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ACOUSTIC-EMISSION CHARACTERISTICS OF PLAIN CONCRETE

ERIC H. WANG CIVIL ENGINEERING RESEARCH FACILITY
UNIVERSITY OF NEW MEXICO
BOX 25, UNIVERSITY STATION
ALBUQUERQUE, NEW MEXICO 87131

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The results of acoustic-emission tests on young concrete specimens and concrete cores from airfield pavements indicate that the Kaiser Effect is not permanent in concrete. That is, there is a recovery such that load cycles applied subsequent to the initial load cycle will produce acoustic-emission signals similar to those obtained during the first load cycle. This report suggests, therefore, that the Kaiser Effect cannot be used to detect the maximum past stress in concrete which has not been subjected to a continuous stress.

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PREFACE

This report documents work performed during the period 1 March 1975 through 30 September 1976 by the University of New Mexico under Contract F29601-76-C-0015 for the Air Force Civil Engineering Center, Air Force Systems Command, Tyndall Air Force Base, Florida 32401. Lt. Col. George D. Ballentine managed the program for the Center.

This report has been reviewed by the Information Officer (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

GEORGE D. BALLENTINE, Lt. Col., USAF
Project Officer

GUY P. YORK, Lt. Col., USAF
Director of Engineering Materials

ROBERT E. BRANDON
Technical Director

ROBERT M. ITEN, Col., USAF
Commander

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INTRODUCTION

BACKGROUND

An area of major concern in the development of a nondestructive pavement evaluation procedure is the determination of the remaining service life of an existing pavement. This determination is complicated; it involves the evaluation of such factors as the number and types of aircraft operations (i.e., past history), the number and extent of environmentally induced stress cycles, pavement composition and construction techniques, and an estimate of future aircraft operations. The influence of these and other factors on the basic fatigue life of the pavement is then coupled with material parameters which influence pavement fatigue so as to project the remaining service life of the pavement. This aspect of pavement evaluation is difficult and the solution to the fatigue life of paving materials constitutes one of the most difficult problems in material science today. However, a recent CERF project (ref. 1) indicates that acoustic-emission techniques may be useful in estimating the service life remaining in an airfield pavement surface course.

Many engineering materials emit a pressure wave which is produced by the energy released when the material is stressed. External loading on a test specimen produces plastic flow, slippage of adjacent particles, crushing of particulate matter, and microcracking, and these actions result in the release of energy. With adequate sensors and signal processing, the pressure (stress) waves--known as *acoustic emissions*--can be detected at the surface of the deforming test specimen. The American Society for Testing and Materials (ref. 2) provides this definition: *acoustic emission is a transient elastic wave generated by the rapid release of energy within the material.*

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1. Bickle, L. W., and Smiel, A. J., *Applicability of Acoustic-Emission Techniques to Civil Engineering Research*, AFWL-TR-74-299, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, June 1975.

2. *Acoustic Emission*, Special Technical Publication No. 505, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1972.

A unique characteristic of some engineering materials that emit acoustical energy is the Kaiser Effect, a phenomenon by which the acoustic activity of a previously stressed specimen is slight or nonexistant until the previous maximum stress is again applied; at which point, the emission signals increase significantly. The Kaiser Effect is used extensively in industry to monitor equipment (e.g., pressure vessels) which must not be stressed beyond certain limits. It is also used extensively in *tattletail* applications to determine maximum past loadings on industrial equipment. The Kaiser Effect can be observed in most metals, and it also occurs in plain Portland cement concrete (ref. 1).

OBJECTIVES

A study was undertaken to determine if acoustic-emission techniques could be used to estimate the maximum past loading on a concrete airfield pavement. This information could then be used to estimate the remaining fatigue life of the pavement. This study was exploratory in nature. Specific objectives were as follows: (1) Thoroughly review the literature collected (ref. 1) as it relates to the uses of acoustic-emission techniques in rock mechanics and plain concrete research, and update that literature search; (2) Review the significant literature which now exists on the fatigue of plain concrete and correlate it with that above; (3) Perform a laboratory study to determine the optimum frequency range which should be used in acoustic-emission testing of plain concrete; and (4) Plan and conduct a laboratory test program to investigate the Kaiser Effect in plain concrete as a means of estimating the life remaining in an existing concrete pavement.

APPROACH

Because very little information exists in the technical literature relative to the acoustic-emission properties of plain concrete, a laboratory test program was developed. Concrete cylinders and beams were fabricated for testing from two different concrete mixes. Cores from aged concrete pavements were provided by the Air Force Civil Engineering Center (AFCEC). These test specimens were tested in uniaxial compression, tensile splitting, flexural, and uniaxial compression to failure following cyclic loading to evaluate their emission characteristics.

SECTION 2
LITERATURE REVIEW

FAILURE OF PLAIN CONCRETE

An explanation of the mechanism of fatigue of concrete may assist the reader in understanding the source of acoustic emissions during load testing of concrete. Both Antrim (ref. 3) and Westerberg (ref. 4) are in essential agreement about the mechanism of fatigue in plain concrete. They believe fatigue failure occurs because small cracks (microcracks) form and propagate and new cracks form under repeated loading less than the static failure load. Microcracks are usually present in concrete before it is loaded. Propagation of existing cracks and initiation of new cracks occur because of the breakdown of the bond between the cement paste and the aggregate; cracks also start at air voids and other flaws where stresses are concentrated. Westerberg believes that the mechanism of failure is the same for both flexure and compression, except that in compression the cracks are mainly parallel to the direction of compression and are induced by transverse tensile stresses. Antrim further believes that the development of the damaging crack pattern depends primarily, if not entirely, on the water/cement ratio of the cement paste. In addition, concretes with different water/cement ratios develop a crack pattern in their cement paste in the same manner as does pure cement paste; i.e., the crack pattern develops slower in cement paste with an open capillary structure than in cement paste with a dense structure, and thus if the cement paste has lost gel water, the crack pattern develops slower. Antrim further states that the aggregate has some influence on the fatigue behavior of the concrete. The explanation offered is that there are bond cracks present at the aggregate interface and that the paste surrounding the aggregate is not necessarily the same as the main body

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3. Antrim, J. D., "The Mechanism of Fatigue in Cement Paste and Plain Concrete," *Highway Research Record No. 210: A Symposium on Concrete Strength*, Highway Research Board, Washington, D. C., 1967, pp. 95-107.

4. Westerberg, B., Statens Institute for Byggnadsforskning Rapport 22: 1969: Uttmatning av betong och armerad betong. En litteraturoversikt (Fatigue of Plain and Reinforced Concrete. A survey of literature), Stockholm, Sweden, Svonsk Byggtjåñst, 1969.

of paste. Failure in fatigue occurs when cracks propagate to such an extent that the maximum stress induced by the applied load can no longer be sustained.

ACOUSTIC-EMISSION TECHNOLOGY AS RELATED TO PLAIN CONCRETE

An extensive literature review of publications concerning specific applications to Portland cement concrete pavements was reported in reference 1. Attention was devoted to articles which revealed that acoustic-emission technology is incipiently ready for field application. However, Bickle and Smiel (ref. 1) could not locate a single citation to published work concerning detection and classification of flaws in concrete by acoustic emissions. Nor, could any published work be found about the application of acoustic-emission techniques to paving materials per-se. Three articles that dealt with the acoustic apparatus used to record emissions from concrete under strain (refs. 5, 6, 7) were found; however, no pertinent material published during the interim following the issuance of reference 1 could be located.*

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5. Wells, D., "An Acoustic Apparatus to Record Emissions from Concrete Under Strain," *Nuclear Engineering and Design*, 12, May 1970, pp. 80-88.

6. Rusch, Von H., "Physikalische Fragen der Betonprufung," *Zement-Kalk-Gips*, V12 N1, January 1959, pp. 1-9. (Presented at the meeting of the German Association of Cement Manufacturers, Wiesbaden, September 23, 1958.) Note: There is a Cement and Concrete Association Library Translation (No. 80) and a translation by Margaret Corbin available at PCS Library, Skokie, Illinois.

7. Schickert, Gerald, "Acoustic Emission Technique Applied to Tests with Concrete Cubes," RILEM. 11eme Symposium International De la Commission 7 NDT, Constanta-Romania, 4 September 1974. Noveaux developments dans l'essai non-destructif des materiaux non metalliques. Vol. 11 Beton-Nouvelles Methodes, Resonance, Ultrasons. Institut Recherche Du Batiment INCERC, Bucaresti 1974.

*After this research was completed, a paper by W. Martin McCabe, Robert M. Koerner, and Arthur E. Lord, Jr., entitled *Acoustic Emission Behavior of Concrete Laboratory Specimens*, appeared in the ACI Journal for July 1976 (pp. 367-371). The ACI paper contends that the Kaiser Effect is quite valid in concrete; the CERF research shows the validity of the Kaiser Effect sometimes and only for immediate reloading; the effect recovers with rest periods and a repeatable Kaiser Effect is revealed. If the Kaiser Effect were valid, it could not be repeated on a given specimen subjected to identical loading cycles.

Reference 2 is the first comprehensive literature survey on acoustic-emission technology. As quoted from the introduction:

> *The papers cover a wide range of topics, from general reviews of the field to specific reports on research findings, technological advances, and applications in different industries. Their collective references, cited in the papers, include most of the published material on acoustic emission technology.*

Although reference 2 deals very little with concrete, some quotations are provided as a means of acquainting the reader with some of the relationships between materials and acoustic emission.

Some observations from *An Introduction to Acoustic Emission*, by R. B. Liptai, et al., are as follows:

> *Emissions from metals are primarily due to dislocation motion (probably does not apply in concrete) accompanying plastic deformation rather than being entirely due to grain boundary sliding as proposed by J. Kaiser.*
>
> *The presence of cracks in structures alters the load at which plastic deformation begins, thus altering the acoustic emission pattern observed as the structure is loaded.*
>
> *Plastic deformation, which results in acoustic emission, occurs at crack tips and other highly stressed regions when a material is loaded.*
>
> *Fatigue crack growth produced by fluctuating loads can be detected by continuous monitoring of acoustic emissions. Also, the amount of crack growth per cycle can be directly determined from acoustic-emission data.*
>
> *The stress in a metallic system may be well below the elastic design limit; however, the region near a flaw or a crack may undergo plastic deformation from localized high stresses. In this situation, the flaw is the generator or source of acoustic-emission activity.*

These observations were made in reference to metals; however, it was initially thought that they should also apply to Portland cement concrete. According to Han-Chin Wu (ref. 8):

> *Although concrete is locally nonhomogeneous and multiphased and contains microcracks, this material may phenomenologically be considered isotropic and homogeneous since the size and orientation of the aggregates are random.*

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8. Han-Chin Wu, "Dual Failure Criterion for Plain Concrete," *Journal of the Engineering Mechanics Division, Proceedings of the ASCE*, Vol. 100, No. EM, December 6, 1974, p. 1167.

