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EFFECT OF SONIC BOOM ON FISH

Robert S. Rucker

Bureau of Sport Fisheries and Wildlife

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Robert R. Rucker
Western Fish Disease Laboratory
Bureau of Sport Fisheries and Wildlife
Fish and Wildlife Service
U.S. Department of Interior

February 1973

FINAL REPORT

Details of illustrations in this document may be better studied on microfiche

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16 Abstract

A program was initiated to study the effect of sonic boom on fish and fish eggs during critical stages of development. During the development of fish eggs they reach a critical period where they become sensitive to vibration or disturbance. This program was designed to determine if the disturbances caused by sonic booms could have a detrimental effect during this period. It consisted of both field and laboratory tests conducted at several National Fish Hatcheries (NFH).

Fish eggs from both trout and salmon were reared in the normal manner, except that when they were in their most critical phase of development they were exposed to sonic booms produced by military airplanes. Egg and fish fry mortalities from exposed groups of eggs were compared to those for control groups of eggs spawned at the same time. These comparisons indicated that the sonic boom exposure caused no increase in mortality.

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PREFACE

The Western Fish Disease Laboratory wishes to thank Messrs. Joseph K. Power, Thomas H. Higgins, 'JB' McCollough and Larry K. Carpenter of the Noise Abatement Division of the Federal Aviation Administration for many valuable discussions, evaluations, and suggestions regarding this study.

Effect of Sonic Boom on Fish

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SUMMARY

A program was initiated to study the effect of sonic booms on fish and fish eggs during critical stages of development. During the development of fish eggs they reach a critical period where they become sensitive to vibration or disturbance. This program was designed to determine if the disturbances caused by sonic booms could have a detrimental effect during this period. It consisted of both field and laboratory tests conducted at several National Fish Hatcheries (NFH).

Fish eggs from both trout and salmon were reared in the normal manner, except that when they were in their most critical phase of development they were exposed to sonic booms produced by military airplanes. Egg and fish fry mortalities from exposed groups of eggs were compared to those for control groups of eggs spawned at the same time. These comparisons indicated that the sonic boom exposure caused no increase in mortality. A typical example of some of the test results are illustrated in the following table for two groups of steelhead trout eggs from the same origin.

	Abernathy NFH Control Group	Carson NFH Sonic Boom Group
	Percent Mortality	
Green egg	18.1	18.8
Eyed egg	15.7	13.4
Fry	3.9	1.1
Total	33.6	30.4

An additional laboratory study was conducted during which fall chinook salmon eggs were exposed in a simulator to sonic booms of varying overpressures at regular intervals during their development. These tests also revealed no noticeable increases in mortality or influence on normal development. They were raised to the feeding (swim-up) stage and compared with a control group of eggs raised in the normal undisturbed manner.

The results of these tests indicate that sonic boom exposure of the magnitude characteristic for commercial airplane operations will not have a detrimental effect on fish spawning in either nature or at normal fish hatcheries.

INTRODUCTION

Sonic booms generated by military supersonic aircraft are not unusual today. With the advent of the commercial supersonic transport, sonic booms may become commonplace over unpopulated areas or over the ocean. The boom is created when an aircraft travels faster then the speed of sound. It sounds like a clap of thunder.

Some previous observations indicated that sonic booms might harm fish eggs. Harold Wolf, pathologist for the California Department of Fish and Game, observed that trout eggs in the critical stage of development at the Mohave hatchery died within 5 minutes after being subjected to a sonic boom. C. R. Messier noted that trout eggs were killed by sonic booms at the Lahontan National Fish Hatchery (NFH), Nevada. Also a boom at the Hagerman NFH, 'aho, was alleged to have cracked concrete raceways but did no harm to eyed trout eggs. These considerations were the motivation for the planned tests.

In nature trout and salmon deposit their eggs in gravel in a stream bed. The eggs develop there, hatch, and the young fish swim out. In artificial rearing, usually the eggs are fertilized in a pan or pail, washed, and placed in trays or baskets for rearing. The eggs are quite resistant to shock before water is added. When water is added, it is absorbed by the eggs; they become adhesive for about one hour and can be killed if disturbed. The eggs then can be handled for about 24 hours. After this period, the eggs or embryos are subject to death if disturbed before the embryo has developed sufficiently to show the eye through the egg membrane (eyed stage). Great care is taken not to jar the eggs during early development (green egg or tender stage) because shock causes a break in the perivitelline membrane and results in a denaturation of the yolk. When this happens the egg turns white and the embryo dies.

An example of shock on developing trout eggs was evidenced by an earthquake on April 13, 1949. Twelve groups of steelhead trout eggs taken on different days were being incubated at the Washington State Department of Game hatchery in Puyallup when an earthquake of 8.14 force caused water to be splashed out of some troughs. Six of the 12 groups of eggs were eyed, so no loss occurred to them from the earthquake. The other six groups of eggs suffered losses dependent on the stage of development. As shown in the following table, eggs are resistant to shock for a day, become critical to shock and then are quite resistant.

Date Eggs Spawned	Age	Number eggs Spawned	Number eggs lost	Percentage eggs lost
3-28	16 days	23,324	3,956	16.0
3-30	14 days	66,000	27,254	41.0
4-2	11 days	42,500	42,500	100.0
4-7	6 days	65,412	5,036	7.6
4-8	5 days	16,600	532	3.2
4-13	1 hour	170,000	0	0.0

Taken from the Progressive Fish-Culturist 11(4):212. 1949

The speed of sound in water is about 4.5 times that in air; therefore, the common sonic boom would cause an acoustic wave in water and not a shock wave. Actually the pressure fluctuation spectrum levels due to surface waves would be higher than levels due to sonic booms. Also there are often acoustic signals in the ocean that equal or exceed the signals due to sonic booms falling on the surface of the ocean. In one experiment with guppies, a bullet was fired over an aquarium generating a pressure differential 275 times greater than that of a supersonic transport. The conclusions were that the fish may react to the passage overhead of a strong shock wave but that they do not suffer any harm.

The effect of the sonic boom, per se, on fish including their eggs, should cause no harm. Harm could be experienced by eggs in a critical stage of development, if a shock wave jarred the equipment. The following experiments were conducted to determine the effect of sonic booms, real and simulated, on fish and their eggs.

LAHONTAN CUTTHROAT TROUT EGG TEST

The U. S. Department of the Interior, Fish and Wildlife Service, Bureau of Sport Fisheries and Wildlife, Division of Fish Hatcheries, has a National Fish Hatchery (NFH) located at Gardnerville, Nevada (see Figure 1). Charles R. Messier, the manager, was responsible for the work there.

Sonic booms had been a common occurance at the Lahontan NFH. Therefore, it was decided to use this hatchery for one site to test the effect of the sonic boom on developing fish eggs. The fish egg incubators were placed in a temporary wood structure erected in an empty concrete raceway (see Figure 2).

Eggs from a wild stock of cutthroat trout (Salmo clarki) were obtained on April 18, 1972, at Summit Lake, Nevada. About 2,000 of these were placed in each of four Heath incubator trays. Figure 3 shows an incubator tray. These are normally maintained in stacks of 16 trays high as shown in Figure 4. The four groups of test eggs at Lahontan NFH were placed in the top tray of each of four stacks of trays. Mortalities were removed from each group of eggs the day following fertilization. The groups of eggs were examined daily and the mortalities recorded as shown in Table 1.

The developing eggs were subjected to a staged sonic boom on April 25, 1972, 7 days after fertilization. A hatcheryman at the site noted: "The Air Force made several passes early in the day of April 25th at 31,000 feet but were unable to muster more than a moderate boom. At 4:00 P.M., they sent an F-111 over and it created a strong boom -- just what we wanted. We had counted the dead eggs prior to the test boom and could see no great increase in mortality afterwards."

The sonic boom signatures were recorded on TDR-1 Recorders Four hydrophones were located at the Lahontan NFH as shown in Figure 5. The magnetic tapes were transposed to oscillograph charts and interpreted by the National Aeronautical Facility Experimental Center. These were summarized in Table 2. According to the recorded data the greatest overpressure was 1.16 psf with an average of 0.94 psf. The "big boom" was produced by an F-111 at top speed at 35,000 feet flying from north to south.

The report from the hatchery manager states: "In conclusion, we feel that it is safe to say that the sonic booms we experienced here during the incubation period had no adverse effect on our trout eggs. The test boom was as strong as any we would be likely to receive here and there was no massive die-off because of it".

CARSON STEELHEAD TROUT EGG TEST

A test to determine the effect of the sonic boom on developing steelhead trout (Salmo gairdneri) eggs was initiated on April 17, 1972. On this date eggs from 15 steelhead were fertilized at the Eagle Creek National Fish Hatchery (NFH), Oregon (see Figure 6). After water hardening the eggs were disinfected in a Wescodyne solution and then divided at random into five one-gallon glass jars. Two hours after the eggs had been fertilized, three of the jars were transported by automobile to the Carson NFH, Washington for the test; two jars were similarly transported to the Abernathy Salmon Cultural Development Center, near Longview, Washington, as the control group for the experiment (see Figure 6).

One batch of eggs at the Carson NFH was incubated on two trays wedged near the surface of the water in a wooden trough placed in an outside concrete raceway (see Circle 1, Figure 7). Another batch of eggs was incubated in a basket and another on two trays wedged in a wooden trough in the hatchery building (see Circle 2, Figure 7). The water supply was from a spring flowing at 6.7° C (44° F). Dead eggs were removed from the trays several times during the green-egg stage. Those in the basket were not picked until eyed.

The eggs were subjected to a sonic boom produced by an F 101 at 1:07 PM on April 25, 1972. The sonic boom caused rattles in the buildings but did not appear to be as severe as others in the area in the past. From Table 2 it is noted that the strongest recording was 1.14 psf with an average of 0.89 psf. The hydrophones were located on the hatchery grounds as shown by the larger white circles in Figure 7. One "S" was 75 yards south of the hatchery, one was next to the hatchery "2"; one was 60 yards north of the hatchery, "N"; and the fourth, "1" was near the outside eggs. The overflight was from south to north. The hydrophone "1" was, eliminated before the next planned overflight.

Just before the overflight all dead eggs were removed from the four trays. At noon the next day there were two dead eggs on one outside tray and no dead eggs on the other three trays. Two days later there were three dead eggs on one outside tray and one dead egg on one of the inside trays. The mortalities experienced by these groups of eggs are presented in Table 3.

The eggs taken to Abernathy, the control group for this test, were placed into two baskets in a deep incubation trough supplied with well water at 11.7° C (53° F). During the green-egg stage they were treated three times with malachite green but some fungus developed in spite of the treatments. The control eggs eyed on May 2, were bumped, dead eggs removed, and the live eggs enumerated on May 8. On May 9 the eggs were placed in trays in an incubator. The eggs hatched May 15 and the fry were placed in a circular tank on June 1 when they had absorbed most of the yolk. The dead and crippled fry were removed and the mortality data are presented in Table 4.

When the data in Tables 3 and 4 are compared as in Table 5, it is apparent that the sonic boom did not cause an increase in mortality to 8-day old stealhead trout eggs. Also it was observed that the fry appeared normal when they reached the first feeding swim-up stage.

LITTLE WHITE SPRING CHINOOK SALMON EGG TEST

A planned overflight at the Carson National Fish Hatchery (NFH) was scheduled for July 18, 1972. It was decided to place spring chinook salmon (Oncorhynchus tshawytscha) green eggs in the Carson NFH and hold a similar group at the Little White NFH as a control (see Figure 6). Eggs from only one spring chinook salmon were available because it was so early in the spawning season. The eggs were taken and fertilized on July 12, and incubated in a tray held in a wooden trough at each hatchery. The overflight at 9:06 AM on July 18 caused a very mild shock wave at Carson but a very severe Boom at Little White. A 100 mile per hour wind at the airplane may have caused a shift in the flight path which resulted in the different boom observations. A flight was called for the next day. At 9:30 AM July 19 the overflight at Carson caused a very severe Boom (see Table 2). The average overpressure was about 2.7 psf and Figure 8 shows two of the measured signatures. No Boom was heard at Little White

The eggs at Little White which were to have been the control group, were "bumped" and enumerated by H. Johnson and R. Rucker on August 18. There were originally 1300 eggs; of these, 6 were "dead" and removed before the Boom; the Boom caused no apparent mortality; 78 "dead" eggs were removed after bumping. The "dead" eggs were mainly not fertilized and showed no development. The total loss was 6.5 percent, which is considered very good.

CARSON SPRING CHINOOK SALMON EGG TEST

The portion of the eggs taken and fertilized at the Little White National Fish Hatchery on July 12, were held in a tray in a wooden trough at the Carson NFH. A very mild sonic boom was observed on July 18, 1972, but on July 19 a very severe boom was produced by an F-101 over this hatchery. The pressures recorded are shown in Table 2.

The eggs at Carson were examined on August 18 by H. Johnson and R. Rucker. Out of about 2000 eggs; 6 were removed before the Boom; there was no loss attributed to the Boom; the eggs were "bumped" and enumerated. Here there was a loss of 418 eggs or 21 percent most of which were infertile. The higher loss was not attributed to Sonic Boom but to infertile eggs, the transport of the eggs, and the effect of much activity about the eggs.

CARSON 8-INCH RAINBOW TROUT TEST

An experiment to determine the effect of a sonic boom on fish was planned for the Carson National Fish Hatchery (NFH). About 300 of the stock of 8-inch rainbow trout at the hatchery were confined to a 6-foot section of a pond just west of the hatchery as shown by the three smaller, white circles in Figure 7 . The dots represent the locations of three hydrophones used for this test: two were on either side of the 6-foot section (Figure 9) and the third was at the head of the raceway. An overflight by an F-101 at Mach 1.2 on July 19, 1972, at 9:30 AM was noted as being loud and recorded as shown in Table 2 as 2.55, 1.90, and 2.14 psf by the hydrophones by the fish. G. Wedemeyer observed a "slight fright response" among these fish at the time of the boom. Blood chemistries were run on these fish to determine any shock effect from the sonic boom. Interrenal tissue and caudal arterial blood samples were taken from these fish at 0, 0.5, 2, 4, 6, 24, and 48 hours after the overflight. Samples of 30 fish were used to overcome physiological variation; the fish were anesthetized to minimize the stress of handling.

Results of the blood chemistry analyses obtained to date are given in Tables 6, 7, and 8 . As shown, the Sonic Boom caused no significant increase in blood sugar (glucose) or blood cortisol levels or decrease in plasma osmolality indicating that no significant stress occurred under the conditions of this experiment. However, it should be noted that the earliest blood sample was not taken until 30 minutes after the Sonic Boom.

CARSON UNFERTILIZED SPRING CHINOOK SALMON EGG TEST

Over 5,000 mature spring chinook salmon were being held in two large ponds just north of the experimental 8-inch rainbow trout when they were boomed on July 19, 1972 (see Figure 7). The planned overflight created pressures as shown in Table 2 with the highest, 4.16 psf, from the hydrophone nearest the mature fish. Observers considered this a very severe sonic boom. The hatcherymen observed one group to show "no reaction", while R. Rucker observed the other group to show "very slight to no reaction" in response to the Sonic Boom.

