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Abstract: This paper describes acoustic emission (AE) results which were measured during the second major experiment on the Cluster Test Coil at JAERI. This is the largest superconducting magnet system to date on which acoustic emission measurement has been carried out.

The amplitudes and the counting rates of AE are shown as functions of coil operating current on three full current excursions. The amplitude results show the on-going process of emission and reduction during successive runs. A strong tendency of the AE counting rate to increase was observed at high currents after successive runs. The phenomenon of amplitude reduction and counting rate increase is attributed to an energy release change from larger single events to numerous smaller events.

Keywords; Acoustic Emission, Superconducting Magnet System, Amplitudes, Counting Rate, Three Full Current Excursion

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* On leave from the MIT Francis Bitter National Magnet Laboratory U.S.A., August 1980 - July 1981.

20 MJ クラスター・テスト・コイルのアコーステック・エミッションの測定

日本原子力研究所 東海研究所 核融合研究部
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（1981年9月4日受理）

本文は原研で行われたクラスター・テスト・コイルの第2回目の実験で測定したアコーステック・エミッション（AE）の結果を記録したものである。クラスター・テスト・コイルは今日迄アコーステック・エミッションの測定の行われた最大の超電導コイルである。

AEの振幅と発生率を電流の関数として示した。この電流は三回の定格電流迄の掃引値である。振幅は電流の掃引のくり返しにより減少することが認められた。一方AEの発生率はくり返しにより高電流領域では増加することが認められた。振幅が減少し，発生率が増える現象はAEの発生が大きなものから数多くの小さなものに移行していることを示している。

＊ 派遣員：MIT Francis Bitter National Magnet Laboratory，U.S.A.

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1. Introduction

Superconducting coils are highly vulnerable to minute heat inputs because of (1) the small heat capacity of materials at low temperature and (2) the small temperature margin existing between the superconducting transition temperature and the coolant temperature. There are many potential sources within a magnet winding capable of producing small perturbations. Such perturbations become more important as superconducting magnet systems increase in scale for practical application, for example, thermonuclear fusion. True magnet system reliability can only be achieved after the actual sources of disturbance are fully identified and strategies developed either to eliminate them or to reduce their magnitude to a tolerable level.

The detection of internal disturbances is particularly well suited to investigation by means of acoustic emission (AE) because of the extreme sensitivity of AE sensors. Therefore, AE detection can be a powerful tool in providing disturbance information in a superconducting coil. However, many different experiences with magnets of various sizes and designs are required before the AE technique can play a major role in magnet design.

Until recently it has been impossible to detect individual energy releases within a coil unless the energy dissipated resulted in either a voltage rise across a coil section or a coil quench. Now, through the use of sensitive AE sensors, extremely minute discrete energy releases can be observed. The energy releases are thought to be due to the following:

- i) mechanical friction in the winding[1)]
- ii) serrated yielding of the conductor[2)]
- iii) debonding of glued insulator[3)]
- iv) magnetic flux motion[4)]
- v) dislocations in structural material

A portion of the energy released during a disturbance is radiated through the coil structure as a damped stress wave. This wave is transformed to an electric oscillation by a piezoelectric acoustic sensor attached to the coil structure. After suitable signal conditioning, these signals can be continously monitored to protect the structure and have warning of an impending quench.[5)6)]

The attachment of AE sensors to the Cluster Test Coils (CTC), the largest magnet system monitored to date, represents the first phase of an AE database investigation at JAERI.

2. Experimental System

2.1 Cluster Test Coil

The Cluster Test Facility was built by JAERI in 1980 for development and testing of large superconducting coils capable of operating at 10T and later at 12T. The facility now consists of two large circular superconducting coils assembled at 30 degrees to one another to allow testing a third coil inserted between them. These two coils are referred to as CTC-1 (fabricated by T company) and CTC-2 (fabricated by M company). Both coils are identical in size and shape and were designed to meet the same electromagnetic specifications. However, the exact design and manufacturing techniques for each coil were left to the individual manufacturer. Table 1 and 2 describe various parameters and stability characteristics for both coils. The CTC system is shown in Fig. 1 and magnetic load lines for series operation of the two coils are shown in Fig. 2.

2.2 Acoustic Emission Data Collection System

A piezoelectric acoustic sensor (trade name COPAL; delivered by MIT) was attached to the outside surface of the stainless steel helium vessel of each of the two Cluster Test Coils. The sensors were pressed against the helium vessel surface using a spring. A thin teflon sheet about 1 mm thick, with a slight coating of vacuum grease on each side, was inserted between the sensor and the stainless steel wall. Acoustic signals from the sensors were pre-amplified and filtered. The frequency band of the band pass filter was empirically selected between 200kHz and 300kHz. The signals were amplified again. At this point, the signal was sent to two processing circuits. Circuit 1 counted the number of signals per unit time having an amplitude greater than a preset voltage level. This discrimination level was empirically changed from 50 μV to 100 μV. Circuit 2 takes an acoustic burst or rapid train of bursts, and processes the oscillation into a signal level proportional to the amplitude of the acoustic event. Fig. 3 shows a schematic of the AE data collection system.

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3. AE Experimental Results

3.1 Coil Operation Process

The first major experiment[7)8)] of the Cluster Test Facility was carried out in August 1980. Because it was the first operation of the facility, each coil was first charged independently of the other and only then were the two coils charged in series. In this experiment, no means of AE measurement existed. The second major experiment was carried out in April 1981 with several improvements of the system. This time, the AE measurement system was attached to the coils to monitor the coil condition. The two coils were charged in series up to the moninal current of 2,145A three times. Table 3 lists the sequence of operation of the CTC during major experiments.

3.2 AE Rate

AE rate versus current data were taken for the three full operating current excursions of the CTC, which are referred to as No.16, No.17, No.22. The results are shown in Fig. 4, Fig. 5 and Fig. 6. The discrimination level, above which the counting rate is recorded, was changed from run to run. Following features can be listed from the results.

i) The AE rate increases with coil current.

ii) The AE rate varies with the charging rate.

iii) During current-hold periods, acoustic activity continued in an erratic fashion at a very low rate.

vi) When current charging was restarted, the AE rate was slightly smaller than that just prior to the hold.

v) A steady transformation in the shape of the curves occurs during succesive charges. For the first charge shown in Fig. 5, the AE rate versus current relationship was nearly linear with some flattening at high currents. For the second charge shown in Fig. 5, the curve changes to a square relationship. And for the third charge shown in Fig. 6, the curve changes to a higher-order polynomial.

