											
Specimen I.D.	B-Tendon	(inches)	T-Tendon	(inches)	LLNL Tendon	(inches)	Averages	Time	meters	feet		
Geometry (cm)	3.594	1.415	3.594	1.415	3.594	1.415	3.594	1.25E-3	3.268	10.72		
Thickness (mm)	15.345	0.604	15.340	0.604	12.530	0.493	14.405	1.75E-3	4.575	15.01	1.307	4.29
Density (kg/m^3)	7,800		7,801		7,788		7,796	2.25E-3	5.882	19.30	1.307	4.29
Frequency, MHz (V_L)	10.00		10.00		10.00		10.00	4.60E-3	12.024	39.45	6.143	20.15
Frequency, MHz (V_S)	5.00		5.00		5.00		5.00		12.192	40.00	0.168	0.55
Longitudinal Velocity (m/s)	5,947	234,132	5,943	233,991	5,935	233,658	5,942					
Shear Velocity (m/s)	3,262	128,424	3,261	128,397	3,252	128,050	3,259	500.00E-6				
Extensional Velocity (m/s)	5,229	205,866	5,227	205,803	5,215	205,310	5,224					
Rayleigh Velocity (m/s)	3,019	118,847	3,018	118,817	3,010	118,511	3,016		Echo at 1.29 feet below concrete at 0.5 ms. Echo at19.3 ft.			
Poisson's Ratio	0.2848		0.2846		0.2854		0.2849					
Young's Modulus (GPa)	213.27	30.93E+6	213.17	30.92E+6	211.79	30.72E+6	212.74					
Shear Modulus (GPa)	83.00	12.04E+6	82.97	12.03E+6	82.39	11.95E+6	82.78					
Lamé Modulus (GPa)	109.87	15.93E+6	109.62	15.90E+6	109.55	15.89E+6	109.68		233.95E-6	concrete Z	7.47E+6	
Bulk Modulus (GPa)	165.20	23.96E+6	164.93	23.92E+6	164.47	23.85E+6	164.87		241.62E-6	Tendon Z	41.38E+3	
Extensional Impedance	41,379		41,372		41,204		41,318		3.75E-3	R	97.8%	
Wavelength(10MHz) m	594.70E-6	0.023	594.34E-6	0.023	593.49E-6	0.023	594.17E-6		3.79E-3			
Wavelength(30kHz) m	0.1743	6.862	0.1742	6.860	0.1738	6.844	0.1741		4.11E-3			
ATTENUATION, dB/m (10MHz)	63.71	1.62	35.58	0.90	34.52	0.88			Phase Velocity:	D/2λ <= 0.3		0.30
dB/λ (10MHz)	0.038		0.021		0.020			5,184.50	5,182.95	5,170.06	5,179.17	m/s
dB per140 λ, R.T.	5.30		2.96		2.87			17,010	17,004	16,962	16,992	Ft/s
dB Difference			2.34		2.43							
83.20E-3	m @ 140λ											
$\alpha = 20*LOG_{10}(EXP(1))*LN(SQRT(A_2*A_0/A_1{}^\wedge 2/(1+A_2*A_0/A_1{}^\wedge 2))/(A_2/A_1))/(2*Thickness)$												
					RodDiameter	35.94E-3	31.75E-3	29.26E-3	25.40E-3			
Conv Constant	8.686				ΔTs	9.22E-6	8.15E-6	7.51E-6	6.52E-6			
Tendon Length	12.192	m	4.663E-3	s	inches	1.415	1.250	1.152	1.000			
λ@30kHz	0.1743	m	214	Hz		Top Hardness = Rc52+; Bottom Hardness=Rc36.5						
No. of λ@30kHz, R.T.	139.897											
						Forebay Tendon						
Specimen I.D.	LoadBlock	LoadBlock	(inches)	Howlett	(inches)	Top	Bottom					
Geometry (cm)	15.240	5.000	1.969	Collar		2.926	2.926	concrete Z	5.25E+6			
Thickness (mm)	52.500	10.870	0.428	14.330	0.564	12.819	12.814	Tendon Z	27.39E+3			
Density (kg/m^3)	7,843	7,843		7,800		7,802	7,805	R	97.9%			
Frequency, MHz (V_L)	10.00	10.00		10.00		10.00	10.00	GripNut Z	82.72E+3			
Frequency, MHz (V_S)	5.00	5.00		5.00		5.00	5.00	R =	25.26%			
Longitudinal Velocity (m/s)	5,915	5,915	232,885	5,965	234,859	5,929	5,929	5,929				
Shear Velocity (m/s)	3,247	3,236	127,388	3,262	128,411	3,255	3,258	3,256	50.800E-3		0.29	λ
Extensional Velocity (m/s)	5,204	5,190	204,339	5,232	206,002	5,216	5,220	5,218				
Rayleigh Velocity (m/s)	3,004	2,995	117,920	3,019	118,873	3,012	3,014	3,013	46.530E+6			
Poisson's Ratio	0.2844	0.2865		0.2868		0.2843	0.2838		76.200E-3	nut dia		
Young's Modulus (GPa)	212.38	211.28	30.64E+6	213.55	30.97E+6	212.30	212.66		27.358E+3	tendon Z		
Shear Modulus (GPa)	82.68	82.11	11.91E+6	82.98	12.04E+6	82.65	82.82		186.123E+3			
Lamé Modulus (GPa)	109.04	110.21	15.98E+6	111.61	16.19E+6	108.94	108.73		40.813E+6	Nut Z		
Bulk Modulus (GPa)	164.16	164.95	23.92E+6	166.93	24.21E+6	164.04	163.94		997.322E-3	2.678E-3		
Longitudinal Impedance	46.39E+6	46.39E+6		46.53E+6		46.26E+6	46.28E+6		997.322E-3	2.678E-3		
Wavelength(10MHz) m	591.50E-6	591.53E-6	0.023	596.54E-6	0.023	592.87E-6	592.90E-6		7.170E-6	Intensity sent into long rod		
Wavelength(30kHz) m	0.1735	0.1730	6.811	0.1744	6.867	0.1739	0.1740		18.34	.25 λ xformer		
ATTENUATION, dB/m (10MHz)		110.02	2.79					Phase Velocity				
dB/λ (10MHz)		0.065					5,029.78	5,186.84	5,190.50	m/s		
							16,502	17,017	17,029	Ft/s		
		OROVILLE, Tendons as Tensioned Strings										
Stress, Tendon, Pa	723.949E+6		723.949E+6		723.949E+6		723.949E+6	Pa	734.48E+3	N		
Length, 40 FT.	12.192		12.192		12.192		12.192	m				
f1	12		12		13		12	Hz				
Stress, Pa	723.949E+6		723.949E+6		723.949E+6		723.949E+6					
Stress, psi	105.000E+3		105.000E+3		105.000E+3		105.000E+3					
	FOREBAY, Tendons as Tensioned Strings, Harmonically Related Tones							105000	=75 percent			
Stress, Tendon, Pa						723.949E+6	723.949E+6	Pa	486.63E+3	N		
Length, 22 FT.						3.35	6.71	m	11 & 22 Ft			
f1						45	23	Hz				
Stress, Pa						723.949E+6	723.949E+6	Pa				
Stress, psi						105.000E+3	105.000E+3	psi				
									5.25	kg/m		
Stress, Tendon, Pa						723.949E+6	723.949E+6	Pa	672.187E-6	Area		
Length, 27 FT.						914.400E-3	8.23	m				
f1						167	19	Hz				
Stress, Pa						723.949E+6	723.949E+6	Pa				
Stress, psi						105.000E+3	105.000E+3	psi				
BARS												
One End Clamped, f1 =						1.90	0.48					
Overtones, 2,3,4						11.89	2.97					
						33.33	8.34					
						65.31	16.34					
	1.375	1.25	1.125	1		25.53	0.32					
	1.415	1.250	1.152	1.000		159.84	1.97					
RodDiameter	35.94E-3	31.75E-3	29.26E-3	25.40E-3		448.11	5.54					
V_L	V_S					878.09	10.85					
5,929	3,255			fD								
		m =	1	2	3	4						
-0.749474	2.130	Sym_N	2,301	6,904	11,507	16,110						
2.130342	4.974	ASym_N	4,603	9,206	13,809	18,411						
4.974445	8.019	Sym_N	2,964	8,893	14,822	20,750						
8.018862	11.115	ASym_N	5,929	11,857	17,786	23,715						
11.115044		Sym_IP	3,255	6,509	9,764	13,019						
		ASym_IP	1,627	4,882	8,137	11,391						
		Sym_IP	3,894	7,788	11,682	15,576						
1.000000		ASym_IP	2,641	5,281	7,922	10,562						
			FREQUENCIES Forebay tendon Diameter									
-1.596635454		Sym_N	78,652	235,957	393,261	550,566						
-1.596635454		ASym_N	157,305	314,609	471,914	629,218						
		Sym_N	101,307	303,921	506,536	709,150						
		ASym_N	202,614	405,229	607,843	810,457						
		Sym_IP	111,231	222,462	333,693	444,925						
		ASym_IP	55,616	166,847	278,078	389,309						
		Sym_IP	133,078	266,156	399,233	532,311						
		ASym_IP	90,241	180,482	270,724	360,965						

	DWR Tendon											
Specimen I.D.	B-Tendon	(Inches)	T-Tendon	(Inches)	LLNL Tendon	(Inches)	Averages	Time	meters	feet		
Geometry (cm)	3.594	1.415	3.594	1.415	3.594	1.415	3.594	1.25E-3	3.268	10.72		
Thickness (mm)	15.345	0.604	15.340	0.604	12.530	0.493	14.405	1.75E-3	4.575	15.01	1.307	4.29
Density (kg/m³)	7,800		7,801		7,788		7,796	2.25E-3	5.882	19.30	1.307	4.29
Frequency, MHz (V_L)	10.00		10.00		10.00		10.00	4.80E-3	12.024	39.45	6.143	20.15
Frequency, MHz (V_S)	5.00		5.00		5.00		5.00		12.192	40.00	0.168	0.55
Longitudinal Velocity (m/s)	5,947	234,132	5,943	233,991	5,935	233,658	5,942					
Shear Velocity (m/s)	3,262	128,424	3,261	128,397	3,252	128,050	3,259	500.00E-6				
Extensional Velocity (m/s)	5,229	205,866	5,227	205,803	5,215	205,310	5,224		Echo at 1.29 feet below concrete at 0.5 ms. Echo at19.3 ft.			
Rayleigh Velocity (m/s)	3,019	118,847	3,018	118,817	3,010	118,511	3,016					
Poisson's Ratio	0.2848		0.2846		0.2854		0.2849					
Young's Modulus (GPa)	213.27	30.93E+6	213.17	30.92E+6	211.79	30.72E+6	212.74					
Shear Modulus (GPa)	83.00	12.04E+6	82.97	12.03E+6	82.39	11.95E+6	82.78					
Lamé Modulus (GPa)	109.87	15.93E+6	109.62	15.90E+6	109.55	15.89E+6	109.68		233.95E-6	concrete Z	7.47E+6	
Bulk Modulus (GPa)	165.20	23.96E+6	164.93	23.92E+6	164.47	23.85E+6	164.87		241.62E-6	Tendon Z	41.38E+3	
Extensional Impedance	41,379		41,372		41,204		41,318		3.75E-3	R_{ext}	97.8%	
Wavelength(10MHz) m	594.70E-6	0.023	594.34E-6	0.023	593.49E-6	0.023	594.17E-6		3.79E-3			
Wavelength(30kHz) m	0.1743	6.862	0.1742	6.860	0.1738	6.844	0.1741		4.11E-3			
ATTENUATION, dB/m (10MHz)	63.71	1.62	35.58	0.90	34.52	0.88			Phase Velocity:	D/2λ <= 0.3		0.30
dB/λ (10MHz)	0.038		0.021		0.020			5,184.50	5,182.95	5,170.06	5,179.17	m/s
dB per140 λ, R.T.	5.30		2.96		2.87			17,010	17,004	16,962	16,992	Ft/s
dB Difference			2.34		2.43							
83.20E-3	m @ 140λ											
α = 20*LOG$_{10}$(EXP(1))*LN(SQRT(A_2*A_0/A_1^2/(1+A_2*A_0/A_1^2))/(A_2/A_1))/(2*Thickness)												
					RodDiameter	35.94E-3	31.75E-3	29.26E-3	25.40E-3			
Conv Constant	8.686				ΔTs	9.22E-6	8.15E-6	7.51E-6	6.52E-6			
Tendon Length	12.192	m	4.663E-3	s	Inches	1.415	1.250	1.152	1.000			
λ@30kHz	0.1743	m	214	Hz		Top Hardness = Rc52+; Bottom Hardness=Rc36.5						
No. of λ@30kHz, R.T.	139.897											
						Forebay Tendon						
Specimen I.D.	LoadBlock	LoadBlock	(Inches)	Howlett	(Inches)	Top	Bottom					
Geometry (cm)	15.240	5.000	1.969	Collar		2.926	2.926	concrete Z	5.25E+6			
Thickness (mm)	52.500	10.870	0.428	14.330	0.564	12.819	12.814	Tendon Z	27.39E+3			
Density (kg/m³)	7,843	7,843		7,800		7,802	7,805	R_{ext}	97.9%			
Frequency, MHz (V_L)	10.00	10.00		10.00		10.00	10.00	GripNut Z	82.72E+3			
Frequency, MHz (V_S)	5.00	5.00		5.00		5.00	5.00	R =	25.26%			
Longitudinal Velocity (m/s)	5,915	5,915	232,885	5,965	234,859	5,929	5,929	5,929				
Shear Velocity (m/s)	3,247	3,236	127,388	3,262	128,411	3,255	3,258	3,256	50.800E-3	0.29	λ	
Extensional Velocity (m/s)	5,204	5,190	204,339	5,232	206,002	5,216	5,220	5,218				
Rayleigh Velocity (m/s)	3,004	2,995	117,920	3,019	118,873	3,012	3,014	3,013	46.530E+6			
Poisson's Ratio	0.2844	0.2865		0.2868		0.2843	0.2838		76.200E-3	nut dia		
Young's Modulus (GPa)	212.38	211.28	30.64E+6	213.55	30.97E+6	212.30	212.66		27.358E+3	tendon Z		
Shear Modulus (GPa)	82.68	82.11	11.91E+6	82.98	12.04E+6	82.65	82.82		186.123E+3			
Lamé Modulus (GPa)	109.04	110.21	15.98E+6	111.61	16.19E+6	108.94	108.73		40.813E+6	Nut Z		
Bulk Modulus (GPa)	164.16	164.95	23.92E+6	166.93	24.21E+6	164.04	163.94		997.322E-3	2.678E-3		
Longitudinal Impedance	46.39E+6	46.39E+6		46.53E+6		46.26E+6	46.28E+6		997.322E-3	2.678E-3		
Wavelength(10MHz) m	591.50E-6	591.53E-6	0.023	596.54E-6	0.023	592.87E-6	592.90E-6		7.170E-6	Intensity sent into long rod		
Wavelength(30kHz) m	0.1735	0.1730	6.811	0.1744	6.867	0.1739	0.1740		18.34	.25 λ xformer		
ATTENUATION, dB/m (10MHz)		110.02	2.79					Phase Velocity				
dB/λ (10MHz)		0.065					5,029.78	5,186.84	5,190.50	m/s		
							16,502	17,017	17,029	Ft/s		
		OROVILLE, Tendons as Tensioned Strings										
Stress, Tendon, Pa	723.949E+6		723.949E+6		723.949E+6		723.949E+6	Pa	734.48E+3	N		
Length, 40 FT.	12.192		12.192		12.192		12.192	m				
f1	12		12		13		12	Hz				
Stress, Pa	723.949E+6		723.949E+6		723.949E+6		723.949E+6					
Stress, psi	105.000E+3		105.000E+3		105.000E+3		105.000E+3					
	FOREBAY, Tendons as Tensioned Strings, Harmonically Related Tones							105000	=75 percent			
Stress, Tendon, Pa						723.949E+6	723.949E+6	Pa	486.63E+3	N		
Length, 22 FT.						3.35	6.71	m	11 & 22 Ft			
f1						45	23	Hz				
Stress, Pa						723.949E+6	723.949E+6	Pa				
Stress, psi						105.000E+3	105.000E+3	psi				
									5.25	kg/m		
Stress, Tendon, Pa						723.949E+6	723.949E+6	Pa	672.187E-6	Area		
Length, 27 FT.						914.400E-3	8.23	m				
f1						167	19	Hz				
Stress, Pa						723.949E+6	723.949E+6	Pa				
Stress, psi						105.000E+3	105.000E+3	psi				
BARS												
One End Clamped, f1 =						1.90	0.48					
Overtones, 2,3,4						11.89	2.97					
						33.33	8.34					
						65.31	16.34					
	1.375	1.25	1.125	1		25.53	0.32					
	1.415	1.250	. 1.152	1.000		159.84	1.97					
RodDiameter	35.94E-3	31.75E-3	29.26E-3	25.40E-3		448.11	5.54					
V_L	V_s					878.09	10.85					
5,929	3,255			fD								
		m =	1	2	3	4						
-0.749474	2.130	Sym_N	2,301	6,904	11,507	16,110						
2.130342	4.974	ASym_N	4,603	9,206	13,809	18,411						
4.974445	8.019	Sym_N	2,964	8,893	14,822	20,750						
8.018862	11.115	ASym_N	5,929	11,857	17,786	23,715						
11.115044		Sym_IP	3,255	6,509	9,764	13,019						
		ASym_IP	1,627	4,882	8,137	11,391						
		Sym_IP	3,894	7,788	11,682	15,576						
1.000000		ASym_IP	2,641	5,281	7,922	10,562						
			FREQUENCIES Forebay tendon Diameter									
-1.596635454		Sym_N	78,652	235,957	393,261	550,566						
-1.596635454		ASym_N	157,305	314,609	471,914	629,218						
		Sym_N	101,307	303,921	506,536	709,150						
		ASym_N	202,614	405,229	607,843	810,457						
		Sym_IP	111,231	222,462	333,693	444,925						
		ASym_IP	55,616	166,847	278,078	389,309						
		Sym_IP	133,078	266,156	399,233	532,311						
		ASym_IP	90,241	180,482	270,724	360,965						