C. A. Tatro in his paper entitled *Design Criteria for Acoustic Emission Experimentation* observed that acoustic-emission technology deals with dimensional changes and that dimensional changes of 10^{-12} in are an easily recognizible threshold. Such changes are six orders of magnitude below the sensitivity threshold of a resistance strain gage (ref. 2).

It is pertinent to quote the conclusions reached by P. P. Gillis in his paper *Dislocation Motions and Acoustic Emissions*:

> *It seems reasonably clear that acoustic emissions are detected in many deformation processes in which dislocations play no role...A grey middle ground is occupied by the nonhomogeneous deformation process accompanying crack propagation; certainly dislocation motion spreads the plastic zone at the crack tip and acoustic emissions are detected, but it is difficult to correlate the two.*
>
> *Technologically, the nonhomogeneous deformations have the greatest significance because of their intimate connection with structural failures and so a substantial effort must be devoted to the detection and identification of their emissions.*

An interesting phenomenon has been reported by J. F. Frederick and D. K. Feldback in *Dislocation Motion as a Source of Acoustic Emission*:

> *Several cases have been reported in which acoustic emission has been observed when a tensile load is removed from a test specimen prior to fracture of the specimen. This "unload" emission is reversible; that is, it occurs on repeated loading and unloading cycles. Furthermore, materials that show an unload emission effect do not show a Kaiser Effect. In other words, they produce acoustic emission (immediately) during reloading instead of not emitting until the value of the previously applied load has been exceeded. The unload acoustic emission is generally an order of magnitude or more smaller than the load emission.*

Factors which influence acoustic-emission detectability, all of which may not apply to concrete, are given by H. L. Dunegan and A. T. Green in *Factors Affecting Acoustic Emission Response from Materials* (table 1).

Wells (ref. 5) performed some acoustic-emission experiments on 3-in and 4-in cubical specimens of Portland cement mortar (cement/sand/water) and of concrete

Table 1. Factors Influencing Acoustic-Emission Detectability (ref. 2)

Factors Resulting in High-Amplitude Signals	Factors Resulting in Low-Amplitude Signals
High Strength	Low Strength
High Strain Rate	Low Strain Rate
Anistropy	Isotropy
Nonhomogeneity	Homogeneity
Thick Section	Thin Section
Twinning Material	Nontwinning Material
Cleavage Fracture	Shear Deformation
Low Temperature	High Temperature
Flawed Material	Unflawed Material
Martensitic Phase Transformation	Diffusion-Controlled Transformation
Crack Propagation	Plastic Deformation
Cast Structure	Wrought Structure
Large Grain Size	Small Grain Size

with various aggregates (maximum particle size of 3/8 in). His conclusions are as follows:

> *Although numerous results have been obtained they are not comparable with each other. However, in some cases, there does seem to be a tendency for a pattern to emerge where a number of small cubes have been tested. The tendency shows that, in some cubes, noise emission starts somewhere over 50 percent ultimate strength and increases as the failure load is approached. This is in line with the findings of Rusch (ref. 6).*
>
> *There is little evidence of any relationship between strain measurements and noise but it may be that strain changes associated with noise are too small to be detected.*

Rusch (ref. 6) reported on the results of acoustic-emission measurements on a concrete prism capped with a thin layer of gypsum. He made the following observations:

> *On repeated load-release-load-increase appreciable noise (acoustic emissions) was renewed only when the formerly attained stress maximum was exceeded.*
>
> *Above 70 to 85 percent of failure load, noises were produced before the previous maximum load was reached.*

In the vicinity of failure load there was considerable noise and noise continued during the unloading process.

According to Dunegan and Greene in *Factors Affecting Acoustic Emission Response from Materials* (ref. 2):

> *Concrete is an example of a widely used composite material containing a brittle matrix and comparatively ductile and high modulus reinforcing members. The permanent deformation mode of this material is primarily cracking of the matrix material, which gives rise to acoustic emission signals of higher amplitude than are found in most metals.*

Schickert (ref. 7) attempted to relate acoustic-emission techniques to the fracture of concrete cubes. He concluded:

> *The method has been effectively applied to analyze the development of fracture of concrete cubes. However test results show quite a big variation.*

Hutton, et al. (ref. 9), describe a method but do not give a program whereby a time-analysis computer provides processed data to a triangulation computer which calculates the geometrical location of the detected sources from several separate transducers. E. V. Waite describes triangulation programs for locating structural flaws on spherical pressure vessels (ref. 10) and on cylindrical vessels (ref. 11). Both programs are based on time-of-arrival differences among three or more unique acoustic transducers.

FATIGUE OF PLAIN CONCRETE

A review of the most recent literature concerning fatigue of concrete, as reported in the *Abeles Symposium* (ref. 12), reveals only three papers dealing

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9. Hutton, P. H., et al., "Assessment of Structural Integrity by Acoustic Emission," *ASTM Materials Research and Standards*, Vol. 11, No. 3, March 1971.

10. Waite, E. V., *ACOUST-S: A Digital Program for Acoustic Triangulation of Spherical Vessels*, Idaho Nuclear Corporation, Idaho Falls, Idaho, March 1970.

11. Waite, E. V., and Moore, K. V., *ACOUST-A: Digital Program for Acoustic Triangulation of Nuclear Vessels*, I.D. - 17,280, November 1968.

12. *Fatigue of Concrete*, Publication SP-41, American Concrete Institute, Committee 215, Abeles Symposium, Detroit, Michigan 1974.

with plain concrete; the balance of the symposium pertained to reinforced concrete. The conclusions of each of the above-mentioned papers are as follows:

(1) M. E. Awad and H. K. Hilsdorf, *Compressive Fatigue Tests on 4" x 4" x 12" Prisms*

> *When concrete is subjected to high repeated compressive stresses, a decrease in either the maximum stress level or the stress range results in an increase of the number of cycles to failure. The increase in failure cycles with decreasing stress range becomes insignificant at high maximum stress levels and small stress ranges.*
>
> *At high stresses, a reduction in the speed of testing results in a significant reduction of the fatigue life of concrete.*
>
> *Under repeated loads the failure strains of concrete increase with decreasing stress level or decreasing range of loading.*
>
> *High repeated or sustained loads may cause a significant strength decrease only after 30 to 70 percent of the number of cycles causing failure have been applied.*
>
> *Damage caused by high repeated loads depends both on the number of applied cycles and the total time the concrete has to sustain high stresses. Based upon this observation an analytical procedure was developed which allows the prediction of the fatigue properties of concrete for various stress ranges and stress rates.*

(2) K. D. Raithby and J. W. Galloway, *Flexure Tests*

> *Flexural fatigue tests on two mix designs of pavement quality concrete and on a lean concrete similar to road base material have shown the importance of moisture condition on fatigue performance and have indicated the way in which fatigue strength increases with age. Changes in fatigue strength follow closely changes in quasi-static flexural strength under these conditions and it appears reasonable to expect to be able to predict long-term fatigue performance from a few short-term tests under appropriate conditions.*
>
> *In view of the importance of moisture condition and concrete age at the time of test there is an obvious need to study the effects of interactions between these factors by using different curing methods; this is being done in the continuing program of research at the Transport and Road Research Laboratory.*
>
> *A limited study of the effects of frequency of loading on fatigue performance has confirmed the conclusions of other research workers that at least up to 20 Hz the rate of loading is unimportant. This conclusion seems to be*

at variance with the fact that the flexural strength is affected strongly by rate of loading. Further research is needed to explain this apparent discrepancy.

(3) S. S. Takhar, I. J. Jordaan, and B. R. Gamble, *Compressive Fatigue Tests on Confined Cylinders*

The fatigue behavior of concrete, as characterized by the S-N curve, is affected by the lateral confining pressure. The presence of this pressure appears to prolong the fatigue life considerably.

The effect of the lateral confining pressure appears to be dependent on the maximum stress level of the fatigue load.

The state of stress is an important variable in the study of the fatigue characteristics of concrete, just as in the case of static strength of concrete, and further research into this area is needed. The task is considerable, as the number of states of stress that should be considered is enormous.

Part II of reference 13 provides a review of the literature on fatigue of plain concrete through 1970 and includes a discussion of four separate appraisals of previously published works. Thus, virtually all known literature on fatigue of plain concrete has been considered.

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13. Forest, J. B., Katona, M. G., and Griffin, D. F., *Layered Pavement Systems - Part I, Layered System Design, - Part II, Fatigue*, TR-R763, Naval Civil Engineering Laboratory, Port Hueneme, California, 1972.

SECTION 3

CONCRETE SPECIMENS

LABORATORY CYLINDERS AND BEAMS

The concrete mixes used in this investigation were proportioned according to the mix design data in table 2; aggregate grading is shown in table 3. Cylinders, 6 in in diameter by 12 in long, and beams, 6 by 6 by 20 in long, were cast from both concrete A and concrete B. The compressive strengths of the two concretes are shown in table 4; the flexural strength of the beams is shown in table 5.

Table 2. Mix Designs for Concrete Specimens

Ingredient	Quantity/yd^3	
	Concrete A	Concrete B
Water/Cement Ratio	0.549	0.704
Water, lb	284	364
Cement, Ideal Type 1, lb	517	517
Coarse Aggregate, lb	1848	1435
Sand, lb	1358	1555
Maximum Particle Size, in	3/4	3/8
Retarder (Zee Con), oz.	88	-
Air Entraining Agent (Pro Tex), oz.	6	-
Slump, in	2	2

Table 3. Grading of Combined Aggregates

Sieve Size	Cumulative Amount Retained by Weight, %	
	Aggregate A	Aggregate B
1 in	0.0	0.0
3/4 in	4.6	0.0
1/2 in	27.9	0.0
3/8 in	42.3	2.0
No. 4	57.9	44.6
No. 8	62.9	55.2
No. 16	68.9	61.8
No. 30	79.8	75.2
No. 50	93.9	92.5
No. 100	98.2	97.8
No. 200	99.0	98.8
Pan	100.0	100.0

Table 4. Compressive Strengths of Concretes

Fog Cure Age, days	Strength of Concrete A, psi*	Fog Cure Age, days	Strength of Concrete B, psi*
7	3870		
14	4370		
		21	3920
28	5150		
60	5370**		
84	5418		
		95	4840
171	6220		

*Average of three specimens for each age.