The discrimination level strongly influences the magnitude of the AE rate curve. However, the shape is much less affected except near the current where the magnitude crosses the dicrimination value.

Very dramatic drops of the AE rate which lasted about 5 - 10 seconds were found several times in the flat plateau of the AE rate characteristic. This sudden drop in the AE rate almost always happened for both coils together and the number of drops decreased in successive full current excursions.

3.3 AE Amplitude

AE amplitude measurement consists of AE voltage spikes recorded as a function of time. These spikes are proportional to the peak magnitude of the AE transmitted by the sensor. AE spikes may be divided into four group as shown in Fig. 7. The features of these groups are as follows.

- Type I : A large acoustic spike appears which is considerably greater than the spike generated around it. This is referred to as a "peak amplitude" spike.
- Type II : This spike occurs throughout the charging process. The amplitude and the occurrence rate increase as the current increases. This is referred as a "high amplitude" spike.
- Type III : This spike has low amplitude with higher rate of occurrence. This is referred to as a "low amplitude" spike.
- Type IV : A frequency greater than 100 pulses per second leads to an increase in the general signal level. This situration is referred to as "semi-continous" spikes.

The training of the peak amplitude spikes, which is defined above, is shown in Fig. 8 for a sequence of three 0A - 2,145A charge. Fig. 9 shows a similar curve for the high amplitude spike. Immediately noticeable from these curves is the marked decrease in the AE amplitude levels after each charge of the coil system. Reduction is most prevalent in the low current region and considerably smaller at higher current levels. In the high-current region, the 6-hour hold (run no.17) seems to have been more effective in reducing emission amplitudes than the simple up-and-down charging cycle.

This kind of training effect is found in AE measurement in ordinary tensile test of structural material. It is called the Kaiser effect.

Fig. 10 shows traces of the actual AE amplitude wave train emitted by both coils at 600A, 1,000A and 2,000A. These waves are taken from the storage by a transient recorder, whose position is shown in Fig. 3, over a three second interval. The pulse train profiles are distinctly different. CTC-1 emits numerous small pulses, whereas, CTC-2 emits fewer but higher energy pulses at regular intervals.

The semi-continous emission, over and above the background level, represents a steady heat input from dissipation energy into the coil and structure. Because this emission is small and probably discretely deposited over much of the coil and structure volume, it leads to a small average heat influx. On the other hand, the sharp spikes represent a significantly greater energy deposition over a short period of time, and probably at one distinct location. This corresponds to a high power heat input somewhere. CTC-2 has more and larger high-power emission to the winding over the low- and medium-current range. However, at currents approaching the maximum operating current, both coils begin to emit more similar pulse trains.

4. Voltage Spikes on Winding Voltmeter

The voltage spikes found on the non-inductive voltmeter at coil terminals were monitered and the results can be briefly described as follows.

i) During the first major experiment of 1980, first each coil was operated separately. For the virgin charge of each coil, voltage spikes were first noted between 300A - 400A. As the current increased, the number and magnitude of the spikes increased. A total of about 100 spikes were noted for CTC-1 and about 200 spikes for CTC-2 during one charge. Later when both coils were operated in series, spikes were again observed to start between 300A - 400A. But only about half the original number of spikes was observed for each coil.

ii) During the second major experiment of 1981, both coils were always charged in series. For all three full-current excursions, voltage spikes always started between 300A - 400A. For the first full charge, a total of about 50 spikes per charge were observed for CTC-1 and 100 spikes per charge for CTC-2. For the second and third full charge, about 20 spikes per charge were noted for each coil; by the third charge both coils showed about the same voltage-spike behavior.

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5. Discussion

5.1 Origin of AE Training Difference between CTC-1 and CTC-2

It is said that AE results depend on the sensor characteristics and placement. However, we can compare the AE results for CTC-1 and CTC-2 on a relative basis. Although CTC-1 and CTC-2 display similar behavior for the first 0A - 2,145A excursion, thereafter CTC-1 emission was significantly reduced upon subsequent charging, whereas CTC-2 showed considerable reluctance to train. This characteristic can be found in Fig. 10. The results indicates that CTC-1 is more inelastic that CTC-2. Thus CTC-1 would pack tightly upon charging but unpack only slightly during discharge. On the other hand, CTC-2, having been packed to the same extent during charging, would spring back to its original shape during discharge.

This explanation can be justified by both the AE amplitude in Fig. 11 and the voltage spikes on the winding.

5.2 Implications for Magnet Technology

Any new large magnet system should include a comprehensive acoustic monitering system to advance the development of maintainance and protection techniques and the technique of localizing disturbances. Such an installation should satisfy the following conditions:

(a) Attachment of sensors directly to the conductor for the purpose of direct AE measurement.

(b) Attachment of an least three sensors to the helium vessel case and several to the supporting structure.

(c) Complete system integration to correlate AE data with non-inductive voltage measurements and strain gauge output.

6. Conclusion

Because this AE measurement is the first in our Laboratory, the measured results are preliminary. However, the qualititative characteristics of AE count rate and amplitude on the 20MJ CTC have been determined for three current excursions. Relative differences of AE characteristics have been found between the two coils. As the CTC nominal current of 2,145A is low compared with the critical current and the

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quenching current, we could not detect a premonitory signal of transition.

The results in the previous sections indicate the usefulness of monitoring large coils with acoustic emission. The ease of collecting AE signals during the operation of the CTC strongly suggests that as coil systems become larger, the AE technique for diagnostics becomes easier. This situation is just the opposite of that for coil voltage detection systems, where excessively large induced voltages must be neutralized. During operation, subtle differences in coil design and fabrication can be discerned with AE diagnostics. The AE rate, AE amplitude, and pulse profiles from each coil can be compared.

More advanced measurements with AE diagnostics will be continued on the next CTC experiment and on the Japanese LCT coil.

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The authors would like to thank Mr. K. Koizumi for many discussions concerning the CTC structural arrangement and Mr. K. Okuno for providing information from the automatic data aquisition system. They gratefully acknowledge the continous encouragement of the Cluster Test Project by Drs. S. Mori, Y. Iso and Y. Obata.