The eggs from these fish were taken and handled in the normal manner except during part of the period when the milt was washed from the eggs with a hose. This might have caused a slight increase in egg mortality. The percent mortality of the separate egg takes is listed in Table 9.

The conclusion from this observation was that the sonic boom did not affect the unspawned eggs.

ABERNATHY FALL CHINOOK SALMON EGG TEST

First Test

It was desired to subject groups of salmon eggs to sonic booms or overpressures of 0.55, 1 and 2 psf daily during early development. Each individual group was to be subjected to one overpressure. To accomplish this, overflights by supersonic aircraft would not be practical. Therefore, a sonic boom simulator was used. Figure 10 shows the sonic boom simulator with the door open and a tray of eggs inserted. The door would be closed and the speakers activated to produce a simulated sonic boom pressure signature. A recording, as shown in Figure 11, was made each time a batch of eggs was subjected to the simulated sonic boom. The power spectrum of the simulated waves compared closely to the spectrum plots for the two live sonic booms shown in Figure 8 (these can be seen in Figures A-5 to A-16 and in Figures A-17 and A-18 respectively).

Forty female and 10 male fall chinook salmon were spawned at the Abernathy Salmon Cultural Center on September 23, 1972 for this experiment. The 203,185 eggs were mixed in a tub and portioned out in a logical manner into 88 numbered Heath incubator trays (Figure 3) in six, lettered stacks (Figure 4). The water supply was from a well flowing at 11.7° C (53° F). The trays were assigned definite treatments using a table of random numbers. The treatments consisted of subjecting the eggs on individual trays to 0, 0.55, 1, and 2 psf overpressures with a duration of 0.2 second for each day after fertilization. This was done for 3 weeks at which time the eggs were eyed and quite resistant to shock or handling. The dead eggs were counted at this time (pre-count).

The eggs were then handled or shocked so that any infertile eggs would absorb water and appear white. At this time an accurate count was made of the eggs on each tray. Again the dead eggs were counted and removed. At the time of hatching the eggs which did not develop were removed and the total egg loss for each treatment was recorded as shown in Table 10. Also a record of the number of eggs and fry which died before the fish were old enough to feed (swim-up stage) is tabulated in Table 10. These observations were important to note any delayed manifestations of the sonic boom.

The total accumulative percent mortality within each lot was calculated after each "pick-off", and the data were tested by analysis of variance for significant differences between levels of sonic boom exposure, days of exposure for all levels, incubator stacks, and rows within stacks. The results were summarized in Table 11.

At the swimup or first feeding stage, none of the variables tested was significantly different. Differences between shock levels contributed to no more than 4.7 percent of the total variance in any of the four tests. Mean percent mortality was 14.1, 14.5, 14.5 and 15.0 percent for the 0, 0.55, 1, and 2 levels respectively. From this, it seems unlikely that sonic boom overpressures had any effect on egg or fry mortality. Overall mortality was somewhat higher than we normally experience, however, it was lower than that of the three previous egg takes for the hatchery this season.

Differences between stacks A-F through hatching probably reflect the effects of handling i.e., those stacks with the highest mortality were the last to go into the incubator. Differences between days up to hatch were marginal and their validity is questionable.

Second Test

A second experiment similar to the first used a group of 19,112 eggs from six females fertilized with the milt from two males on October 4, 1972. These were divided among 15 trays. Lots of eggs were randomly exposed to 0, 0.55, 1.00,2.00, 4.00, and 4.00x psf overpressure on either 6 or 9 days after fertilization. The 4.00x level consisted of five exposures of 4 psf at 5-second intervals on a single lot of eggs. The results as shown in Table 12 are more variable; however, a comparison of total accumulative percent mortality between the 0 control and 4.00x levels again suggests no effects from the sonic exposure. Mortality in the H stack of the incubator for some unknown reason was double that in the G stack, and thus precluded any worthwhile statistical testing.

RECOMMENDATION

It is suggested that the pressure created by a pebble, a stone, and a boulder dropped into a pool be determined as a comparison to a sonic boom disturbance.

CONCLUSION

The data presented in this report indicate that sonic booms have no effect on developing fish eggs or on fish.

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APPENDIX

Sonic Boom Simulator

Pressure Chamber

It was desired to subject developing salmon eggs to daily sonic booms or overpressures of 0.55, 1, or 2 psf. To accomplish this, overflights by supersonic aircraft would not be practical. Therefore, a contract was awarded to Telephonics Division of Instrument Systems Corporation, Huntington, N.Y., to design and fabricate a sonic boom simulator practical for small scale studies.

A sealed pressure chamber of 3/4 inch plywood approximately 3' X 4' X 4' was lined with sound absorbing material to reduce internal reflections. Twelve high compliance loudspeakers were mounted on the top arranged in an array of three rows of four speakers each, to provide a uniform pressure profile throughout the chamber. Access to the chamber was provided by a plexiglass front door secured with five hold-down clamps and sealed with a soft rubber gasket (see Figure A-1). A hydrophone was incorporated to monitor the pressure profile. It was shown that the underwater pressure profile was essentially identical to the pressure waveform in air. The chamber was designed to accommodate either a Heath incubator fish egg tray with water or a tank of water. It could also be used for birds, their eggs, or for small animals.

Electronic's Unit

The 12 loudspeakers in the Pressure Chamber were activated by an electronics unit consisting of function generator, amplifiers, power supplies, and operating controls (see Figure A-1). The equipment was housed in a standard 19-inch rack cabinet with a top access door for maintenance or servicing. When the actuate button was depressed, the pulse generator produced a pulse of either 50, 100 or 200 milliseconds as selected by the time duration selector switch. This pulse unclamped the ramp generator which produced a negative going ramp whose slope was controlled by the selected time duration and by the voltage representing overpressure. The ramp length was controlled by the selected pulse width. In addition to unclamping the ramp generator, the pulse opened a switch allowing a voltage equal to one half the maximum ramp voltage to be applied to the summing amplifier. This pedestal voltage was summed with the ramp thus producing a symmetrical N-wave voltage waveform at the summing amplifier output.

The N-wave produced by the function generator was amplified by the 100 watt power amplifier which drove the loudspeakers. This power amplifier was DC coupled circuit employing complementary darlington power transistors.

The electronics unit also contained a microphone amplifier which provided 40 dB of gain for the dynamic hydrophone used to monitor pressure in the chamber. Regulated DC power supplies provided +28VDC, +20VDC, -20VDC, and ±VDC to the various circuits. A single 115V, 60 Hz line cord provided input power for the entire system.

Recorder

The "N wave" generated by the simulator had a very sharp rise time with excellent stability. This was demonstrated on the oscilloscope and documented by the Statos I Recorder - Model 153, produced by Varian Data Machines, Palo Alto, Cal. The hydrophone suspended in the Pressure Chamber was connected to the Recorder through an amplifier in the Control Unit which converted the simulated sound overpressure into a signal that could be recorded on the Statos I Recorder. The Recorder used an electrostatic process for depositing a toner onto a specially treated moving chart paper to display the recorded impulses.

A recording of the pressure signature was made each time a group of eggs was subjected to a simulated sonic boom. A typical recording is shown in Figure 11. The recorder is shown under operating conditions on the right side of Figure 10.

The electronic equipment was located adjacent to a new rack of Heath incubator trays. This rack consisted of six sections of 16 trays each. The top tray of each section was empty. Water at 11.7° C (53° F) temperature flowed through a control faucet into each top tray and then cascaded down through each tray of each section. This allowed all turbulence in the water to be smoothed out in the top tray before flowing to the other trays. The relative location of the incubator and electronic equipment was as indicated in Figure A-2.

Wave Analysis

The sonic boom simulator was set up in the ComputerTechnology Laboratory at the University of Washington, Seattle, Washington, with a fish egg tray containing water. This was to simulate the equipment set-up which was used at the Abernathy Salmon Cultural Center. The simulated sonic boom frequency analysis test set-up is shown in Figure A-3. A Tektronix oscilloscope connected to the microphone in the Simulator was used as the voltage measuring device. A standard audio oscillator w s used as a frequency calibration device for the A/D converter system. One "boom" was recorded and processed at each of the 12 sets of pressure— time duration conditions. The sample timing interval for each test was adjusted so that approximately 32 sample intervals were made to span the duration of the N-wave signal -- out of a total of 1024 samples taken for each test (this number was fixed by the use of a 1024 point discrete Fourier transform program in the processing of the signal data).

As in all analysis processes, some compromises had to be made. The use of a small ratio of samples covering the desired wave form to total samples ($^{32}/_{1024}$) provides high frequency resolution (e.g. approximately 1/6 cps between output spectral data points). Making the ratio too small, however, will cause erroneously higher values for the high frequency output spectral points. Also, spanning the desired signal with too few points causes a loss of definition (true shape of the output spectral plot).

It is felt that the parameters used in this test program are near optimum for the computer system capabilities. An "ideal N-wave" (same $^{32}/_{1024}$ ratio) was computer generated and passed through the signal processing program as a test case, see Figure A-4 — it shows a true sonic boom spectrum shape and good frequency resolution, but with the spectral magnitudes starting to deviate slightly upward from the perfect 6db/octave drop-off at the extreme high frequency end of the plot. Although only four analyses are of importance in this report (Figures A-5 to A-8) the rest are presented (Figures A-9 to A- 16) for future use of the Sonic Boom Simulator.

Figures A-17 and A-18 show the spectrum shape for the two sonic boom signatures measured at the Carson NFH on July 19, 1972 (Figure 8). These are shown for comparison with those produced in the simulator. The shapes are quite close with the deviation occurring mainly at the higher frequencies.

ACKNOWLEDGMENTS

Appreciation is acknowledged to the Division of Hatcheries, Region 1, Bureau of Sport Fisheries and Wildife, Fish and Wildlife Service, United States Department of the Interior, and especially the staffs of the Carson, Little White Salmon, and Eagle Creek National Fish Hatcheries for their cooperation and help in carrying out this program. Thanks are due Joe L. Banks who was responsible for the work carried out at the Salmon Cultural Development Center. Dr. Laurel J. Lewis and Gail H. Allwine, of the Computer Technology Laboratory at the University of Washington, Seattle, Washington did the computer work for determining the wave spectrums. Edward J. Kane, Aeronautical Engineer, The Boeing Commercial Airplane Company, analyzed the sonic boom tapes and helped in the preparation of the manuscript.

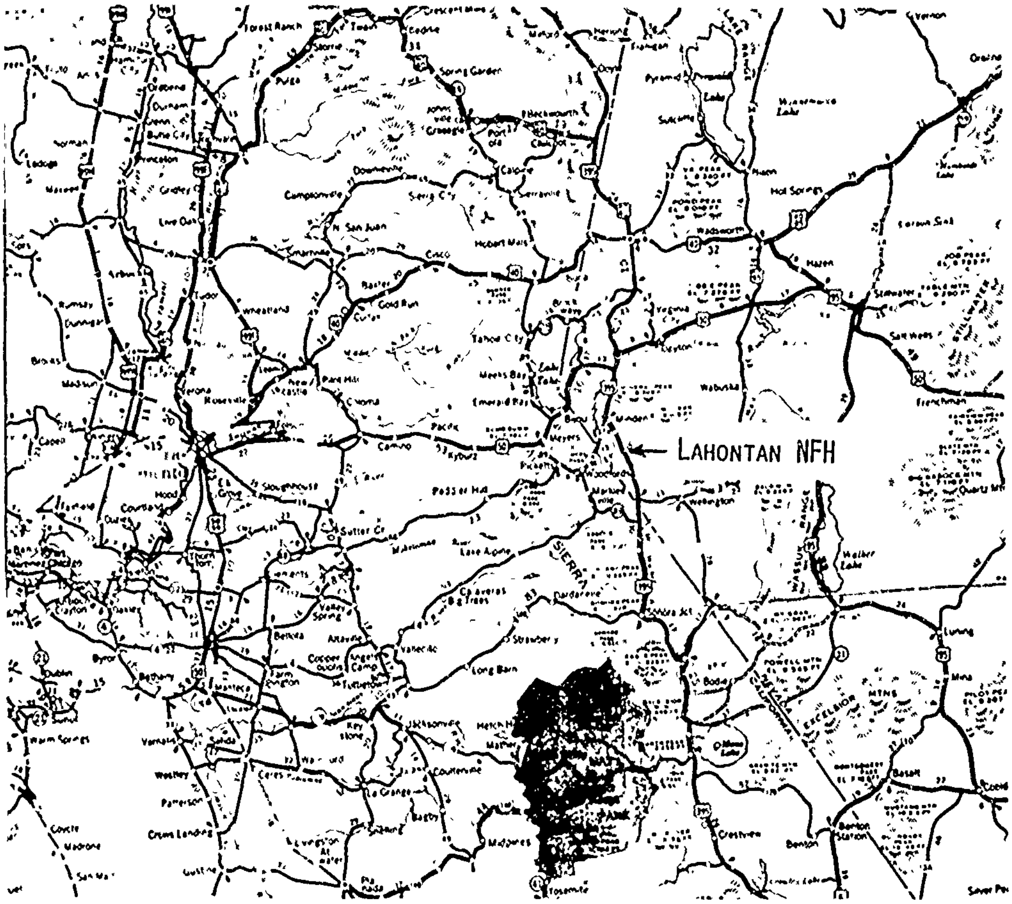


Figure 1. Location map for the Lahontan NFH, Nevada.

Figure 2. Temporary wooden structure (indicated by arrow) was erected in an empty raceway at the Lahontan NFH and housed the fish eggs and TDR-1 Recorders.

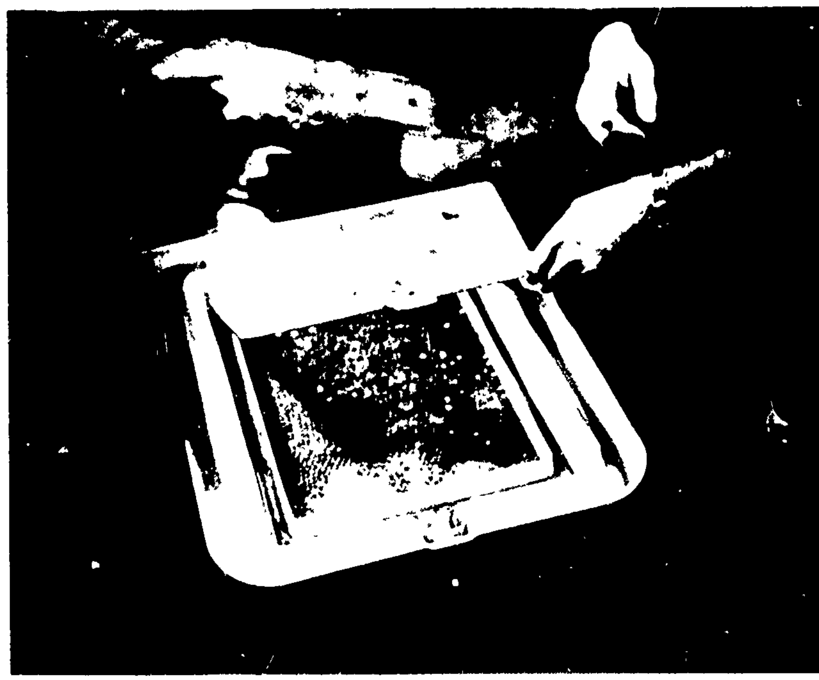


Figure 3. Fish eggs -- the white ones are dead -- in a Heath incubator tray.