LLNL TIME SERIES									
V_L	5,934.91	233,658			Notch	32.042	Feet	3.778E-3	seconds
V_S	3,252.46	128,050			End	33.708	Feet	3.975E-3	seconds
V_E	5,214.86	205,310	5,170.05	16,962.09					
2.25 MHz			30 kHz		inches	feet			
Inch	Time	deltaT	Feet	Time	Freq.	Freq.		Spectra	
1.00	8.56E-6	9.24E-6	1.00	117.91E-6	101,773	8,481		10.623	Feet
2.00	17.12E-6	18.49E-6	2.00	235.82E-6	50,886	4,241		8.791	Inch
3.00	25.68E-6	delta f	3.00	353.73E-6	33,924	2,827		6.890	Inch
4.00	34.24E-6	108,190	4.00	471.64E-6	25,443	2,120		4.635	Inch
5.00	42.80E-6		5.00	589.55E-6	20,355	1,696		3.591	Inch
6.00	51.36E-6		6.00	707.46E-6	16,962	1,414		1.700	Inch
7.00	59.92E-6		7.00	825.37E-6	14,539	1,212		0.910	Inch
8.00	68.48E-6		8.00	943.28E-6	12,722	1,060		0.777	Inch
9.00	77.04E-6		9.00	1.061E-3	11,308	942		0.655	Inch
10.00	85.60E-6		10.00	1.179E-3	10,177	848		0.625	Inch
11.00	94.15E-6		11.00	1.297E-3	9,252	771		0.538	Inch
12.00	102.71E-6		12.00	1.415E-3	8,481	707			
13.00	111.27E-6		13.00	1.533E-3	7,829	652			
14.00	119.83E-6		14.00	1.651E-3	7,269	606			
15.00	128.39E-6		15.00	1.769E-3	6,785	565			
16.00	136.95E-6		16.00	1.887E-3	6,361	530			
17.00	145.51E-6		17.00	2.004E-3	5,987	499			
18.00	154.07E-6		18.00	2.122E-3	5,654	471			
19.00	162.63E-6		19.00	2.240E-3	5,356	446			
20.00	171.19E-6		20.00	2.358E-3	5,089	424			
21.00	179.75E-6		21.00	2.476E-3	4,846	404			
22.00	188.31E-6		22.00	2.594E-3	4,626	386			
23.00	196.87E-6		23.00	2.712E-3	4,425	369			
24.00	205.43E-6		24.00	2.830E-3	4,241	353			
25.00	213.99E-6		25.00	2.948E-3	4,071	339			
26.00	222.55E-6		26.00	3.066E-3	3,914	326			
27.00	231.11E-6		27.00	3.184E-3	3,769	314			
28.00	239.67E-6		28.00	3.301E-3	3,635	303			
29.00	248.23E-6		29.00	3.419E-3	3,509	292			
30.00	256.79E-6		30.00	3.537E-3	3,392	283			
31.00	265.35E-6		31.00	3.655E-3	3,283	274			
32.00	273.90E-6		32.00	3.773E-3	3,180	265			
33.00	282.46E-6		33.00	3.891E-3	3,084	257			
34.00	291.02E-6		34.00	4.009E-3	2,993	249			
35.00	299.58E-6		35.00	4.127E-3	2,908	242			
36.00	308.14E-6		36.00	4.245E-3	2,827	236			
37.00	316.70E-6		37.00	4.363E-3	2,751	229			
38.00	325.26E-6		38.00	4.481E-3	2,678	223			
39.00	333.82E-6		39.00	4.598E-3	2,610	217			
40.00	342.38E-6		40.00	4.716E-3	2,544	212			

Designed



				TRANSDUCER SANDWICH						
Ceramic Rings	EC-64/PZT-4		**Cost = $60.00 for elements(minimum Charge $250)**				**$ 19.23**			
F	35,000	Hz								
F Constant	2,026	Hz•m		**28,875**	**6,125**					
d_{33}	295.0E-12	m/v	Capacitance							
Excitation	500	v	1.265E-9	Panametrics 5800 PR						
E_o	66.7E+9	N/m²	7.588E-9	271.66	volts, max.					
ρ_0	7,500	kg/m³	Solution of P. Langevin's equations for a sandwich transducer operating at 30 kHz.							
OD	31.928E-3	m								
ID	11.430E-3	m								
A_o	698.014E-6	m²								
L_o	6.350E-3	m		0.4684	Ceramic					
V_o	2,981	m/s		1.5708	Front Plate					
Z_o	15.608E+3	Rayles		1.1024	Back Plate					
Steel Back Plate				3.1416	3.1416					
E_1	211.793E+9	N/m²								
ρ_1	**7,800**	**kg/m³**	**Displacement**	**885.00E-9**	m					
Dia	35.941E-3	m		34.843E-6	inch					
A_1	981.075E-6	m²	480.843E-9	18.931E-6	inch					
Vel	5,218	m/s	Inches	0.250	Element Length					
λ_1	**149.087E-3**	**m/cy**		**1.500**	**Stack height**					
$\lambda_1/2$	74.544E-3	m/cy		3.606	Transducer height					
$\lambda_1/4$	37.272E-3	m/cy		98.548E-6	**6.570E+6**					
Z_1	39.931E+3	Rayles			**4.586E+3**					
L_1	15.608E-3	m	0.105	λ	**0.6145**	**Inches**				
Steel Front Plate										
E_2	**211.793E+9**	**N/m²**		**Element Stack**						
ρ_2	**7,800**	**kg/m³**		Capacitance	7.588E-9					
Dia	35.941E-3	m		Energy	948.503E-6					
A_2	981.075E-6	m²								
Vel	5,218	m/s	WAVELENGTH @ 30,000				$\lambda_2/4$ Forebay		Steel Candidate	
λ_2	149.087E-3	m/cy	173.94E-3	6.848			52,885	Z_o Rayles	7,826	
$\lambda_2/2$	74.544E-3	m/cy	86.968E-3	3.424			40.678E-3	m dia	5,200	5199.86
$\lambda_2/4$	37.272E-3	m/cy	43.484E-3	1.712			1.6015	inches dia		
Z_2	39.931E+3	Rayles					43.332E-3	m length	1,368.77	
Z_{out}	**102.155E+3**	**Rayles**					**1.7060**	**inches length**	12.755E-3	m
L_2	**37.272E-3**	**m**	**0.250**	**λ**	**1.4674**	**Inches**	**$\lambda_2/2$ Taper**		0.5022	inches dia.
							3.4120	Length inches	1,368.50	
1/4x28 Class 8	3.86	Inch					2.510E-3	Area input	6.544E-3	
Maximum Load	14.438E+3	N	20.684E+6	N/m²			56.535E-3	m Dia	0.2576	
Maximum Load	3,246	lbs	3,000	psi			2.2258	Inches Dia		
							672.779E-6	Area output		
							29.268E-3	m dia		
							1.1523	inches dia		

Equation 1, from "The Design of Piezoelectric Sandwich Transducer". This solution resolves to Pi. This resulted in plate thickness of 15.6 mm and 36.9 mm for each end. Six elements are stacked in series, mechanically. Total height <3.6". Torque is 135 lb-in. All units in SI (metric) unless otherwise marked. Compression of the EDO, EC-64, generates a positive voltage on the numbered side of the element. A negative going pulse on the negative side of the element should compress the element.

							$\lambda_2/4$ Oroville			
							65,008	Z_o Rayles		
							45.100E-3	m dia		
							1.7756	**inches dia**		
							43.332E-3	**m length**		
1 1/8	Tendon						1.7060	inches length		
Ceramic Rings	EC-64/PZT-4		35,652				$\lambda_2/2$ Taper			
F	42,555	Hz	35,108				3.4120	Length inches		
F Constant	2,026	Hz•m			7,447		2.510E-3	Area input		
d_{33}	295.0E-12	m/v	Capacitance				56.535E-3	m Dia		
Excitation	500	v	1.033E-9	Panametrics 5800 PR			2.2258	**Inches Dia**		
E_o	66.7E+9	N/m²	6.197E-9	300.61	volts, max.		1.017E-3	**Area output**		
ρ_0	7,500	kg/m³	Solution of P. Langevin's equations for a sandwich transducer operating at 30 kHz.				35.977E-3	m dia		
OD	28.575E-3	m					1.4164	inches dia		
ID	9.525E-3	m								
A_o	570.046E-6	m²								
L_o	6.350E-3	m		0.5695	Ceramic					
V_o	**2,981**	**m/s**		1.5708	Front Plate					
Z_o	**12.747E+3**	**Rayles**		1.0013	Back Plate					
Steel Back Plate				**3.1416**	**3.1416**					
E_1	**211.790E+9**	**N/m²**								
ρ1	**7,788**	**kg/m³**	Displacement	**885.00E-9**	**m**					
Dia	**29.255E-3**	**m**		**34.843E-6**	**Inch**					
A_1	**638.719E-6**	**m²**	532.084E-9	20.948E-6	inch					
Vel	**5,215**	**m/s**	**Inches**	0.250	**Element Length**					
λ_1	122.547E-3	m/cy		1.500	Stack height					
$\lambda_1/2$	61.274E-3	m/cy		3.233	Transducer height					
$\lambda_1/4$	30.637E-3	m/cy								
Z_1	25.941E+3	Rayles								
L_1	12.767E-3	m	0.104	λ	0.5026	Inches				
Steel **Back Plate**										
E_2	**211.790E+9**	**N/m²**		**Element Stack**						
ρ2	**7,788**	**kg/m³**		**Capacitance**	**6.197E-9**					
Dia	**28.517E-3**	**m**		**Energy**	**774.612E-6**					
A_2										
Vel	**5,215**	**m/s**								
λ_2	**122.547E-3**	**m/cy**		**28.575E-3**	**182,502**	**36,500**				
$\lambda_2/2$	**61.274E-3**	**m/cy**	**Diameter =**	**1.125**	**2[illegible]**					
$\lambda_2/4$	**30.637E-3**	**m/cy**		**Z =**	**26.046E+3**					
Z_2	**24.582E+3**	**Rayles**								
Z_{out}	**52.794E+3**	**Rayles**								
L_2	**30.637E-3**	**m**	**0.250**	**λ**	**1.2062**	**Inches**				
1/4x28 Class 8	3.48	Inch								
Maximum Load	11.791E+3	N	20.684E+6	N/m²						
Maximum Load	2,651	lbs	3,000	psi						
			98.549E-6	6.570E+6						
				3.745E+3						