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Table 1 Manufacturing and Electromagnetic Parameters of Cluster Test Coils

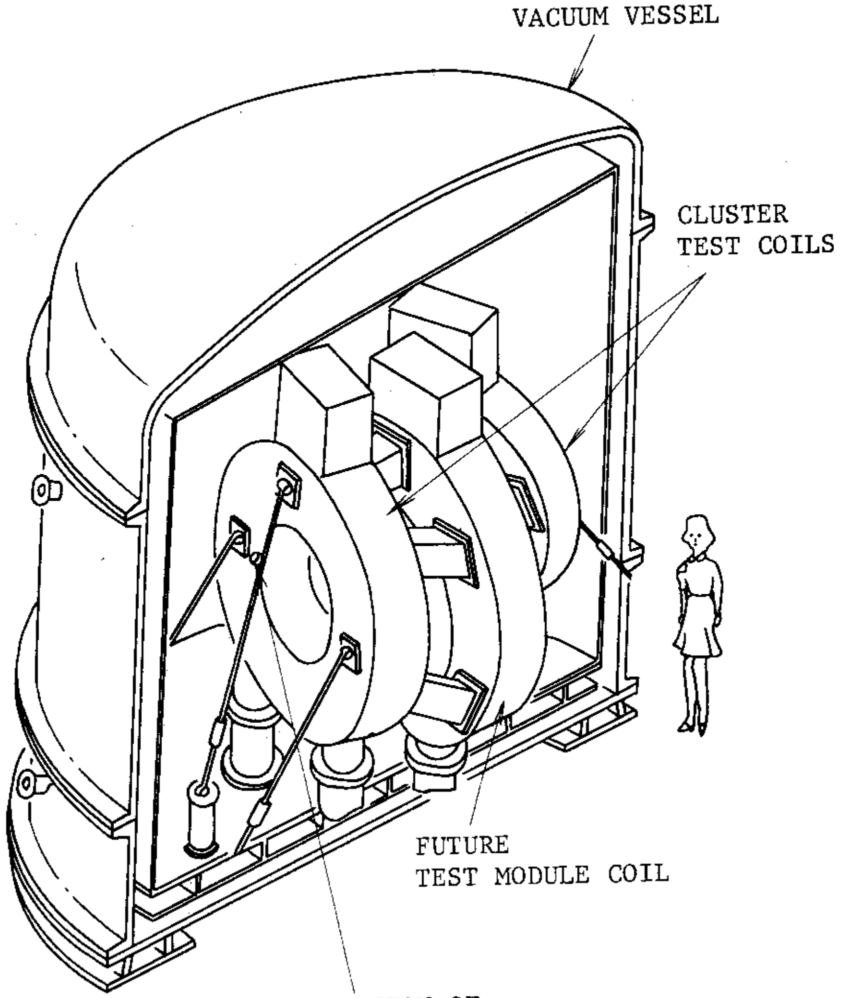
	CTC-1	CTC-2
Coil Shape	Circular	
Maximum Field	7.0 T	
Inner Winding Diameter Outer " Width "	1.05 meters 1.95 meters 0.25 meters	
Rated Current	2,145 A	
Average Current Density	30 A/mm^2	
Number of Turns	1,560	
Stored Energy : Two Coils in Series	20.8 MJ	
Inductance : 1 Coil Both Coils	3.9 H/coil 9.0 H/two coils in series	
Type of Winding	Double Pancake (12)	Single Pancakes (26)
Type of Cooling	Pool Cooling	
Between Turn Insulation Thickness :	Glass Epoxy Tape 0.20 mm	0.34 mm
Between Pancake Spacer Thickness :	Glass Fiber Epoxy Plate 2.5 mm	2.7 mm
Conductor Joint	Cold Welding	Soft Soldering
Cooling Channel Gap	2.5 mm	2.7 mm
Spacer Covering Percentage	30%	25%
304L Coil Case Thickness	30 - 50 mm (depending on parts)	
Weight	6.6 Tons / Coil	

Table 2 Stability Parameters of Cluster Test Conductors

	CTC-1	CTC-2
Operating Current (7T)	2,145 A	2,145 A
Critical Current (7T)	2,850 A	3,650 A
Critical Temperature	9.5 K	9.5 K
Cu Resistivity (7T)	4.7×10^{-8} Ω-m	4.3×10^{-8} Ω-m
Cu Cross Sectional Area	0.434 cm^2	0.458 cm^2
Cooling Perimeter	1.84 cm	1.12 cm
Heat Flux (Minimum)	0.2 W/cm^2	0.27 W/cm^2
Heat Flux (Average)	0.33 W/cm^2	0.38 W/cm^2
Stekly Current	1,843 A	1,795 A
Maddox Current	2,368 A	2,130 A

Table 3 Cluster Test Coil Experiment History

	Run No.	CTF Coils In Operation			Current (Amperes)	Ramping Rate (Amperes / Minute)			Notes
		1	2	1+2		Charge	Discharge	Dump	
First Experiment (August 1980)	1 - 1	●			0 - 50	20	20		
	2 - 1a	●			0 - 90	20		×	
	2 - 1b	●			0 - 1072	35	50		
	3 - 1	●			0 - 2145	40			
		●			2145 - 200		40		
		●			200 - 0			×	
	1 - 2		●		0 - 50	20	20		
	2 - 2		●		0 - 95	20		×	
	3 - 2		●		0 - 2145	20			
			●		2145 - 1300		20		
			●		1300 - 858		40		
			●		858 - 0			×	
	4			●	0 - 50	20	20		
	5			●	0 - 100	20		×	
	6			●	0 - 100	35		×	
	7			●	0 - 700	35	35		
	8			●	0 - 1287	35			
				●	1287 - 2145	25			
				●	2145 - 858		25		
				●	858 - 0			×	
	9			●	0 - 1287	50		×	
	10			●	0 - 1072	50		×	
Second Experiment (April 1980)	11			●	0 - 50				
	12			●	0 - 50				
	13			●	0 - 430	33			
				●	430 - 142		60		
				●	142 - 0			×	
	14			●	0 - 100	33		×	
	15			●	0 - 100	40	60		
	16			●	0 - 1276	50			
				●	1276 - 2145	25			
				●	2145 - 1276		25		
				●	1276 - 0		50		
	17			●	0 - 1287	60			
				●	1287 - 2145	40			6-hr. hold
				●	2145 - 1287		40		
				●	1287 - 0		60		
	18			●	0 - 430	60		×	⊗
	19			●	0 - 858	60		×	acoustic
	20			●	0 - 1276	60		×	activity
	21			●	0 - 1276	60		×	continues
	22			●	0 - 1276	60			15 minutes
				●	1276 - 2145		40	⊗	after
	23			●	0 - 200	10	25		dump