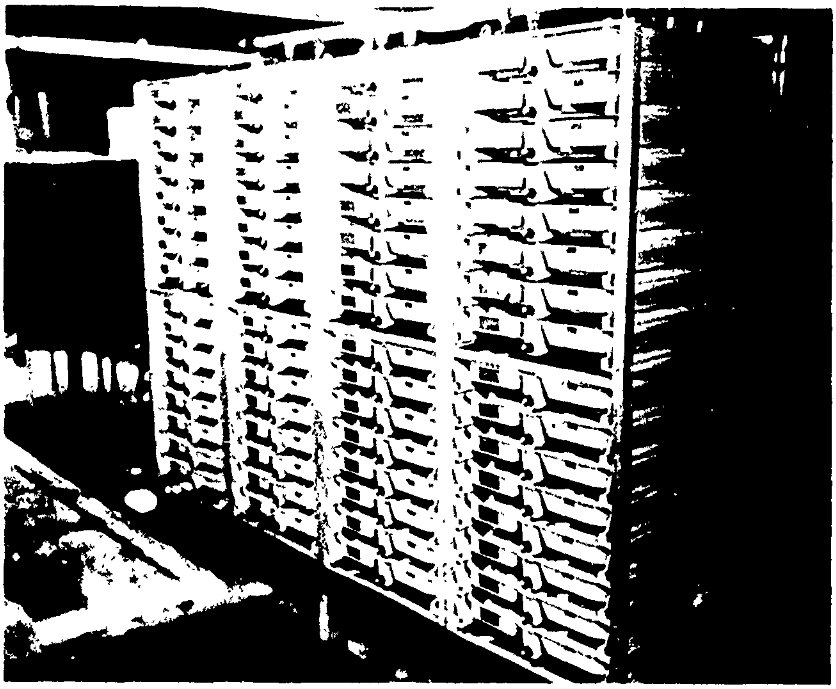


Figure 4. Stacks of 16 Heath incubator trays. Water flows by gravity through each tray.

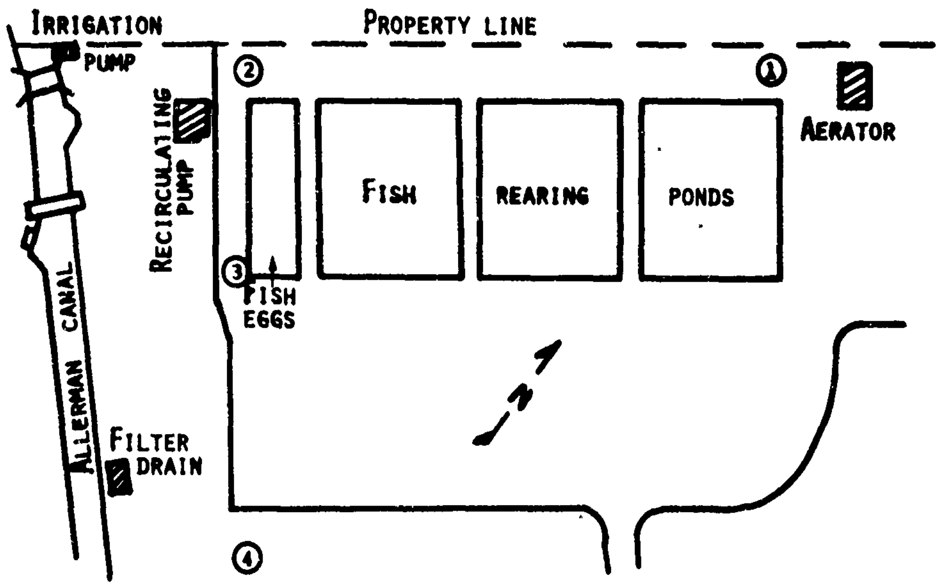


Figure 5. Location of hydrophones at the Lahontan NFH.

Flight of the F 111 was north to south.

Distances from hydrophones to egg incubator:

1 - 340 feet   3 - 20 feet

2 - 140 feet   4 - 300 feet

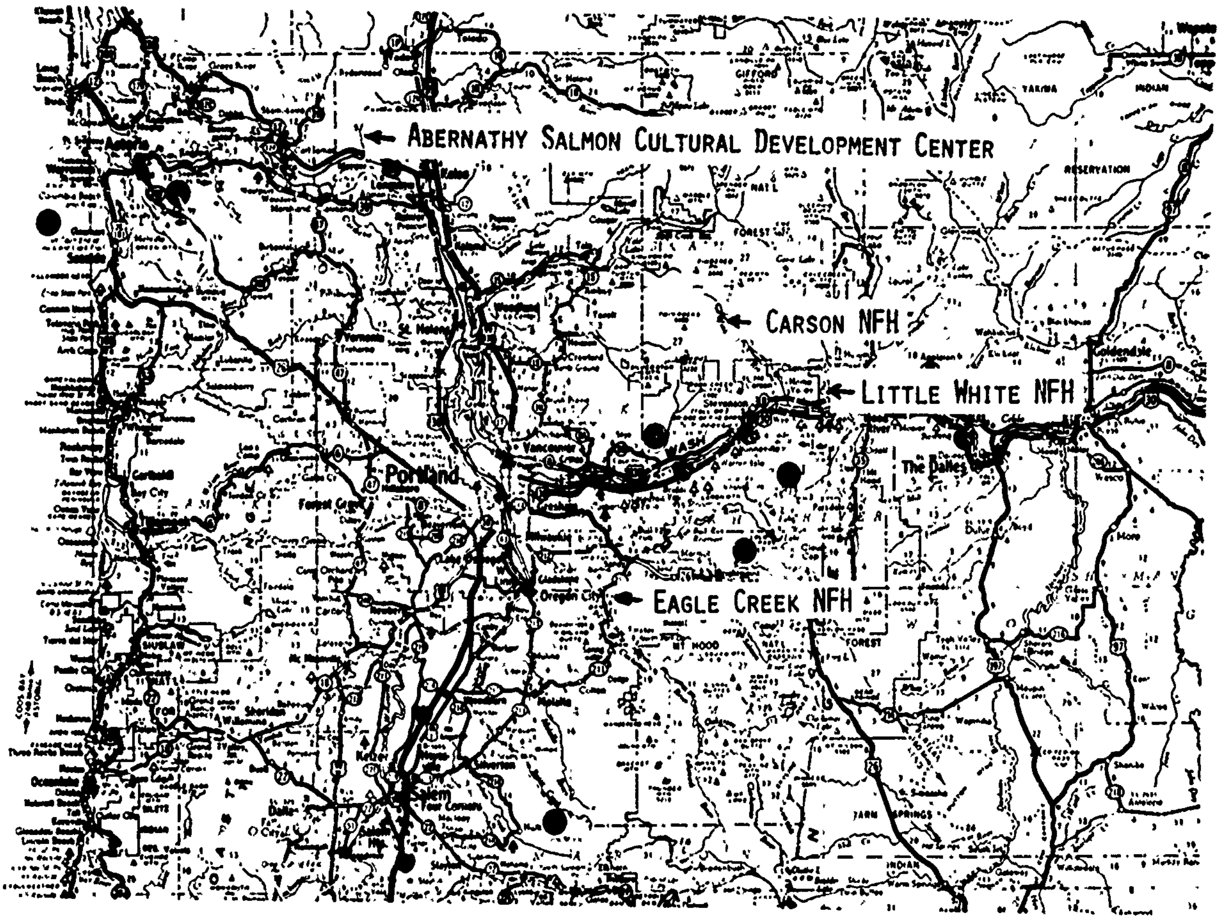


Figure 6. Location map for sites of activity areas.

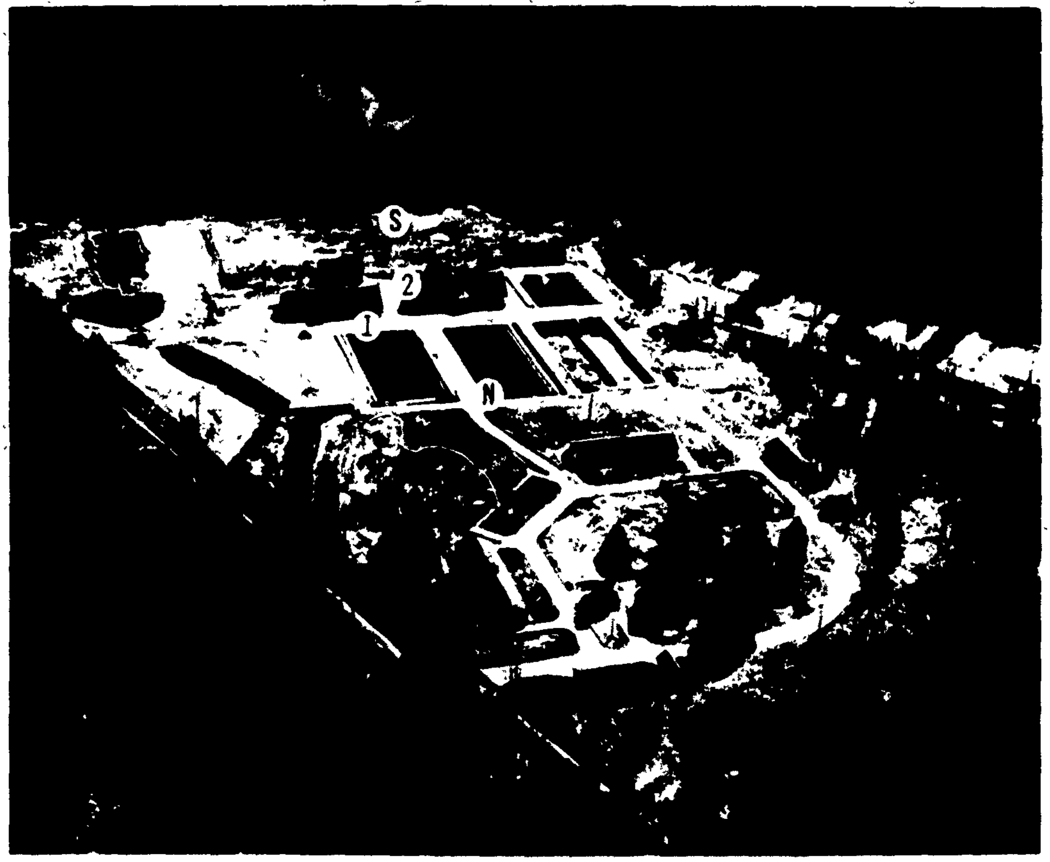


Figure 7. Carson NFH showing the locations of seven hydrophones as white circles. Note the two brood fish ponds right of center.

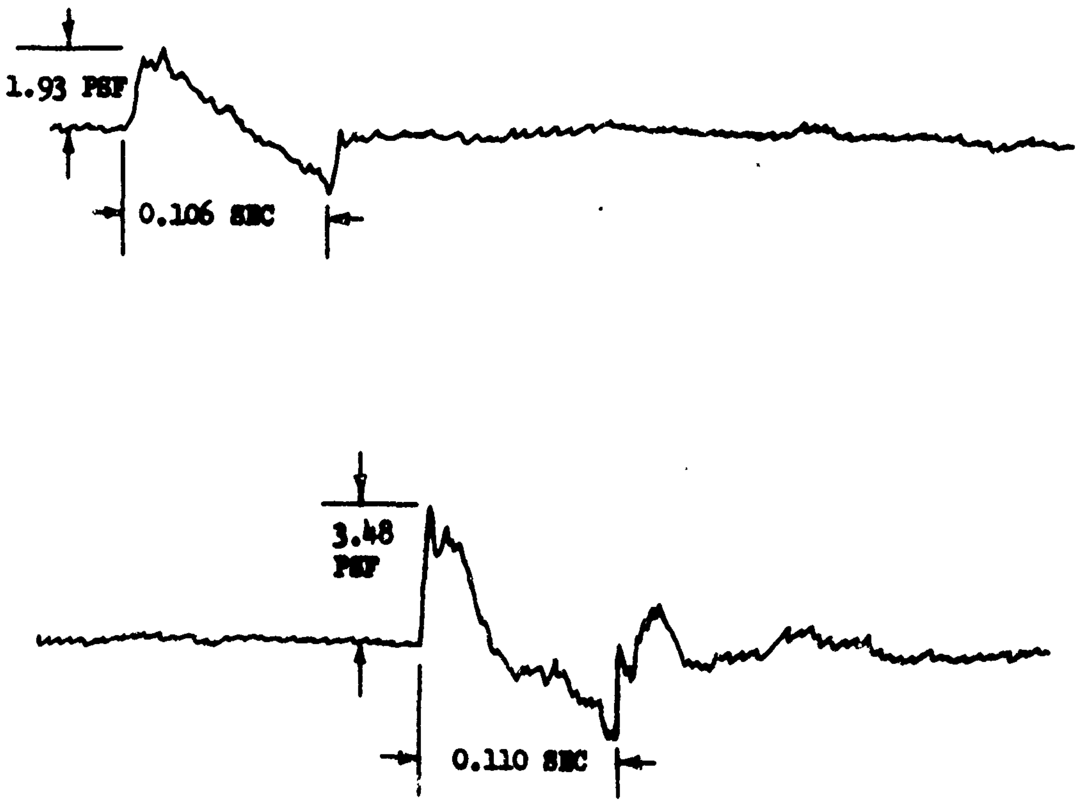


Figure 8. Typical traces of a recorder at two microphone stations at Carson NFH, July 19, 1972.

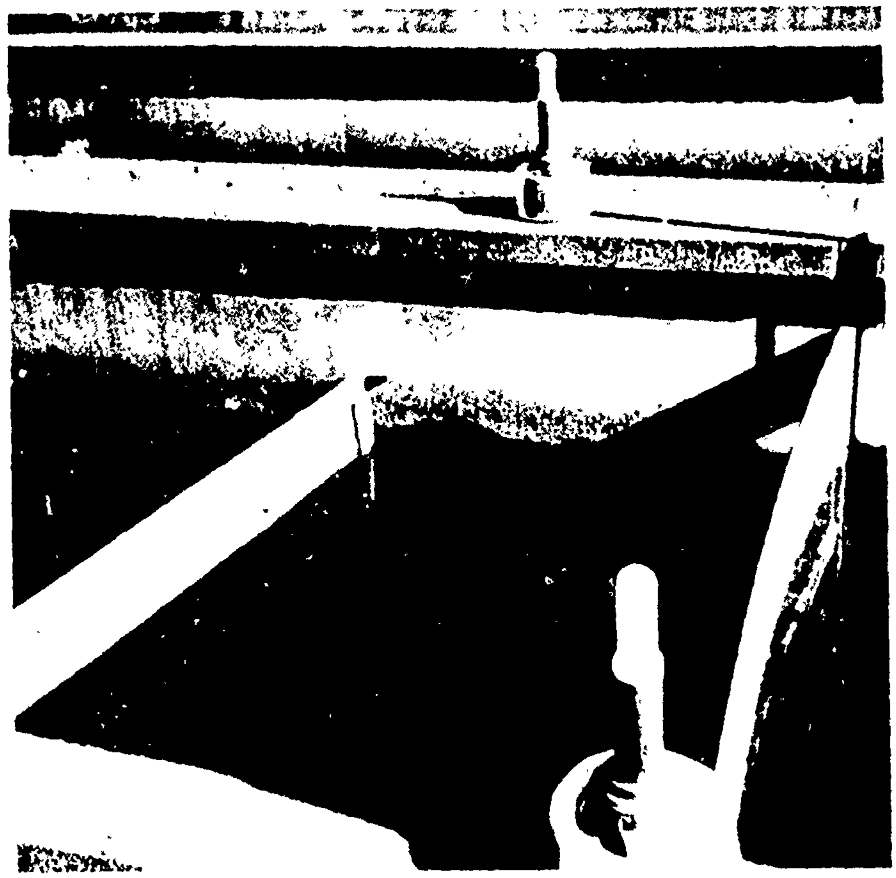


Figure 9. Two hydrophones on either side of the holding area for the experimental 8-inch rainbow trout.