**Taken from curve of strength versus age.

Table 5. Flexural Strength of Beams

Fog Cure Age, days	Strength of Concrete A, psi*	Fog Cure Age, days	Strength of Concrete B, psi*
		40	630
		95	745
116	730		
139	765		
171	735		

*Average of three specimens for each age.

FIELD CORES

Aged concrete cores from four airfield pavements were provided by AFCEC for acoustic-emission testing. The properties of these specimens are shown in table 6.

Table 6. Properties of Field Cores

Airfield	Length, in	Diameter, in	Length/Diameter Ratio	Cross-Sectional Area, in^2	Ultimate Compressive Strength, psi
Buckley B	7.62	3.99	1.91	12.50	7050
Davis - M 54	8.01	3.98	2.01	12.44	5640
Davis - M 94	7.62	4.01	1.90	12.63	4870
Keesler K-6	5.10	3.99	1.28	12.50	8640
Keesler K-68	6.29	4.00	1.57	12.57	8730
Mather R2-2 (Top)	8.02	3.98	2.02	12.44	3710
Mather R2-2 (Bottom)	6.75	3.98	1.70	12.44	6650
Buckley A	8.14	3.99	2.04	12.50	6460

SECTION 4
INSTRUMENTATION

The instrumentation required for detecting and recording acoustic emissions is aptly described in references 1 and 2. By means of an X-Y recorder and other appropriate equipment, acoustic emissions can be related simultaneously to two of the following parameters: (1) loading on specimen; (2) strain in specimen; and (3) time. The equipment used in this study was as follows:

(1) Dunegan/Endevco Model 3000 Series System
  (a) Acoustic Emission Preamplifier, Model 801-P
  (b) Totalizer (including filters), Model 301
  (c) Reset Lock, Model 402
  (d) Audio Amplifier, Model 702

(2) Hewlett-Packard Model 7046A X-Y Recorder

If either strain or load is to be recorded, a load cell and/or extensometer (or other strain gage) on the specimen is connected through signal conditioners to the X-Y plotter.

One objective of this investigation was to determine the optimum frequency range for acoustic-emission testing of plain concrete. Thus a flat frequency response, acoustic-emission transducer was procured and tested. This transducer was a Dunegan/Endevco Model S9201 AB 73 with a certified calibration range of 100 to 1000 kHz. Although this transducer is considered to have a flat frequency response, the peak relative response was 200 kHz. By observing on an oscilloscope the performance of the transducer on plain concrete, it was determined that the optimum frequency range is between 100 and 300 kHz. There appeared to be no significant difference between the performance of Model S9201 and Model S140B, the latter having a resonant frequency of 160 kHz. A more sophisticated method for testing the transducers on concrete not only would have cost considerably more but would have revealed little more than the method used.

With either of the above-mentioned transducers, the following instrument settings appeared to be optimum for concrete and were used in all tests unless otherwise noted:

Acoustic Emission (Rate-Memory Mode)

Gain	91 dB (includes 40 dB in the preamplifier)
Filter Bandwidth	100 - 300 kHz
Multiplier	10 (1.0 for cores)
Reset Clock	1 sec

Plotter

Time (X-Axis)	50 sec/in
Acoustic Emissions (Y1-Axis)	0.5 V/in
Load on Specimen (Y2-Axis)	50 mV/in (10 mV/in for cores)

SECTION 5
EXPERIMENTAL PROCEDURES

A transducer was affixed to each specimen with plastic tape. At the location on the specimen where the transducer was to be located, a thin film of General Electric Silicone Dielectric Compound (grease) G-624 was applied.

Because of the extremely sensitive nature of the pickup system, noise caused by any of the following could be detected by the transducer:

(1) Slippage of transducer on surface of specimen (caused by differential tension in the tape on either side of the transducer)

(2) Crushing of granules of material at load-testing machine head/specimen interface (seating noise)

(3) Capping material on ends of concrete cylinders

(4) Movement of specimen surface at contact area of transducer (caused by strain in the specimen)

(5) Movement of contact areas of specimen over load-testing machine heads (caused by strain in the specimen)

(6) Electrical, electronic, or other spurious energy waves in the vicinity of the transducer

Of the above, (3) and (6) were the most significant. Slippage (1) was minimized by physically adjusting the transducer to its most stable position after the tape had been applied. Crushing (2) was compensated for by adopting an initial seating load of approximately 10 percent of the maximum load to be applied. When the load was released, it was released only to the seating load and not to zero. This procedure, which virtually eliminates seating noise upon reloading, was adopted on the recommendation of A. T. Green and is described in reference 14.

14. *Acoustic Emission Inspection Monitoring Contract Service Description*, Acoustic Emission Technology Corp., Sacramento, California, Copyright 1974.

Customarily, capping of concrete cylinders (3) is used to assure parallel plane faces when the specimens are tested in axial compression. However, for purposes of this investigation, either grinding or lapping to achieve flat parallel end faces would have been more ideal. Unfortunately this could not be accomplished at CERF. The capping compound used at CERF is a quick-setting sulfur-based compound known as *Cylcap*. A 3-in-diameter by 6-in-long cylinder of Cylcap was cast and tested for acoustic emissions by the load/release/load increase method. The noise level for this material was about the same as that for concrete. To further explore the acoustic emissions of Cylcap, a 6-in-diameter by 12-in-long cylinder of 6061-T6 aluminum, with and without caps, was tested. After being subjected to a maximum load of 120,000 psi, the cylinder was capped and retested for acoustic emissions. The level of acoustic emission for the capped cylinder was extremely low, probably because the caps were relatively thin (about 0.25 in). The caps were removed and the cylinder was tested again. It showed a greater level of acoustic emission than with the caps. Thus it was concluded that Cylcap would not disguise the final results on concrete. Ultra Cal was also investigated as a capping material. Although it shows very little acoustic emission under load, its cure time is too long for practical purposes. Other bearing materials investigated included nylon pads and corrugated cardboard. However, both of these materials were noisy acoustically. The bending action of the cardboard over the edges of the cylinder readily induced relatively high acoustic emissions. The field cores were sawed to length and the ends were machine lapped. Ordinary thin blotter paper was ultimately selected as the bearing material for the concrete specimens to minimize the abrasion effects of the testing machine head/specimen interface induced by strain in the specimen.

Movements (4 and 5) were considered to be of no real significance after reviewing the results of many tests. Interference (6) was a problem on one occasion when broadcasting from a local radio station was picked up by the transducer.

The criteria for satisfactory testing conditions are as follows:

(1) Select the lowest decibel level at which no counting occurs when the transducer is supported in air.

(2) Under a sustained seating load (approximately 10 sec) there are no emissions from the test specimen.

The following tests were conducted on the concrete specimens fabricated from the concrete mixes previously described:

Cylinders

(1) Axial compression with load/release/load increase by steps without preloading

(2) Same as (1) for one specimen but with 13,000 precyclic loadings between 500 and 17,500 lb

(3) Tensile splitting with load/release/load increase

Beams

(1) Flexure with load/release/load increase by steps without preloading

(2) Same as (1) with 13,000 precyclic loadings between 500 and 5,000 lb

Field cores were subjected to test (1) described above for the cylinders.

To eliminate as much as possible the seating noises, an initial seating load of from above zero to approximately 10 percent of the maximum load was utilized in testing the specimens for acoustic emission. Loading was increased to some arbitrary level and then reduced to the seating load. This was repeated in increasing steps until the maximum load to be applied was achieved.

SECTION 6
TEST RESULTS

The results of the first 50 or so tests on the concrete cylinders generally appeared to be anomalous. For example, some specimens (the comparatively young immature ones) did not exhibit the Kaiser Effect when tested shortly after being removed from an ambience of 100 percent relative humidity. Other specimens displayed the Kaiser Effect; however, upon retesting (after a rest period), it was evident that the Kaiser Effect was temporary rather than permanent; i.e., acoustic activity occurred at stress levels well below the previous maximum stress.

The aluminum cylinder used to investigate Cylcap also demonstrated a temporary Kaiser Effect. To verify this beyond doubt, the cylinder was machined on all surfaces to remove any oxide film and coated with light mineral oil to minimize oxidation. When this rather noisy specimen was tested, it clearly exhibited the Kaiser Effect when subjected to repeated stress cycles without a significant rest period. However, after a 24-hr rest period, the specimen again became acoustically active at stress levels well below the previous maximum; this indicates complete recovery.

No references were found in which the time duration of the Kaiser Effect was discussed. Therefore, T. T. Anderson, chairman of both the ASTM Acoustic Emission Working Group and the Terminology Subcommittee, was contacted to discuss the Group's definition of the Kaiser Effect.* He indicated that the word *immediately* in this definition means that a time factor is involved and that as a function of time some, if not all, materials recover from the Kaiser Effect. At Mr. Anderson's suggestion Clement Tatro, an author of two articles in reference 2, was contacted. Mr. Tatro further verified the fact that the Kaiser Effect is generally temporary. He stated that some aluminum can recover

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* *The Kaiser Effect is the immediately irreversible characteristic of acoustic-emission phenomenon resulting from an applied stress. If the effect is present there is little or no acoustic emission until previously applied stress levels are exceeded* (ref. 2).

within a few minutes. Apparently, people active in the field of acoustic-emission technology are aware of the sometimes fleeting character of the Kaiser Effect. However, neither Anderson nor Tatro knew of any pertinent documentation that could be cited. Materials other than aluminum were not discussed and it is not known whether or not the Kaiser Effect is permanent in any material. CERF received a copy of a paper (ref. 15) from Eiji Isono, chief researcher of Welding Research Center, Products Research and Development Laboratories, Nippon Steel Corporation, Japan. Isono et al. performed some pressure tests on steel pipe (type of steel unknown). One specimen left for 34 days at a temperature between 5° and 15°C showed slight recovery of the Kaiser Effect; one specimen left for 59 days at a temperature between 10° and 20°C showed complete recovery. Isono et al. also reported some research by others: Nielsen et al. (ref. 16) found that *the Kaiser Effect is recovered a little in some of the testing of model pressure vessels*; Kirby et al. (ref. 17) reported *there exists no recovery of the Kaiser Effect in mild steel vessels when the vessels are pressurized 9 or 18 times during 5 weeks*. In 1961, Richard Goodman (ref. 18) conducted some experiments on the acoustic activity of cylindrical samples of rocks (2.75 in in diameter by 5 in in length) in axial compression. The rock types included Berea Sandstone, Boise Sandstone, and medium-grained Quartz Diorite. He reported: *During its first compression, a rock generates subaudible rock noise at all stress levels; however, ... there is a minimum in the audio pulse rate at stress levels from about 40 to 80 percent of the crushing strength. If the stress is never carried past the point of acceleration in the rock-noise rate, then in second and later cycles of loading, fewer subaudible pulses are detected. These occur repetitively at certain levels of stress*

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15. Isono, Eiji, Udagawa, Tateshi, and Ogasawara, Masao, *Recovery of the Kaiser Effect*, Presented at U.S./Japan Joint Symposium on Acoustic Emission, Tokyo, July 1972. (English summary and paper in Japanese with necessary figures and tables received by letter from Eiji Isono, dated October 21, 1975.)
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18. Goodman, Richard B., "Subaudible Noise During Compression of Rocks," *Geological Society of America Bulletin*, V. 74 (pt 1), April 1963, pp. 487-490.

during both loading and unloading. On the other hand, should loading be carried appreciably beyond the point of accelerated rock-noise activity, then the number of bursts of sonic energy remains high and, in fact, may increase in second and later load cycles. The recovery of noise-generating capacity was established for all specimens. The rest period required between tests for recovery of 25 percent of the activity of the initial test was 2 hr for each of the two types of sandstone and 9 hr for the Quartz Diorite.