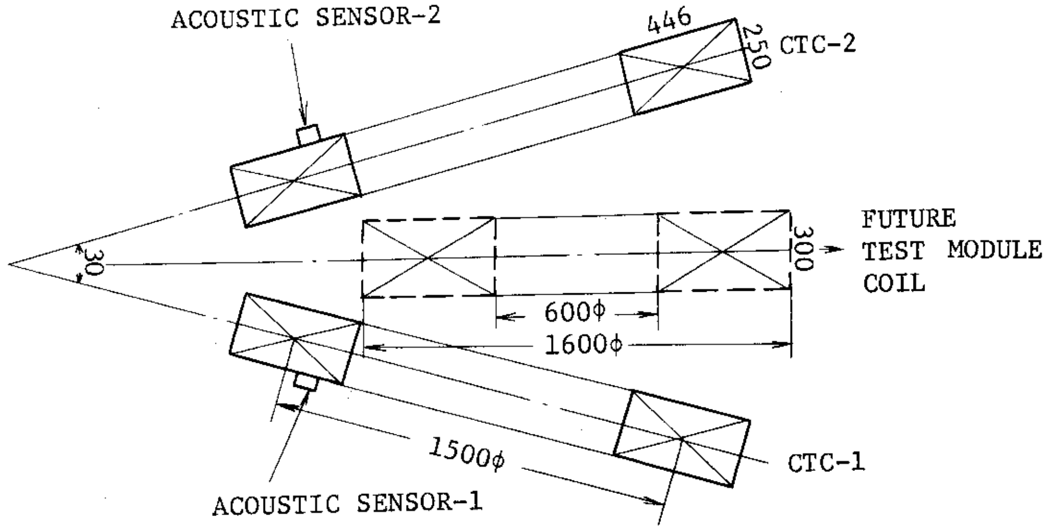


Fig. 1 Cluster Test Coil Set Position and Acoustic Sensor Location

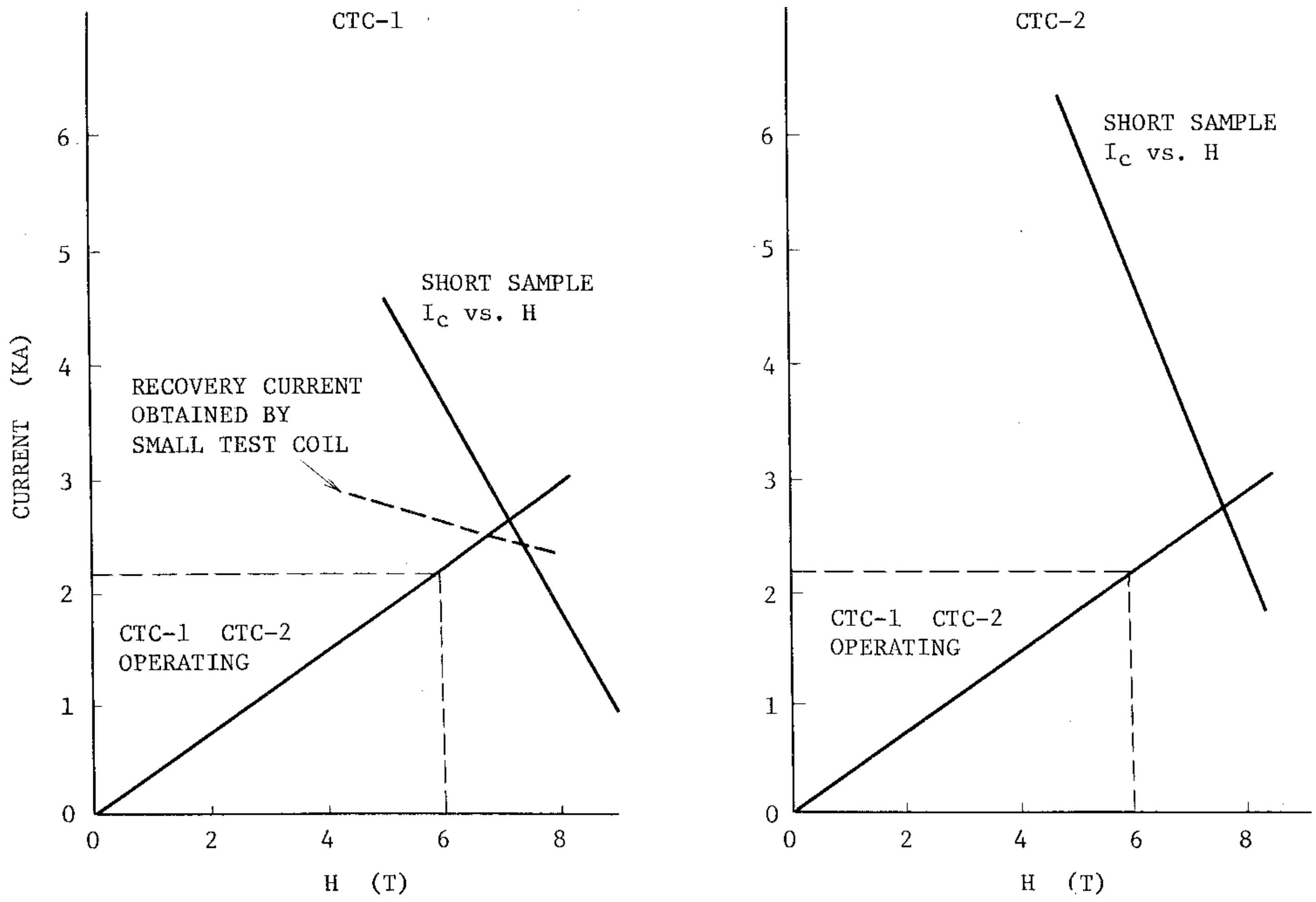


Fig. 2 Load Line Characteristics of CTF Coils