Figure 10. Sonic Boom Simulator Chamber with door open exposing Heath fish egg incubator tray. At right is electronic recorder unit.

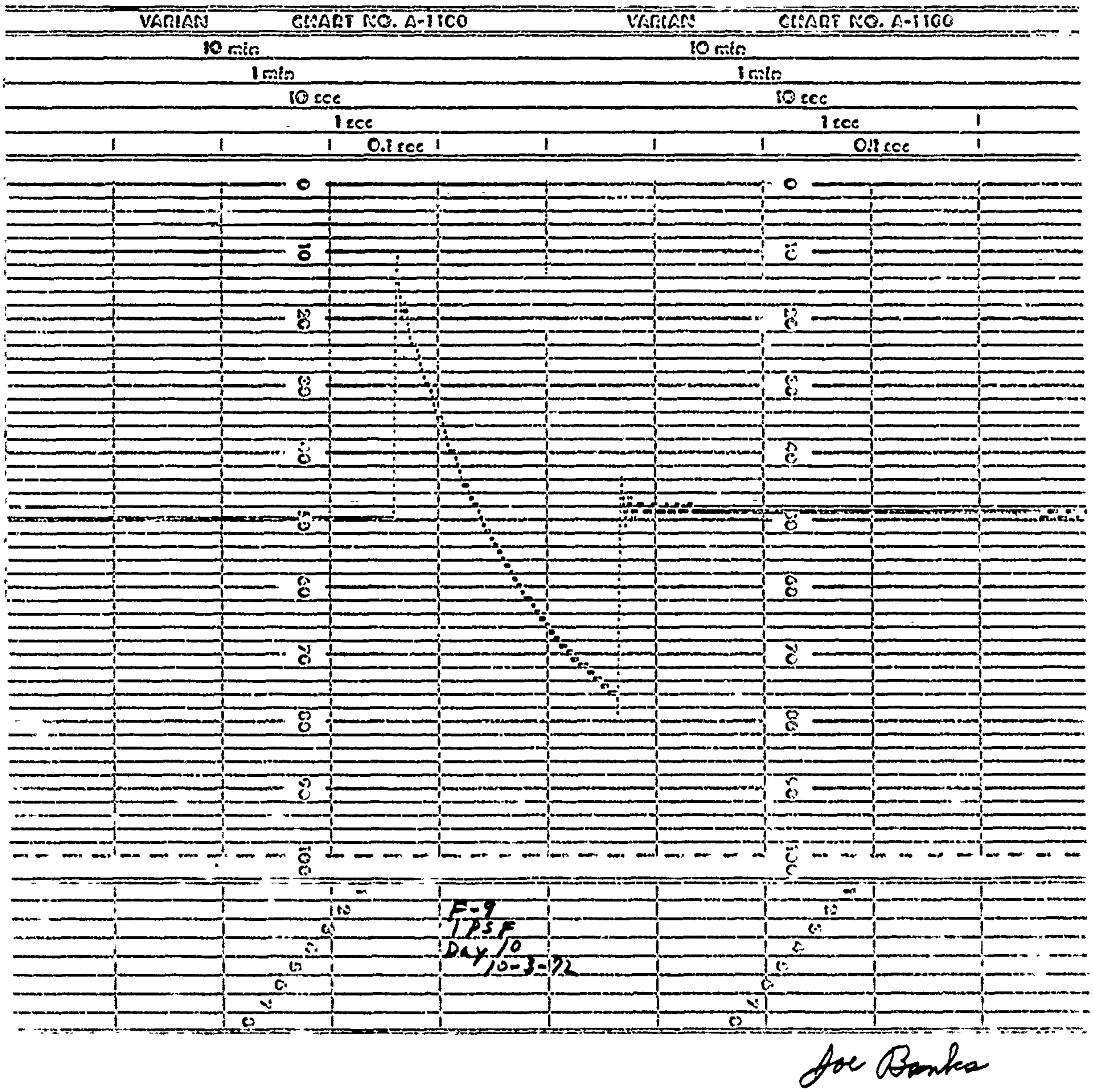


Figure 11. A typical recording produced by the Statos 1 Recorder - Model 153.

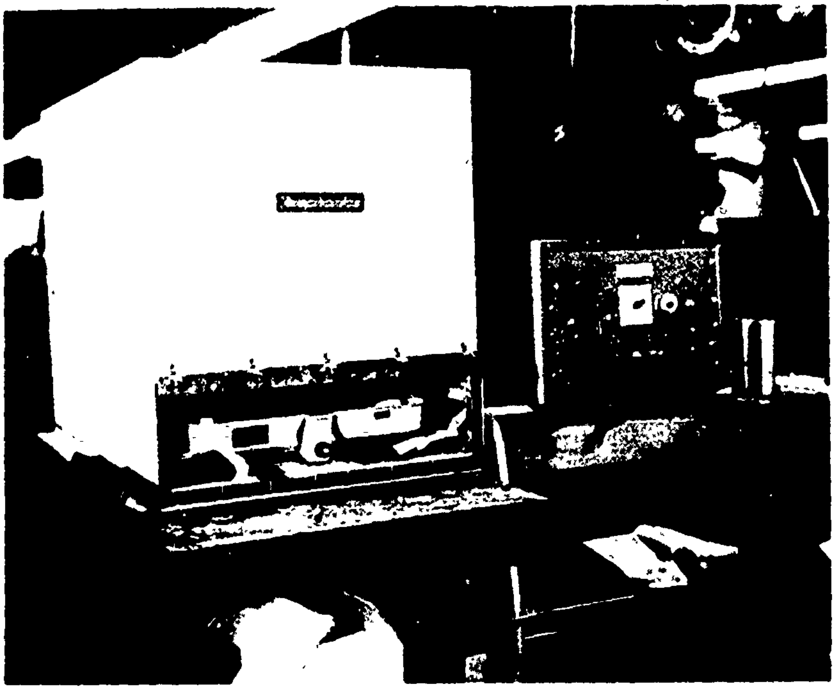


Figure A-1. Sonic Boom simulator sound chamber, door open exposing Heath fish egg incubator tray. At right is electronics unit.

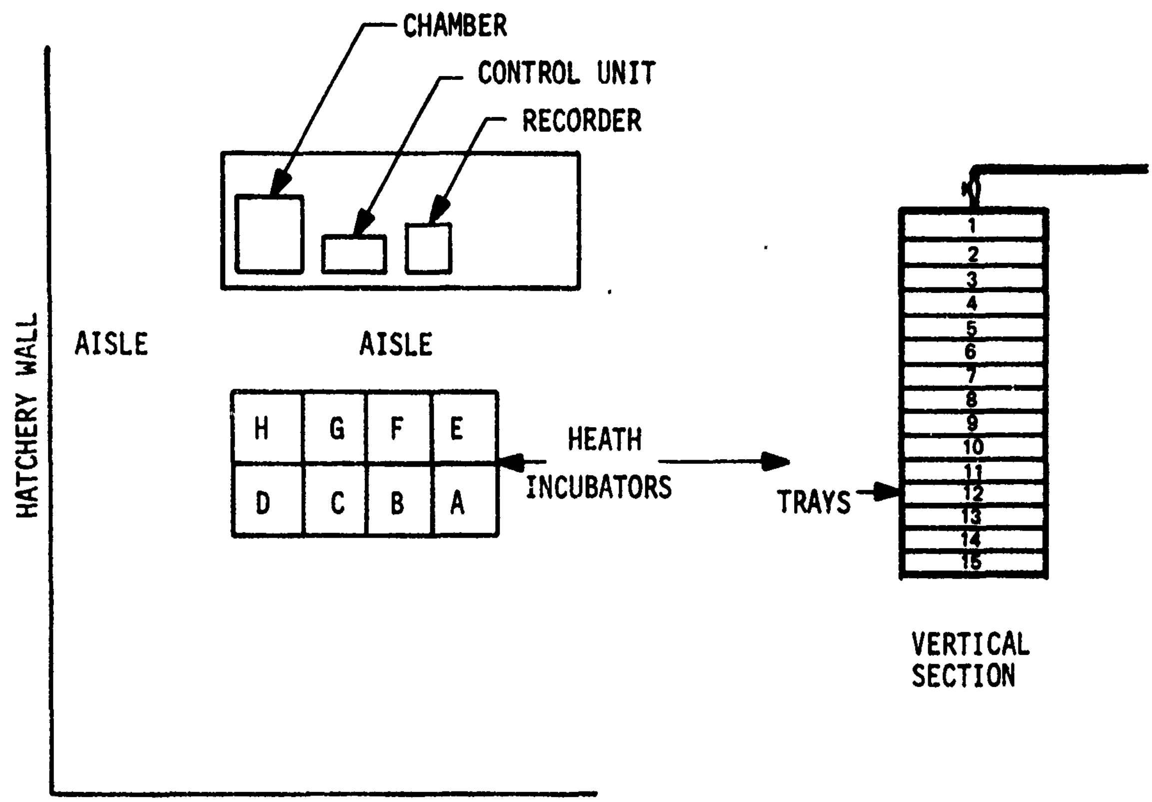


Figure A-2. Test area layout at Abernathy Salmon Cultural Center.

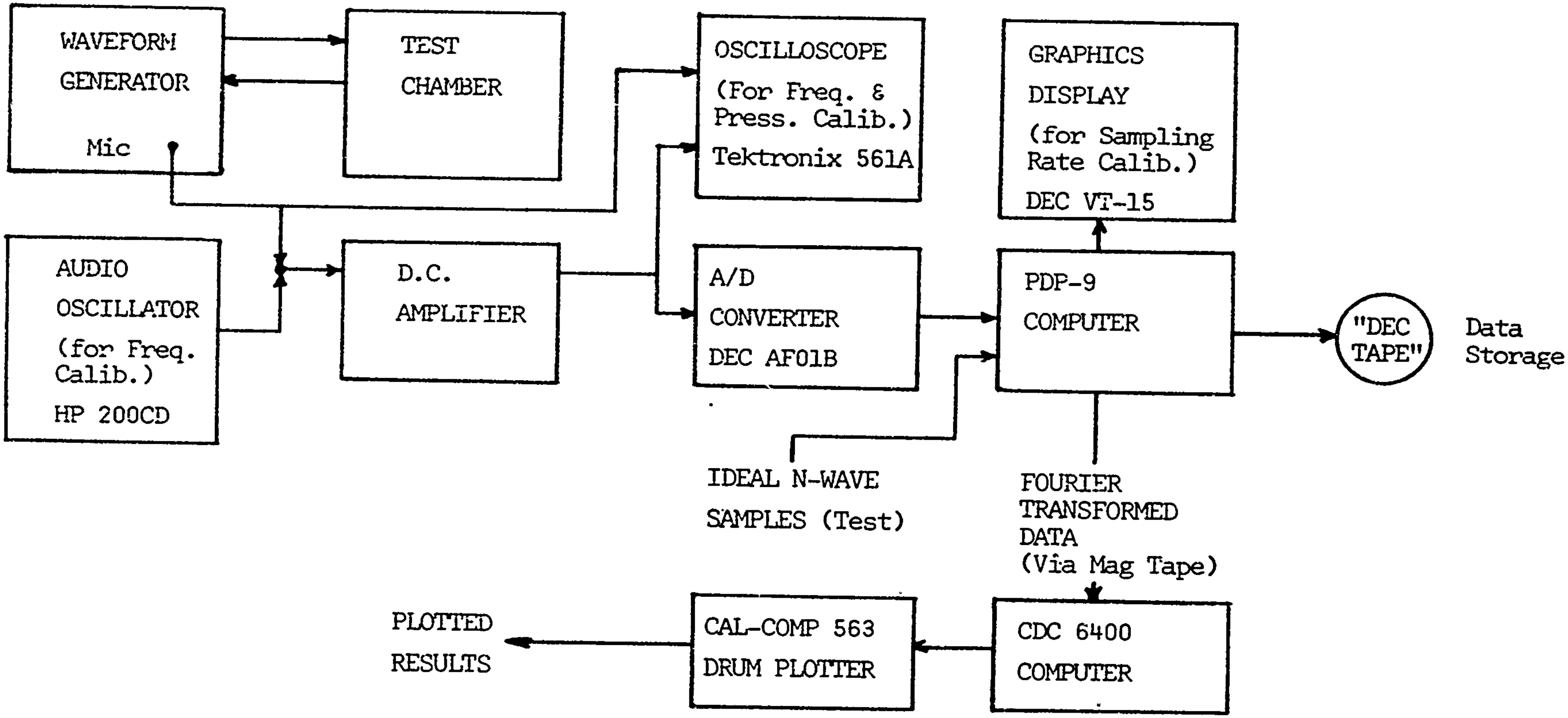


Figure A-3. Sonic boom frequency analysis test set-up.