Piezo-ceramic elements, 1" OD by 0.45" ID by 0.25" Thick

					TENDON FLEXURE, LLNL ROD													
V_L	5,934.91	233,658	Diameter, m	35.940E-3														
V_S	3,252.46	128,050																
V_E	5,214.86	205,310	5,170.05	16,962.09	Feet/sec													
$I^{0.5}$	8.99E-3	8.99E-3	Frequency Calculations															
A	22.40		1.566	1.569														
frequency	2	Hz		33.708	Feet													
Length	33.708	Feet																
Constants	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00		
frequency	1	4	8	13														
Feet	40.256	66.811	93.562	120.287	33.378	60.144	86.740	113.479	15.958	40.256	66.811	93.562	26.722	53.457	80.197	106.914		
							Table in Feet, Length of Tendon										Node Points in Feet	
Hertz	Free-Free; Clamped-Clamped				Clamped-Hinged; Hinged-Free				Clamped-Free				Hinged-Hinged				Tone & Freq.	33.708
33.71	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00	1	7.557
1	42.221	70.072	98.128	126.158	35.008	63.079	90.974	119.018	16.737	42.221	70.072	98.128	28.026	56.066	84.111	112.132	1.0-2.0 Hz	26.151
2	29.855	49.548	69.387	89.207	24.754	44.604	64.328	84.158	11.835	29.855	49.548	69.387	19.817	39.645	59.475	79.289		
3	24.376	40.456	56.654	72.838	20.212	36.419	52.524	68.715	9.663	24.376	40.456	56.654	16.181	32.370	48.561	64.739	2	4.453
4	21.110	35.036	49.064	63.079	17.504	31.540	45.487	59.509	8.368	21.110	35.036	49.064	14.013	28.033	42.055	56.066	4-5 Hz	16.854
5	18.882	31.337	43.884	56.420	15.656	28.210	40.685	53.226	7.485	18.882	31.337	43.884	12.534	25.073	37.616	50.147		29.255
6	17.237	28.607	40.061	51.504	14.292	25.752	37.140	48.589	6.833	17.237	28.607	40.061	11.442	22.889	34.338	45.778		
7	15.958	26.485	37.089	47.683	13.232	23.842	34.385	44.984	6.326	15.958	26.485	37.089	10.593	21.191	31.791	42.382	3	3.182
8	14.927	24.774	34.694	44.604	12.377	22.302	32.164	42.079	5.917	14.927	24.774	34.694	9.909	19.822	29.738	39.645	8-9 Hz	11.993
9	14.074	23.357	32.709	42.053	11.669	21.026	30.325	39.673	5.579	14.074	23.357	32.709	9.342	18.689	28.037	37.377		21.715
10	13.351	22.159	31.031	39.895	11.070	19.947	28.769	37.637	5.293	13.351	22.159	31.031	8.863	17.730	26.598	35.459		30.526
20	9.441	15.669	21.942	28.210	7.828	14.105	20.342	26.613	3.742	9.441	15.669	21.942	6.267	12.537	18.808	25.073		
30	7.708	12.793	17.916	23.033	6.391	11.517	16.610	21.730	3.056	7.708	12.793	17.916	5.117	10.236	15.356	20.472	4	2.474
40	6.676	11.079	15.515	19.947	5.535	9.974	14.384	18.818	2.646	6.676	11.079	15.515	4.431	8.865	13.299	17.730	10-11 Hz	9.337
50	5.971	9.910	13.877	17.841	4.951	8.921	12.866	16.832	2.367	5.971	9.910	13.877	3.963	7.929	11.895	15.858		16.854
60	5.451	9.046	12.668	16.287	4.519	8.143	11.745	15.365	2.161	5.451	9.046	12.668	3.618	7.238	10.859	14.476		24.371
70	5.046	8.375	11.729	15.079	4.184	7.539	10.873	14.225	2.000	5.046	8.375	11.729	3.350	6.701	10.053	13.402		31.234
80	4.720	7.834	10.971	14.105	3.914	7.052	10.171	13.307	1.871	4.720	7.834	10.971	3.133	6.268	9.404	12.537		
90	4.450	7.386	10.344	13.298	3.690	6.649	9.590	12.546	1.764	4.450	7.386	10.344	2.954	5.910	8.866	11.820		
100	4.222	7.007	9.813	12.616	3.501	6.308	9.097	11.902	1.674	4.222	7.007	9.813	2.803	5.607	8.411	11.213		
200	2.985	4.955	6.939	8.921	2.475	4.460	6.433	8.416	1.183	2.985	4.955	6.939	1.982	3.964	5.948	7.929		
300	2.438	4.046	5.665	7.284	2.021	3.642	5.252	6.871	0.966	2.438	4.046	5.665	1.618	3.237	4.856	6.474		
400	2.111	3.504	4.906	6.308	1.750	3.154	4.549	5.951	0.837	2.111	3.504	4.906	1.401	2.803	4.206	5.607		
500	1.888	3.134	4.388	5.642	1.566	2.821	4.068	5.323	0.748	1.888	3.134	4.388	1.253	2.507	3.762	5.015		
600	1.724	2.861	4.006	5.150	1.429	2.575	3.714	4.859	0.683	1.724	2.861	4.006	1.144	2.289	3.434	4.578		
700	1.596	2.648	3.709	4.768	1.323	2.384	3.438	4.498	0.633	1.596	2.648	3.709	1.059	2.119	3.179	4.238		
800	1.493	2.477	3.469	4.460	1.238	2.230	3.216	4.208	0.592	1.493	2.477	3.469	0.991	1.982	2.974	3.964		
900	1.407	2.336	3.271	4.205	1.167	2.103	3.032	3.967	0.558	1.407	2.336	3.271	0.934	1.869	2.804	3.738		
1,000	1.335	2.216	3.103	3.989	1.107	1.995	2.877	3.764	0.529	1.335	2.216	3.103	0.886	1.773	2.660	3.546		
2,000	0.944	1.567	2.194	2.821	0.783	1.410	2.034	2.661	0.374	0.944	1.567	2.194	0.627	1.254	1.881	2.507		
3,000	0.771	1.279	1.792	2.303	0.639	1.152	1.661	2.173	0.306	0.771	1.279	1.792	0.512	1.024	1.536	2.047		
4,000	0.668	1.108	1.552	1.995	0.554	0.997	1.438	1.882	0.265	0.668	1.108	1.552	0.443	0.886	1.330	1.773		
5,000	0.597	0.991	1.388	1.784	0.495	0.892	1.287	1.683	0.237	0.597	0.991	1.388	0.396	0.793	1.190	1.586		
6,000	0.545	0.905	1.267	1.629	0.452	0.814	1.174	1.537	0.216	0.545	0.905	1.267	0.362	0.724	1.086	1.448		
7,000	0.505	0.838	1.173	1.508	0.418	0.754	1.087	1.423	0.200	0.505	0.838	1.173	0.335	0.670	1.005	1.340		
8,000	0.472	0.783	1.097	1.410	0.391	0.705	1.017	1.331	0.187	0.472	0.783	1.097	0.313	0.627	0.940	1.254		
9,000	0.445	0.739	1.034	1.330	0.369	0.665	0.959	1.255	0.176	0.445	0.739	1.034	0.295	0.591	0.887	1.182		
10,000	0.422	0.701	0.981	1.262	0.350	0.631	0.910	1.190	0.167	0.422	0.701	0.981	0.280	0.561	0.841	1.121		
20,000	0.299	0.495	0.694	0.892	0.248	0.446	0.643	0.842	0.118	0.299	0.495	0.694	0.198	0.396	0.595	0.793		
30,000	0.244	0.405	0.567	0.728	0.202	0.364	0.525	0.687	0.097	0.244	0.405	0.567	0.162	0.324	0.486	0.647		
40,000	0.211	0.350	0.491	0.631	0.175	0.315	0.455	0.595	0.084	0.211	0.350	0.491	0.140	0.280	0.421	0.561		
50,000	0.189	0.313	0.439	0.564	0.157	0.282	0.407	0.532	0.075	0.189	0.313	0.439	0.125	0.251	0.376	0.501		
60,000	0.172	0.286	0.401	0.515	0.143	0.258	0.371	0.486	0.068	0.172	0.286	0.401	0.114	0.229	0.343	0.458		
70,000	0.160	0.265	0.371	0.477	0.132	0.238	0.344	0.450	0.063	0.160	0.265	0.371	0.106	0.212	0.318	0.424		
80,000	0.149	0.248	0.347	0.446	0.124	0.223	0.322	0.421	0.059	0.149	0.248	0.347	0.099	0.198	0.297	0.396		
90,000	0.141	0.234	0.327	0.421	0.117	0.210	0.303	0.397	0.056	0.141	0.234	0.327	0.093	0.187	0.280	0.374		
100,000	0.134	0.222	0.310	0.399	0.111	0.199	0.288	0.376	0.053	0.134	0.222	0.310	0.089	0.177	0.266	0.355		
F-F	0.224;0.776	0.132;0.5;0.868	0.094;0.356;0.644;0.906	0.073;0.277;0.5;0.723;0.927					0	0.774	0.5; 0.868	0.356;0.644;0.906	0.00	0.50	0.333;0.667	0.25;0.5;0.75		
C-C	0	0.5	0.359;0.641	0.278;0.5;0.722														
C-H					0	0.56	0.384;0.692	0.294;0.529;0.765										
H-F					0.736	0.446;0.853	0.308;0.616;0.898	0.235;0.471;0.707;0.922										

FOREBAY TIME SERIES						
V_L	5,928.85	233,419				
V_S	3,256.13	128,194				
V_E	5,218.06	204,277	5,188.64	17,023.08		
2.25 MHz			30 kHz		inches	feet
Inch	Time	deltaT	Feet	Time	Freq.	Freq.
1.00	8.57E-6	7.51E-6	1.00	117.49E-6	102,139	8,512
2.00	17.14E-6	15.02E-6	2.00	234.98E-6	51,069	4,256
3.00	25.70E-6	delta f	3.00	352.46E-6	34,046	2,837
4.00	34.27E-6	133,163	4.00	469.95E-6	25,535	2,128
5.00	42.84E-6		5.00	587.44E-6	20,428	1,702
6.00	51.41E-6		6.00	704.93E-6	17,023	1,419
7.00	59.98E-6		7.00	822.41E-6	14,591	1,216
8.00	68.55E-6		8.00	939.90E-6	12,767	1,064
9.00	77.11E-6		9.00	1.057E-3	11,349	946
10.00	85.68E-6		10.00	1.175E-3	10,214	851
11.00	94.25E-6		11.00	1.292E-3	9,285	774
12.00	102.82E-6		12.00	1.410E-3	8,512	709
13.00	111.39E-6		13.00	1.527E-3	7,857	655
14.00	119.96E-6		14.00	1.645E-3	7,296	608
15.00	128.52E-6		15.00	1.762E-3	6,809	567
16.00	137.09E-6		16.00	1.880E-3	6,384	532
17.00	145.66E-6		17.00	1.997E-3	6,008	501
18.00	154.23E-6		18.00	2.115E-3	5,674	473
19.00	162.80E-6		19.00	2.232E-3	5,376	448
20.00	171.37E-6		20.00	2.350E-3	5,107	426
21.00	179.93E-6		21.00	2.467E-3	4,864	405
22.00	188.50E-6		22.00	2.585E-3	4,643	387
23.00	197.07E-6		23.00	2.702E-3	4,441	370
24.00	205.64E-6		24.00	2.820E-3	4,256	355
25.00	214.21E-6		25.00	2.937E-3	4,086	340
26.00	222.77E-6		26.00	3.055E-3	3,928	327
27.00	231.34E-6		27.00	3.172E-3	3,783	315
28.00	239.91E-6		28.00	3.290E-3	3,648	304
29.00	248.48E-6		29.00	3.407E-3	3,522	294
30.00	257.05E-6		30.00	3.525E-3	3,405	284
31.00	265.62E-6		31.00	3.642E-3	3,295	275
32.00	274.18E-6		32.00	3.760E-3	3,192	266
33.00	282.75E-6		33.00	3.877E-3	3,095	258
34.00	291.32E-6		34.00	3.995E-3	3,004	250
35.00	299.89E-6		35.00	4.112E-3	2,918	243
36.00	308.46E-6		36.00	4.230E-3	2,837	236
37.00	317.03E-6		37.00	4.347E-3	2,761	230
38.00	325.59E-6		38.00	4.465E-3	2,688	224
39.00	334.16E-6		39.00	4.582E-3	2,619	218
40.00	342.73E-6		40.00	4.700E-3	2,553	213
freq.	11,045.00	14,201.00	26,036.00	27,219.00	157,000.00	163,710.00
inches	10.57	8.22	4.48	4.29	0.74	0.71
inches	5.80	4.51	2.46	2.35	0.41	0.39
inches	9.30	7.23	3.95	3.77	0.65	0.63
inches	5.35	3.46				
inches	2.07					

5058 PR
30 kHz - DEEP
PRR = 20
Damping = 100
Pulse Height = 100 - 200
Attenuation = 0 / 2 dB
Filter = 0.3 / 0.5

2.25 MHz - 18 inches
PRR = 100
Damping = 50
Pulse Height = 100
Attenuation = 0 / 0 dB
Filter = 1/0 / OUT

Set graph for ± 2 volts FSD

Pier 1 is West Side

From Top looking down:

1 2
3 4

<=TENDON RANGE

			TENDON FLEXURE, FOREBAY																
V_L	5,928.85	233,419	Diameter, m	29.255E-3															
V_S	3,256.13	128,194																	
V_E	5,218.06	205,435	5,188.64	17,023.08	Feet/sec														
$I^{0.5}$	7.31E-3	7.31E-3	Frequency Calculations																
A	22.4		3.004	3.009															
frequency	3	Hz		22.000	Feet														
Length	22.000	Feet																	
Constants	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00			
frequency	3	6	11	18															
Feet	22.032	36.566	51.206	65.833	18.268	32.917	47.473	62.107	8.734	22.032	36.566	51.206	14.625	29.257	43.892	58.514			
						Table in Feet, Length of Tendon											Node Points in Feet		
Hertz	Free-Free; Clamped-Clamped				Clamped-Hinged; Hinged-Free				Clamped-Free				Hinged-Hinged				Tone & Freq.	22	27
22.000	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00	1	0.00	0.00
1	38.161	63.334	88.692	114.027	31.641	57.013	82.226	107.573	15.127	38.161	63.334	88.692	25.331	50.675	76.023	101.349	1-4 Hz		
2	26.984	44.784	62.715	80.629	22.374	40.315	58.142	76.065	10.697	26.984	44.784	62.715	17.912	35.832	53.756	71.665			
3	22.032	36.566	51.206	65.833	18.268	32.917	47.473	62.107	8.734	22.032	36.566	51.206	14.625	29.257	43.892	58.514	2	11.00	13.50
4	19.080	31.667	44.346	57.013	15.821	28.507	41.113	53.786	7.564	19.080	31.667	44.346	12.665	25.337	38.011	50.675	5-9 Hz		
5	17.066	28.324	39.664	50.994	14.150	25.497	36.773	48.108	6.765	17.066	28.324	39.664	11.328	22.662	33.998	45.325			
6	15.579	25.856	36.208	46.551	12.917	23.276	33.569	43.916	6.176	15.579	25.856	36.208	10.341	20.688	31.036	41.376	3	7.90	9.69
7	14.423	23.938	33.522	43.098	11.959	21.549	31.078	40.659	5.718	14.423	23.938	33.522	9.574	19.153	28.734	38.306	9-18 Hz	14.10	17.31
8	13.492	22.392	31.357	40.315	11.187	20.157	29.071	38.033	5.348	13.492	22.392	31.357	8.956	17.916	26.878	35.832			
9	12.720	21.111	29.564	38.009	10.547	19.004	27.409	35.858	5.042	12.720	21.111	29.564	8.444	16.892	25.341	33.783	4	6.12	7.51
10	12.067	20.028	28.047	36.058	10.006	18.029	26.002	34.017	4.784	12.067	20.028	28.047	8.010	16.025	24.040	32.049	15-28 Hz	11.00	13.50
20	8.533	14.162	19.832	25.497	7.075	12.749	18.386	24.054	3.383	8.533	14.162	19.832	5.664	11.331	16.999	22.662		15.88	19.49
30	6.967	11.563	16.193	20.818	5.777	10.409	15.012	19.640	2.762	6.967	11.563	16.193	4.625	9.252	13.880	18.504			
40	6.034	10.014	14.023	18.029	5.003	9.015	13.001	17.009	2.392	6.034	10.014	14.023	4.005	8.012	12.020	16.025			
50	5.397	8.957	12.543	16.126	4.475	8.063	11.628	15.213	2.139	5.397	8.957	12.543	3.582	7.166	10.751	14.333			
60	4.927	8.176	11.450	14.721	4.085	7.360	10.615	13.888	1.953	4.927	8.176	11.450	3.270	6.542	9.814	13.084			
70	4.561	7.570	10.601	13.629	3.782	6.814	9.828	12.857	1.808	4.561	7.570	10.601	3.028	6.057	9.086	12.114			
80	4.266	7.081	9.916	12.749	3.538	6.374	9.193	12.027	1.691	4.266	7.081	9.916	2.832	5.666	8.500	11.331			
90	4.022	6.676	9.349	12.019	3.335	6.010	8.667	11.339	1.595	4.022	6.676	9.349	2.670	5.342	8.013	10.683			
100	3.816	6.333	8.869	11.403	3.164	5.701	8.223	10.757	1.513	3.816	6.333	8.869	2.533	5.067	7.602	10.135			
200	2.698	4.478	6.271	8.063	2.237	4.031	5.814	7.607	1.070	2.698	4.478	6.271	1.791	3.583	5.376	7.166			
300	2.203	3.657	5.121	6.583	1.827	3.292	4.747	6.211	0.873	2.203	3.657	5.121	1.462	2.926	4.389	5.851			
400	1.908	3.167	4.435	5.701	1.582	2.851	4.111	5.379	0.756	1.908	3.167	4.435	1.267	2.534	3.801	5.067			
500	1.707	2.832	3.966	5.099	1.415	2.550	3.677	4.811	0.677	1.707	2.832	3.966	1.133	2.266	3.400	4.532			
600	1.558	2.586	3.621	4.655	1.292	2.328	3.357	4.392	0.618	1.558	2.586	3.621	1.034	2.069	3.104	4.138			
700	1.442	2.394	3.352	4.310	1.196	2.155	3.108	4.066	0.572	1.442	2.394	3.352	0.957	1.915	2.873	3.831			
800	1.349	2.239	3.136	4.031	1.119	2.016	2.907	3.803	0.535	1.349	2.239	3.136	0.896	1.792	2.688	3.583			
900	1.272	2.111	2.956	3.801	1.055	1.900	2.741	3.586	0.504	1.272	2.111	2.956	0.844	1.689	2.534	3.378			
1,000	1.207	2.003	2.805	3.606	1.001	1.803	2.600	3.402	0.478	1.207	2.003	2.805	0.801	1.602	2.404	3.205			
2,000	0.853	1.416	1.983	2.550	0.708	1.275	1.839	2.405	0.338	0.853	1.416	1.983	0.566	1.133	1.700	2.266			
3,000	0.697	1.156	1.619	2.082	0.578	1.041	1.501	1.964	0.276	0.697	1.156	1.619	0.462	0.925	1.388	1.850			
4,000	0.603	1.001	1.402	1.803	0.500	0.901	1.300	1.701	0.239	0.603	1.001	1.402	0.401	0.801	1.202	1.602			
5,000	0.540	0.896	1.254	1.613	0.447	0.806	1.163	1.521	0.214	0.540	0.896	1.254	0.358	0.717	1.075	1.433			
6,000	0.493	0.818	1.145	1.472	0.408	0.736	1.062	1.389	0.195	0.493	0.818	1.145	0.327	0.654	0.981	1.308			
7,000	0.456	0.757	1.060	1.363	0.378	0.681	0.983	1.286	0.181	0.456	0.757	1.060	0.303	0.606	0.909	1.211			
8,000	0.427	0.708	0.992	1.275	0.354	0.637	0.919	1.203	0.169	0.427	0.708	0.992	0.283	0.567	0.850	1.133			
9,000	0.402	0.668	0.935	1.202	0.334	0.601	0.867	1.134	0.159	0.402	0.668	0.935	0.267	0.534	0.801	1.068			
10,000	0.382	0.633	0.887	1.140	0.316	0.570	0.822	1.076	0.151	0.382	0.633	0.887	0.253	0.507	0.760	1.013			
20,000	0.270	0.448	0.627	0.806	0.224	0.403	0.581	0.761	0.107	0.270	0.448	0.627	0.179	0.358	0.538	0.717			
30,000	0.220	0.366	0.512	0.658	0.183	0.329	0.475	0.621	0.087	0.220	0.366	0.512	0.146	0.293	0.439	0.585			
40,000	0.191	0.317	0.443	0.570	0.158	0.285	0.411	0.538	0.076	0.191	0.317	0.443	0.127	0.253	0.380	0.507			
50,000	0.171	0.283	0.397	0.510	0.142	0.255	0.368	0.481	0.068	0.171	0.283	0.397	0.113	0.227	0.340	0.453			
60,000	0.156	0.259	0.362	0.466	0.129	0.233	0.336	0.439	0.062	0.156	0.259	0.362	0.103	0.207	0.310	0.414			
70,000	0.144	0.239	0.335	0.431	0.120	0.215	0.311	0.407	0.057	0.144	0.239	0.335	0.096	0.192	0.287	0.383			
80,000	0.135	0.224	0.314	0.403	0.112	0.202	0.291	0.380	0.053	0.135	0.224	0.314	0.090	0.179	0.269	0.358			
90,000	0.127	0.211	0.296	0.380	0.105	0.190	0.274	0.359	0.050	0.127	0.211	0.296	0.084	0.169	0.253	0.338			
100,000	0.121	0.200	0.280	0.361	0.100	0.180	0.260	0.340	0.048	0.121	0.200	0.280	0.080	0.160	0.240	0.320			
F-F	0.224;0.776	0.132;0.5;0.868	0.094;0.356;0.644;0.906	0.073;0.277;0.5;0.723;0.927					0	0.774	0.5; 0.868	0.356;0.644;0.906	0.00	0.50	0.333;0.667	0.25;0.5;0.75			
C-C	0	0.5	0.359;0.641	0.278;0.5;0.722															
C-H					0	0.56	0.384;0.692	0.294;0.529;0.765											
H-F					0.736	0.446;0.853	0.308;0.616;0.898	0.235;0.471;0.707;0.922											