Figures 1 through 6 reveal the results of significance for young concrete found in this investigation. These figures are examples from approximately 70 tests. These clearly show that the Kaiser Effect is of a temporary nature and cannot be relied upon as an indicator of previous loading history for plain concrete. Acoustic emissions were detected in all of the concrete specimens tested, regardless of the type of loading. Stronger and more positive emissions resulted during the axial compression tests than during either the tensile-splitting or flexural tests. Undoubtedly this can be attributed to the greater stress induced in the compression mode.

In the lower stages of loading, acoustic emissions do not occur until the previous load has been reached and the Kaiser Effect is clearly demonstrated (fig. 1); however, in the upper stages of loading, emissions occur long before the previous load has been reached. In addition, there are emissions during unloading at 225 sec. This specimen was loaded to its ultimate; however, it did not shatter and the load was reduced before the specimen came apart. The very intense emissions during this period are quite evident between 375 and 425 sec.

Figure 2 shows the recovery of the Kaiser Effect in a concrete A specimen following nearly 3 days of rest and again at an additional 4 days of rest.

Figure 3 shows the typical low-intensity acoustic emissions for saturated immature concrete B specimens at 3 months. Generally, concrete removed from the fog room and stored in the very low relative humidity of the open air showed stronger and more intense emissions. Unfortunately, there was no control on moisture content of specimens removed from the fog room; therefore, it was not possible to relate emission intensity directly to the state of wetness or dryness, or to age.

Figure 4 shows the typical acoustic emission pattern related to load as a function of time for a beam; results are similar to those for a cylinder but with much lower magnitudes of acoustic emissions. The maximum loading applied in the test reported in figure 4a was 7,000 lb; yet emission activity is indicated in figure 4b at load levels below this value. Data of this type serve to further indicate that the Kaiser Effect is temporary in concrete; that is, given a rest period the effect will recover.

Figure 5 presents the results of an emission test on concrete subjected to cyclic loading. The test specimen was subjected to 13,000 cycles of load, which varied from 500 to 17,500 lb applied at a rate of 35 cycles/min. Forty minutes elapsed between the time the specimen was removed from the MTS machine and the initial reloading shown in figure 5. Note that acoustic activity occurred well before the previous maximum load of 17,500 lb had been reached.

The field cores were taken from airfield pavements and thus were probably never subjected to a stress in excess of 300 psi. Of the eight cores tested, only one specimen showed initial acoustic emissions at a higher stress level (480 psi); all remaining cores exhibited initial acoustic activity at 48 psi or less. This value is not considered realistic for the airfields represented by the field cores. Furthermore, all the cores exhibited the Kaiser Effect upon *immediate* reloading, but after rest periods ranging from 20 min to 20 hr, acoustic activity again occurred when the specimens were reloaded. This indicates that the Kaiser Effect was not permanent.

The results of an axial compression test on an aluminum cylinder (6061-T6) are shown in figure 6. It may be noted in figure 6a that the Kaiser Effect was immediately repeatable; however, it was with a greatly reduced intensity of acoustic emission. There was little or no further recovery after a rest period of 1.5 hr (fig. 6b) nor after a further rest period of 3.25 hr (fig. 6c). Figure 6d shows almost complete recovery after an additional rest period of 19.25 hr.

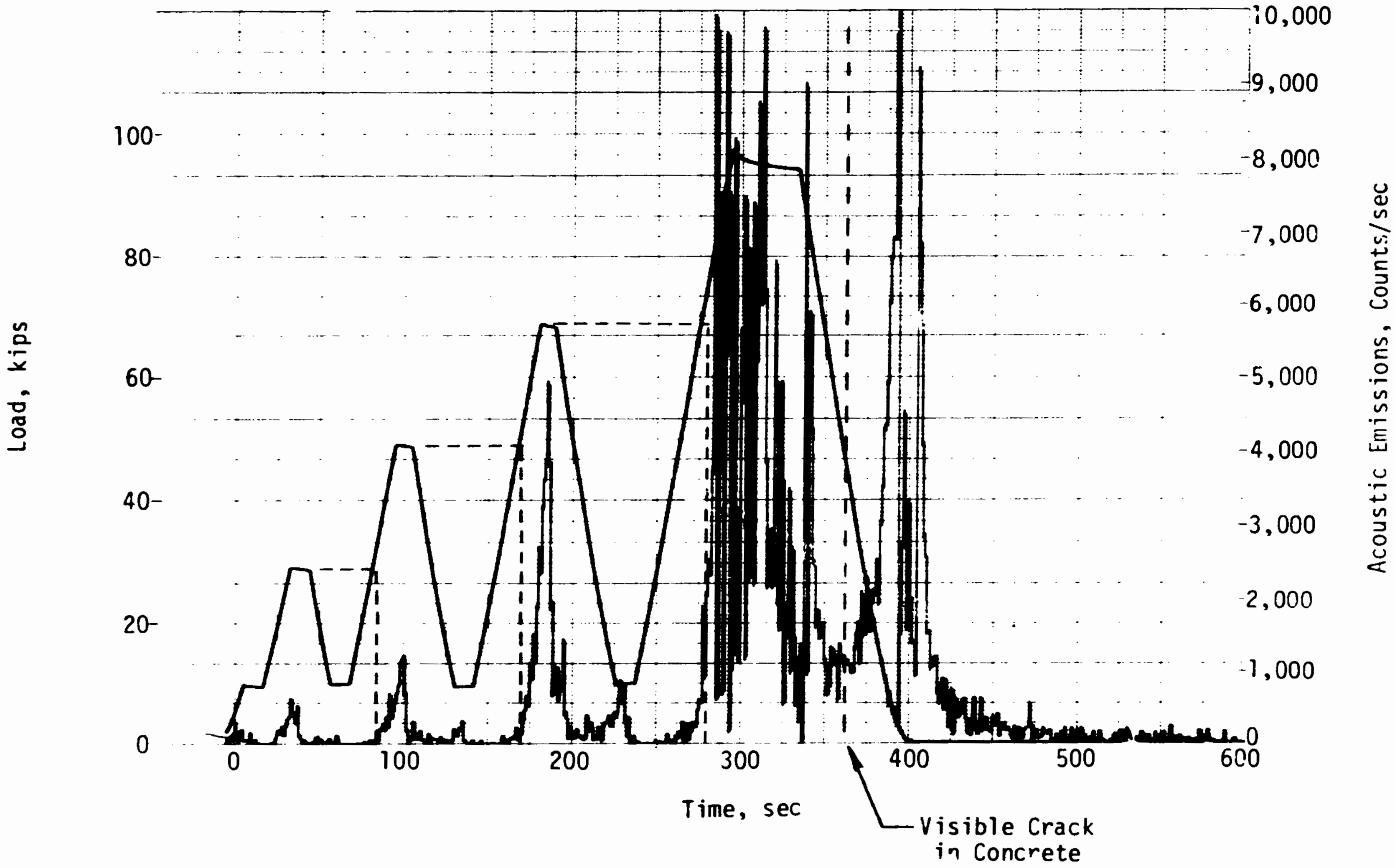
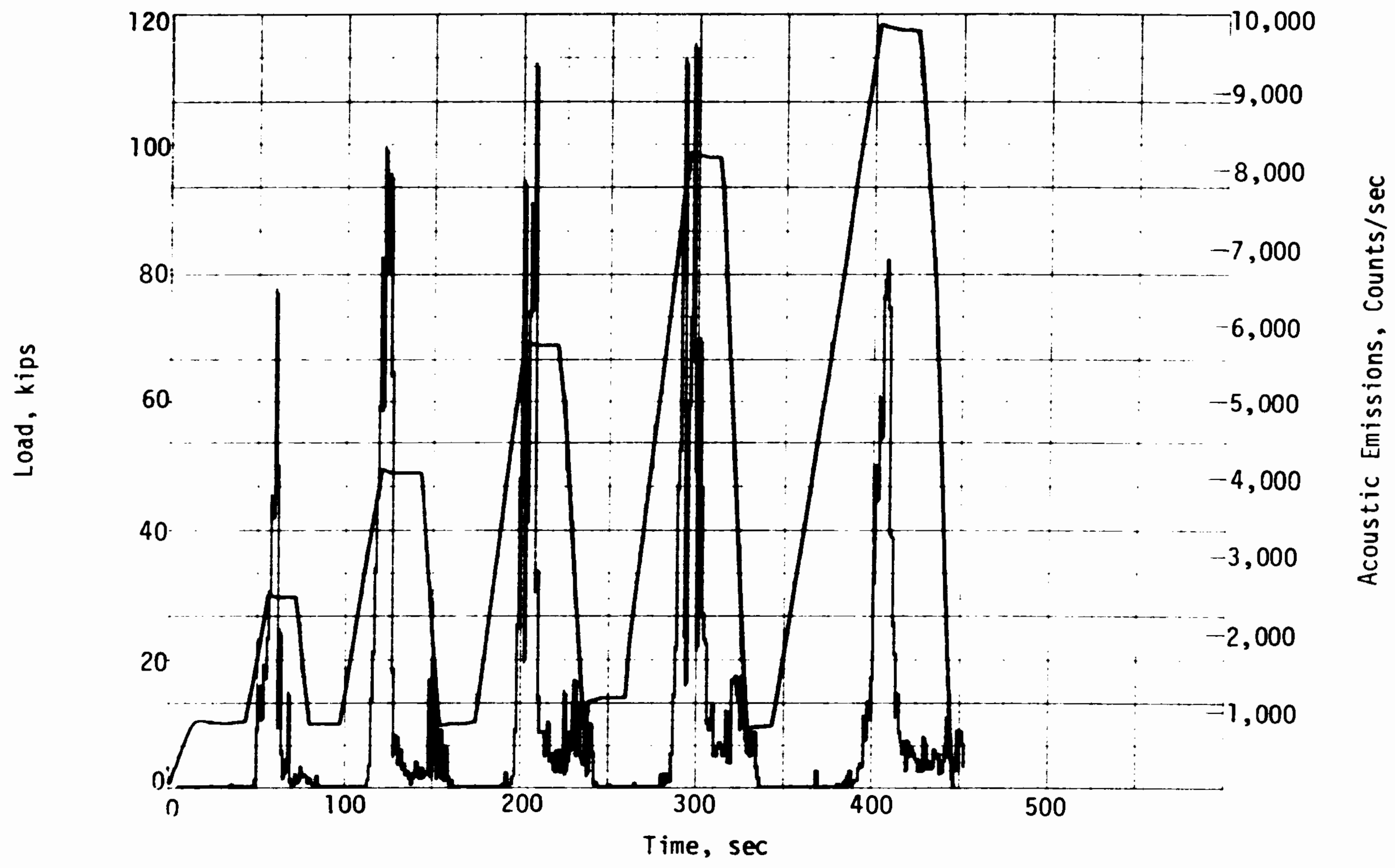
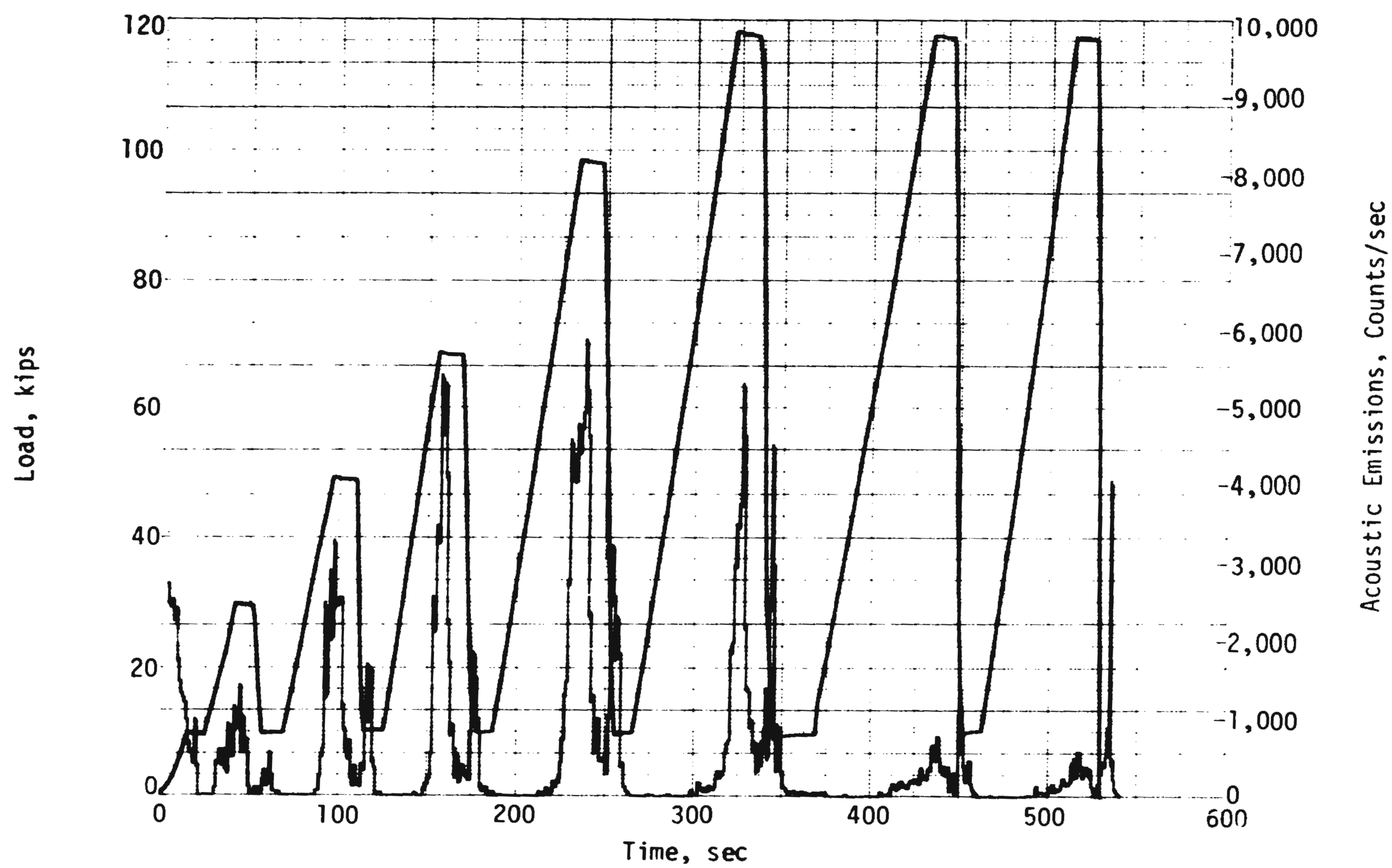