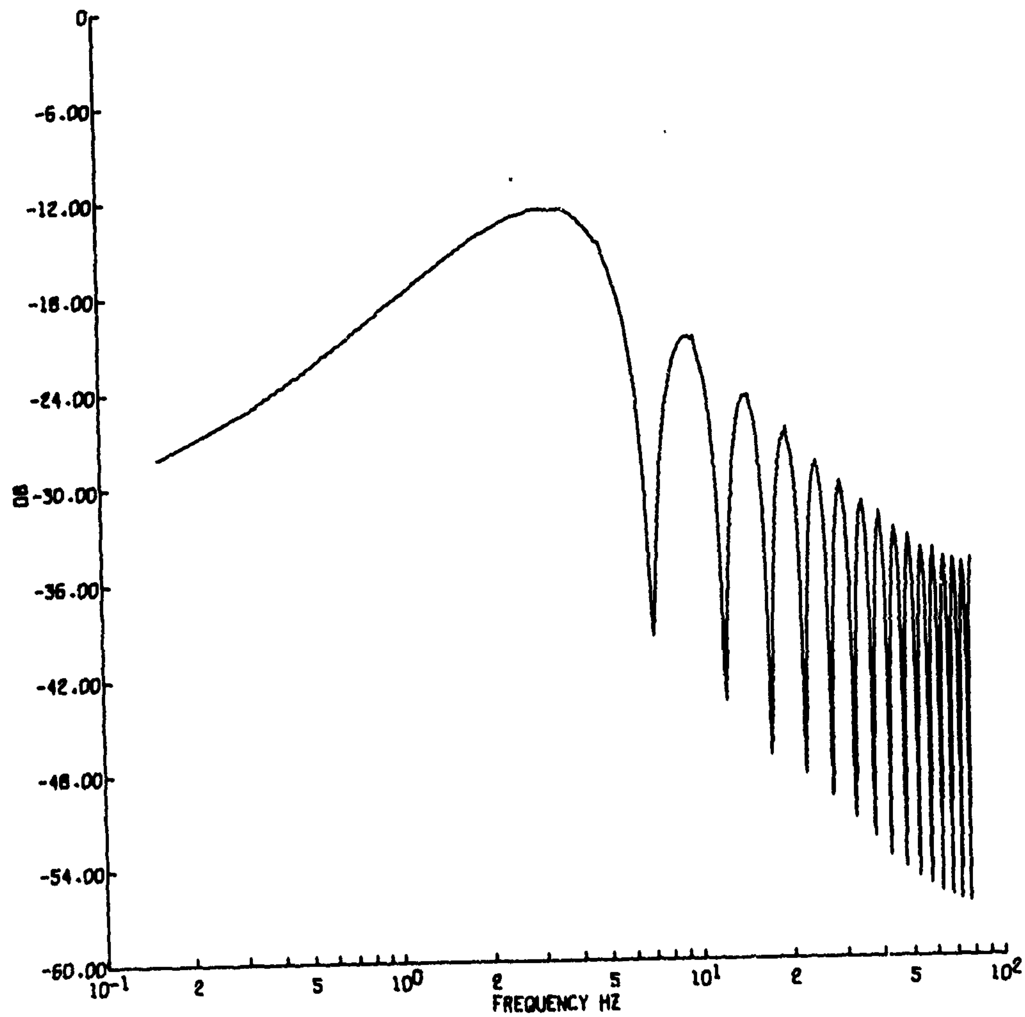


Figure A-4. Power spectral density for "Ideal N-wave" plot.

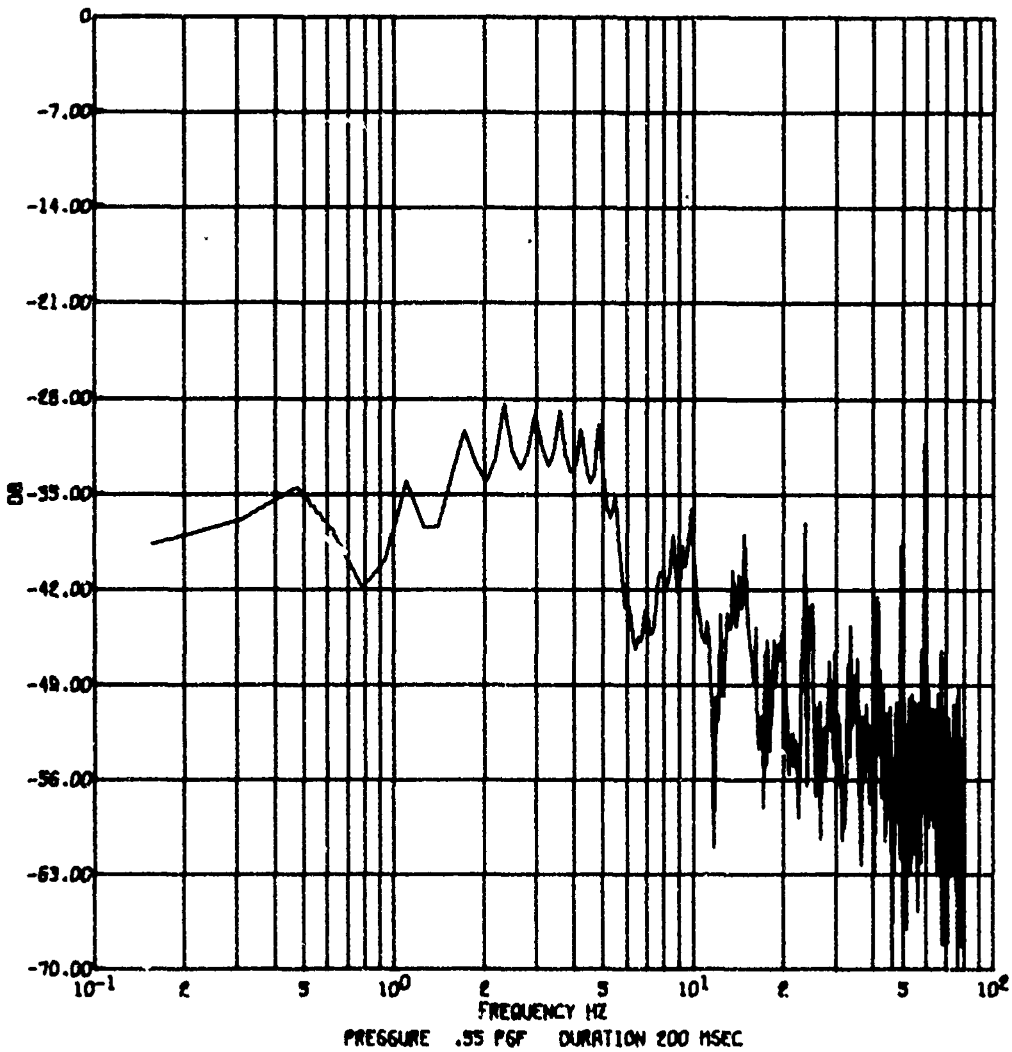


Figure A-5. Power spectral density for 0.55 psf simulated sonic boom for 200 msec.

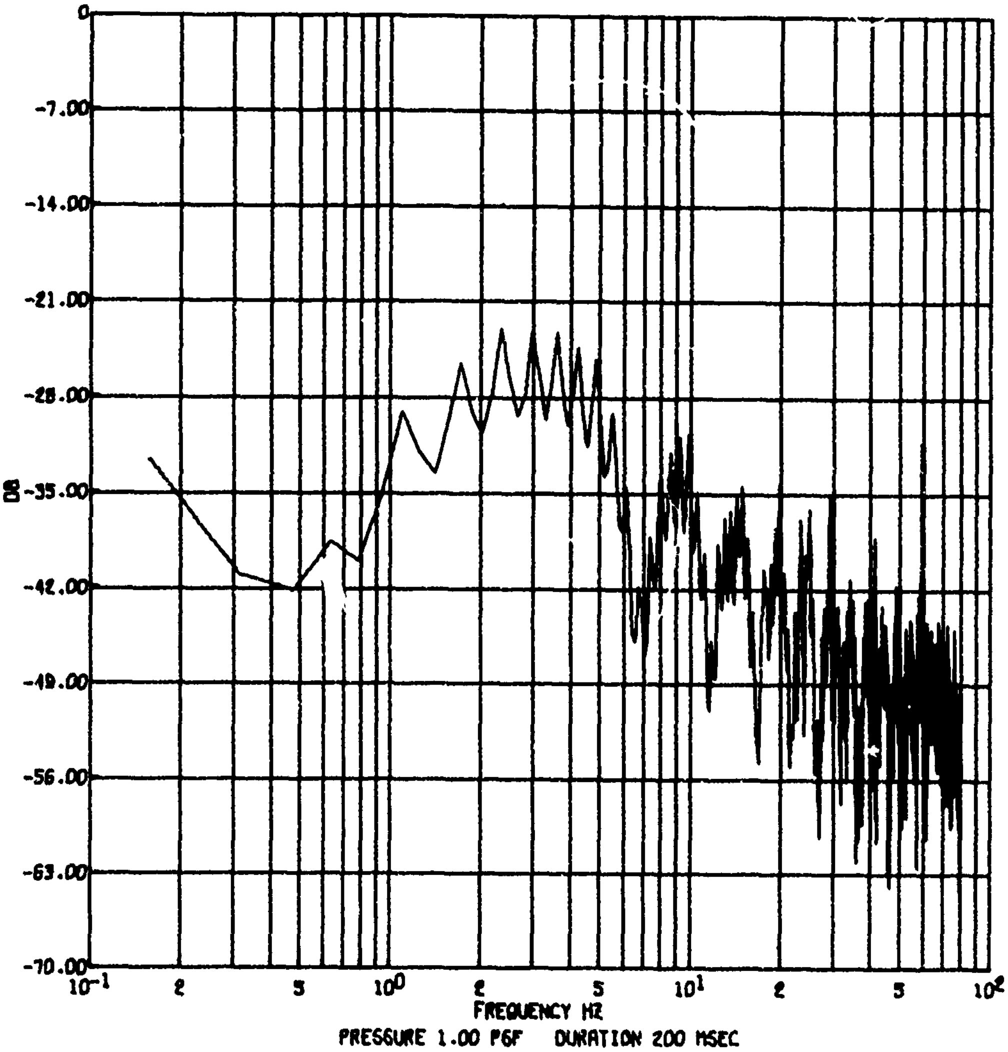


Figure A-6. Power spectral density for 1.00 psf simulated sonic boom for 200 msec.

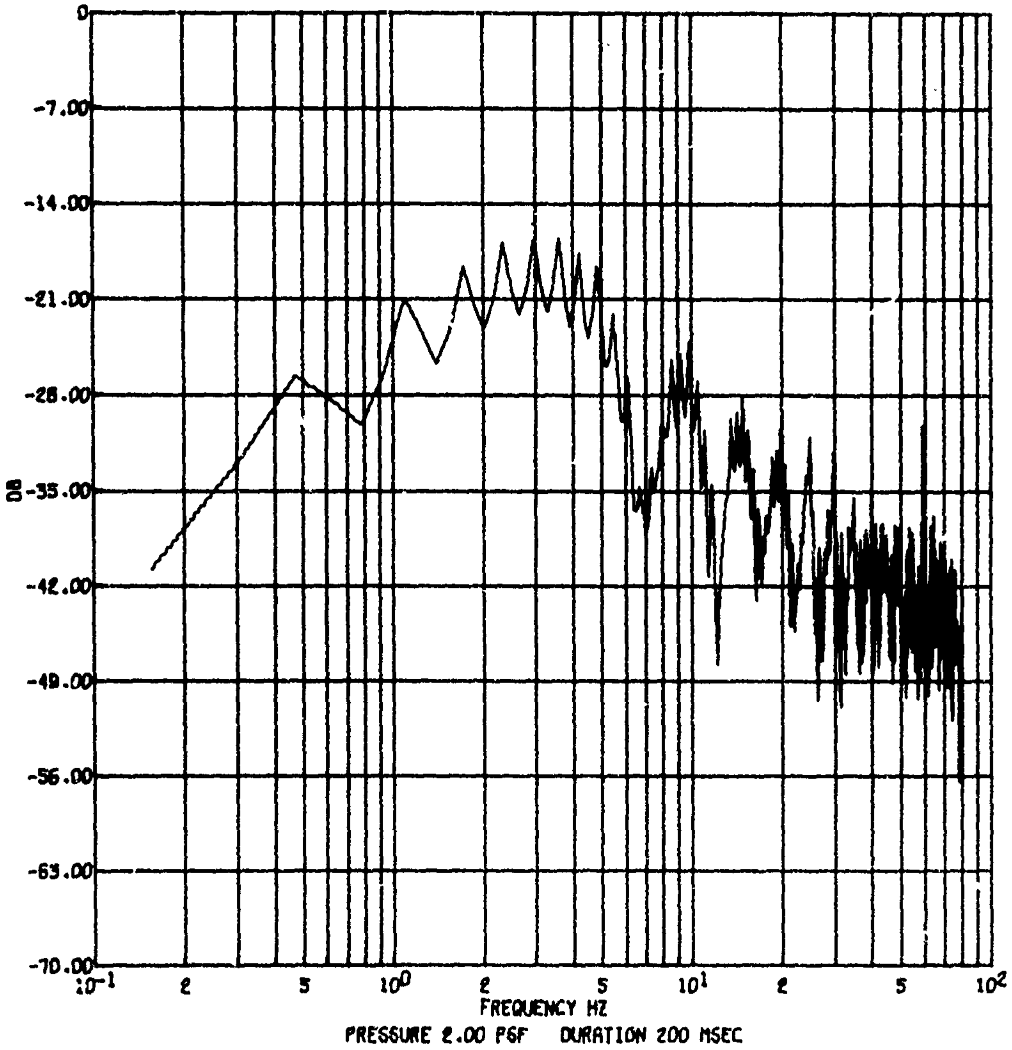


Figure A-7. Power spectral density for 2.00 psf simulated sonic boom for 200 msec.

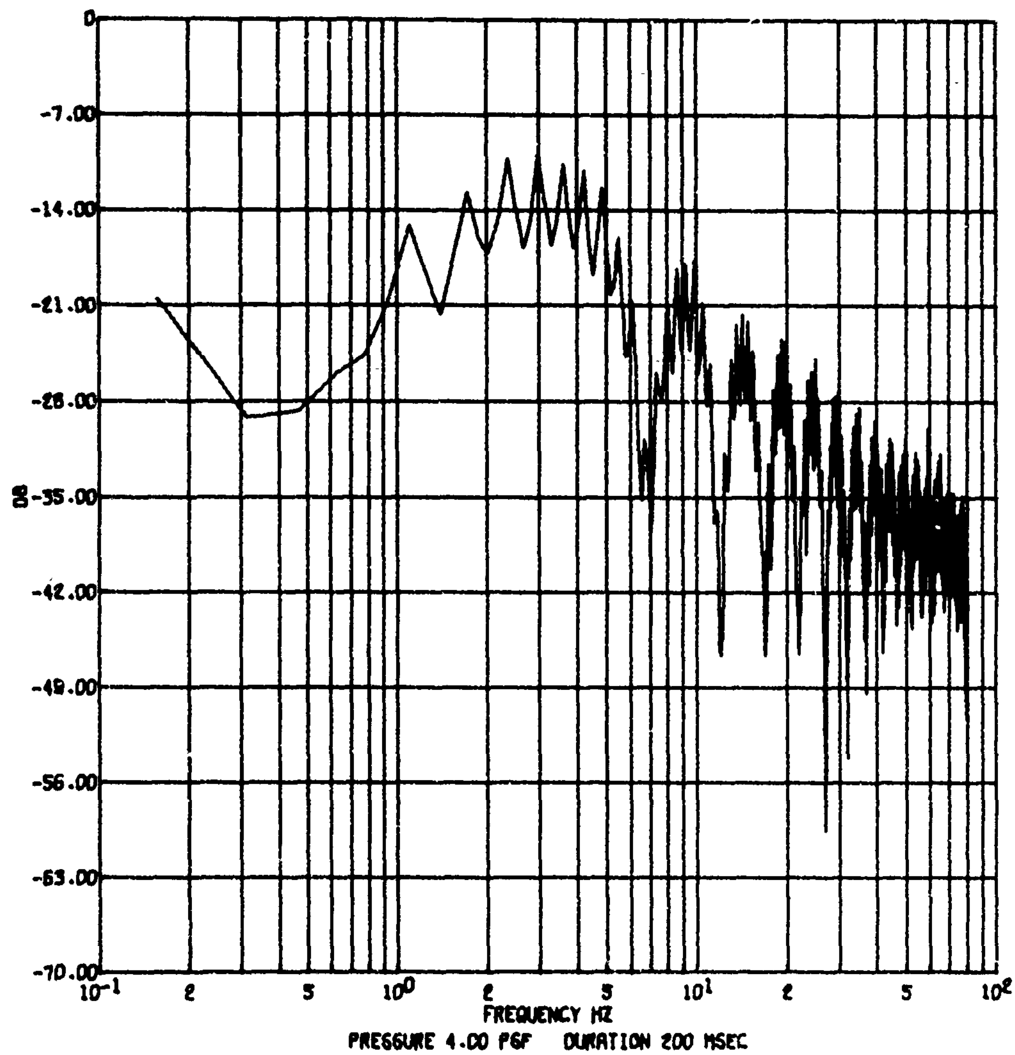


Figure A-8. Power spectral density for 4.00 psf simulated sonic boom for 200 msec.