FLEXURAL VIBRATIONS: DWR-LLNL Steel										
E	211.793E+9						f_L	f_S		
ρ	7,788			Air Impedance	444.792		82,567	45,249	1.375"	
γ	0.2854			Concrete Z	13.80E+6		101,434	55,588	1.125"	
C_E	5,170.05	5,188.64		5,441.13	V_P		289	158	36.0'	
Trial f	10.00	54.03		5,214.86	V_B					
53.50	35.940E-3	Bars-Rods		4,599.68	V_L'					
Plates	29.255E-3	36.78	27 Feet =	8.2296						
39.46	(af)^0.5	36.72	34 feet =	10.274						
Hertz	m/s		Feet		Rayles		Transmission Intensity		DISPLACEMENTS, IN	
frequency	1.375" Rod C_F	1.125" Rod C_F	1.375" Rod L	1.125" Rod L	Z_1.375"	Z_1.125"	Coeff. Concrete		PROPORTIONALITY	
1	55	50	9.053	8.180	429.8E+3	388.4E+3	11.72%	10.65%	8.783	7.937
2	25	22	20.242	18.292	192.2E+3	173.7E+3	5.42%	4.91%	1.964	1.775
3	30	27	16.528	14.935	235.4E+3	212.7E+3	6.60%	5.98%	1.604	1.449
4	35	32	14.313	12.934	271.8E+3	245.6E+3	7.58%	6.87%	1.389	1.255
5	39	35	12.802	11.569	303.9E+3	274.6E+3	8.43%	7.65%	1.242	1.122
6	43	39	11.687	10.561	332.9E+3	300.8E+3	9.20%	8.35%	1.134	1.025
7	46	42	10.820	9.778	359.6E+3	324.9E+3	9.90%	8.99%	1.050	0.949
8	49	45	10.121	9.146	384.4E+3	347.4E+3	10.55%	9.58%	0.982	0.887
9	52	47	9.542	8.623	407.7E+3	368.4E+3	11.15%	10.13%	0.926	0.837
10	55	50	9.053	8.180	429.8E+3	388.4E+3	11.72%	10.65%	0.878	0.794
20	78	71	6.401	5.784	607.8E+3	549.2E+3	16.16%	14.72%	0.621	0.561
30	96	86	5.227	4.723	744.4E+3	672.7E+3	19.42%	17.73%	0.507	0.458
40	110	100	4.526	4.090	859.6E+3	776.7E+3	22.08%	20.18%	0.439	0.397
50	123	112	4.048	3.658	961.0E+3	868.4E+3	24.35%	22.28%	0.393	0.355
60	135	122	3.696	3.340	1.053E+6	951.3E+3	26.34%	24.13%	0.359	0.324
70	146	132	3.422	3.092	1.137E+6	1.028E+6	28.13%	25.80%	0.332	0.300
80	156	141	3.201	2.892	1.216E+6	1.098E+6	29.76%	27.32%	0.311	0.281
90	166	150	3.018	2.727	1.289E+6	1.165E+6	31.26%	28.72%	0.293	0.265
100	175	158	2.863	2.587	1.359E+6	1.228E+6	32.65%	30.02%	0.278	0.251
200	247	223	2.024	1.829	1.922E+6	1.737E+6	42.92%	39.72%	0.196	0.177
300	302	273	1.653	1.494	2.354E+6	2.127E+6	49.79%	46.29%	0.160	0.145
400	349	315	1.431	1.293	2.718E+6	2.456E+6	54.99%	51.31%	0.139	0.125
500	390	353	1.280	1.157	3.039E+6	2.746E+6	59.16%	55.37%	0.124	0.112
600	427	386	1.169	1.056	3.329E+6	3.008E+6	62.63%	58.78%	0.113	0.102
700	462	417	1.082	0.978	3.596E+6	3.249E+6	65.59%	61.71%	0.105	0.095
800	494	446	1.012	0.915	3.844E+6	3.474E+6	68.16%	64.26%	0.098	0.089
900	524	473	0.954	0.862	4.077E+6	3.684E+6	70.42%	66.53%	0.093	0.084
1,000	552	499	0.905	0.818	4.298E+6	3.884E+6	72.43%	68.56%	0.088	0.079
2,000	780	705	0.640	0.578	6.078E+6	5.492E+6	84.91%	81.46%	0.062	0.056
3,000	956	864	0.523	0.472	7.444E+6	6.727E+6	91.05%	88.13%	0.051	0.046
4,000	1,104	997	0.453	0.409	8.596E+6	7.767E+6	94.60%	92.18%	0.044	0.040
5,000	1,234	1,115	0.405	0.366	9.610E+6	8.684E+6	96.80%	94.82%	0.039	0.035
6,000	1,352	1,222	0.370	0.334	10.527E+6	9.513E+6	98.19%	96.62%	0.036	0.032
7,000	1,460	1,319	0.342	0.309	11.371E+6	10.275E+6	99.07%	97.86%	0.033	0.030
8,000	1,561	1,410	0.320	0.289	12.156E+6	10.985E+6	99.60%	98.71%	0.031	0.028
9,000	1,656	1,496	0.302	0.273	12.893E+6	11.651E+6	99.88%	99.29%	0.029	0.026
10,000	1,745	1,577	0.286	0.259	13.591E+6	12.281E+6	99.99%	99.66%	0.028	0.025
20,000	2,468	2,230	0.202	0.183	19.220E+6	17.369E+6	97.31%	98.69%	0.020	0.018
30,000	3,023	2,731	0.165	0.149	23.540E+6	21.272E+6	93.20%	95.46%	0.016	0.014
40,000	3,490	3,154	0.143	0.129	27.182E+6	24.563E+6	89.34%	92.13%	0.014	0.013
50,000	3,902	3,526	0.128	0.116	30.390E+6	27.462E+6	85.91%	89.04%	0.012	0.011
60,000	4,275	3,863	0.117	0.106	33.291E+6	30.083E+6	82.87%	86.23%	0.011	0.010
70,000	4,617	4,172	0.108	0.098	35.958E+6	32.494E+6	80.17%	83.69%	0.010	0.009
80,000	4,936	4,460	0.101	0.091	38.441E+6	34.737E+6	77.75%	81.39%	0.010	0.009
90,000	5,934.91	5,928.85	0.059	0.054	46.221E+6	46.174E+6	70.82%	70.86%	0.010	0.010
100,000	5,934.91	5,928.85	0.056	0.051	46.221E+6	46.174E+6	70.82%	70.86%	0.009	0.009
V_L	V_S									
5,934.91	3,252.46		fD LLNL					fD Forebay		
		m =	1	2	3	4	m =	1	2	3
-0.759	2.126	Sym_N	2,300	6,900	11,499	16,099	Sym_N	2,302	6,900	11,499
2.126	4.971	ASym_N	4,600	9,199	13,799	18,399	ASym_N	4,600	9,199	13,799
4.971	8.017	Sym_N	2,967	8,902	14,837	20,772	Sym_N	2,967	8,902	14,837
8.017	11.114	ASym_N	5,935	11,870	17,805	23,740	ASym_N	5,935	11,870	17,805
11.114		Sym_IP	3,252	6,505	9,757	13,010	Sym_IP	3,252	6,505	9,757
		ASym_IP	1,626	4,879	8,131	11,384	ASym_IP	1,626	4,879	8,131
		Sym_IP	3,888	7,777	11,665	15,553	Sym_IP	3,888	7,777	11,665
1.000000		ASym_IP	2,631	6,153	9,922	13,755	ASym_IP	2,638	6,158	9,926
			FREQUENCIES for 1.375" thickness				FREQUENCIES for 1.125" thickness			
-1.613255219		Sym_N	63.991E+3	191.973E+3	319.955E+3	447.937E+3	78.702E+3	235.841E+3	393.068E+3	550.295E+3
-1.61325639		ASym_N	127.982E+3	255.964E+3	383.946E+3	511.928E+3	157.227E+3	314.454E+3	471.681E+3	628.908E+3
		Sym_N	82.567E+3	247.701E+3	412.835E+3	577.968E+3	101.434E+3	304.302E+3	507.171E+3	710.039E+3
V_L	V_S	ASym_N	165.134E+3	330.268E+3	495.401E+3	660.535E+3	202.868E+3	405.736E+3	608.605E+3	811.473E+3
5,928.85	3,256.13	Sym_IP	90.497E+3	180.994E+3	271.491E+3	361.988E+3	111.176E+3	222.353E+3	333.529E+3	444.705E+3
		ASym_IP	45.249E+3	135.746E+3	226.243E+3	316.740E+3	55.588E+3	166.764E+3	277.941E+3	389.117E+3
-0.747301098	2.131	Sym_IP	108.190E+3	216.380E+3	324.570E+3	432.760E+3	132.912E+3	265.825E+3	398.737E+3	531.649E+3
2.131	4.975	ASym_IP	73.205E+3	171.207E+3	276.085E+3	382.729E+3	90.175E+3	210.485E+3	339.276E+3	470.262E+3
4.975	8.019	Sym_N	343	1,029	1,715	2,401	280	838	1,397	1,956
8.019	11.115	ASym_N	686	1,372	2,058	2,744	559	1,118	1,677	2,236
11.115		Sym_N	443	1,328	2,213	3,098	361	1,082	1,803	2,524
	6.7056	ASym_N	885	1,770	2,655	3,540	721	1,442	2,163	2,885
1.000000002	8.2296	Sym_IP	485	970	1,455	1,940	395	790	1,186	1,581
		ASym_IP	243	728	1,213	1,698	198	593	988	1,383
		Sym_IP	580	1,160	1,740	2,319	472	945	1,417	1,890
		ASym_IP	393	918	1,480	2,052	321	748	1,206	1,672
			22 feet Length Left				27 feet Length Right			

FOREBAY FLEXURAL VIBRATIONS: CONCRETE nondescript										
E	21.720E+9	2.50					V_L	V_S		
ρ	2,300	3.83		Air Impedance	444.792		4,264	2,598	15"	
γ	0.2051			Water Z	1,490,000		2,781	1,694	23"	
C_E	3,072.80			3,139.57	V_P		21,322	12,988	3.0"	
Trial f	1.00			3,072.83	V_B		5.54	34.72	97.22	Hz
	0.381000	Bars-Rods		2,799.15	V_L'	316 SS	77.98	Impedance	7.474E+6	
Plates	0.584200						625,314.02	Waveguide F	Refl.Coef. =	(1.0000)
30.10	(af)^0.5	28.02								
Hertz	m/s		Feet		Rayles		Intensity		DISPLACEMENTS, IN	
frequency	15" Plate C_F	23" Plate C_F	1.25 ' Plate L	1.92 ' Plate L	Z_15"	Z_23"	Transmission Coeff. Water		PROPORTIONALITY	
1	47	58	76.409	94.616	107.1E+3	132.7E+3	25.03%	30.03%	7.4133	9.1797
2	66	82	54.029	66.903	151.5E+3	187.6E+3	33.51%	39.73%	5.2420	6.4910
3	81	100	44.115	54.626	185.6E+3	229.8E+3	39.39%	46.30%	4.2801	5.2999
4	93	115	38.205	47.308	214.3E+3	265.3E+3	43.97%	51.32%	3.7066	4.5899
5	104	129	34.171	42.313	239.6E+3	296.6E+3	47.73%	55.39%	3.3153	4.1053
6	114	141	31.194	38.627	262.4E+3	324.9E+3	50.93%	58.79%	3.0265	3.7476
7	123	153	28.880	35.761	283.4E+3	351.0E+3	53.71%	61.72%	2.8020	3.4696
8	132	163	27.015	33.452	303.0E+3	375.2E+3	56.17%	64.28%	2.6210	3.2455
9	140	173	25.470	31.539	321.4E+3	398.0E+3	58.38%	66.54%	2.4711	3.0599
10	147	182	24.163	29.920	338.8E+3	419.5E+3	60.37%	68.57%	2.3443	2.9029
20	208	258	17.086	21.157	479.1E+3	593.3E+3	73.64%	81.47%	1.6577	2.0526
30	255	316	13.950	17.274	586.8E+3	726.6E+3	81.09%	88.14%	1.3535	1.6760
40	295	365	12.081	14.960	677.6E+3	839.0E+3	85.95%	92.19%	1.1721	1.4514
50	329	408	10.806	13.381	757.5E+3	938.0E+3	89.38%	94.83%	1.0484	1.2982
60	361	447	9.864	12.215	829.8E+3	1.028E+6	91.90%	96.63%	0.9571	1.1851
70	390	483	9.133	11.309	896.3E+3	1.110E+6	93.81%	97.86%	0.8861	1.0972
80	417	516	8.543	10.578	958.2E+3	1.187E+6	95.28%	98.71%	0.8288	1.0263
90	442	547	8.054	9.973	1.016E+6	1.259E+6	96.43%	99.29%	0.7814	0.9676
100	466	577	7.641	9.462	1.071E+6	1.327E+6	97.33%	99.66%	0.7413	0.9180
200	659	816	5.403	6.690	1.515E+6	1.876E+6	99.99%	98.68%	0.5242	0.6491
300	807	999	4.411	5.463	1.856E+6	2.298E+6	98.81%	95.45%	0.4280	0.5300
400	932	1,154	3.820	4.731	2.143E+6	2.653E+6	96.77%	92.12%	0.3707	0.4590
500	1,042	1,290	3.417	4.231	2.396E+6	2.966E+6	94.57%	89.02%	0.3315	0.4105
600	1,141	1,413	3.119	3.863	2.624E+6	3.249E+6	92.40%	86.22%	0.3026	0.3748
700	1,232	1,526	2.888	3.576	2.834E+6	3.510E+6	90.33%	83.68%	0.2802	0.3470
800	1,317	1,631	2.701	3.345	3.030E+6	3.752E+6	88.39%	81.38%	0.2621	0.3246
900	1,397	1,730	2.547	3.154	3.214E+6	3.980E+6	86.57%	79.28%	0.2471	0.3060
1,000	1,473	1,824	2.416	2.992	3.388E+6	4.195E+6	84.86%	77.36%	0.2344	0.2903
2,000	2,083	2,579	1.709	2.116	4.791E+6	5.933E+6	72.38%	64.18%	0.1658	0.2053
3,000	2,551	3,159	1.395	1.727	5.868E+6	7.266E+6	64.60%	56.48%	0.1353	0.1676
4,000	2,946	3,648	1.208	1.496	6.776E+6	8.390E+6	59.11%	51.23%	0.1172	0.1451
5,000	3,294	4,078	1.081	1.338	7.575E+6	9.380E+6	54.94%	47.31%	0.1048	0.1298
6,000	3,608	4,468	0.986	1.221	8.298E+6	10.276E+6	51.62%	44.24%	0.0957	0.1185
7,000	3,897	4,826	0.913	1.131	8.963E+6	11.099E+6	48.89%	41.74%	0.0886	0.1097
8,000	4,166	5,159	0.854	1.058	9.582E+6	11.865E+6	46.58%	39.65%	0.0829	0.1026
9,000	4,419	5,472	0.805	0.997	10.163E+6	12.585E+6	44.60%	37.86%	0.0781	0.0968
10,000	4,658	5,768	0.764	0.946	10.713E+6	13.266E+6	42.88%	36.31%	0.0741	0.0918
20,000	6,587	8,157	0.540	0.669	15.151E+6	18.761E+6	32.61%	27.27%	0.0524	0.0649
30,000	8,068	9,990	0.441	0.546	18.556E+6	22.977E+6	27.52%	22.88%	0.0428	0.0530
40,000	9,316	11,536	0.382	0.473	21.426E+6	26.532E+6	24.32%	20.14%	0.0371	0.0459
50,000	10,415	12,897	0.342	0.423	23.955E+6	29.663E+6	22.05%	18.22%	0.0332	0.0411
60,000	11,409	14,128	0.312	0.386	26.242E+6	32.495E+6	20.34%	16.77%	0.0303	0.0375
70,000	12,324	15,260	0.289	0.358	28.344E+6	35.098E+6	18.98%	15.63%	0.0280	0.0347
80,000	13,175	16,314	0.270	0.335	30.301E+6	37.522E+6	17.87%	14.69%	0.0262	0.0325
90,000	13,974	17,303	0.255	0.315	32.140E+6	39.798E+6	16.94%	13.91%	0.0247	0.0306
100,000	14,730	18,239	0.242	0.299	33.878E+6	41.950E+6	16.14%	13.25%	0.0234	0.0290
V_L	V_S									
3,250	1,979		fD					Echoes	Time	Freq.
		m =	1	2	3	4		V_E	123.991E-6	4.033E+3
-0.285210	2.519	Sym_N	1,400	4,199	6,998	9,797			190.120E-6	2.630E+3
2.518660	5.297	ASym_N	2,799	5,598	8,397	11,197				
5.297090	8.256	Sym_N	1,625	4,874	8,124	11,373		V_L	117.248E-6	4.264E+3
8.255602	11.297	ASym_N	3,250	6,499	9,749	12,998			179.780E-6	2.781E+3
11.296525		Sym_IP	1,979	3,959	5,938	7,917				
		ASym_IP	990	2,969	4,948	6,928		V_S	192.492E-6	2.598E+3
		Sym_IP	2,496	4,991	7,487	9,983			295.155E-6	1.694E+3
1.000000		ASym_IP	2,001	4,208	6,558	8,974				
			FREQUENCIES for 15" thickness				FREQUENCIES for 23" thickness			
-0.718345898		Sym_N	3,673	11,020	18,367	25,714	2,396	7,187	11,979	16,770
-0.718345805		ASym_N	7,347	14,694	22,041	29,387	4,791	9,583	14,374	19,166
		Sym_N	4,264	12,793	21,322	29,851	2,781	8,344	13,906	19,468
		ASym_N	8,529	17,058	25,587	34,116	5,562	11,125	16,687	22,249
		Sym_IP	5,195	10,390	15,585	20,780	3,388	6,776	10,164	13,552
		ASym_IP	2,598	7,793	12,988	18,183	1,694	5,082	8,470	11,858
		Sym_IP	6,550	13,101	19,651	26,201	4,272	8,544	12,816	17,088
		ASym_IP	5,252	11,045	17,213	23,554	3,425	7,203	11,226	15,361