Figure 1. Acoustic Emissions During Step Loading to Failure Without Complete Disintegration of Concrete



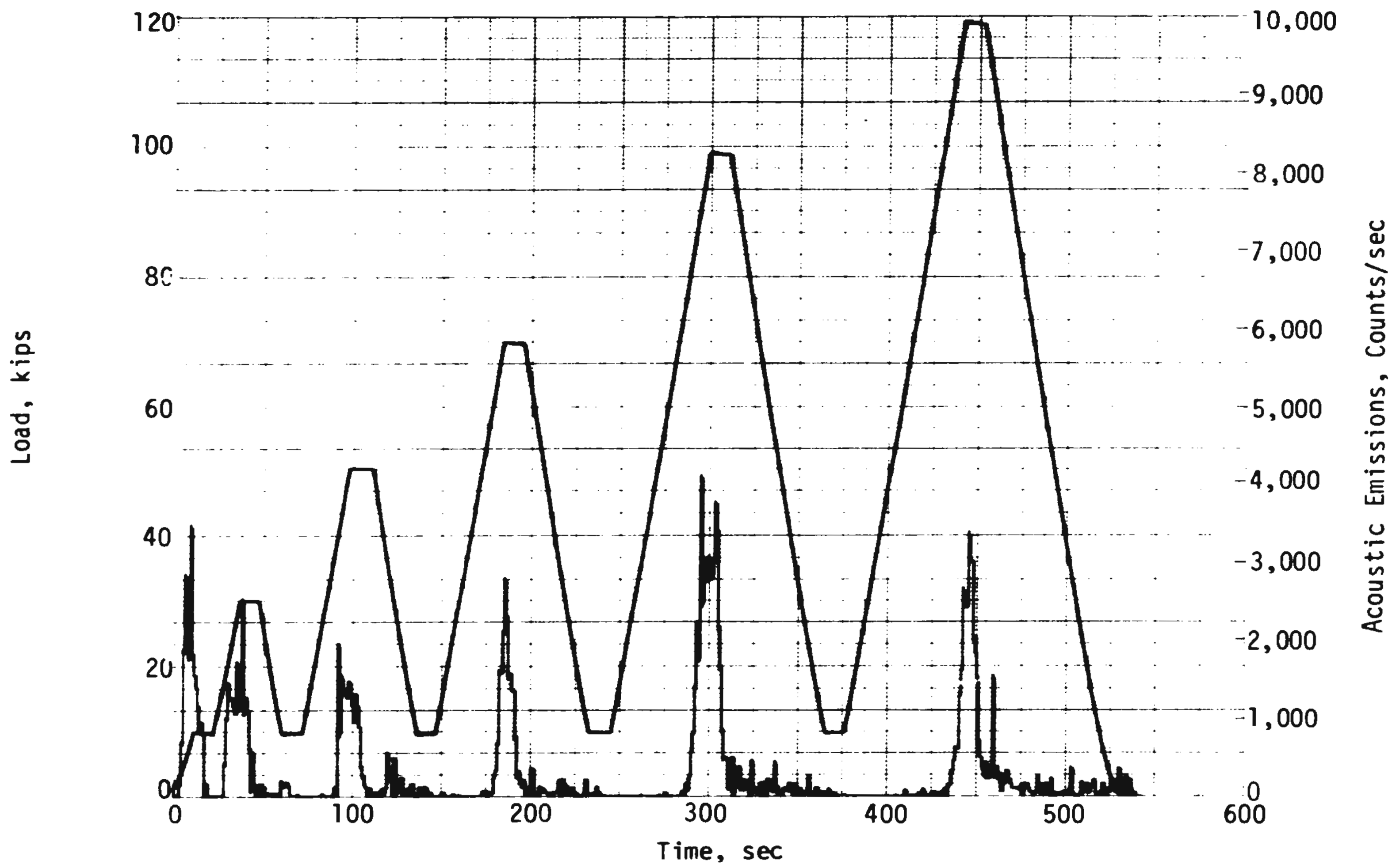
(a) Step Loading Showing Kaiser Effect at First Loading of Cylinder 104-A

Figure 2. Recovery of Kaiser Effect in Concrete A Specimen (1 of 3)



(b) Recovery of Kaiser Effect After 68-Hour Rest

Figure 2. Recovery of Kaiser Effect in Concrete A Specimen (2 of 3)



(c) Recovery of Kaiser Effect After Second Rest of 95 Hours

Figure 2. Recovery of Kaiser Effect in Concrete A Specimen (3 of 3)