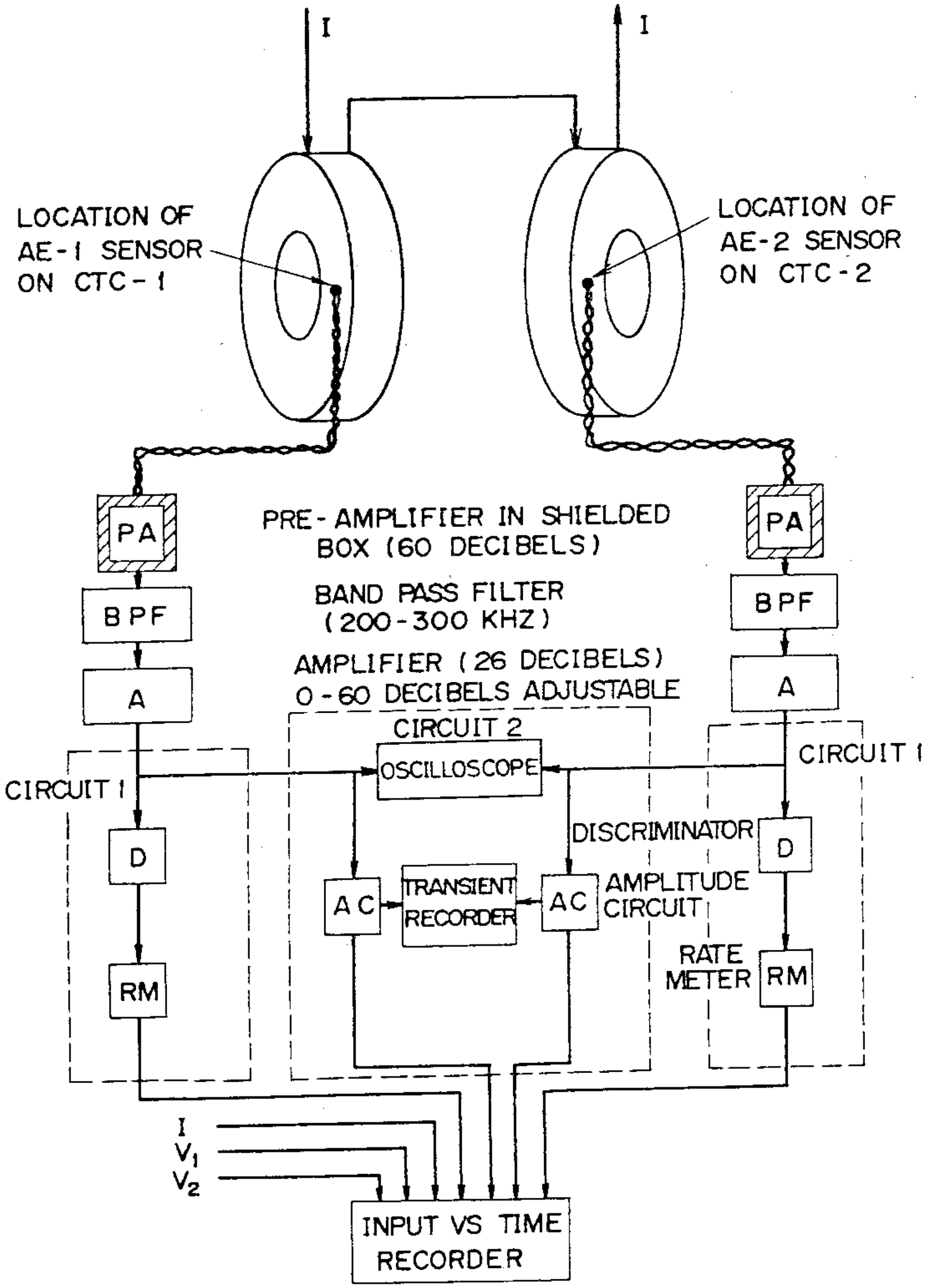


Fig. 3 Schematic of Acoustic Emission Data Collection System

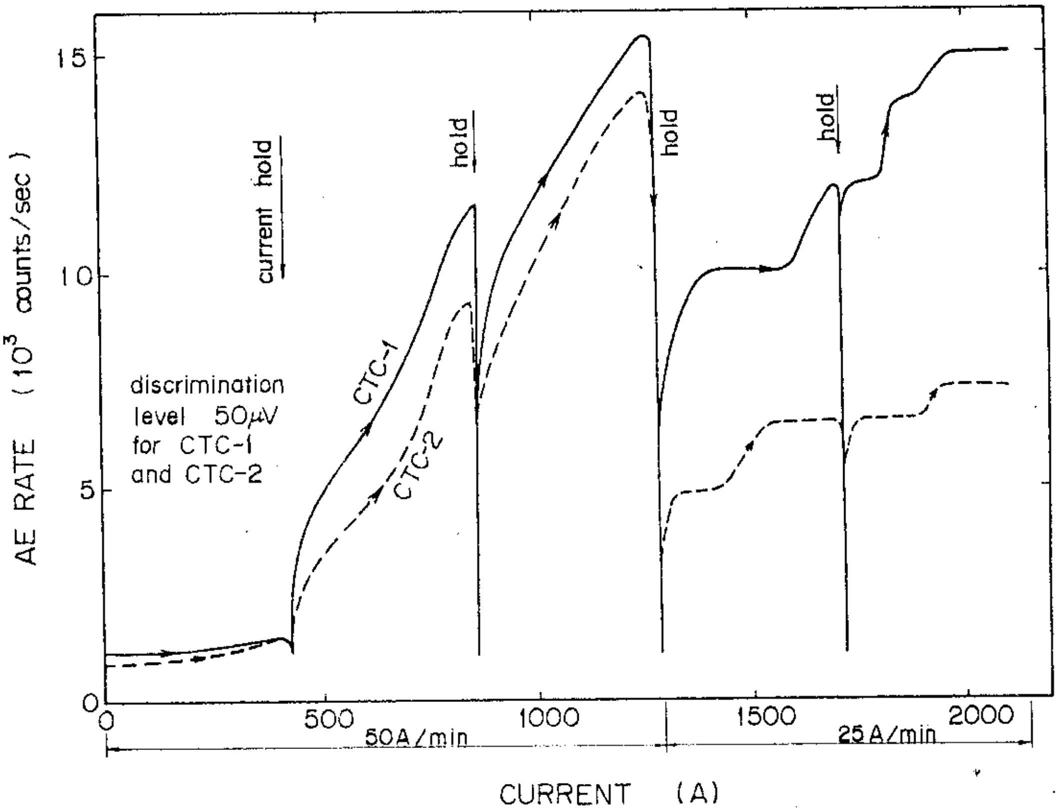


Fig. 4 AE Rate versus Coil Current : First 0A-2,145A Excursion (run no.16)