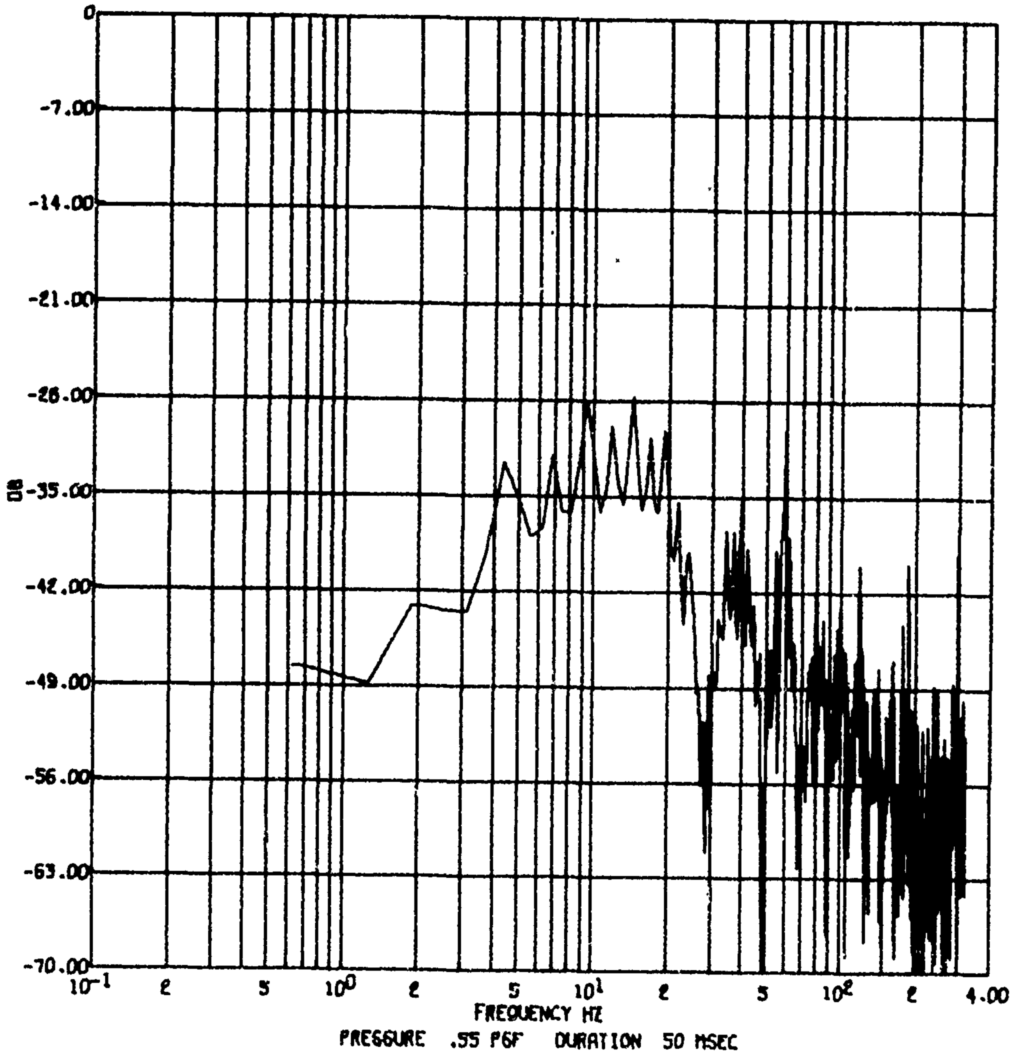


Figure A-9. Power spectral density for 0.55 psf simulated sonic boom for 50 msec.

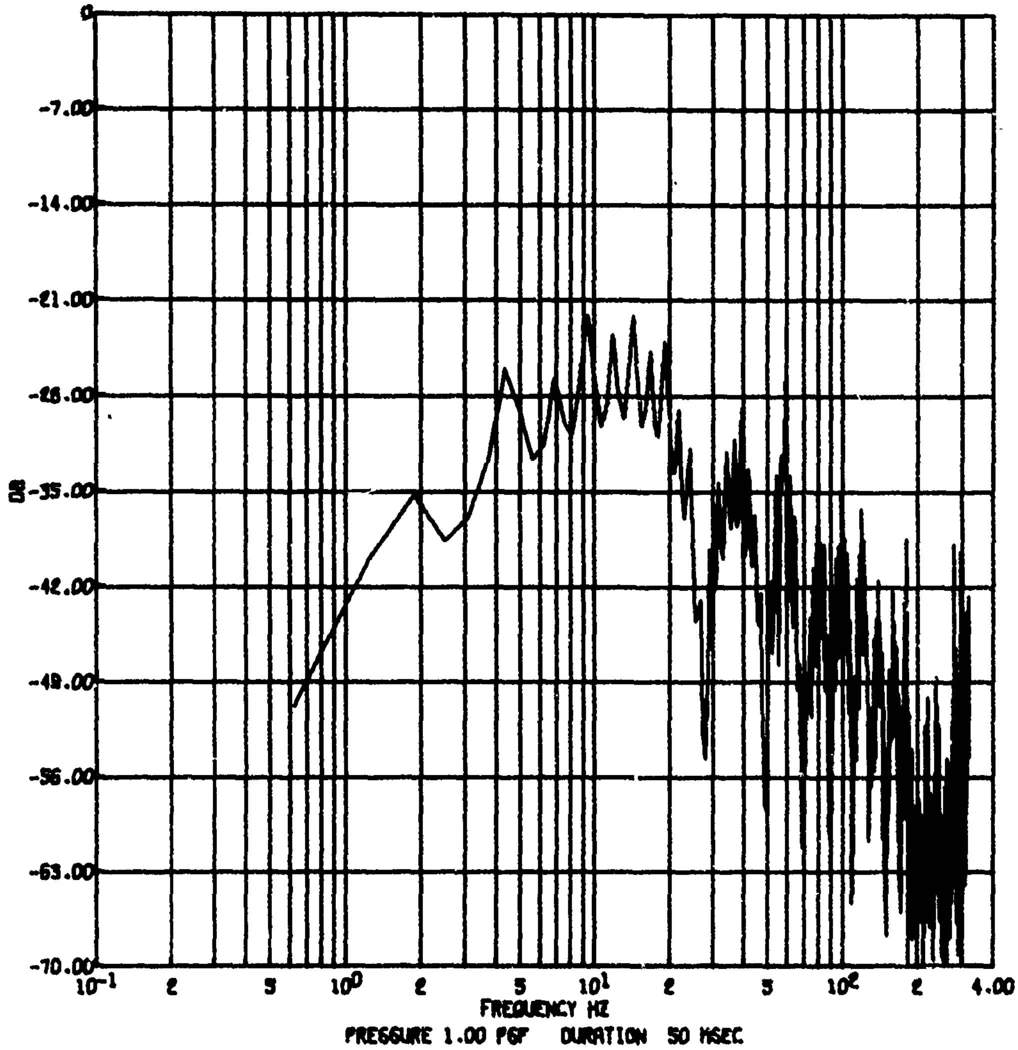


Figure A-10. Power spectral density for 1.00 psf simulated sonic boom for 50 msec.

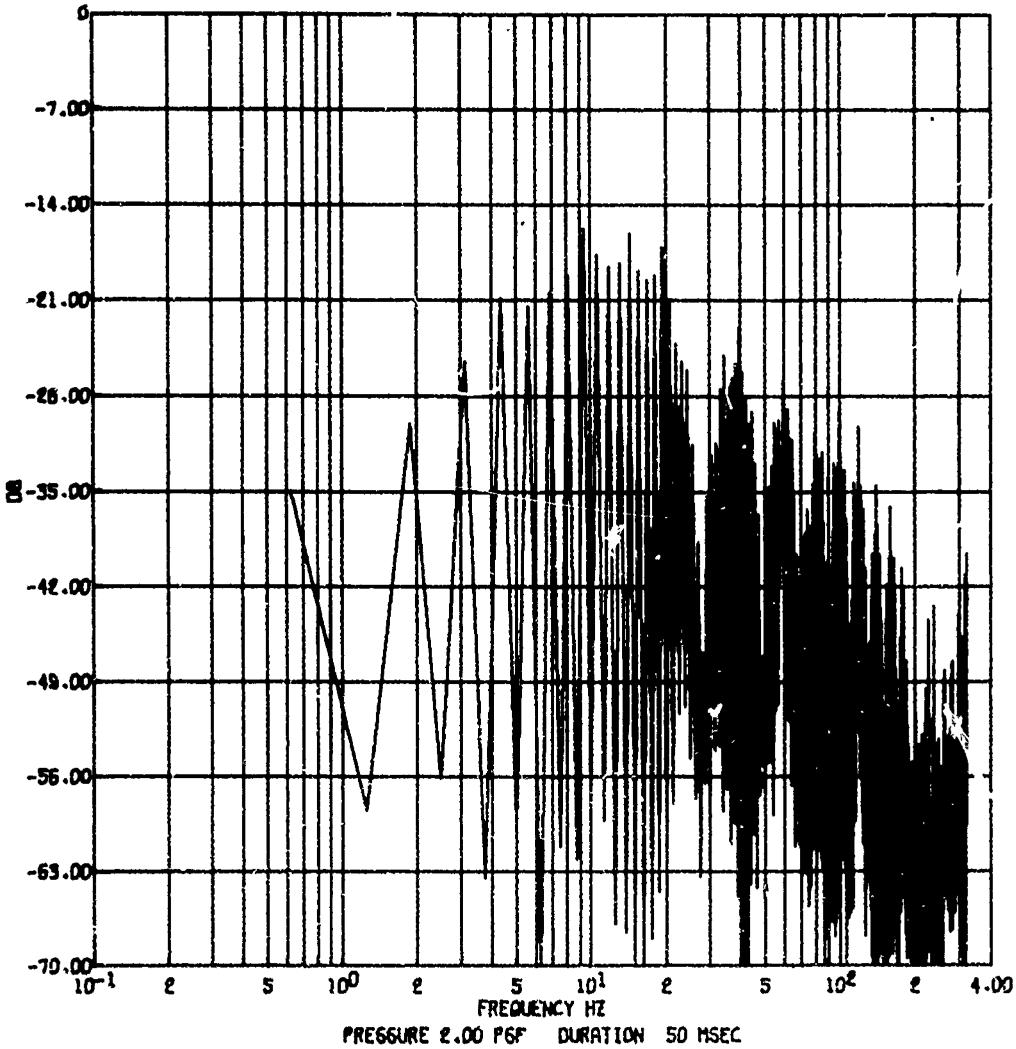


Figure A-11. Power spectral density for 2.00 psf simulated sonic boom for 50 msec.

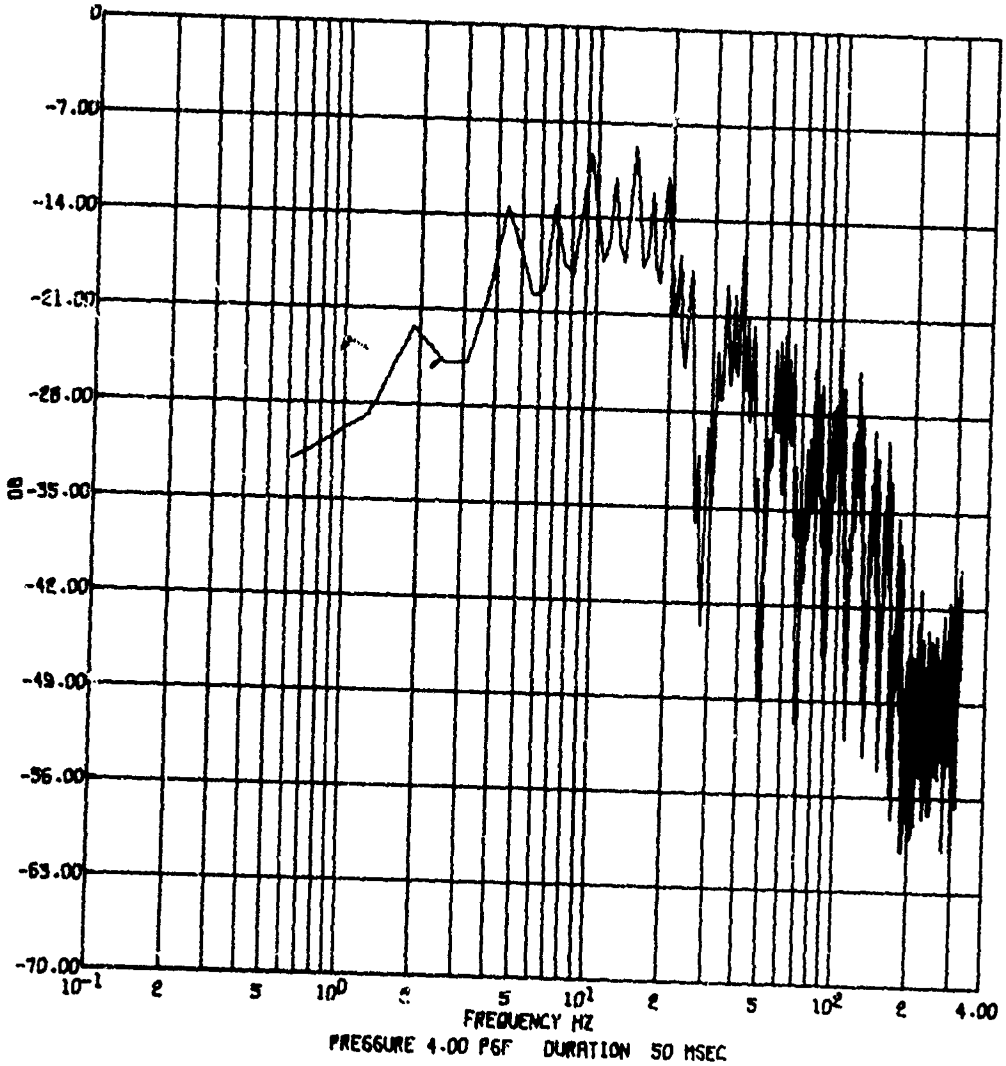


Figure A-12. Power spectral density for 4.00 psf simulated sonic boom for 50 msec.