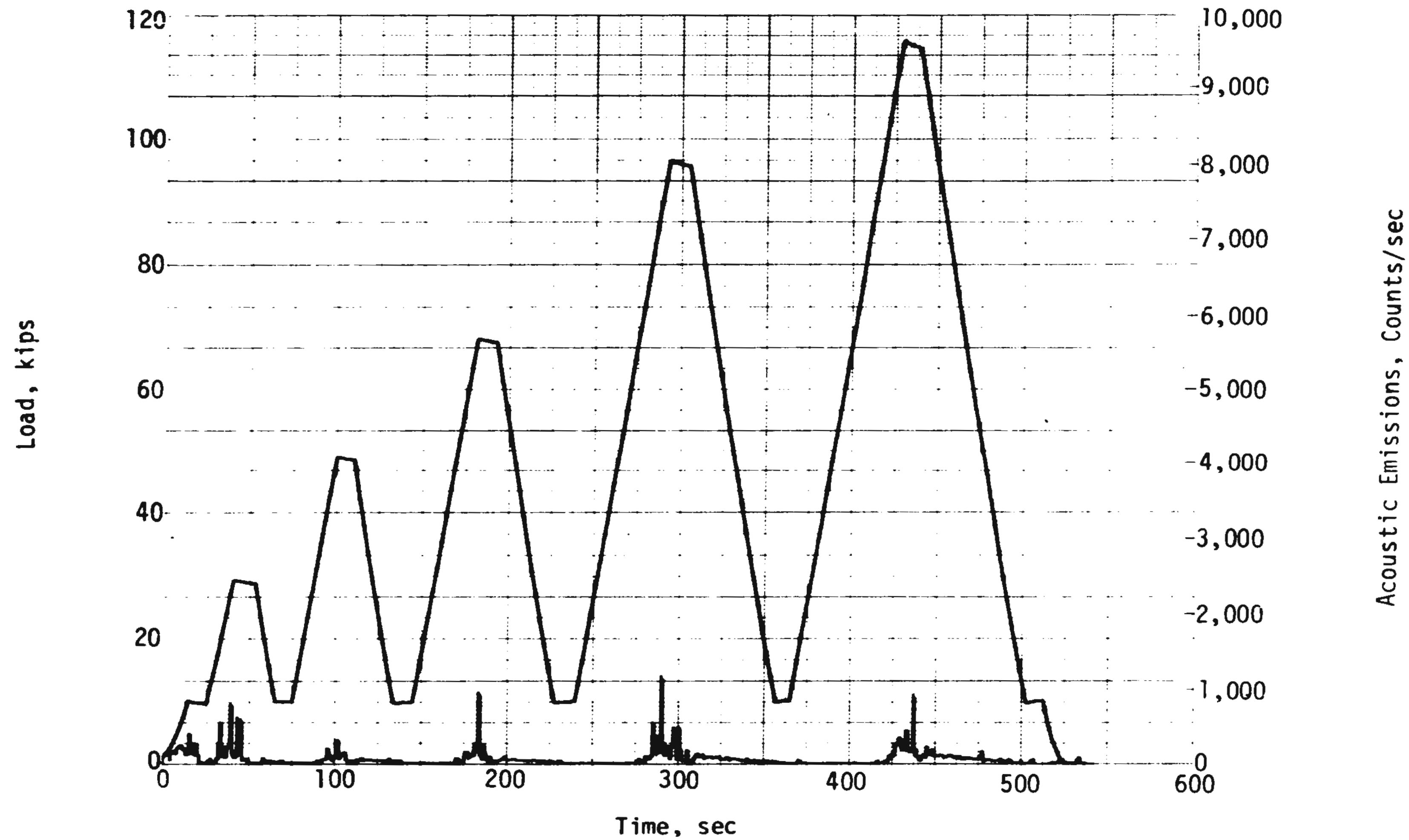
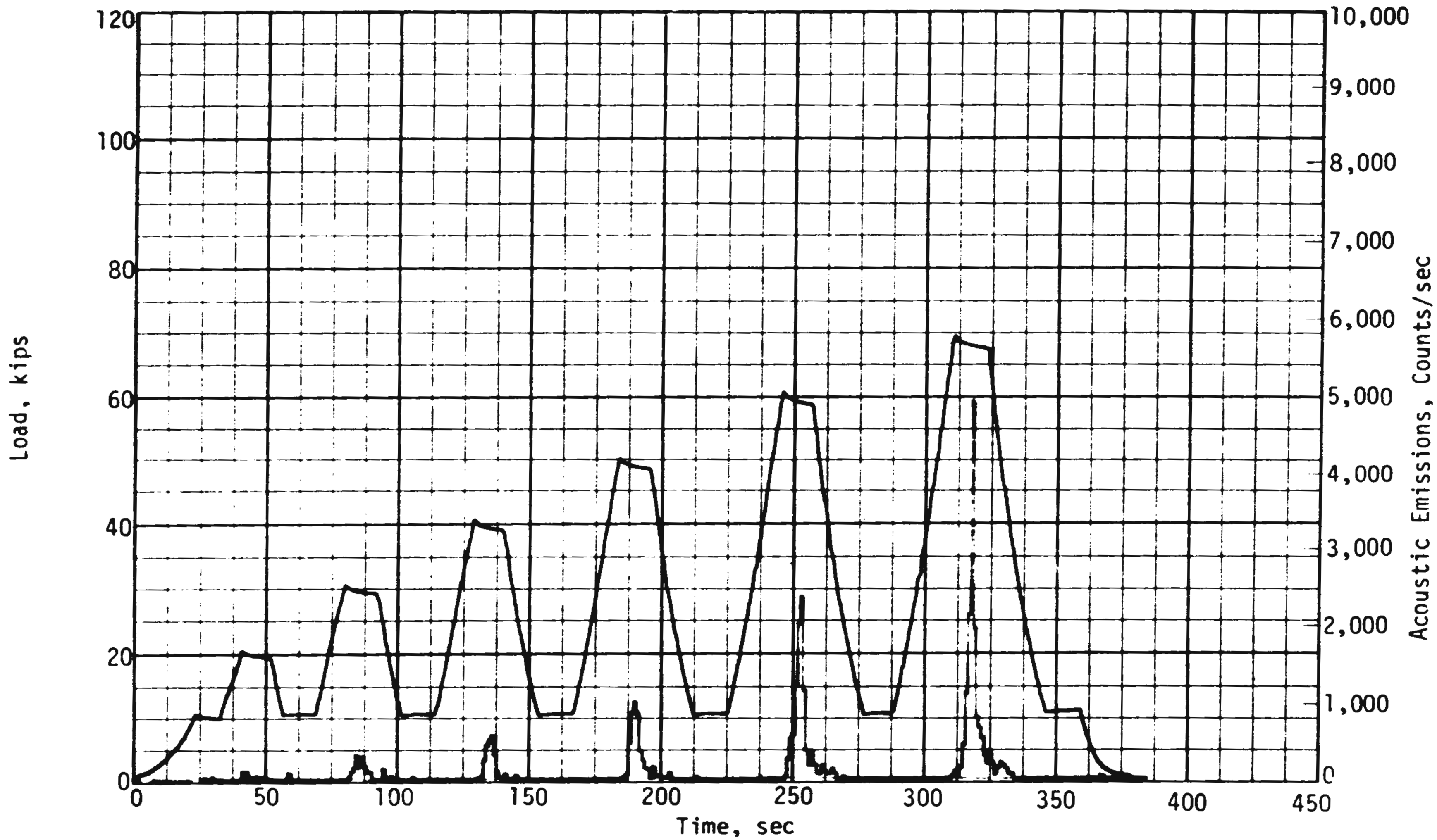
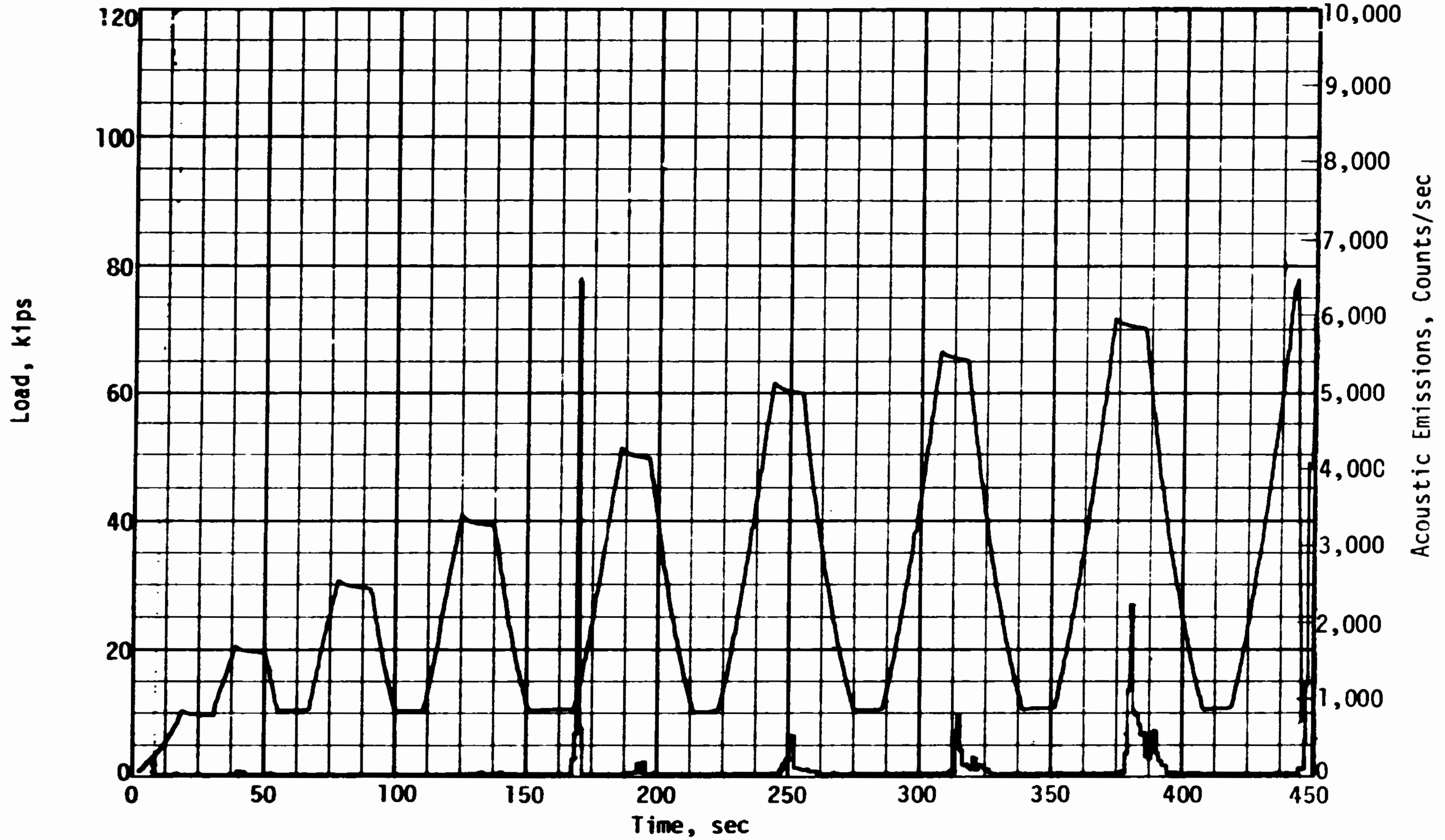


Figure 3. Acoustic Emission Versus Load for Saturated Immature Concrete B



(a) Initial Load and Resulting AE Activity

Figure 4. Acoustic Emission Versus Load as Function of Time for a Concrete Beam (1 of 2)



(b) Emission Activity for Same Beam After 18-Hour Rest

Figure 4. Acoustic Emission Versus Load as Function of Time for a Concrete Beam (2 of 2)