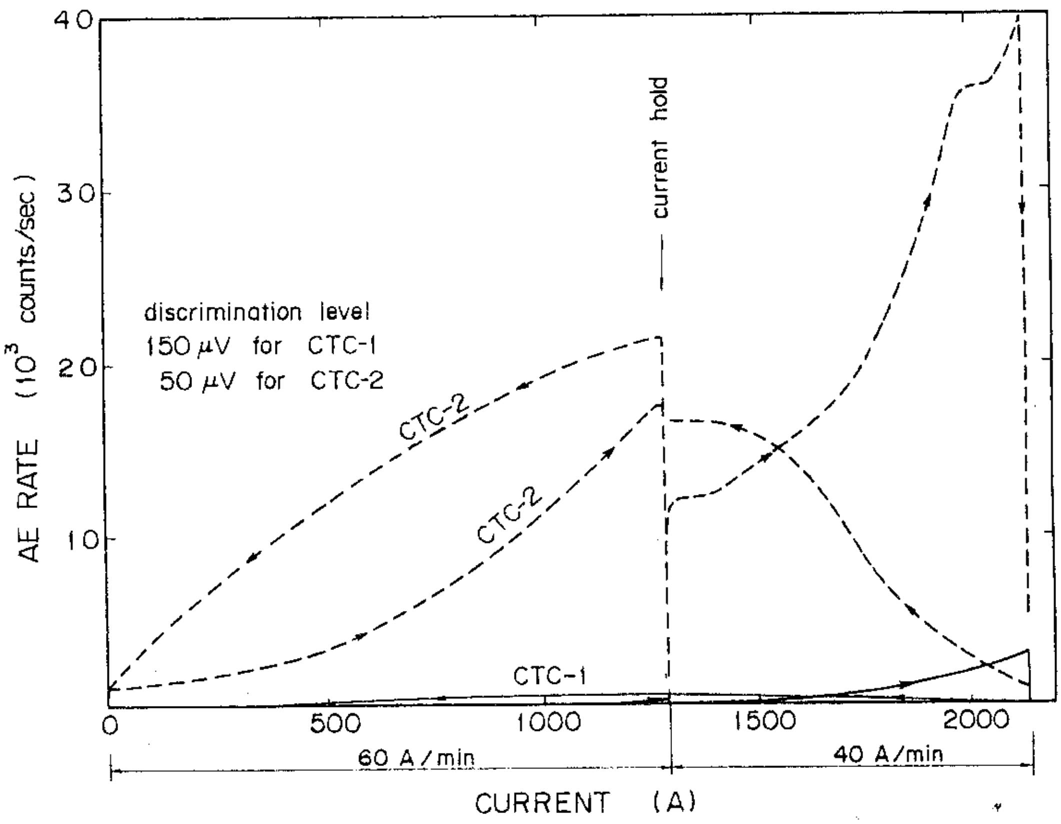


Fig. 5 AE Rate versus Coil Current : Second 0A-2,145A Excursion (run no.17)

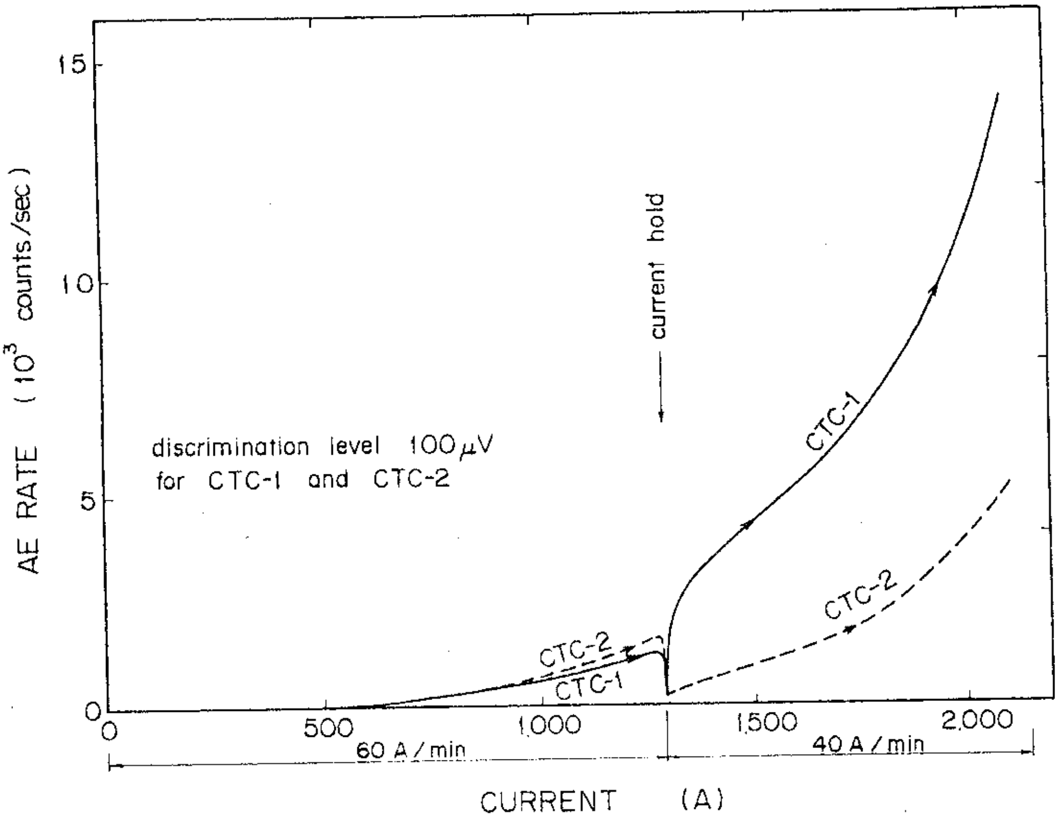


Fig. 6 AE Rate versus Coil Current : Third 0A-2,145A-0A Excursion (run no.22)