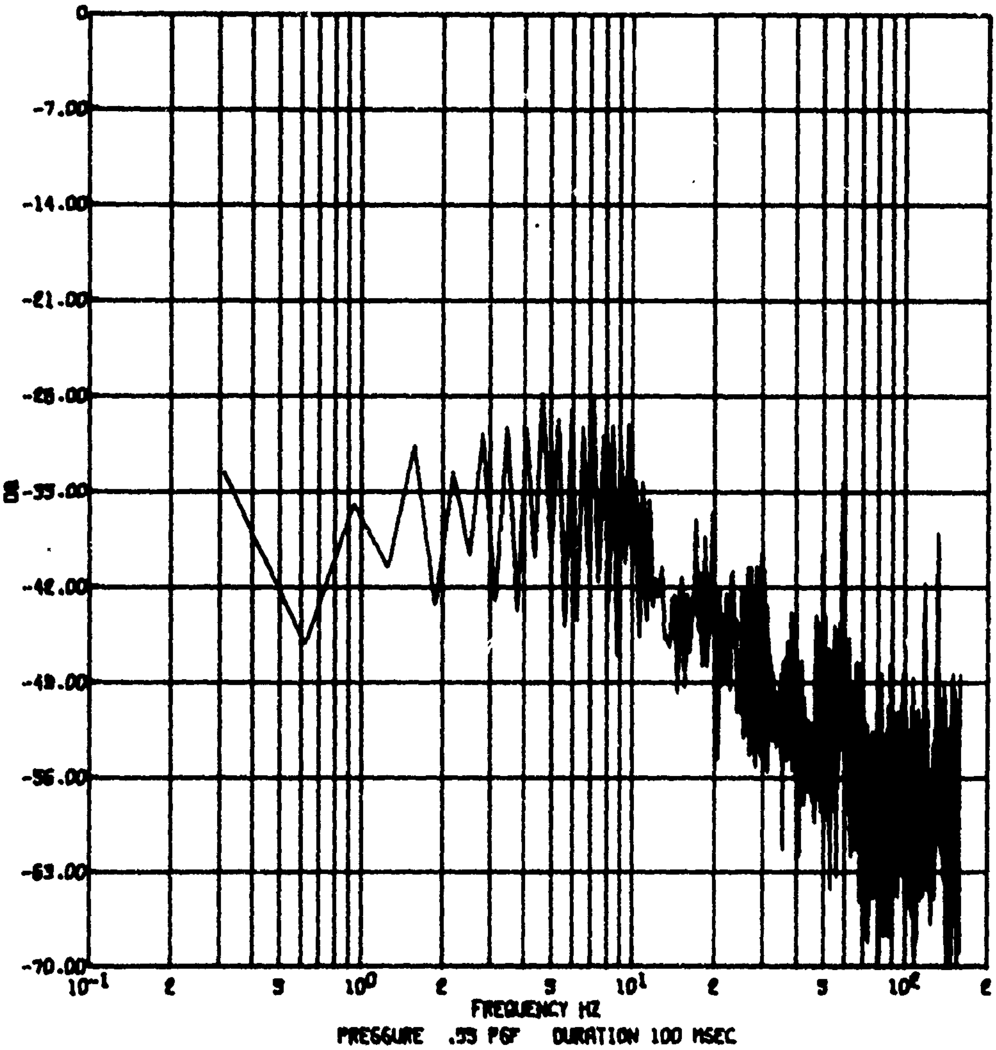


Figure A-13. Power spectral density for 0.55 psf simulated sonic boom for 100 msec.

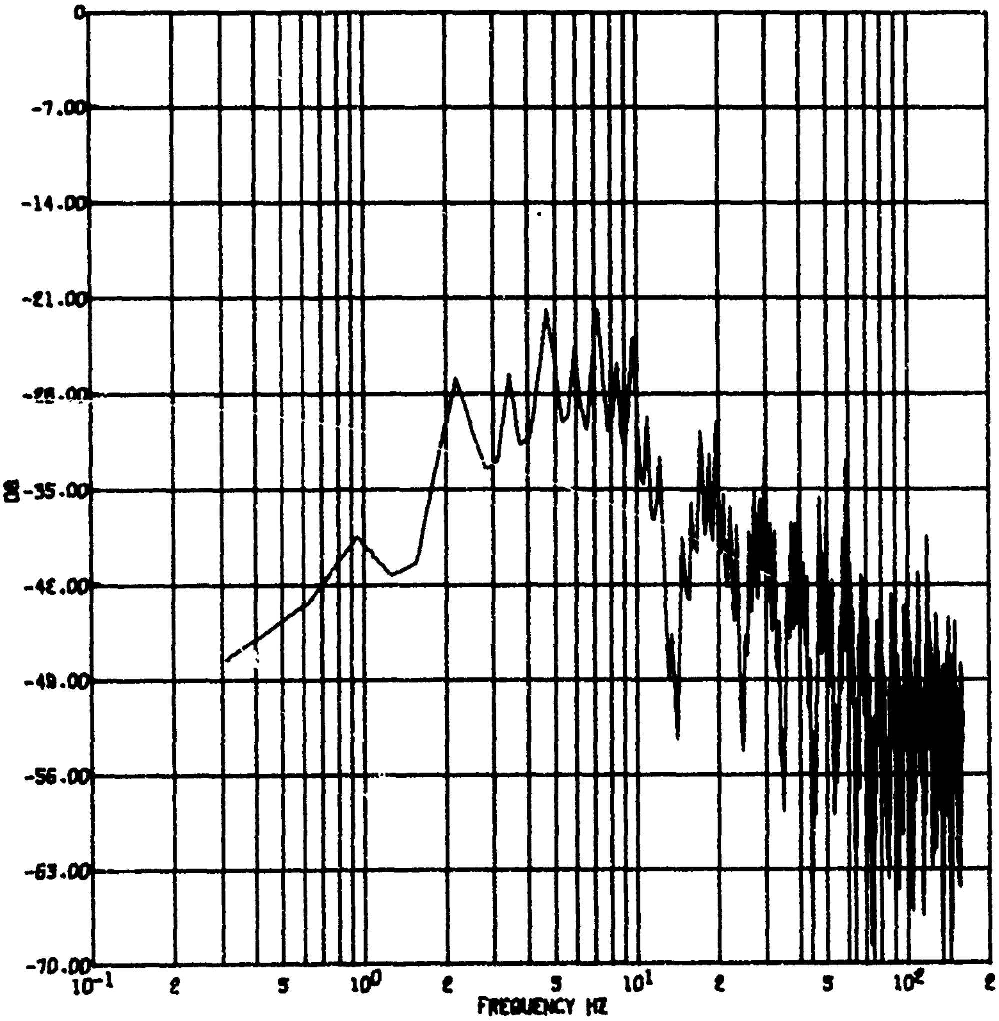


Figure A-14. Power spectral density for 1.00 psf simulated sonic boom for 100 msec.

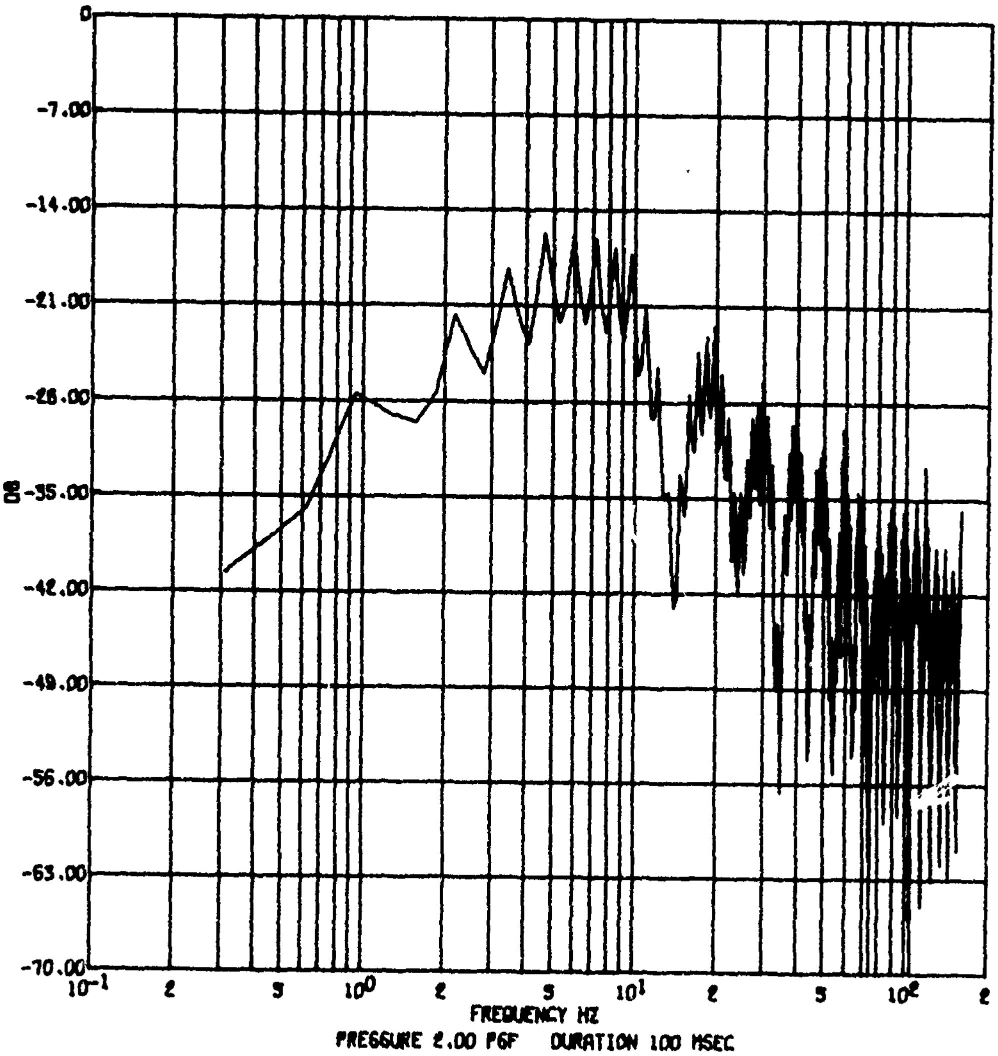


Figure A-15. Power spectral density for 2.00 psf simulated sonic boom for 100 msec.

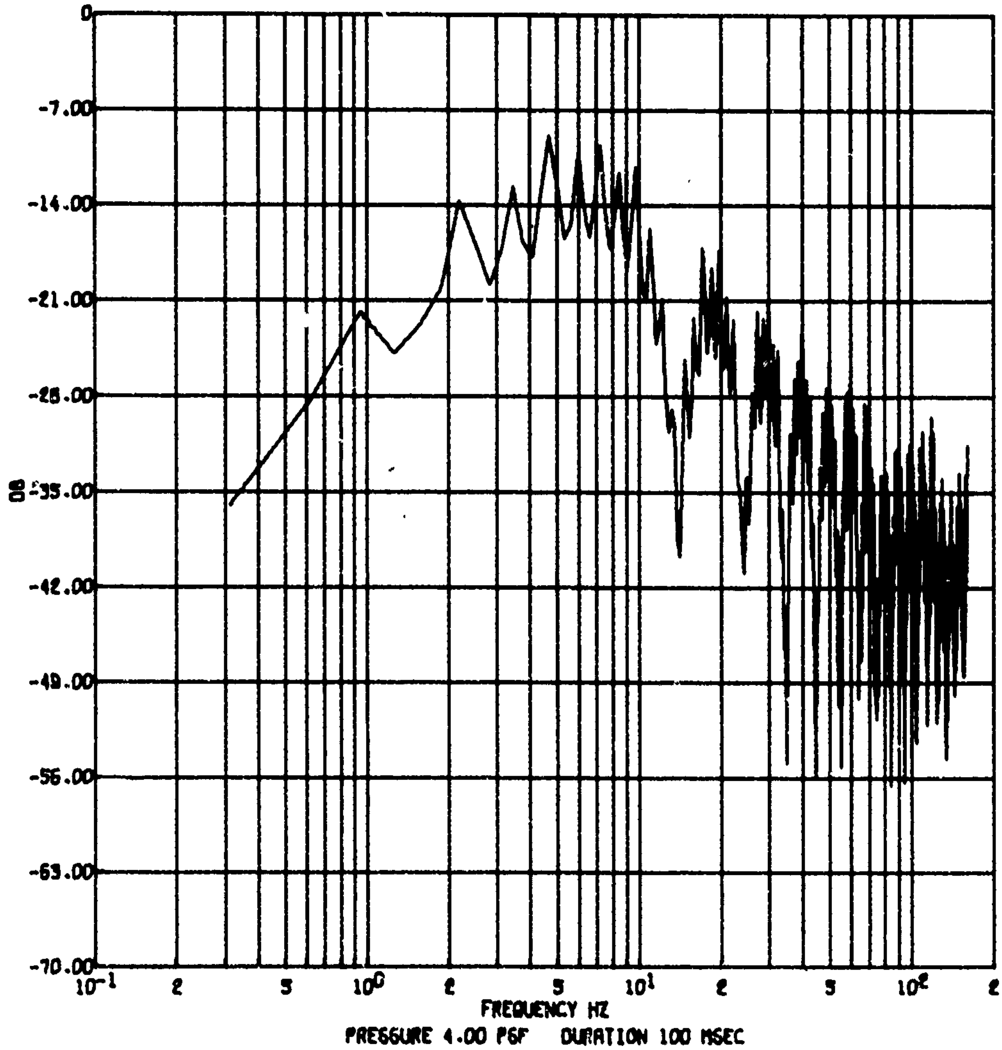
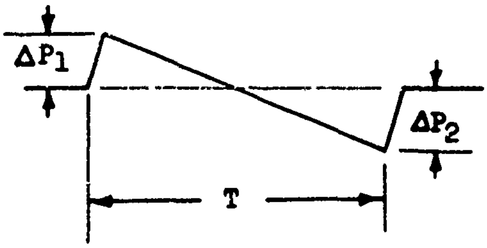


Figure A-16. Power spectral density for 4.00 psf simulated sonic boom for 100 msec.

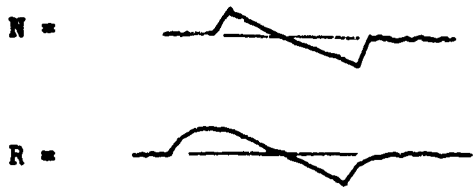
Table 1: Egg mortality data of four groups of cutthroat trout (*Salmo clarki*) eggs taken on April 18, 1972 and subjected to a sonic boom on April 25 at the Lahontan NFH. Test terminated on May 3 when eggs were well eyed or developed. Initial high mortality in group C was due to extra handling during picture taking on the evening of April 18.