OROVILLE DAM TIME SERIES						
V_L	5,945.16	234,061				
V_S	3,261.63	128,411				
V_E	5,228.20	205,835	5,183.37	17,005.81		
5 MHz			30 kHz		inches	feet
Inch	Time	deltaT	Feet	Time	Freq.	Freq.
1	8.54E-6	9.21E-6	1	117.61E-6	102,035	8,503
2	17.09E-6	18.43E-6	2	235.21E-6	51,017	4,251
3	25.63E-6		3	352.82E-6	34,012	2,834
4	34.18E-6	108,546	4	470.43E-6	25,509	2,126
5	42.72E-6		5	588.03E-6	20,407	1,701
6	51.27E-6		6	705.64E-6	17,006	1,417
7	59.81E-6		7	823.25E-6	14,576	1,215
8	68.36E-6		8	940.85E-6	12,754	1,063
9	76.90E-6		9	1.058E-3	11,337	945
10	85.45E-6		10	1.176E-3	10,203	850
11	93.99E-6		11	1.294E-3	9,276	773
12	102.54E-6		12	1.411E-3	8,503	709
13	111.08E-6		13	1.529E-3	7,849	654
14	119.63E-6		14	1.646E-3	7,288	607
15	128.17E-6		15	1.764E-3	6,802	567
16	136.72E-6		16	1.882E-3	6,377	531
17	145.26E-6		17	1.999E-3	6,002	500
18	153.81E-6		18	2.117E-3	5,669	472
19	162.35E-6		19	2.235E-3	5,370	448
20	170.90E-6		20	2.352E-3	5,102	425
21	179.44E-6		21	2.470E-3	4,859	405
22	187.98E-6		22	2.587E-3	4,638	386
23	196.53E-6		23	2.705E-3	4,436	370
24	205.07E-6		24	2.823E-3	4,251	354
25	213.62E-6		25	2.940E-3	4,081	340
26	222.16E-6		26	3.058E-3	3,924	327
27	230.71E-6		27	3.175E-3	3,779	315
28	239.25E-6		28	3.293E-3	3,644	304
29	247.80E-6		29	3.411E-3	3,518	293
30	256.34E-6		30	3.528E-3	3,401	283
31	264.89E-6		31	3.646E-3	3,291	274
32	273.43E-6		32	3.763E-3	3,189	266
33	281.98E-6		33	3.881E-3	3,092	258
34	290.52E-6		34	3.999E-3	3,001	250
35	299.07E-6		35	4.116E-3	2,915	243
36	307.61E-6		36	4.234E-3	2,834	236
37	316.16E-6		37	4.351E-3	2,758	230
38	324.70E-6		38	4.469E-3	2,685	224
39	333.25E-6		39	4.587E-3	2,616	218
40	341.79E-6		40	4.704E-3	2,551	213

							TENDON FLEXURE, OROVILLE DAM											
V_L	5,945.16	234,061	Diameter, m	35.940E-3														
V_S	3,261.63	128,411																
V_E	5,228.20	205,835	5,183.37	17,005.81	Feet/sec													
$I^{0.5}$	8.99E-3	8.99E-3	Frequency Calculations															
A	22.40		1.173	1.175														
frequency	2	Hz		33.751	Feet													
Length	33.751	Feet																
Constants	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00		
frequency	1	4	8	13														
Feet	40.308	66.897	93.682	120.442	33.421	60.221	86.852	113.625	15.978	40.308	66.897	93.682	26.756	53.526	80.300	107.051		
							Table in Feet, Length of Tendon										Node Points in Feet	
Hertz	Free-Free; Clamped-Clamped				Clamped-Hinged; Hinged-Free				Clamped-Free				Hinged-Hinged				Tone & Freq.	39
33.75	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00	1	0.000
1	42.221	70.072	98.128	126.158	35.008	63.079	90.974	119.018	16.737	42.221	70.072	98.128	28.026	56.066	84.111	112.132	1.0-2.0 Hz	
2	29.855	49.548	69.387	89.207	24.754	44.604	64.328	84.158	11.835	29.855	49.548	69.387	19.817	39.645	59.475	79.289		
3	24.376	40.456	56.654	72.838	20.212	36.419	52.524	68.715	9.663	24.376	40.456	56.654	16.181	32.370	48.561	64.739	2	19.500
4	21.110	35.036	49.064	63.079	17.504	31.540	45.487	59.509	8.368	21.110	35.036	49.064	14.013	28.033	42.055	56.066	4-5 Hz	
5	18.882	31.337	43.884	56.420	15.656	28.210	40.685	53.226	7.485	18.882	31.337	43.884	12.534	25.073	37.616	50.147		
6	17.237	28.607	40.061	51.504	14.292	25.752	37.140	48.589	6.833	17.237	28.607	40.061	11.442	22.889	34.338	45.778		
7	15.958	26.485	37.089	47.683	13.232	23.842	34.385	44.984	6.326	15.958	26.485	37.089	10.593	21.191	31.791	42.382	3	14.001
8	14.927	24.774	34.694	44.604	12.377	22.302	32.164	42.079	5.917	14.927	24.774	34.694	9.909	19.822	29.738	39.645	8-9 Hz	24.999
9	14.074	23.357	32.709	42.053	11.669	21.026	30.325	39.673	5.579	14.074	23.357	32.709	9.342	18.689	28.037	37.377		
10	13.351	22.159	31.031	39.895	11.070	19.947	28.769	37.637	5.293	13.351	22.159	31.031	8.863	17.730	26.598	35.459		
20	9.441	15.669	21.942	28.210	7.828	14.105	20.342	26.613	3.742	9.441	15.669	21.942	6.267	12.537	18.808	25.073		
30	7.708	12.793	17.916	23.033	6.391	11.517	16.610	21.730	3.056	7.708	12.793	17.916	5.117	10.236	15.356	20.472	4	10.842
40	6.676	11.079	15.515	19.947	5.535	9.974	14.384	18.818	2.646	6.676	11.079	15.515	4.431	8.865	13.299	17.730	10-11 Hz	19.500
50	5.971	9.910	13.877	17.841	4.951	8.921	12.866	16.832	2.367	5.971	9.910	13.877	3.963	7.929	11.895	15.858		28.158
60	5.451	9.046	12.668	16.287	4.519	8.143	11.745	15.365	2.161	5.451	9.046	12.668	3.618	7.238	10.859	14.476		
70	5.046	8.375	11.729	15.079	4.184	7.539	10.873	14.225	2.000	5.046	8.375	11.729	3.350	6.701	10.053	13.402		
80	4.720	7.834	10.971	14.105	3.914	7.052	10.171	13.307	1.871	4.720	7.834	10.971	3.133	6.268	9.404	12.537		
90	4.450	7.386	10.344	13.298	3.690	6.649	9.590	12.546	1.764	4.450	7.386	10.344	2.954	5.910	8.866	11.820		
100	4.222	7.007	9.813	12.616	3.501	6.308	9.097	11.902	1.674	4.222	7.007	9.813	2.803	5.607	8.411	11.213		
200	2.985	4.955	6.939	8.921	2.475	4.460	6.433	8.416	1.183	2.985	4.955	6.939	1.982	3.964	5.948	7.929		
300	2.438	4.046	5.665	7.284	2.021	3.642	5.252	6.871	0.966	2.438	4.046	5.665	1.618	3.237	4.856	6.474		
400	2.111	3.504	4.906	6.308	1.750	3.154	4.549	5.951	0.837	2.111	3.504	4.906	1.401	2.803	4.206	5.607		
500	1.888	3.134	4.388	5.642	1.566	2.821	4.068	5.323	0.748	1.888	3.134	4.388	1.253	2.507	3.762	5.015		
600	1.724	2.861	4.006	5.150	1.429	2.575	3.714	4.859	0.683	1.724	2.861	4.006	1.144	2.289	3.434	4.578		
700	1.596	2.648	3.709	4.768	1.323	2.384	3.438	4.498	0.633	1.596	2.648	3.709	1.059	2.119	3.179	4.238		
800	1.493	2.477	3.469	4.460	1.238	2.230	3.216	4.208	0.592	1.493	2.477	3.469	0.991	1.982	2.974	3.964		
900	1.407	2.336	3.271	4.205	1.167	2.103	3.032	3.967	0.558	1.407	2.336	3.271	0.934	1.869	2.804	3.738		
1,000	1.335	2.216	3.103	3.989	1.107	1.995	2.877	3.764	0.529	1.335	2.216	3.103	0.886	1.773	2.660	3.546		
2,000	0.944	1.567	2.194	2.821	0.783	1.410	2.034	2.661	0.374	0.944	1.567	2.194	0.627	1.254	1.881	2.507		
3,000	0.771	1.279	1.792	2.303	0.639	1.152	1.661	2.173	0.306	0.771	1.279	1.792	0.512	1.024	1.536	2.047		
4,000	0.668	1.108	1.552	1.995	0.554	0.997	1.438	1.882	0.265	0.668	1.108	1.552	0.443	0.886	1.330	1.773		
5,000	0.597	0.991	1.388	1.784	0.495	0.892	1.287	1.683	0.237	0.597	0.991	1.388	0.396	0.793	1.190	1.586		
6,000	0.545	0.905	1.267	1.629	0.452	0.814	1.174	1.537	0.216	0.545	0.905	1.267	0.362	0.724	1.086	1.448		
7,000	0.505	0.838	1.173	1.508	0.418	0.754	1.087	1.423	0.200	0.505	0.838	1.173	0.335	0.670	1.005	1.340		
8,000	0.472	0.783	1.097	1.410	0.391	0.705	1.017	1.331	0.187	0.472	0.783	1.097	0.313	0.627	0.940	1.254		
9,000	0.445	0.739	1.034	1.330	0.369	0.665	0.959	1.255	0.176	0.445	0.739	1.034	0.295	0.591	0.887	1.182		
10,000	0.422	0.701	0.981	1.262	0.350	0.631	0.910	1.190	0.167	0.422	0.701	0.981	0.280	0.561	0.841	1.121		
20,000	0.299	0.495	0.694	0.892	0.248	0.446	0.643	0.842	0.118	0.299	0.495	0.694	0.198	0.396	0.595	0.793		
30,000	0.244	0.405	0.567	0.728	0.202	0.364	0.525	0.687	0.097	0.244	0.405	0.567	0.162	0.324	0.486	0.647		
40,000	0.211	0.350	0.491	0.631	0.175	0.315	0.455	0.595	0.084	0.211	0.350	0.491	0.140	0.280	0.421	0.561		
50,000	0.189	0.313	0.439	0.564	0.157	0.282	0.407	0.532	0.075	0.189	0.313	0.439	0.125	0.251	0.376	0.501		
60,000	0.172	0.286	0.401	0.515	0.143	0.258	0.371	0.486	0.068	0.172	0.286	0.401	0.114	0.229	0.343	0.458		
70,000	0.160	0.265	0.371	0.477	0.132	0.238	0.344	0.450	0.063	0.160	0.265	0.371	0.106	0.212	0.318	0.424		
80,000	0.149	0.248	0.347	0.446	0.124	0.223	0.322	0.421	0.059	0.149	0.248	0.347	0.099	0.198	0.297	0.396		
90,000	0.141	0.234	0.327	0.421	0.117	0.210	0.303	0.397	0.056	0.141	0.234	0.327	0.093	0.187	0.280	0.374		
100,000	0.134	0.222	0.310	0.399	0.111	0.199	0.288	0.376	0.053	0.134	0.222	0.310	0.089	0.177	0.266	0.355		
F-F	0.224;0.776	0.132;0.5;0.868	0.094;0.356;0.644;0.906	0.073;0.277;0.5;0.723;0.927					0	0.774	0.5; 0.868	0.356;0.644;0.906	0.00	0.50	0.333;0.667	0.25;0.5;0.75		
C-C	0	0.5	0.359;0.641	0.278;0.5;0.722														
C-H					0	0.56	0.384;0.692	0.294;0.529;0.765										
H-F					0.736	0.446;0.853	0.308;0.616;0.898	0.235;0.471;0.707;0.922										