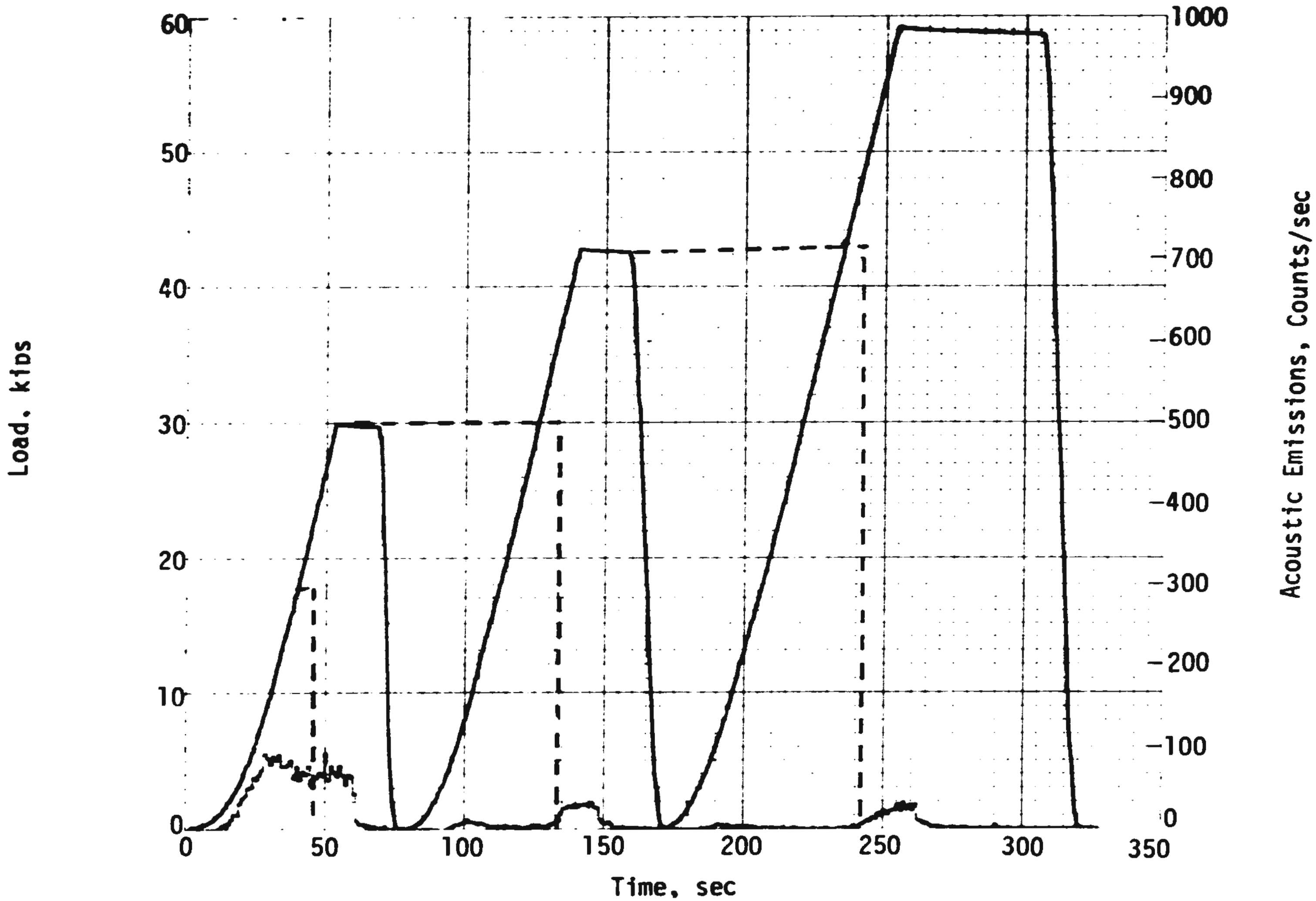
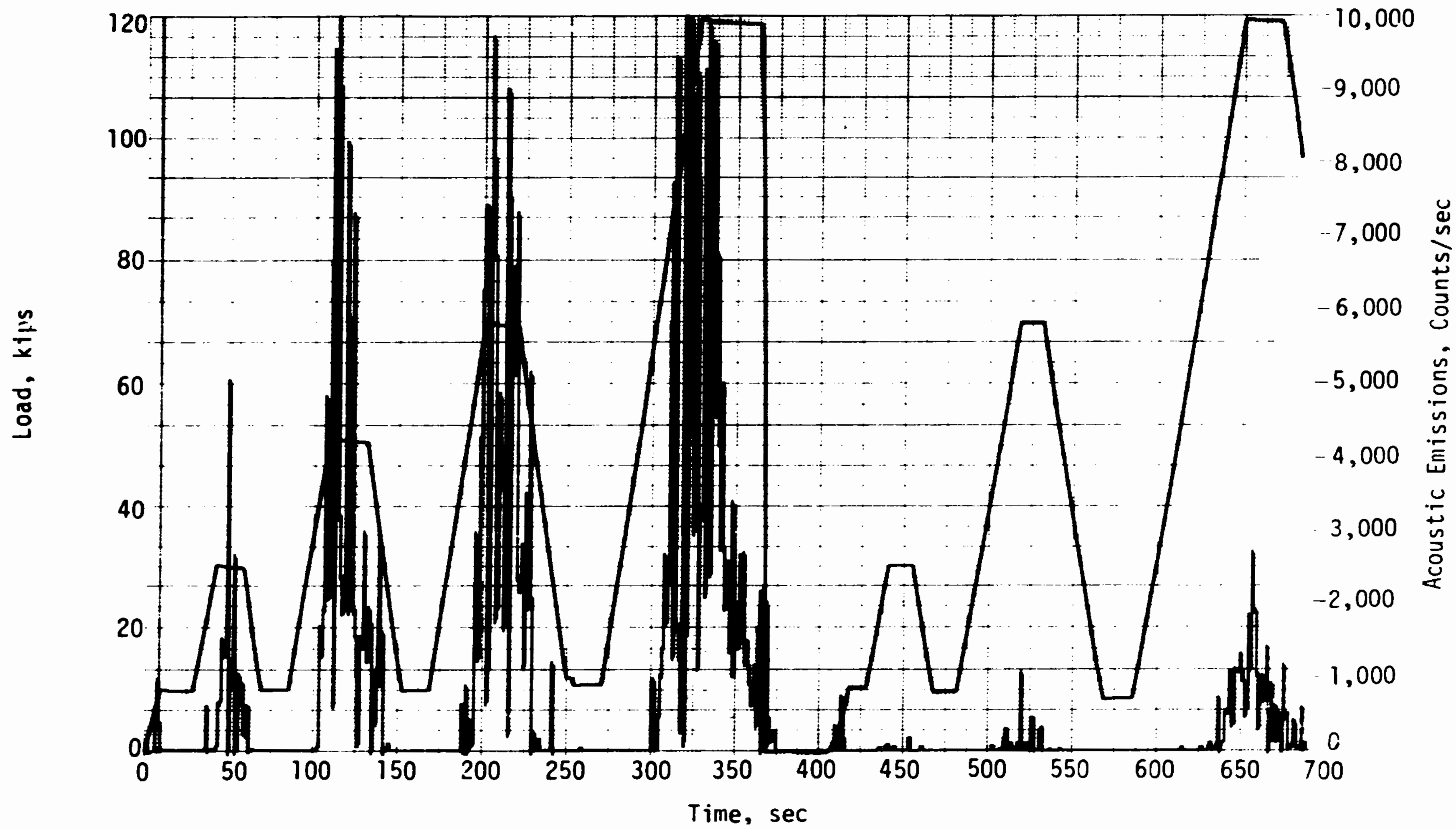
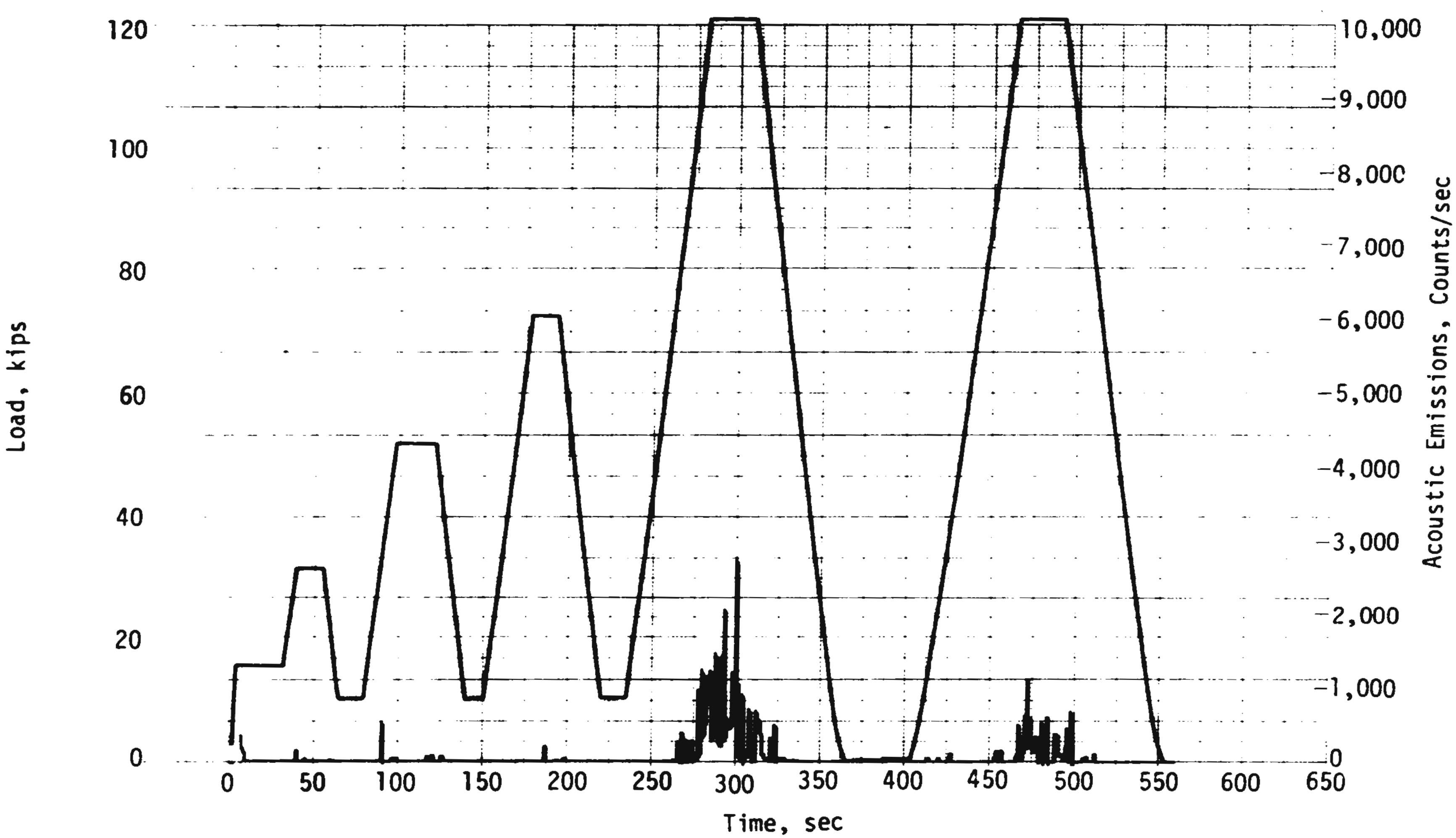