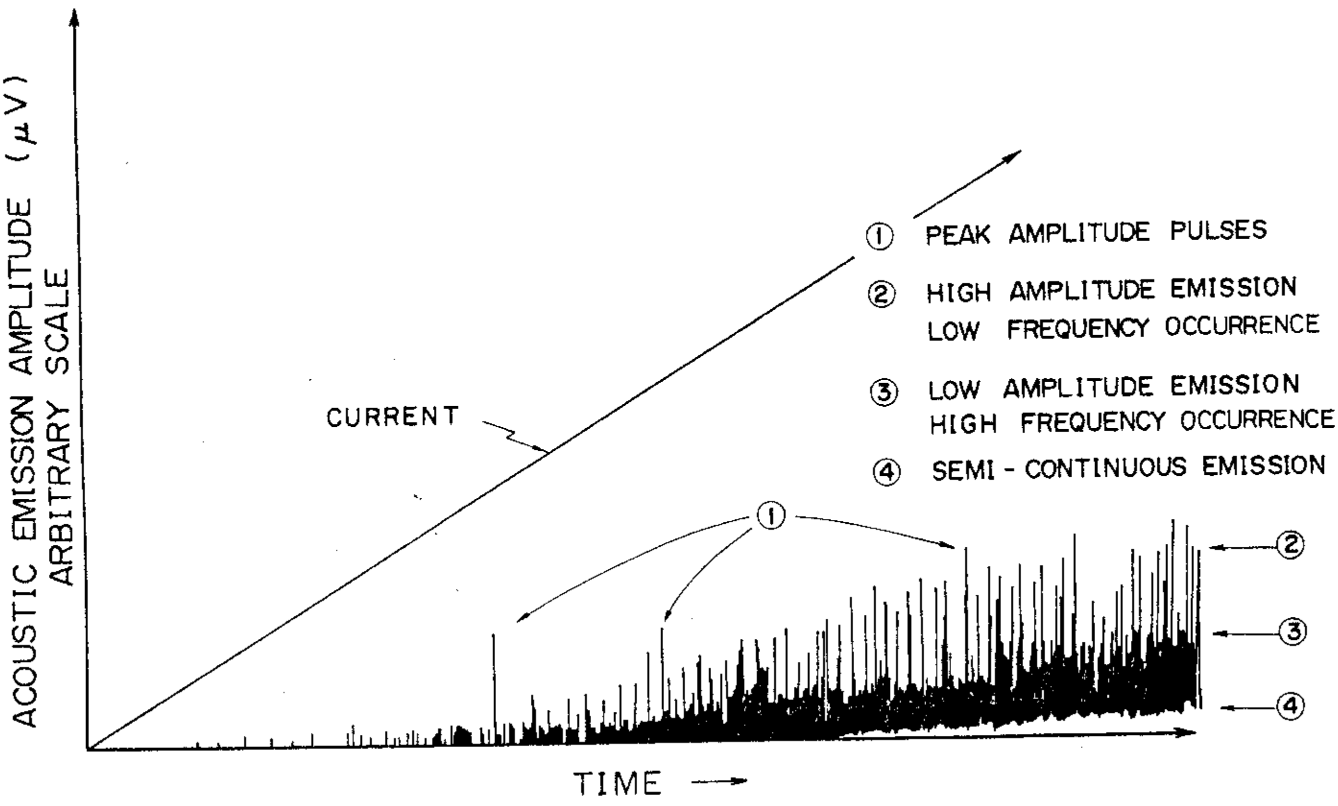


Fig. 7 Amplitude Characteristics of Acoustic Emission

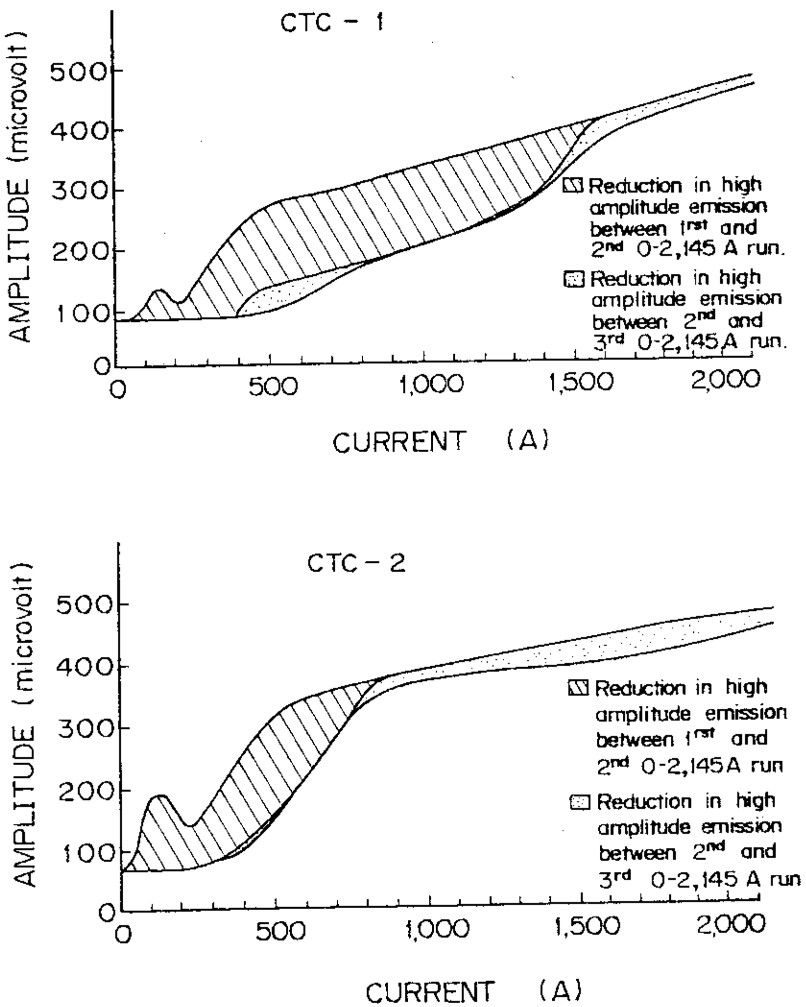


Fig. 8 Peak Amplitude versus Current Curves showing after Each Full Current Charge