LLNL TIME SERIES									
V_L	5,934.91	233,658			Notch	34.059	Feet	3.976E-3	seconds
V_S	3,252.46	128,050			End	35.787	Feet	4.180E-3	seconds
V_E	5,214.86	205,310	5,170.15	17,109.13					
2.25 MHz			30 kHz		inches	feet			
Inch	Time	deltaT	Feet	Time	Freq.	Freq.			
1.00	8.56E-6	9.24E-6	1.00	116.90E-6	102,655	8,555			
2.00	17.12E-6	18.49E-6	2.00	233.79E-6	51,327	4,277			
3.00	25.68E-6		3.00	350.69E-6	34,218	2,852			
4.00	34.24E-6		4.00	467.59E-6	25,664	2,139			
5.00	42.80E-6		5.00	584.48E-6	20,531	1,711			
6.00	51.36E-6		6.00	701.38E-6	17,109	1,426			
7.00	59.92E-6		7.00	818.28E-6	14,665	1,222			
8.00	68.48E-6		8.00	935.17E-6	12,832	1,069			
9.00	77.04E-6		9.00	1.052E-3	11,406	951			
10.00	85.60E-6		10.00	1.169E-3	10,265	855			
11.00	94.15E-6		11.00	1.286E-3	9,332	778			
12.00	102.71E-6		12.00	1.403E-3	8,555	713			
13.00	111.27E-6		13.00	1.520E-3	7,897	658			
14.00	119.83E-6		14.00	1.637E-3	7,332	611			
15.00	128.39E-6		15.00	1.753E-3	6,844	570			
16.00	136.95E-6		16.00	1.870E-3	6,416	535			
17.00	145.51E-6		17.00	1.987E-3	6,039	503			
18.00	154.07E-6		18.00	2.104E-3	5,703	475			
19.00	162.63E-6		19.00	2.221E-3	5,403	450			
20.00	171.19E-6		20.00	2.338E-3	5,133	428			
21.00	179.75E-6		21.00	2.455E-3	4,888	407			
22.00	188.31E-6		22.00	2.572E-3	4,666	389			
23.00	196.87E-6		23.00	2.689E-3	4,463	372			
24.00	205.43E-6		24.00	2.806E-3	4,277	356			
25.00	213.99E-6		25.00	2.922E-3	4,106	342			
26.00	222.55E-6		26.00	3.039E-3	3,948	329			
27.00	231.11E-6		27.00	3.156E-3	3,802	317			
28.00	239.67E-6		28.00	3.273E-3	3,666	306			
29.00	248.23E-6		29.00	3.390E-3	3,540	295			
30.00	256.79E-6		30.00	3.507E-3	3,422	285			
31.00	265.35E-6		31.00	3.624E-3	3,311	276			
32.00	273.90E-6		32.00	3.741E-3	3,208	267			
33.00	282.46E-6		33.00	3.858E-3	3,111	259			
34.00	291.02E-6		34.00	3.974E-3	3,019	252			
35.00	299.58E-6		35.00	4.091E-3	2,933	244			
36.00	308.14E-6		36.00	4.208E-3	2,852	238			
37.00	316.70E-6		37.00	4.325E-3	2,774	231			
38.00	325.26E-6		38.00	4.442E-3	2,701	225			
39.00	333.82E-6		39.00	4.559E-3	2,632	219			
40.00	342.38E-6		40.00	4.676E-3	2,566	214			

TENDON FLEXURE, LLNL ROD																		
V_L	5,934.91	233,658	Diameter, m	35.940E-3														
V_E	5,214.86	205,310	17,109.13	Feet/sec														
V_s	3,252.46	128,050																
$I^{0.5}$	8.99E-3	8.99E-3																
A	22.40		1.404	1.406														
frequency	1	Hz	35.761															
Length	35.761	Feet																
	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00		
	947	4	8	13														
	1.378	2.287	3.203	4.118	1.143	2.059	2.969	3.885	0.546	1.378	2.287	3.203	0.915	1.830	2.745	3.660		
frequency	Table in Feet, Length of Tendon																Node Points in Feet	
Hertz	Free-Free; Clamped-Clamped				Clamped-Hinged; Hinged-Free				Clamped-Free				Hinged-Hinged				Tone & Freq.	35.756
35.76	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00	1	8.016
1	42.403	70.375	98.553	126.704	35.159	63.352	91.368	119.532	16.809	42.403	70.375	98.553	28.147	56.309	84.475	112.617	0.5-2.0 Hz	27.740
2	29.984	49.763	69.687	89.593	24.861	44.797	64.607	84.522	11.886	29.984	49.763	69.687	19.903	39.816	59.733	79.632		
3	24.482	40.631	56.899	73.153	20.299	36.576	52.751	69.012	9.705	24.482	40.631	56.899	16.251	32.510	48.771	65.019	2	4.723
4	21.202	35.187	49.276	63.352	17.579	31.676	45.684	59.766	8.405	21.202	35.187	49.276	14.074	28.154	42.237	56.309	4-5 Hz	17.878
5	18.963	31.473	44.074	56.664	15.724	28.332	40.861	53.457	7.517	18.963	31.473	44.074	12.588	25.182	37.778	50.364		31.033
6	17.311	28.730	40.234	51.727	14.354	25.863	37.301	48.799	6.862	17.311	28.730	40.234	11.491	22.988	34.487	45.976		
7	16.027	26.599	37.249	47.890	13.289	23.945	34.534	45.179	6.353	16.027	26.599	37.249	10.639	21.283	31.928	42.565	3	3.375
8	14.992	24.881	34.844	44.797	12.431	22.398	32.303	42.261	5.943	14.992	24.881	34.844	9.952	19.908	29.866	39.816	7-8 Hz	12.722
9	14.134	23.458	32.851	42.235	11.720	21.117	30.456	39.844	5.603	14.134	23.458	32.851	9.382	18.770	28.158	37.539		23.034
10	13.409	22.255	31.165	40.067	11.118	20.034	28.893	37.799	5.316	13.409	22.255	31.165	8.901	17.806	26.713	35.613		32.381
20	9.482	15.736	22.037	28.332	7.862	14.166	20.430	26.728	3.759	9.482	15.736	22.037	6.294	12.591	18.889	25.182		
30	7.742	12.849	17.993	23.133	6.419	11.566	16.681	21.824	3.069	7.742	12.849	17.993	5.139	10.280	15.423	20.561	4	2.624
40	6.705	11.127	15.583	20.034	5.559	10.017	14.446	18.900	2.658	6.705	11.127	15.583	4.450	8.903	13.357	17.806	10-20 Hz	9.904
50	5.997	9.953	13.937	17.919	4.972	8.959	12.921	16.904	2.377	5.997	9.953	13.937	3.981	7.963	11.947	15.926		17.878
60	5.474	9.085	12.723	16.357	4.539	8.179	11.796	15.432	2.170	5.474	9.085	12.723	3.634	7.269	10.906	14.539		25.852
70	5.068	8.411	11.779	15.144	4.202	7.572	10.921	14.287	2.009	5.068	8.411	11.779	3.364	6.730	10.097	13.460		33.132
80	4.741	7.868	11.019	14.166	3.931	7.083	10.215	13.364	1.879	4.741	7.868	11.019	3.147	6.295	9.445	12.591		
90	4.470	7.418	10.388	13.356	3.706	6.678	9.631	12.600	1.772	4.470	7.418	10.388	2.967	5.935	8.904	11.871		
100	4.240	7.037	9.855	12.670	3.516	6.335	9.137	11.953	1.681	4.240	7.037	9.855	2.815	5.631	8.447	11.262		
200	2.998	4.976	6.969	8.959	2.486	4.480	6.461	8.452	1.189	2.998	4.976	6.969	1.990	3.982	5.973	7.963		
300	2.448	4.063	5.690	7.315	2.030	3.658	5.275	6.901	0.970	2.448	4.063	5.690	1.625	3.251	4.877	6.502		
400	2.120	3.519	4.928	6.335	1.758	3.168	4.568	5.977	0.840	2.120	3.519	4.928	1.407	2.815	4.224	5.631		
500	1.896	3.147	4.407	5.666	1.572	2.833	4.086	5.346	0.752	1.896	3.147	4.407	1.259	2.518	3.778	5.036		
600	1.731	2.873	4.023	5.173	1.435	2.586	3.730	4.880	0.686	1.731	2.873	4.023	1.149	2.299	3.449	4.598		
700	1.603	2.660	3.725	4.789	1.329	2.394	3.453	4.518	0.635	1.603	2.660	3.725	1.064	2.128	3.193	4.257		
800	1.499	2.488	3.484	4.480	1.243	2.240	3.230	4.226	0.594	1.499	2.488	3.484	0.995	1.991	2.987	3.982		
900	1.413	2.346	3.285	4.223	1.172	2.112	3.046	3.984	0.560	1.413	2.346	3.285	0.938	1.877	2.816	3.754		
1,000	1.341	2.225	3.117	4.007	1.112	2.003	2.889	3.780	0.532	1.341	2.225	3.117	0.890	1.781	2.671	3.561		
2,000	0.948	1.574	2.204	2.833	0.786	1.417	2.043	2.673	0.376	0.948	1.574	2.204	0.629	1.259	1.889	2.518		
3,000	0.774	1.285	1.799	2.313	0.642	1.157	1.668	2.182	0.307	0.774	1.285	1.799	0.514	1.028	1.542	2.056		
4,000	0.670	1.113	1.558	2.003	0.556	1.002	1.445	1.890	0.266	0.670	1.113	1.558	0.445	0.890	1.336	1.781		
5,000	0.600	0.995	1.394	1.792	0.497	0.896	1.292	1.690	0.238	0.600	0.995	1.394	0.398	0.796	1.195	1.593		
6,000	0.547	0.909	1.272	1.636	0.454	0.818	1.180	1.543	0.217	0.547	0.909	1.272	0.363	0.727	1.091	1.454		
7,000	0.507	0.841	1.178	1.514	0.420	0.757	1.092	1.429	0.201	0.507	0.841	1.178	0.336	0.673	1.010	1.346		
8,000	0.474	0.787	1.102	1.417	0.393	0.708	1.022	1.336	0.188	0.474	0.787	1.102	0.315	0.630	0.944	1.259		
9,000	0.447	0.742	1.039	1.336	0.371	0.668	0.963	1.260	0.177	0.447	0.742	1.039	0.297	0.594	0.890	1.187		
10,000	0.424	0.704	0.986	1.267	0.352	0.634	0.914	1.195	0.168	0.424	0.704	0.986	0.281	0.563	0.845	1.126		
20,000	0.300	0.498	0.697	0.896	0.249	0.448	0.646	0.845	0.119	0.300	0.498	0.697	0.199	0.398	0.597	0.796		
30,000	0.245	0.406	0.569	0.732	0.203	0.366	0.528	0.690	0.097	0.245	0.406	0.569	0.163	0.325	0.488	0.650		
40,000	0.212	0.352	0.493	0.634	0.176	0.317	0.457	0.598	0.084	0.212	0.352	0.493	0.141	0.282	0.422	0.563		
50,000	0.190	0.315	0.441	0.567	0.157	0.283	0.409	0.535	0.075	0.190	0.315	0.441	0.126	0.252	0.378	0.504		
60,000	0.173	0.287	0.402	0.517	0.144	0.259	0.373	0.488	0.069	0.173	0.287	0.402	0.115	0.230	0.345	0.460		
70,000	0.160	0.266	0.372	0.479	0.133	0.239	0.345	0.452	0.064	0.160	0.266	0.372	0.106	0.213	0.319	0.426		
80,000	0.150	0.249	0.348	0.448	0.124	0.224	0.323	0.423	0.059	0.150	0.249	0.348	0.100	0.199	0.299	0.398		
90,000	0.141	0.235	0.329	0.422	0.117	0.211	0.305	0.398	0.056	0.141	0.235	0.329	0.094	0.188	0.282	0.375		
100,000	0.134	0.223	0.312	0.401	0.111	0.200	0.289	0.378	0.053	0.134	0.223	0.312	0.089	0.178	0.267	0.356		
F-F	0.224;0.776	0.132;0.5;0.868	0.094;0.356;0.644;0.906	0.073;0.277;0.5;0.723;0.927					0	0.774	0.5; 0.868	0.356;0.644;0.906	0.00	0.50	0.333;0.667	0.25;0.5;0.75		
C-C	0	0.5	0.359;0.641	0.278;0.5;0.722														
C-H					0	0.56	0.384;0.692	0.294;0.529;0.765										
H-F					0.736	0.446;0.853	0.308;0.616;0.898	0.235;0.471;0.707;0.922										

FOREBAY TIME SERIES						
V_L	5,928.85	233,419				
V_E	5,218.06	204,281	5,188.73	17,119.61		
V_S	3,256.13	128,194				
2.25 MHz			30 kHz		inches	feet
Inch	Time	deltaT	Feet	Time	Freq.	Freq.
1.00	8.57E-6	7.51E-6	1.00	116.83E-6	102,140	8,560
2.00	17.14E-6	15.02E-6	2.00	233.65E-6	51,070	4,280
3.00	25.70E-6		3.00	350.48E-6	34,047	2,853
4.00	34.27E-6		4.00	467.30E-6	25,535	2,140
5.00	42.84E-6		5.00	584.13E-6	20,428	1,712
6.00	51.41E-6		6.00	700.95E-6	17,023	1,427
7.00	59.98E-6		7.00	817.78E-6	14,591	1,223
8.00	68.55E-6		8.00	934.60E-6	12,768	1,070
9.00	77.11E-6		9.00	1.051E-3	11,349	951
10.00	85.68E-6		10.00	1.168E-3	10,214	856
11.00	94.25E-6		11.00	1.285E-3	9,285	778
12.00	102.82E-6		12.00	1.402E-3	8,512	713
13.00	111.39E-6		13.00	1.519E-3	7,857	658
14.00	119.96E-6		14.00	1.636E-3	7,296	611
15.00	128.52E-6		15.00	1.752E-3	6,809	571
16.00	137.09E-6		16.00	1.869E-3	6,384	535
17.00	145.66E-6		17.00	1.986E-3	6,008	504
18.00	154.23E-6		18.00	2.103E-3	5,674	476
19.00	162.80E-6		19.00	2.220E-3	5,376	451
20.00	171.37E-6		20.00	2.337E-3	5,107	428
21.00	179.93E-6		21.00	2.453E-3	4,864	408
22.00	188.50E-6		22.00	2.570E-3	4,643	389
23.00	197.07E-6		23.00	2.687E-3	4,441	372
24.00	205.64E-6		24.00	2.804E-3	4,256	357
25.00	214.21E-6		25.00	2.921E-3	4,086	342
26.00	222.77E-6		26.00	3.037E-3	3,928	329
27.00	231.34E-6		27.00	3.154E-3	3,783	317
28.00	239.91E-6		28.00	3.271E-3	3,648	306
29.00	248.48E-6		29.00	3.388E-3	3,522	295
30.00	257.05E-6		30.00	3.505E-3	3,405	285
31.00	265.62E-6		31.00	3.622E-3	3,295	276
32.00	274.18E-6		32.00	3.738E-3	3,192	267
33.00	282.75E-6		33.00	3.855E-3	3,095	259
34.00	291.32E-6		34.00	3.972E-3	3,004	252
35.00	299.89E-6		35.00	4.089E-3	2,918	245
36.00	308.46E-6		36.00	4.206E-3	2,837	238
37.00	317.03E-6		37.00	4.323E-3	2,761	231
38.00	325.59E-6		38.00	4.439E-3	2,688	225
39.00	334.16E-6		39.00	4.556E-3	2,619	219
40.00	342.73E-6		40.00	4.673E-3	2,554	214

5058 PR
30 kHz - DEEP
PRR = 20
Damping = 100
Pulse Height = 100 - 200
Attenuation = 0 / 2 dB
Filter = 0.3 / 0.5

2.25 MHz - 18 inches
PRR = 100
Damping = 50
Pulse Height = 100
Attenuation = 0 / 0 dB
Filter = 1/0 / OUT

Set graph for ± 2 volts FSD

Pier 1 is West Side

From Top looking down:

1 2
3 4

<=TENDON RANGE

TENDON FLEXURE, FOREBAY

V_L	5,928.85	233,419	Diameter, m	29.255E-3															
V_E	5,218.06	205,435	17,119.61	Feet/sec															
V_s	3,256.13	128,194																	
$I^{0.5}$	7.31E-3	7.31E-3																	
A	22.4																		
frequency	2	Hz																	
Length	27.060	Feet																	
	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00			
	2	6	11	18															
	27.060	44.910	62.892	80.857	22.437	40.429	58.307	76.281	10.727	27.060	44.910	62.892	17.962	35.934	53.908	71.868			
frequency	Table in Feet, Length of Tendon																Node Points in Feet		
Hertz	Free-Free; Clamped-Clamped				Clamped-Hinged; Hinged-Free				Clamped-Free				Hinged-Hinged				Tone & Freq.	22	27
27.060	22.40	61.70	121.00	200.00	15.40	50.00	104.00	178.00	3.52	22.40	61.70	121.00	9.87	39.50	88.90	158.00	1	0.00	0.00
1	38.269	63.513	88.943	114.350	31.731	57.175	82.459	107.877	15.170	38.269	63.513	88.943	25.403	50.818	76.238	101.636	1-4 Hz		
2	27.060	44.910	62.892	80.857	22.437	40.429	58.307	76.281	10.727	27.060	44.910	62.892	17.962	35.934	53.908	71.868			
3	22.094	36.669	51.351	66.020	18.320	33.010	47.608	62.283	8.759	22.094	36.669	51.351	14.666	29.340	44.016	58.680	2	11.00	13.50
4	19.134	31.756	44.472	57.175	15.865	28.587	41.229	53.939	7.585	19.134	31.756	44.472	12.701	25.409	38.119	50.818	5-9 Hz		
5	17.114	28.404	39.777	51.139	14.190	25.569	36.877	48.244	6.784	17.114	28.404	39.777	11.360	22.727	34.095	45.453			
6	15.623	25.929	36.311	46.683	12.954	23.342	33.664	44.041	6.193	15.623	25.929	36.311	10.371	20.746	31.124	41.493	3	7.90	9.69
7	14.464	24.006	33.617	43.220	11.993	21.610	31.166	40.774	5.734	14.464	24.006	33.617	9.601	19.207	28.815	38.415	10-20 Hz	14.10	17.31
8	13.530	22.455	31.446	40.429	11.219	20.214	29.154	38.140	5.363	13.530	22.455	31.446	8.981	17.967	26.954	35.934			
9	12.756	21.171	29.648	38.117	10.577	19.058	27.486	35.959	5.057	12.756	21.171	29.648	8.468	16.939	25.413	33.879	4	6.12	7.51
10	12.102	20.085	28.126	36.161	10.034	18.080	26.076	34.114	4.797	12.102	20.085	28.126	8.033	16.070	24.109	32.140	10-30 Hz	11.00	13.50
20	8.557	14.202	19.888	25.569	7.095	12.785	18.438	24.122	3.392	8.557	14.202	19.888	5.680	11.363	17.047	22.727		15.88	19.49
30	6.987	11.596	16.239	20.877	5.793	10.439	15.055	19.696	2.770	6.987	11.596	16.239	4.638	9.278	13.919	18.556			
40	6.051	10.042	14.063	18.080	5.017	9.040	13.038	17.057	2.399	6.051	10.042	14.063	4.017	8.035	12.054	16.070			
50	5.412	8.982	12.578	16.171	4.487	8.086	11.661	15.256	2.145	5.412	8.982	12.578	3.592	7.187	10.782	14.374			
60	4.940	8.199	11.483	14.762	4.096	7.381	10.645	13.927	1.958	4.940	8.199	11.483	3.279	6.561	9.842	13.121			
70	4.574	7.591	10.631	13.667	3.793	6.834	9.856	12.894	1.813	4.574	7.591	10.631	3.036	6.074	9.112	12.148			
80	4.279	7.101	9.944	12.785	3.548	6.392	9.219	12.061	1.696	4.279	7.101	9.944	2.840	5.682	8.524	11.363			
90	4.034	6.695	9.375	12.054	3.345	6.027	8.692	11.371	1.599	4.034	6.695	9.375	2.678	5.357	8.036	10.713			
100	3.827	6.351	8.894	11.435	3.173	5.717	8.246	10.788	1.517	3.827	6.351	8.894	2.540	5.082	7.624	10.164			
200	2.706	4.491	6.289	8.086	2.244	4.043	5.831	7.628	1.073	2.706	4.491	6.289	1.796	3.593	5.391	7.187			
300	2.209	3.667	5.135	6.602	1.832	3.301	4.761	6.228	0.876	2.209	3.667	5.135	1.467	2.934	4.402	5.868			
400	1.913	3.176	4.447	5.717	1.587	2.859	4.123	5.394	0.759	1.913	3.176	4.447	1.270	2.541	3.812	5.082			
500	1.711	2.840	3.978	5.114	1.419	2.557	3.688	4.824	0.678	1.711	2.840	3.978	1.136	2.273	3.409	4.545			
600	1.562	2.593	3.631	4.668	1.295	2.334	3.366	4.404	0.619	1.562	2.593	3.631	1.037	2.075	3.112	4.149			
700	1.446	2.401	3.362	4.322	1.199	2.161	3.117	4.077	0.573	1.446	2.401	3.362	0.960	1.921	2.882	3.841			
800	1.353	2.246	3.145	4.043	1.122	2.021	2.915	3.814	0.536	1.353	2.246	3.145	0.898	1.797	2.695	3.593			
900	1.276	2.117	2.965	3.812	1.058	1.906	2.749	3.596	0.506	1.276	2.117	2.965	0.847	1.694	2.541	3.388			
1,000	1.210	2.008	2.813	3.616	1.003	1.808	2.608	3.411	0.480	1.210	2.008	2.813	0.803	1.607	2.411	3.214			
2,000	0.856	1.420	1.989	2.557	0.710	1.278	1.844	2.412	0.339	0.856	1.420	1.989	0.568	1.136	1.705	2.273			
3,000	0.699	1.160	1.624	2.088	0.579	1.044	1.505	1.970	0.277	0.699	1.160	1.624	0.464	0.928	1.392	1.856			
4,000	0.605	1.004	1.406	1.808	0.502	0.904	1.304	1.706	0.240	0.605	1.004	1.406	0.402	0.804	1.205	1.607			
5,000	0.541	0.898	1.258	1.617	0.449	0.809	1.166	1.526	0.215	0.541	0.898	1.258	0.359	0.719	1.078	1.437			
6,000	0.494	0.820	1.148	1.476	0.410	0.738	1.065	1.393	0.196	0.494	0.820	1.148	0.328	0.656	0.984	1.312			
7,000	0.457	0.759	1.063	1.367	0.379	0.683	0.986	1.289	0.181	0.457	0.759	1.063	0.304	0.607	0.911	1.215			
8,000	0.428	0.710	0.994	1.278	0.355	0.639	0.922	1.206	0.170	0.428	0.710	0.994	0.284	0.568	0.852	1.136			
9,000	0.403	0.669	0.938	1.205	0.334	0.603	0.869	1.137	0.160	0.403	0.669	0.938	0.268	0.536	0.804	1.071			
10,000	0.383	0.635	0.889	1.143	0.317	0.572	0.825	1.079	0.152	0.383	0.635	0.889	0.254	0.508	0.762	1.016			
20,000	0.271	0.449	0.629	0.809	0.224	0.404	0.583	0.763	0.107	0.271	0.449	0.629	0.180	0.359	0.539	0.719			
30,000	0.221	0.367	0.514	0.660	0.183	0.330	0.476	0.623	0.088	0.221	0.367	0.514	0.147	0.293	0.440	0.587			
40,000	0.191	0.318	0.445	0.572	0.159	0.286	0.412	0.539	0.076	0.191	0.318	0.445	0.127	0.254	0.381	0.508			
50,000	0.171	0.284	0.398	0.511	0.142	0.256	0.369	0.482	0.068	0.171	0.284	0.398	0.114	0.227	0.341	0.455			
60,000	0.156	0.259	0.363	0.467	0.130	0.233	0.337	0.440	0.062	0.156	0.259	0.363	0.104	0.207	0.311	0.415			
70,000	0.145	0.240	0.336	0.432	0.120	0.216	0.312	0.408	0.057	0.145	0.240	0.336	0.096	0.192	0.288	0.384			
80,000	0.135	0.225	0.314	0.404	0.112	0.202	0.292	0.381	0.054	0.135	0.225	0.314	0.090	0.180	0.270	0.359			
90,000	0.128	0.212	0.296	0.381	0.106	0.191	0.275	0.360	0.051	0.128	0.212	0.296	0.085	0.169	0.254	0.339			
100,000	0.121	0.201	0.281	0.362	0.100	0.181	0.261	0.341	0.048	0.121	0.201	0.281	0.080	0.161	0.241	0.321			
F-F	0.224;0.776	0.132;0.5;0.868	0.094;0.356;0.644;0.906	0.073;0.277;0.5;0.723;0.927					0	0.774	0.5; 0.868	0.356;0.644;0.906	0.00	0.50	0.333;0.667	0.25;0.5;0.75			
C-C	0	0.5	0.359;0.641	0.278;0.5;0.722															
C-H					0	0.56	0.384;0.692	0.294;0.529;0.765											
H-F					0.736	0.446;0.853	0.308;0.616;0.898	0.235;0.471;0.707;0.922											

FLEXURAL VIBRATIONS: DWR-LLNL Steel										
E	211.793E+9						f_L	f_S		
ρ	7,788			Air Impedance	444.792		82,567	45,249	1.375"	
γ	0.2854			Concrete Z	13.80E+6		101,434	55,588	1.125"	
C_E	5,214.86	5,218.06		5,441.13	V_P		272	149	36.0'	
Trial f	10.00	54.26		5,214.86	V_B					
53.73	35.940E-3	Bars-Rods		4,599.68	V_L'					
Plates	29.255E-3	36.89								
39.63	(af)^0.5	36.88	36 feet =	10.908						
Hertz	m/s		Feet		Rayles		Transmission Intensity		DISPLACEMENTS, IN	
frequency	1.375" Rod C_F	1.125" Rod C_F	1.375" Rod λ	1.125" Rod λ	Z_1.375"	Z_1.125"	Coeff. Concrete		PROPORTIONALITY	
1	55	50	18.18	16.41	431.638E+3	389.467E+3	11.76%	10.68%	347.280	313.351
2	25	22	40.66	36.69	193.034E+3	174.175E+3	5.44%	4.92%	77.654	70.067
3	30	27	33.20	29.95	236.418E+3	213.320E+3	6.62%	6.00%	63.404	57.210
4	35	32	28.75	25.94	272.992E+3	246.321E+3	7.61%	6.89%	54.910	49.545
5	39	35	25.72	23.20	305.214E+3	275.395E+3	8.47%	7.67%	49.113	44.315
6	43	39	23.47	21.18	334.345E+3	301.680E+3	9.24%	8.37%	44.834	40.453
7	46	42	21.73	19.61	361.134E+3	325.852E+3	9.94%	9.01%	41.508	37.453
8	50	45	20.33	18.34	386.069E+3	348.350E+3	10.59%	9.61%	38.827	35.034
9	53	47	19.17	17.29	409.488E+3	369.481E+3	11.19%	10.16%	36.607	33.030
10	55	50	18.18	16.41	431.638E+3	389.467E+3	11.76%	10.68%	34.728	31.335
20	78	71	12.86	11.60	610.428E+3	550.790E+3	16.23%	14.76%	24.556	22.157
30	96	87	10.50	9.47	747.619E+3	674.577E+3	19.50%	17.77%	20.050	18.091
40	111	100	9.09	8.20	863.276E+3	778.934E+3	22.16%	20.23%	17.364	15.668
50	124	112	8.13	7.34	965.172E+3	870.875E+3	24.44%	22.33%	15.531	14.013
60	136	122	7.42	6.70	1.057E+6	953.996E+3	26.44%	24.19%	14.178	12.793
70	147	132	6.87	6.20	1.142E+6	1.030E+6	28.24%	25.86%	13.126	11.844
80	157	141	6.43	5.80	1.221E+6	1.102E+6	29.87%	27.38%	12.278	11.079
90	166	150	6.06	5.47	1.295E+6	1.168E+6	31.37%	28.79%	11.576	10.445
100	175	158	5.75	5.19	1.365E+6	1.232E+6	32.76%	30.09%	10.982	9.909
200	248	224	4.07	3.67	1.930E+6	1.742E+6	43.06%	39.80%	7.765	7.007
300	304	274	3.32	3.00	2.364E+6	2.133E+6	49.95%	46.38%	6.340	5.721
400	351	316	2.88	2.59	2.730E+6	2.463E+6	55.15%	51.41%	5.491	4.955
500	392	354	2.57	2.32	3.052E+6	2.754E+6	59.32%	55.47%	4.911	4.431
600	429	387	2.35	2.12	3.343E+6	3.017E+6	62.80%	58.88%	4.483	4.045
700	464	418	2.17	1.96	3.611E+6	3.259E+6	65.76%	61.81%	4.151	3.745
800	496	447	2.03	1.83	3.861E+6	3.483E+6	68.33%	64.37%	3.883	3.503
900	526	474	1.92	1.73	4.095E+6	3.695E+6	70.59%	66.64%	3.661	3.303
1,000	554	500	1.82	1.64	4.316E+6	3.895E+6	72.60%	68.66%	3.473	3.134
2,000	784	707	1.29	1.16	6.104E+6	5.508E+6	85.05%	81.56%	2.456	2.216
3,000	960	866	1.05	0.95	7.476E+6	6.746E+6	91.17%	88.21%	2.005	1.809
4,000	1,108	1,000	0.91	0.82	8.633E+6	7.789E+6	94.69%	92.25%	1.736	1.567
5,000	1,239	1,118	0.81	0.73	9.652E+6	8.709E+6	96.87%	94.88%	1.553	1.401
6,000	1,358	1,225	0.74	0.67	10.573E+6	9.540E+6	98.25%	96.67%	1.418	1.279
7,000	1,466	1,323	0.69	0.62	11.420E+6	10.304E+6	99.11%	97.90%	1.313	1.184
8,000	1,568	1,414	0.64	0.58	12.209E+6	11.016E+6	99.63%	98.74%	1.228	1.108
9,000	1,663	1,500	0.61	0.55	12.949E+6	11.684E+6	99.90%	99.31%	1.158	1.045
10,000	1,753	1,581	0.58	0.52	13.650E+6	12.316E+6	100.00%	99.68%	1.098	0.991
20,000	2,479	2,236	0.41	0.37	19.303E+6	17.417E+6	97.24%	98.66%	0.777	0.701
30,000	3,036	2,739	0.33	0.30	23.642E+6	21.332E+6	93.09%	95.40%	0.634	0.572
40,000	3,505	3,163	0.29	0.26	27.299E+6	24.632E+6	89.21%	92.06%	0.549	0.495
50,000	3,919	3,536	0.26	0.23	30.521E+6	27.539E+6	85.77%	88.95%	0.491	0.443
60,000	4,293	3,874	0.23	0.21	33.435E+6	30.168E+6	82.72%	86.14%	0.448	0.405
70,000	4,637	4,184	0.22	0.20	36.113E+6	32.585E+6	80.02%	83.60%	0.415	0.375
80,000	4,957	4,473	0.20	0.18	38.607E+6	34.835E+6	77.59%	81.29%	0.388	0.350
90,000	5,934.91	5,928.85	0.06	0.05	46.221E+6	46.174E+6	70.82%	70.86%	0.413	0.413
100,000	5,934.91	5,928.85	0.06	0.05	46.221E+6	46.174E+6	70.82%	70.86%	0.372	0.371
V_L	V_S									
5,934.91	3,252.46	fD LLNL					fD Forebay			
		m =	1	2	3	4	m =	1	2	3
-0.759	2.126	Sym_N	2,300	6,900	11,499	16,099	Sym_N	2,302	6,900	11,499
2.126	4.971	ASym_N	4,600	9,199	13,799	18,399	ASym_N	4,600	9,199	13,799
4.971	8.017	Sym_N	2,967	8,902	14,837	20,772	Sym_N	2,967	8,902	14,837
8.017	11.114	ASym_N	5,935	11,870	17,805	23,740	ASym_N	5,935	11,870	17,805
11.114		Sym_IP	3,252	6,505	9,757	13,010	Sym_IP	3,252	6,505	9,757
		ASym_IP	1,626	4,879	8,131	11,384	ASym_IP	1,626	4,879	8,131
		Sym_IP	3,888	7,777	11,665	15,553	Sym_IP	3,888	7,777	11,665
1.000000		ASym_IP	2,631	6,153	9,922	13,755	ASym_IP	2,638	6,158	9,926
		FREQUENCIES for 1.375" thickness					FREQUENCIES for 1.125" thickness			
-1.613255219		Sym_N	63.991E+3	191.973E+3	319.955E+3	447.937E+3	78.702E+3	235.841E+3	393.068E+3	550.295E+3
-1.61325639		ASym_N	127.982E+3	255.964E+3	383.946E+3	511.928E+3	157.227E+3	314.454E+3	471.681E+3	628.908E+3
		Sym_N	82.567E+3	247.701E+3	412.835E+3	577.968E+3	101.434E+3	304.302E+3	507.171E+3	710.039E+3
V_L	V_S	ASym_N	165.134E+3	330.268E+3	495.401E+3	660.535E+3	202.868E+3	405.736E+3	608.605E+3	811.473E+3
5,928.85	3,256.13	Sym_IP	90.497E+3	180.994E+3	271.491E+3	361.988E+3	111.176E+3	222.353E+3	333.529E+3	444.705E+3
		ASym_IP	45.249E+3	135.746E+3	226.243E+3	316.740E+3	55.588E+3	166.764E+3	277.941E+3	389.117E+3
-0.747301098	2.131	Sym_IP	108.190E+3	216.380E+3	324.570E+3	432.760E+3	132.912E+3	265.825E+3	398.737E+3	531.649E+3
2.131	4.975	ASym_IP	73.205E+3	171.207E+3	276.085E+3	382.729E+3	90.175E+3	210.485E+3	339.276E+3	470.262E+3
4.975	8.019	Sym_N	343	1,029	1,715	2,401	280	838	1,397	1,956
8.019	11.115	ASym_N	686	1,372	2,058	2,744	559	1,118	1,677	2,236
11.115		Sym_N	443	1,328	2,213	3,098	361	1,082	1,803	2,524
	6.7056	ASym_N	885	1,770	2,655	3,540	721	1,442	2,163	2,885
1.000000002	8.2296	Sym_IP	485	970	1,455	1,940	395	790	1,186	1,581
		ASym_IP	243	728	1,213	1,698	198	593	988	1,383
		Sym_IP	580	1,160	1,740	2,319	472	945	1,417	1,890
		ASym_IP	393	918	1,480	2,052	321	748	1,206	1,672
			22 feet Length Left				27 feet Length Right			