Figure 5. Emission Activity of Specimen Subjected to Cyclic Loading Before AE Testing



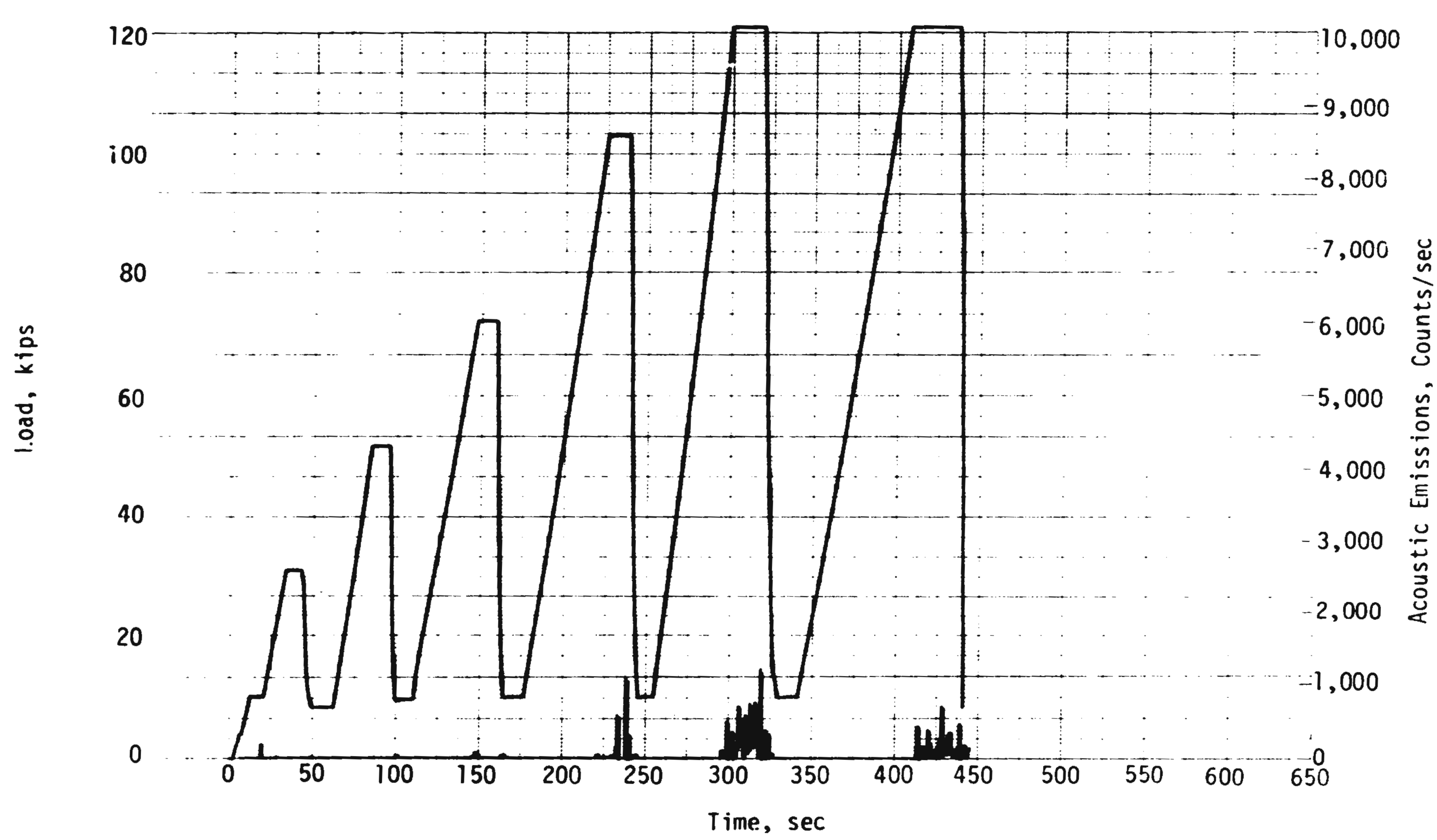
(a) Initial Step Loading with Immediate Reloading; Load and Acoustic Emission Versus Time on October 14, 1975, at 0930 Hours

Figure 6. Specimen of Aluminum 6061-T6, 6-Inch Diameter by 12 Inches, Loaded in Axial Compression with Blotting Paper on Ends of Cylinders (1 of 4)



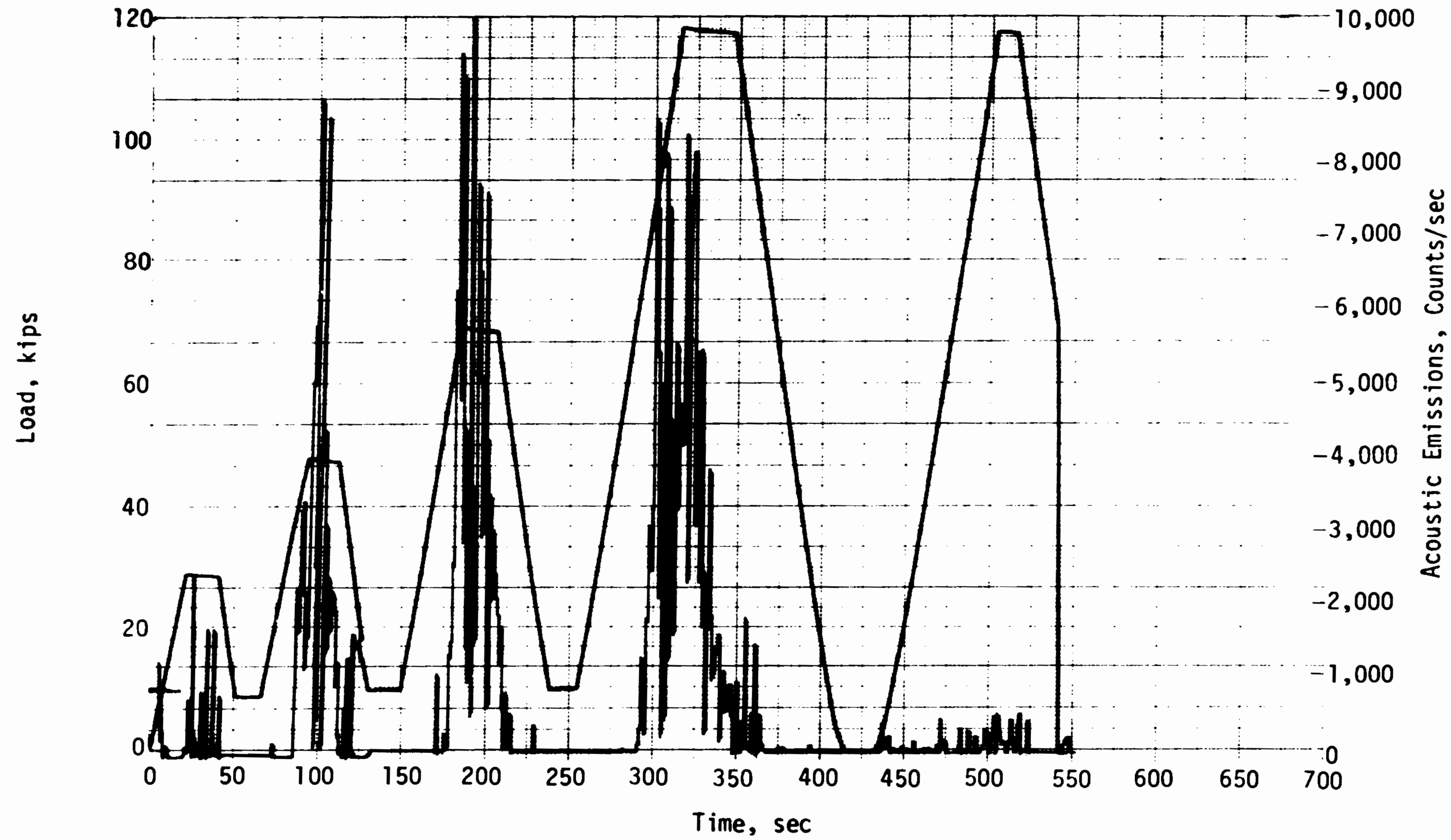
(b) Figure 6a repeated at 1100 Hours After 1.5-Hour Rest

Figure 6. Specimen of Aluminum 6061-T6, 6-Inch Diameter by 12 Inches, Loaded in Axial Compression with Blotting Paper on Ends of Cylinders (2 of 4)



(c) Figure 6b Repeated at 1415 Hours After 3.25-Hour Rest

Figure 6. Specimen of Aluminum 6061-T6, 6-Inch Diameter by 12 Inches, Loaded in Axial Compression with Blotting Paper on Ends of Cylinders (3 of 4)



(d) Figure 6c Repeated on October 14, 1975, at 0930 Hours After 19.25-Hour Rest

Figure 6. Specimen of Aluminum 6061-T6, 6-Inch Diameter by 12 Inches, Loaded in Axial Compression with Blotting Paper on Ends of Cylinders (4 of 4)

SECTION 7
CONCLUSIONS AND RECOMMENDATIONS

As a result of this study it was concluded that the Kaiser Effect was of a temporary nature and therefore not a reliable indicator of the loading history for plain concrete.

Acoustic-emission technology may be a useful tool in locating and monitoring flaws and flaw growth. It is recommended that consideration be given to utilizing this technology to ascertain the extent to which cracks and crack growth occur as a function of time in pavement runways. The burden of proof should be on the manufacturer of acoustical equipment and he should demonstrate his capability in this area before being granted a contract to monitor any given runway. Certainly there is no question that increasing numbers of cracks and crack growth would be excellent indications of the condition of the material. Acoustic-emission testing is totally nondestructive and large areas could be tested with very little interruption of normal runway use.

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