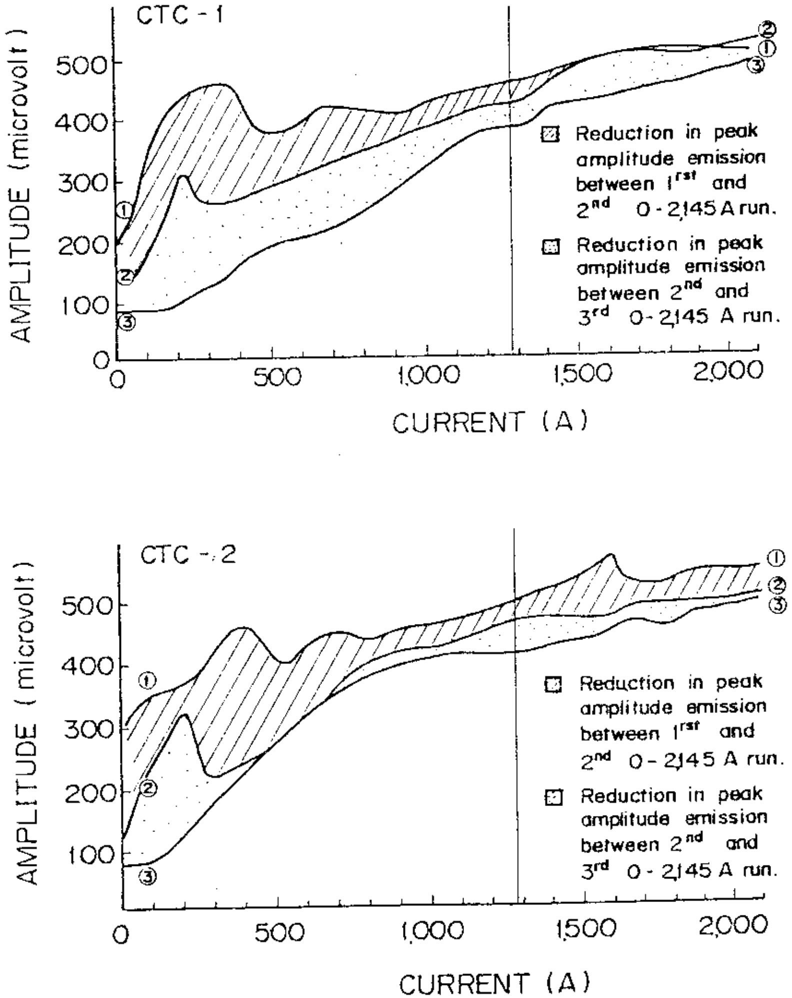


Fig. 9 High Amplitude versus Current Curves showing the Reduction in High Amplitude Emission after Each Full Current Charge

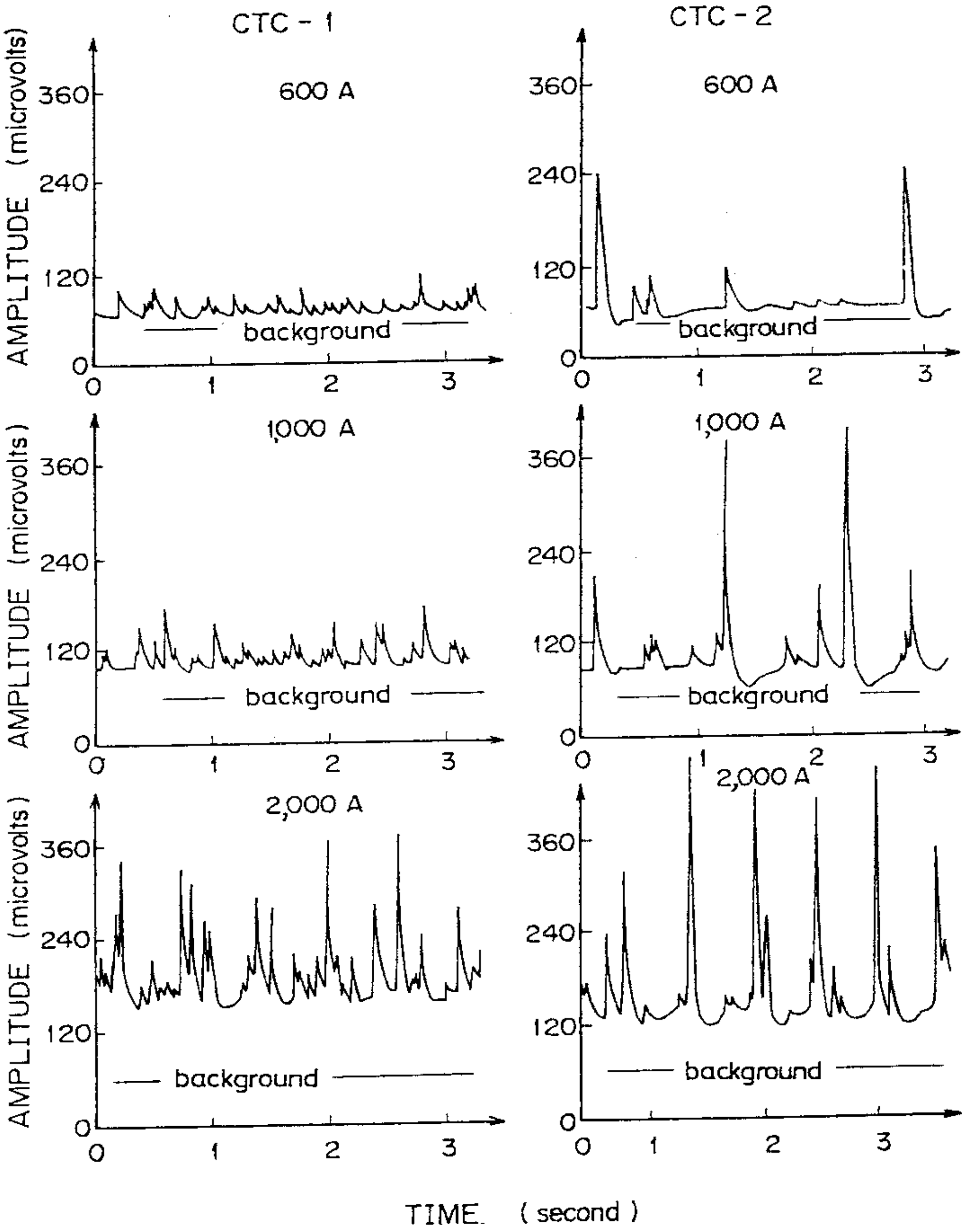


Fig. 10 Acoustic Emission Wave recorded by Transient Recorder at 600A, 1,000A and 2,000A