	Frequencies for LLNL Rod Length			
Sym_N	211	633	1,054	1,476
ASym_N	422	843	1,265	1,687
Sym_N	272	816	1,360	1,904
ASym_N	544	1,088	1,632	2,176
Sym_IP	298	596	895	1,193
ASym_IP	149	447	745	1,044
Sym_IP	356	713	1,069	1,426
ASym_IP	241	564	910	1,261
	36 Feet Length			

FOREBAY FLEXURAL VIBRATIONS: CONCRETE nondescript

E	21.720E+9	2.50					V_L	V_S		
ρ	2,300	3.83		Air Impedanc	444.792		4,264	2,598	15"	
γ	0.2051			Water Z	1,490,000		2,781	1,694	23"	
C_E	3,072.80			3,139.57	V_P		21,322	12,988	3.0"	
Trial f	1.00			3,072.83	V_B		5.54	34.72	97.22	Hz
	0.381000	Bars-Rods		2,799.15	V_L'	316 SS	77.98	Impedance	7.474E+6	
Plates	0.584200						625,314.02	Waveguide F	Refl.Coef. =	(1.0000)
30.10	(af)^0.5	28.02								
Hertz	m/s		Feet		Rayles		Intensity		DISPLACEMENTS, IN	
frequency	15" Plate C_F	23" Plate C_F	15" Plate λ	23" Plate λ	Z_15"	Z_23"	Transmission Coeff. Water		PROPORTIONALITY	
1	47	58	152.82	189.23	107.132E+3	132.659E+3	25.03%	30.03%	291.8615	361.4058
2	66	82	108.06	133.81	151.507E+3	187.608E+3	33.51%	39.73%	206.3772	255.5525
3	81	100	88.23	109.25	185.558E+3	229.772E+3	39.39%	46.30%	168.5063	208.6577
4	93	115	76.41	94.62	214.263E+3	265.318E+3	43.97%	51.32%	145.9307	180.7029
5	104	129	68.34	84.63	239.554E+3	296.634E+3	47.73%	55.39%	130.5244	161.6256
6	114	141	62.39	77.25	262.418E+3	324.947E+3	50.93%	58.79%	119.1519	147.5433
7	123	153	57.76	71.52	283.444E+3	350.983E+3	53.71%	61.72%	110.3133	136.5985
8	132	163	54.03	66.90	303.014E+3	375.216E+3	56.17%	64.28%	103.1886	127.7762
9	140	173	50.94	63.08	321.395E+3	397.977E+3	58.38%	66.54%	97.2872	120.4686
10	147	182	48.33	59.84	338.780E+3	419.504E+3	60.37%	68.57%	92.2947	114.2865
20	208	258	34.17	42.31	479.108E+3	593.269E+3	73.64%	81.47%	65.2622	80.8128
30	255	316	27.90	34.55	586.785E+3	726.603E+3	81.09%	88.14%	53.2864	65.9834
40	295	365	24.16	29.92	677.561E+3	839.009E+3	85.95%	92.19%	46.1474	57.1433
50	329	408	21.61	26.76	757.536E+3	938.040E+3	89.38%	94.83%	41.2754	51.1105
60	361	447	19.73	24.43	829.839E+3	1.028E+6	91.90%	96.63%	37.6792	46.6573
70	390	483	18.27	22.62	896.329E+3	1.110E+6	93.81%	97.86%	34.8841	43.1962
80	417	516	17.09	21.16	958.215E+3	1.187E+6	95.28%	98.71%	32.6311	40.4064
90	442	547	16.11	19.95	1.016E+6	1.259E+6	96.43%	99.29%	30.7649	38.0955
100	466	577	15.28	18.92	1.071E+6	1.327E+6	97.33%	99.66%	29.1861	36.1406
200	659	816	10.81	13.38	1.515E+6	1.876E+6	99.99%	98.68%	20.6377	25.5552
300	807	999	8.82	10.93	1.856E+6	2.298E+6	98.81%	95.45%	16.8506	20.8658
400	932	1,154	7.64	9.46	2.143E+6	2.653E+6	96.77%	92.12%	14.5931	18.0703
500	1,042	1,290	6.83	8.46	2.396E+6	2.966E+6	94.57%	89.02%	13.0524	16.1626
600	1,141	1,413	6.24	7.73	2.624E+6	3.249E+6	92.40%	86.22%	11.9152	14.7543
700	1,232	1,526	5.78	7.15	2.834E+6	3.510E+6	90.33%	83.68%	11.0313	13.6599
800	1,317	1,631	5.40	6.69	3.030E+6	3.752E+6	88.39%	81.38%	10.3189	12.7776
900	1,397	1,730	5.09	6.31	3.214E+6	3.980E+6	86.57%	79.28%	9.7287	12.0469
1,000	1,473	1,824	4.83	5.98	3.388E+6	4.195E+6	84.86%	77.36%	9.2295	11.4287
2,000	2,083	2,579	3.42	4.23	4.791E+6	5.933E+6	72.38%	64.18%	6.5262	8.0813
3,000	2,551	3,159	2.79	3.45	5.868E+6	7.266E+6	64.60%	56.48%	5.3286	6.5983
4,000	2,946	3,648	2.42	2.99	6.776E+6	8.390E+6	59.11%	51.23%	4.6147	5.7143
5,000	3,294	4,078	2.16	2.68	7.575E+6	9.380E+6	54.94%	47.31%	4.1275	5.1110
6,000	3,608	4,468	1.97	2.44	8.298E+6	10.276E+6	51.62%	44.24%	3.7679	4.6657
7,000	3,897	4,826	1.83	2.26	8.963E+6	11.099E+6	48.89%	41.74%	3.4884	4.3196
8,000	4,166	5,159	1.71	2.12	9.582E+6	11.865E+6	46.58%	39.65%	3.2631	4.0406
9,000	4,419	5,472	1.61	1.99	10.163E+6	12.585E+6	44.60%	37.86%	3.0765	3.8096
10,000	4,658	5,768	1.53	1.89	10.713E+6	13.266E+6	42.88%	36.31%	2.9186	3.6141
20,000	6,587	8,157	1.08	1.34	15.151E+6	18.761E+6	32.61%	27.27%	2.0638	2.5555
30,000	8,068	9,990	0.88	1.09	18.556E+6	22.977E+6	27.52%	22.88%	1.6851	2.0866
40,000	9,316	11,536	0.76	0.95	21.426E+6	26.532E+6	24.32%	20.14%	1.4593	1.8070
50,000	10,415	12,897	0.68	0.85	23.955E+6	29.663E+6	22.05%	18.22%	1.3052	1.6163
60,000	11,409	14,128	0.62	0.77	26.242E+6	32.495E+6	20.34%	16.77%	1.1915	1.4754
70,000	12,324	15,260	0.58	0.72	28.344E+6	35.098E+6	18.98%	15.63%	1.1031	1.3660
80,000	13,175	16,314	0.54	0.67	30.301E+6	37.522E+6	17.87%	14.69%	1.0319	1.2778
90,000	13,974	17,303	0.51	0.63	32.140E+6	39.798E+6	16.94%	13.91%	0.9729	1.2047
100,000	14,730	18,239	0.48	0.60	33.878E+6	41.950E+6	16.14%	13.25%	0.9229	1.1429
V_L	V_S									
3,250	1,979			fD						
		m =	1	2	3	4				
-0.285210	2.519	Sym_N	1,400	4,199	6,998	9,797				
2.518660	5.297	ASym_N	2,799	5,598	8,397	11,197				
5.297090	8.256	Sym_N	1,625	4,874	8,124	11,373				
8.255602	11.297	ASym_N	3,250	6,499	9,749	12,998				
11.296525		Sym_IP	1,979	3,959	5,938	7,917				
		ASym_IP	990	2,969	4,948	6,928				
		Sym_IP	2,496	4,991	7,487	9,983				
1.000000		ASym_IP	2,001	4,208	6,558	8,974				
		FREQUENCIES for 15" thickness					FREQUENCIES for 23" thickness			
-0.718345898		Sym_N	3,673	11,020	18,367	25,714	2,396	7,187	11,979	16,770
-0.718345805		ASym_N	7,347	14,694	22,041	29,387	4,791	9,583	14,374	19,166
		Sym_N	4,264	12,793	21,322	29,851	2,781	8,344	13,906	19,468
		ASym_N	8,529	17,058	25,587	34,116	5,562	11,125	16,687	22,249
		Sym_IP	5,195	10,390	15,585	20,780	3,388	6,776	10,164	13,552
		ASym_IP	2,598	7,793	12,988	18,183	1,694	5,082	8,470	11,858
		Sym_IP	6,550	13,101	19,651	26,201	4,272	8,544	12,816	17,088
		ASym_IP	5,252	11,045	17,213	23,554	3,425	7,203	11,226	15,361

OROVILLE DAM TIME SERIES				
V_L	5,945.16	234,061		
V_E	5,228.20	205,835		
V_S	3,261.63	128,411		
5 MHz			30 kHz	
Inch	Time	deltaT	Feet	Time
1	8.54E-6	9.21E-6	1	116.60E-6
2	17.09E-6	18.43E-6	2	233.20E-6
3	25.63E-6		3	349.80E-6
4	34.18E-6		4	466.39E-6
5	42.72E-6		5	582.99E-6
6	51.27E-6		6	699.59E-6
7	59.81E-6		7	816.19E-6
8	68.36E-6		8	932.79E-6
9	76.90E-6		9	1.049E-3
10	85.45E-6		10	1.166E-3
11	93.99E-6		11	1.283E-3
12	102.54E-6		12	1.399E-3
13	111.08E-6		13	1.516E-3
14	119.63E-6		14	1.632E-3
15	128.17E-6		15	1.749E-3
16	136.72E-6		16	1.866E-3
17	145.26E-6		17	1.982E-3
18	153.81E-6		18	2.099E-3
19	162.35E-6		19	2.215E-3
20	170.90E-6		20	2.332E-3
21	179.44E-6		21	2.449E-3
22	187.98E-6		22	2.565E-3
23	196.53E-6		23	2.682E-3
24	205.07E-6		24	2.798E-3
25	213.62E-6		25	2.915E-3
26	222.16E-6		26	3.032E-3
27	230.71E-6		27	3.148E-3
28	239.25E-6		28	3.265E-3
29	247.80E-6		29	3.381E-3
30	256.34E-6		30	3.498E-3
31	264.89E-6		31	3.615E-3
32	273.43E-6		32	3.731E-3
33	281.98E-6		33	3.848E-3
34	290.52E-6		34	3.964E-3
35	299.07E-6		35	4.081E-3
36	307.61E-6		36	4.198E-3
37	316.16E-6		37	4.314E-3
38	324.70E-6		38	4.431E-3
39	333.25E-6		39	4.547E-3
40	341.79E-6		40	4.664E-3

LLNL ROD Supported at one end, Free at the other					
TRANSVERSE VIBRATIONS					
FUNDAMENTAL					
Failure Location	Unknown	meter above bottom anchor			
Extensional Velocity	5,215	m/s	205,309	Inches/sec	
Rod Diameter	35.940E-3	m	1.415	Inches	
Number of wires	1	Forming Cable			
Est. Area of Cable	1.014E-3	m^2			
Est. Dia. of Cable	35.940E-3	m	1.415	Inches	
Est. Length	10.97	m	36.00	Feet	
Fundamental = f_1	1.91	Hz			
First Tone	1.91	Hz			
Flexural Velocity	84	m/s	3,295	Inches/sec	
Nodes					
0	10.97	m from free end	36.00	Feet	
FIRST OVERTONE					
Failure Location	Unknown	meter above bottom anchor			
Extensional Velocity	5,215	m/s	205,309	Inches/sec	
Rod Diameter	35.940E-3	m	1.415	Inches	
Number of wires	1	Forming Cable			
Est. Area of Cable	1.014E-3	m^2			
Est. Dia. of Cable	35.940E-3	m	1.415	Inches	
Est. Length	10.97	m	36.00	Feet	
Fundamental	1.91	Hz			
Second Tone	6.20	Hz			
Flexural Velocity	91	m/s	3,570	Inches/sec	
Nodes					
0	10.97	m from free end	36.00	Feet	
1	2.38	m from free end	7.79	Feet	
SECOND OVERTONE					
Failure Location	Unknown	meter above bottom anchor			
Extensional Velocity	5,215	m/s	205,309	Inches/sec	
Rod Diameter	35.940E-3	m	1.415	Inches	
Number of wires	1	Forming Cable			
Est. Area of Cable	1.014E-3	m^2			
Est. Dia. of Cable	35.940E-3	m	1.415	Inches	
Est. Length	10.97	m	36.00	Feet	
Fundamental	1.91	Hz			
Third Tone	12.87	Hz			
Flexural Velocity	113	m/s	4,448	Inches/sec	
Nodes					
0	10.97	m from free end	36.00	Feet	
1	5.49	m from free end	18.00	Feet	
2	1.45	m from free end	4.76	Feet	
THIRD OVERTONE					
Failure Location	Unknown	meter above bottom anchor			
Extensional Velocity	5,215	m/s	205,309	Inches/sec	
Rod Diameter	35.940E-3	m	1.415	Inches	
Number of wires	1	Forming Cable			
Est. Area of Cable	1.014E-3	m^2			
Est. Dia. of Cable	35.940E-3	m	1.415	Inches	
Est. Length	10.97	m	36.00	Feet	
Fundamental	1.91	Hz			
Fourth Tone	21.93	Hz			
Flexural Velocity	137	m/s	5,413	Inches/sec	
Nodes					
0	10.97	m from free end	36.00	Feet	
1	7.07	m from free end	23.18	Feet	
2	3.90	m from free end	12.81	Feet	
3	1.04	m from free end	3.40	Feet	
FOURTH OVERTONE					
Failure Location	Unknown	meter above bottom anchor			
Extensional Velocity	5,215	m/s	205,309	Inches/sec	
Rod Diameter	35.940E-3	m	1.415	Inches	
Number of wires	1.00	Forming Cable			
Est. Area of Cable	1.014E-3	m^2			
Est. Dia. of Cable	35.940E-3	m	1.415	Inches	
Est. Length	10.97	m	36.00	Feet	
Fundamental	1.91	Hz			
Fourth Tone	33.75	Hz			
Flexural Velocity	165	m/s	6,480	Inches/sec	
Nodes					
0	10.97	m from free end	36.00	Feet	
1	8.53	m from free end	28.00	Feet	
2	6.10	m from free end	20.00	Feet	
3	3.66	m from free end	12.00	Feet	
4	0.21	m from free end	0.70	Feet	
period	0.029628171	1.2192		1.2192	0.111111111
2.25 cycles	0.066663385			3.6576	0.333333333
velocity, flex	164.600102			6.096	0.555555556
				8.5344	0.777777778