		Group			
Date		A	B	C	D
April	18	0	0	0	0
	19	14	30	96	21
	20	1	6	2	0
	21	0	0	0	0
	22	6	1	1	0
	23	2	0	0	0
Sonic	24	7	6	32	9
boom	25	10	0	0	1
exposure	26	7	15	0	11
	27	0	3	0	2
	28	1	0	1	0
	29	3	6	0	1
	30	0	0	0	0
May	1	2	1	0	2
	2	3	2	0	0
	3	Test terminated -- eyes well developed			
		56	70	132	47

SYMBOL DEFINITION



WAVE TYPE DEFINITION



Date	Location	P_1 (PSF)	P_2 (PSF)	T (SEC)	Wave Type
4-25-72	Carson	0.84	0.93	0.139	N
"	Fish	0.82	0.89	0.123	N
"	Hatchery	0.75	0.61	0.136	N
"	"	1.14	0.99	0.119	N
"	"	0.89	← Avg. ΔP_1 for flight		
7-19-72	Carson	2.55	1.39	0.112	N
"	Fish	1.90	1.51	0.113	N
"	Hatchery	2.14	1.64	0.107	N
"	"	1.93	1.74	0.106	N
"	"	3.48	2.52	0.110	N
"	"	4.16	2.26	0.104	N
"	"	2.69	← Avg. ΔP_1 for flight		
8-25-72	Carson Fish Hatchery	0.68	0.62	0.166	R
4-25-72	Lahontan	0.81	1.24	0.137	N
"	Fish	1.16	1.20	0.138	N
"	Hatchery	0.84	1.14	0.133	R
"	"	0.96	1.51	0.132	N
"	"	0.94	← Avg. ΔP_1 for flight		

Table 2. Summary of sonic boom data from TDR-1 Recordors.

Table 3: Mortality data of steelhead trout eggs incubated at the Carson NFH and subjected to a sonic boom when 8 days old.

	Inside Basket	Inside Trays	Outside Trays	Total Eggs
Number green eggs	14,396	4,876	4,989	24,261
Green egg mortality	3,053 21.2%	758 15.5%	741 14.9%	4,552 18.8%
Number eyed eggs	11,343	4,118	4,248	19,709
Eyed egg mortality	1,782 15.7%	476 11.6%	387 9.1%	2,645 13.4%
Number fry	9,561	3,642	3,861	17,064
Fry mortality	125 1.3%	34 0.9%	25 0.7%	184 1.1%
Total fingerlings	9,436	3,608	3,836	16,880
Total mortality green egg to swim-up	4,960 34.5%	1,268 26.0%	1,153 23.1%	7,381 30.4%

Table 4: Mortality data of steelhead trout eggs incubated at the Abernathy Salmon Cultural Development Center as the control group without exposure to sonic boom.

Number green eggs	15,285
Green egg mortality	2,759 - 18.1%
Number eyed eggs	12,526
Eyed egg mortality	1,971 - 15.7%
Number fry	10,555
Fry mortality	411 - 3.9%
Total fingerlings	10,144
Total mortality green egg to swim-up	5,141 - 33.6%

Table 5: Mortality data of steelhead trout eggs: a control group and one group subjected to sonic boom.

	Abernathy Control	Carson Sonic Boom
	Percent Mortality	
Green egg	18.1	18.8
Eyed egg	15.7	13.4
Fry	3.9	1.1
Total	33.6	30.4

Table 6. Blood glucose levels expressed as mg/100 ml in yearling rainbow trout before and after an approximate 2 psf sonic boom. Normal values are recorded as "0" time. 50° F. water temperature. $\bar{x}$=mean, σ^2=variance, σ=standard deviation, γ=coefficient of skewness, $S\bar{x}$=stand. error of mean. *There were no significant differences.*

Fish	Time after Boom in hours						
	0	0.5	2	4	6	24	48
1	-	69.0	86.2	-	89.5	63.5	58.0
2	78.1	60.6	-	90.3	66.8	43.2	49.8
3	46.7	54.8	43.4	49.5	-	57.6	36.2
4	52.4	64.8	62.8	82.8	83.8	44.7	29.0
5	-	-	61.2	64.5	53.8	83.9	45.9
6	43.8	59.0	68.4	64.5	79.3	65.0	43.5
7	60.0	63.8	39.3	77.4	45.3	47.1	80.7
8	50.5	66.9	64.3	52.7	64.0	57.1	74.9
9	41.0	68.5	64.8	20.4	76.5	37.2	39.1
10	57.1	35.8	-	35.5	50.4	79.4	43.0
11	76.2	76.4	-	48.4	80.4	63.0	49.3
12	40.0	42.1	61.2	73.1	87.8	39.7	62.8
13	34.3	37.4	40.8	68.8	78.2	39.7	83.6
14	58.1	-	49.0	22.6	57.2	57.1	41.5
15	43.8	46.4	68.9	84.9	64.6	35.7	40.1
16	58.1	59.0	66.3	43.0	69.1	51.1	90.8
17	58.1	59.0	86.2	102.2	50.4	39.7	62.8
18	62.9	52.7	91.8	75.3	59.5	42.2	38.6
19	87.6	47.4	79.1	59.1	63.4	35.7	52.7
20	58.1	68.5	56.1	66.7	65.7	34.7	43.5
21	26.7	35.8	41.3	95.7	62.3	40.7	58.0
22	53.3	-	-	75.3	56.6	42.7	46.4
23	31.4	68.0	78.1	-	60.6	37.7	54.1
24	25.7	37.9	56.1	-	65.7	47.6	53.1
25	52.4	46.9	41.8	31.2	55.5	47.1	61.4
26	67.6	-	55.1	32.3	62.9	54.6	43.5
27	77.1	-	55.6	-	93.5	34.7	40.6
28	-	-	44.9	-	-	94.8	43.4
29	-	-	-	-	-	35.7	-
30	-	-	66.3				
$\bar{x}$	53.6	55.5	61.2	61.6	67.0	50.1	53.4
σ^2	258.3	156.4	167.0	541.5	167.0	242.5	285.2
σ	16.1	12.5	12.9	23.3	12.9	15.6	16.9
$S\bar{x}$	3.2	2.7	2.6	4.8	2.5	2.9	3.2
γ	.16	-.24	.31	-.17	.45	1.31	1.05

Table 7. Blood cortisol levels expressed as μg/100 ml in yearling rainbow trout before and after an approximate 2 psf sonic boom. Normal values are recorded as "0" time. 50° F. water temperature. $\bar{x}$=mean, σ^2=variance, σ=standard deviation, $S\bar{x}$=stand. error of mean, γ=coefficient of skewness. *There were no significant differences.*

Fish No.	Time after Boom in hours					
	0	0.5	2	4	24	48
1	0.0	0.1	0.0	0.0	0.5	1.8
2	3.5	2.4	1.7	-	-	1.4
3	-	0.1	2.3	0.1	1.4	0.9
4	0.0	0.1	0.7	0.0	0.9	2.7
5	0.0	-	0.0	0.0	0.5	0.5
6	3.5	1.3	0.7	0.0	1.4	0.0
7	11.2	3.0	1.7	0.0	0.9	0.9
8	1.5	0.7	2.3	0.0	1.9	1.8
9	15.0	0.1	-	0.0	-	2.7
10	5.4	0.1	0.0	0.0	0.5	0.0
11	5.4	-	0.7	-	0.5	0.0
12	13.1	0.0	-	0.1	0.0	1.4
13	0.0	0.7	0.0	0.0	1.9	0.9
14	0.0	4.7	-	0.0	0.9	0.9
15	0.0	0.7	2.3	0.0	1.4	0.9
16	-	0.7	0.0	1.7	1.9	0.5
17	49.7	0.1	0.0	-	1.9	0.0
18	32.3	0.0	0.0	0.0	0.9	0.9
19	0.0	2.4	-	-	0.0	0.9
20	0.0	0.0	0.0	0.0	1.9	0.5
21	9.2	0.7	0.0	0.0	0.0	0.5
22	0.0	10.9	-	0.0	0.0	0.5
23	13.1	0.7	0.0	0.0	-	0.9
24	24.7	0.0	2.3	0.0	0.9	0.5
25	20.8	1.3	0.0	-	0.0	0.5
26	53.3	-	0.0	-	0.5	0.9
27	3.5	-	1.0	-	0.9	0.9
28	-	-	-	-	0.0	0.9
29	-	-	0.0	-	0.9	-
30	-	-	0.0	-	-	-
$\bar{x}$	10.6	1.3	0.7	0.1	0.9	0.9
σ^2	227.5	5.7	0.8	0.2	0.5	0.5
σ	15.1	2.4	0.9	0.4	0.7	0.7
$S\bar{x}$	3.0	0.5	0.2	0.1	0.1	0.1
γ	3.6	3.1	1.0	4.1	0.2	1.2

Table 8. Plasma osmolality expressed as mOsm in yearling rainbow trout before and after an approximate 2 psf sonic boom. Normal values are recorded as "0" time. 50° F. water temperature. $\bar{x}$=mean, σ^2=variance, σ=standard deviation, $S\bar{x}$=stand. error of mean, γ=coefficient of skewness. *There were no significant differences.*

Fish	Time after Boom in hours						
	0	0.5	2	4	6	24	48
1	392.1	469.3	-	-	495.8	492.8	489.2
2	484.7	382.3	459.2	407.4	504.6	464.9	428.6
3	553.0	484.8	481.8	466.4	482.8	519.0	533.2
4	528.9	471.8	590.2	-	584.2	509.1	325.9
5	478.0	519.4	398.7	581.7	513.4	489.3	351.1
6	448.6	391.1	540.9	464.2	497.2	480.6	453.8
7	449.4	419.2	438.5	414.0	460.4	546.3	463.9
8	523.3	394.7	389.8	487.3	497.8	402.9	517.3
9	568.2	415.1	507.1	387.9	433.4	410.5	491.4
10	499.3	415.0	539.4	407.9	500.3	521.1	457.1
11	490.0	446.1	429.9	374.6	457.0	448.6	496.7
12	475.2	379.2	525.4	449.8	558.1	522.8	429.9
13	486.3	414.4	358.9	476.1	514.8	485.6	401.5
14	490.3	-	457.6	333.8	515.6	479.4	403.2
15	478.2	366.1	519.0	-	533.8	462.4	389.8
16	477.1	405.8	383.5	486.2	433.8	593.1	422.9
17	-	419.0	-	415.9	534.8	485.9	425.8
18	470.1	429.2	484.9	439.6	493.8	474.0	496.9
19	-	418.2	655.8	499.2	498.7	436.4	377.1
20	543.3	463.8	436.0	521.2	513.0	411.4	475.9
21	465.4	337.0	478.8	505.8	518.2	511.7	422.0
22	503.6	-	-	454.2	512.8	545.7	491.2
23	455.4	494.8	403.4	429.3	519.9	537.2	457.7
24	459.0	489.0	502.3	509.4	451.6	527.8	451.6
25	-	439.4	398.2	492.9	456.5	474.7	454.0
26	497.8	-	448.1	452.6	492.6	503.6	428.3
27	436.2	-	-	-	-	499.0	467.3
28	-	-	427.9	-	508.2	432.6	493.6
29	-	-	493.6	-	-	491.8	502.2
30	-	-	491.2	-	-	-	-
$\bar{x}$	485.6	428.9	470.8	454.7	499.4	488.3	448.2
σ^2	1526.8	2065.0	4613.7	3014.6	1211.1	1948.4	2454.4
σ	39.1	45.4	67.9	54.9	34.8	44.1	49.5
$S\bar{x}$	7.8	9.5	13.3	11.4	6.7	8.2	9.2
γ	.09	.12	.68	.02	.03	-.05	-.56

Table 9: **Percent mortality of spring chinook salmon eggs taken at the Carson NFH after exposure to a sonic boom.**

Date	Percent Mortality
August 9, 1972	2.7
10	5.6
16	4.1
22a	14.2
22b	6.6
23a	9.7
23b	19.2
25	8.5
29a	14.9
29b	17.4
30a	12.8
30b	15.8
September 1	23.9
6	23.8
av.	13.9

Table 10: Abernathy Salmon Cultural Center fall chinook salmon egg and fry mortalities correlated with simulated sonic boom overpressures: 203,185 eggs distributed among 88 trays.

Percent mortality to:

	0 psf		0.55 psf		1 psf		2 psf	
Age of egg in days	Hatch	Swim up	Hatch	Swim up	Hatch	Swim up	Hatch	Swim up
0	4.2	12.4	5.6	11.3	13.6	20.2	5.8	10.4
1	4.3	10.5	6.8	10.2	5.4	10.4	4.1	11.0
2	4.3	9.9	4.8	12.1	7.0	13.4	4.7	11.5
3	6.7	12.4	5.2	11.6	4.7	12.7	5.0	11.5
4	6.9	15.1	6.3	12.2	4.7	10.3	6.5	13.0
5	4.7	7.3	17.6	24.1	9.2	16.5	4.6	16.0
6	16.6	24.0	13.8	22.8	3.3	6.8	9.3	17.0
7	14.1	19.9	9.4	15.2	20.1	23.6	5.9	14.4
8	6.7	14.7	4.6	9.9	7.2	12.7	4.9	10.0
9	6.1	16.9	4.8	11.3	17.9	24.0	6.5	11.9
10	4.0	12.3	13.9	15.6	4.6	6.3	21.8	29.5
11	9.5	12.2	7.6	9.9	7.9	15.9	3.4	10.4
12	5.0	12.3	16.4	22.6	5.5	9.1	2.0	3.7
13	7.8	11.4	5.0	13.0	6.6	13.6	7.5	10.6
14	4.9	12.5	6.3	16.1	14.4	21.9	4.7	10.2
15	4.9	12.1	7.5	9.3	2.4	4.8	5.5	12.9
16	12.2	23.0	7.5	11.8	4.6	9.8	23.5	29.1
17	10.6	22.0	5.5	9.2	14.9	22.3	6.8	14.2
18	3.3	4.4	5.8	14.4	6.0	12.9	15.9	22.4
19	6.2	14.3	13.6	19.1	7.4	13.3	8.9	18.0
20	11.7	19.1	6.1	12.4	15.3	23.7	2.4	5.0
21	6.2	12.5	20.2	25.5	6.3	13.9	31.1	36.5

Table 11: Abernathy Salmon Cultural Center fall chinook salmon egg and fry percent total accumulative mortalities correlated with simulated sonic boom overpressures, age, rows and stacks in incubator by means of analysis of variance.

Variable	Day 24 & 25 Pre-count	Day 32 Post-count	Day 45 Hatch	Day 74 & 75 Swimup
levels 0, .55, 1.00, 2.00	not significant	not significant	not significant	not significant
Days 0 - 22	significant	significant*	significant*	not significant
Rows 1 - 15	not significant	not significant	not significant	not significant
Stacks A - F	significant	significant	significant	not significant

*Marginal

Table 12: Percent total accumulative mortality to the feeding stage from Abernathy second test using greater overpressures on salmon eggs.

	psf levels						
Days	0	.55	1.00	2.00	4.00	4.00x	$\bar{x}$
6	[illegible]	10.61	8.25	9.50	15.65	8.26	10.735
9	[illegible]	16.26	14.86	38.28	19.65	9.94	18.087
$\bar{x}$	10.835	13.435	11.555	23.890	17.650	9.100	

	rows						
Stacks	1	2	3	4	5	6	$\bar{x}$
G	8.26	8.25	9.94	9.53	9.50	12.14	9.603
H	16.26	38.28	10.61	19.65	14.86	15.65	19.218
$\bar{X}$	12.260	23.265	10.275	14.590	12.180	13.895	